VOLTAGE BREAKDOWN INITIATED BY ELECTROSTATIC MICRODISCHARGES OF METAL-VACUUM INTERFACE. A MODEL PROPOSAL

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Summary

- The context of this research.
- Generation mechanism the microdischarges: Breakdown Induced by Rupture of Dielectric layer (BIRD) model.
- The role of electron emission: FN equation modified.
- Relation with the breakdown
- Conclusions

The context of this research

- At the Consorzio RFX – Padova the Facility for the realization of the full scale Prototype of the Neutral Beam Injector for ITER – **Neutral Beam Test Facility** - is under construction. It will be the *lighter* to ignite the DT reaction inside the Thermonuclear plasma.

- The Facility comprises two experiments: Spider, for the optimization of the plasma source, and Mitica, that is the complete neutral beam generator (Source+Accelerator+Neutralizator).

- Its main parameters are:

  - Beam Energy 1 MeV
  - Beam Current 40 A (D^-)
  - Neutral Beam Power 16 MW
  - Pulse duration 1 h
  - Acceleration steps 5 (200 kV)

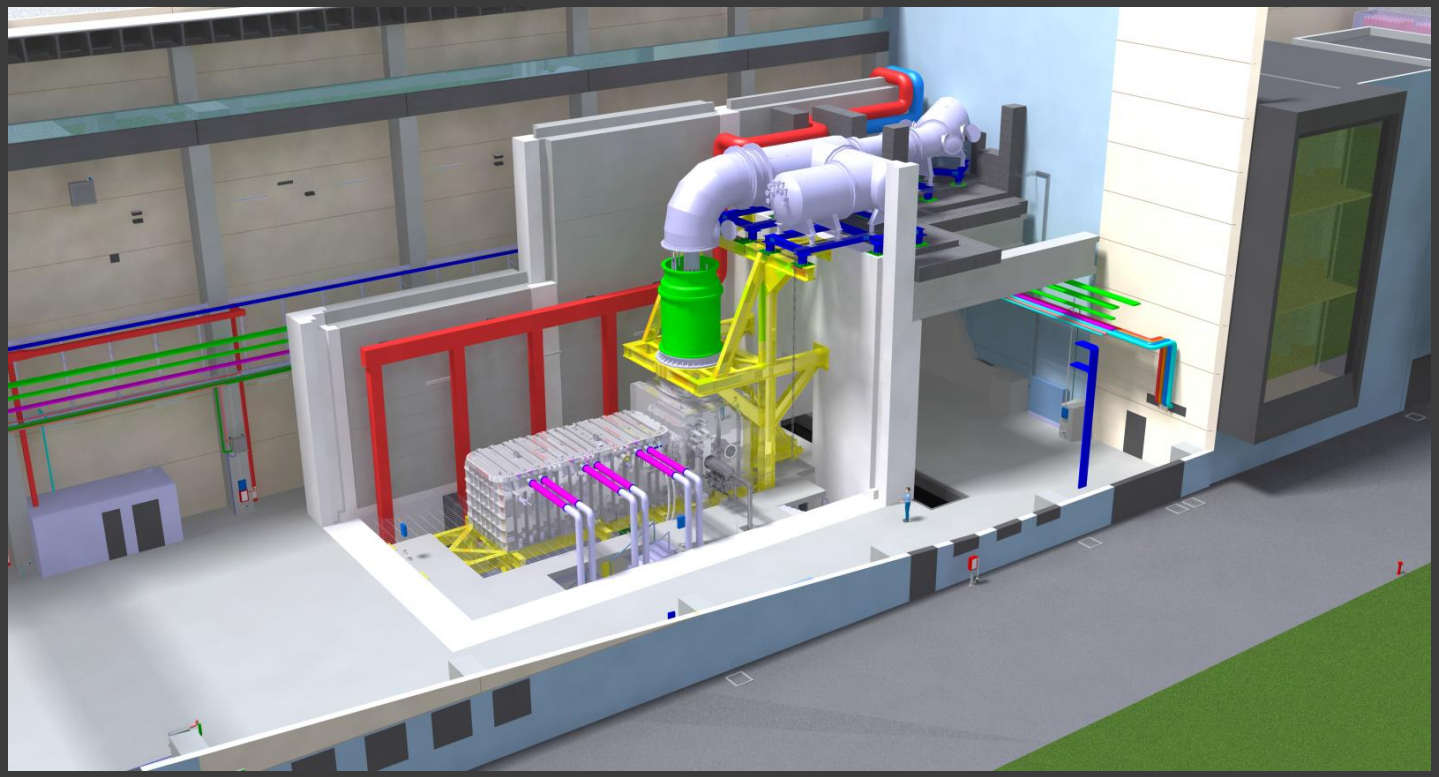
The context of this research

NBTF Experiment building.
It hosts the Source Experiment (Spider) and the Neutral Beam Generator Experiment (Mitica)

The context of this research

Experiment building.
Internal view – biological concrete screen of Mitica

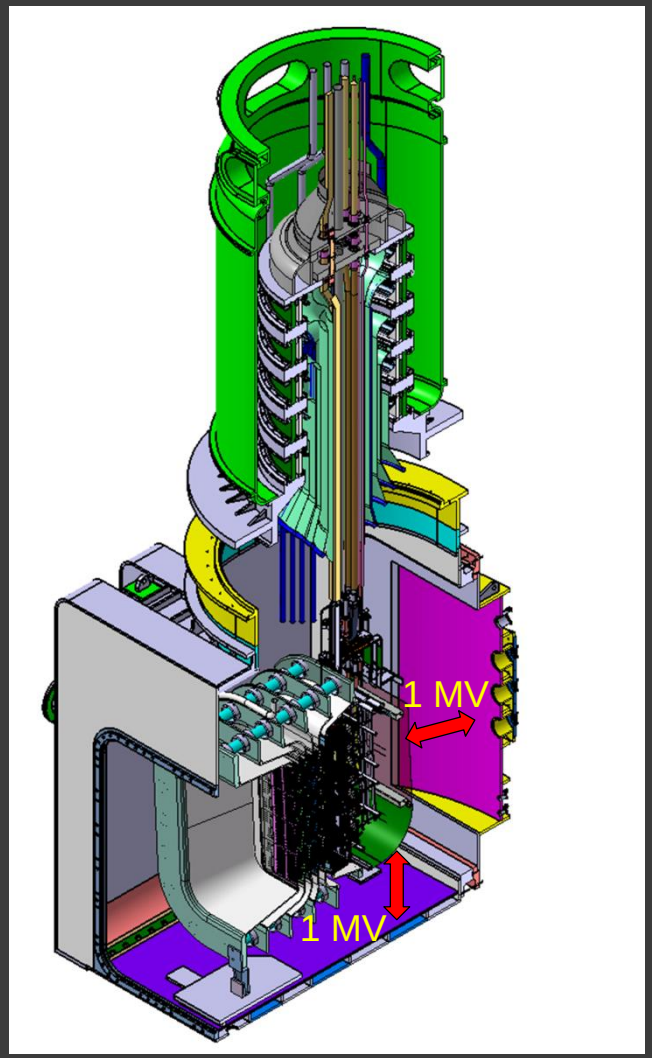
The context of this research



Pictorial view of Mitica

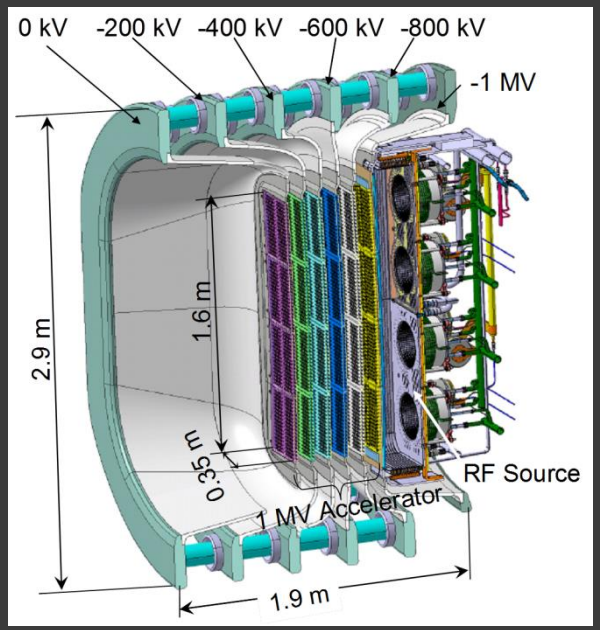
The context of this research

Cut view of the Beam Generator.



Issues for 1 MVdc Voltage Holding

- Long duration time (several hours)
- Large electrodes area (several m^2)
- Minimum gap 30 cm @ 1 MV
- Long voltage conditioning time
- Large number of post spacers
- ….

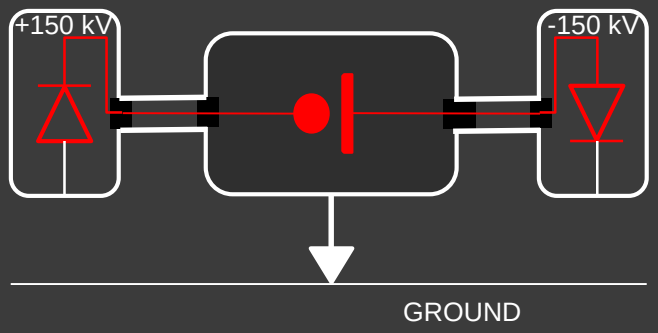


The context of this research

To tackle these issues, Consorzio RFX had to develop a specific expertise.

- Development of a Voltage Breakdown Predictive Model, as a tool for electrode design/optimization (4° MeVarc 2013).
- Realization of the NBTF ancillary lab, the High Voltage Padova Test Facility, HVPTF, aimed at testing (up to 800 kV) electrode surface treatment, post spacer prototypes, voltage conditioning techniques.
- Pre-breakdown phenomena modelling.

The context of this research
HVPTF test lab



MAIN CHARACTERISTICS	
Power Supply	• Manufacturer: Heinzinger • Structure: Symmetrical Cockcroft-Walton • Insulation: SF6 @ 4.5 bar • AC frequency: 23 kHz • Stage: N=15 • Units: 2, negative and positive
Ratings	V = 400.000 V dc I = 0.001 A
HV cables	50 mm^2 - XLPE – copper screen
Feedthrough PS	SF6 @ 4.5 bar - Oil
Feedthrough Tank	Alumina – SF6 @ 1.0 bar
Grounding	Coaxial return current – Tank grounded.

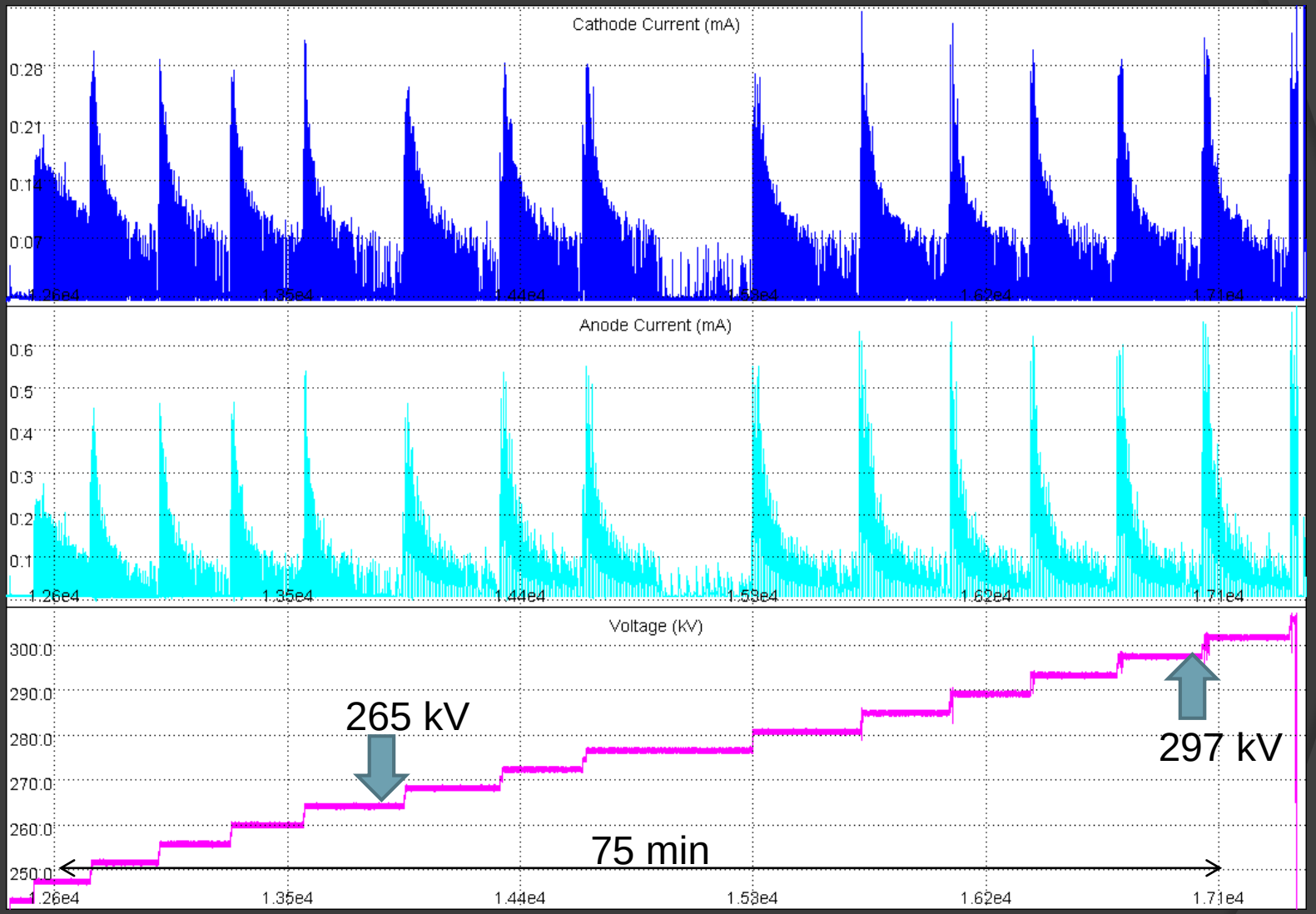
Geometry of electrodes

Sphere Φ=40 mm
Disk D=108 mm
Gap d=30 mm

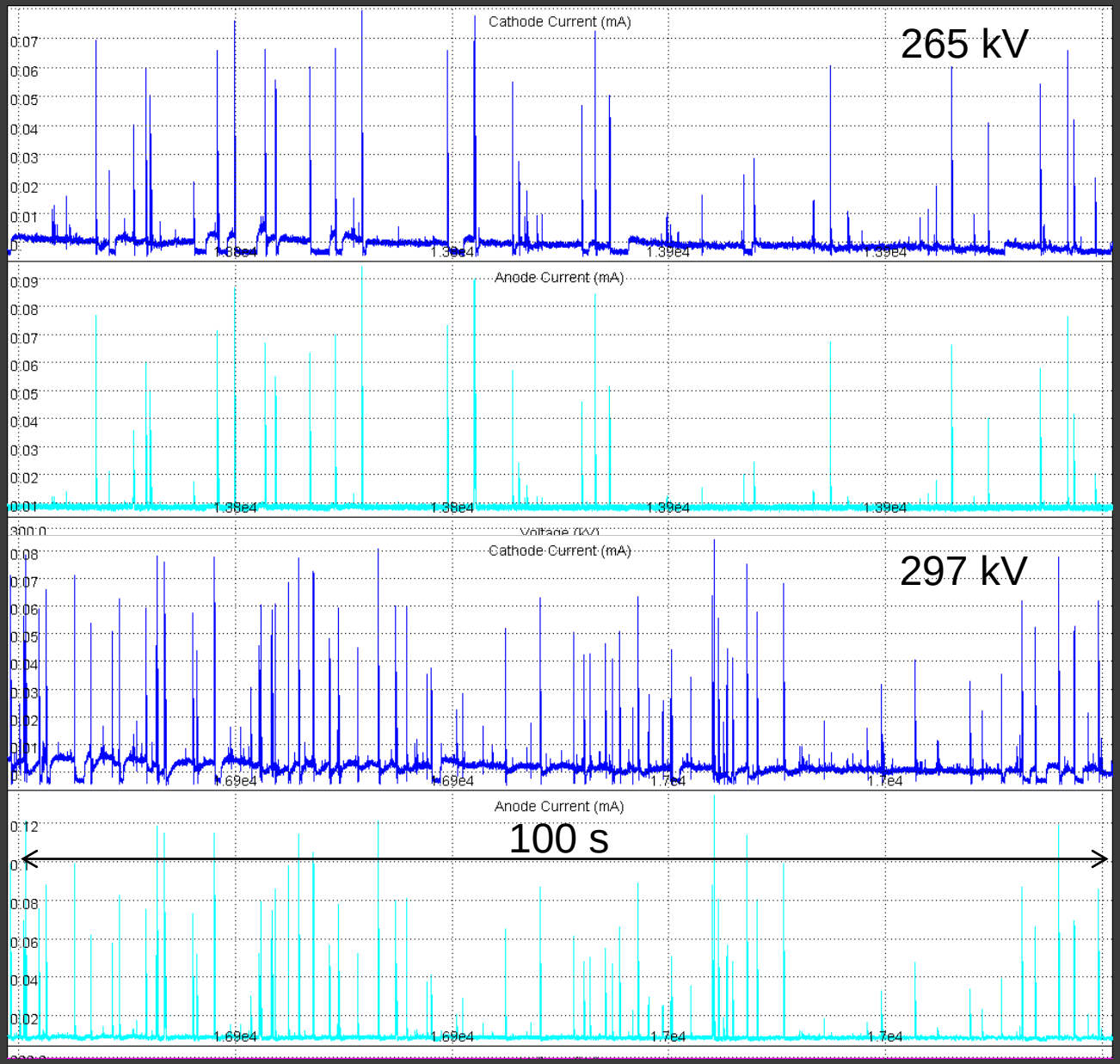
The BIRD model

- Experimental finding: during voltage conditioning (voltage applied with increasing voltage steps) current bursts (microdischarges) associated to X ray and pressure bursts appear above a precise dc voltage.
  1. Occurrence at constant voltage.
  2. Intermittency, frequency decreasing with time.
  3. Number of bursts increases with voltage.

The BIRD model



The BIRD model



The BIRD model

Present explanation for bursts:

- *Thermal instability of the emitting tip (t≈1μs – 1ms).*
- *Clash of levitating microparticles on the opposite electrode.*

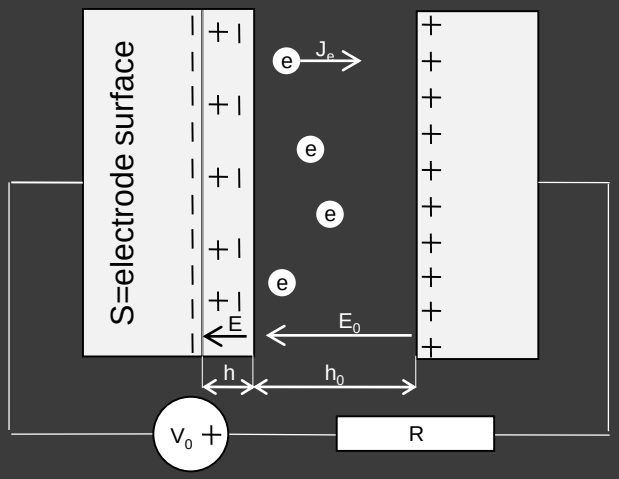
Both explanations are not compatible with the burst time scale.

Conjecture: the burst is associated to the breakdown of a dielectric layer.

The BIRD model

This dielectric is the interface layer between cathode and vacuum.

- For most the metals the layer is an oxide; trapped gas (O_2, N_2, H_2O…) are also present.
  - Low conductivity ($\gamma \approx 10^{-10}$ [S]).
  - Permittivity ($\varepsilon_r > 5$).
  - FN like emission present ($J_e \neq 0$).



- When voltage is applied, the electric field inside the layer (h thickness) evolves in time depending on the system parameters.
- The burst occurs when the electric field inside the layer exceed its dielectric rigidity: $E > E_d$.

The BIRD model

System equations

$$\epsilon_0 \frac{dE_0}{dt} = \frac{V_0 - h_0 \cdot E_0 - h \cdot E}{R \cdot S} - J_e$$

$$\epsilon_r \cdot \epsilon_0 \frac{dE}{dt} = \frac{V_0 - h_0 \cdot E_0 - h \cdot E}{R \cdot S} - \gamma \cdot E$$

- Under the effect of electric field, the layer is deployed of electrons by means of a Fowler-Nordheim emission mechanism (J_e).

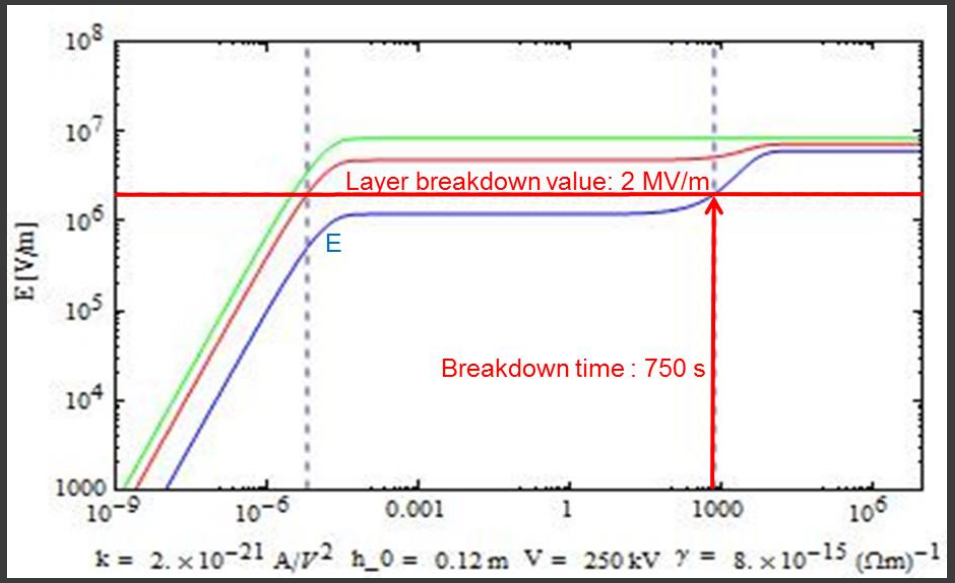
- The J_e is proportional to the surface charge (electrons): $\varepsilon_0(E_0 - E)$ and to the tearing electric field acting on the surface electrons: $\bar{E} = \frac{E_0+E}{2}$:

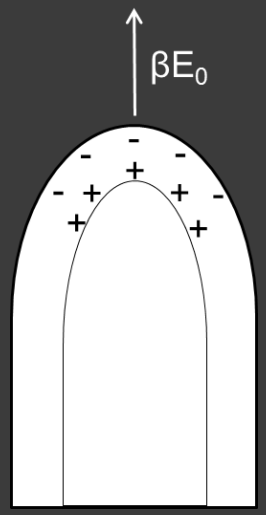
$$J_e \sim (\bar{E} - E_d) \cdot \varepsilon_0(E_0 - E);\ E = \frac{E_0}{\varepsilon_r},\ \rightarrow J_e = k_1 \cdot E_0^2 \cdot \left(1 - \frac{k_2}{E_0}\right);\ k_2 = \frac{2\varepsilon_r - 1}{\epsilon_r} E_d$$

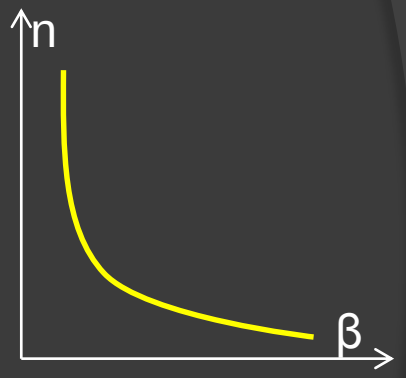
Note that the expression of J_e is the approximation of the classical FN equation for E_0 large enough: $J_e = k_1 \cdot E_0^2 \cdot e^{-\frac{k_2}{E_0}}$

The BIRD model

Results from the model: Electric Field Evolution







The model is valid for an ideal cathode, perfectly smooth.

For real cathode with protrusions (surface distribution n(β) of Electric Field Amplification Factor), electric field evolution applies to the protrusion tip.

The BIRD model

Time to burst: $\tau \sim \frac{\varepsilon_0 \epsilon_r}{2k_1} \frac{1}{(\beta E_0 - E_d)} ln\left(\frac{\frac{\varepsilon_r - 1}{\varepsilon_r + 1}}{1 - \frac{2\varepsilon_r}{\varepsilon_r + 1} \frac{E_d}{\beta E_0}} \right)$;

The burst occurs when $\beta > \frac{2\varepsilon_r}{\varepsilon_r + 1} \frac{E_d}{E_0}$ (for γ=0)

for $\beta \geq \varepsilon_r \frac{E_d}{E_0}$ the burst occurs immediately

- The dielectric conductivity γ increases the minimum electric field for the burst occurrence (β_{min})
- At the application of voltage, bursts occur first to the highest β protrusion (shortest times), then to lowest β, until the $\beta_{min} = \frac{2\varepsilon_r}{\varepsilon_r + 1} \frac{E_d}{E_0}$ value is reached.
- At the next voltage steps (higher E_0), the process repeats; the number of bursts is higher because higher is the number of tips with lower *β.*
- The ultimate voltage (end of voltage conditioning) is reached when the electrons/ions/particles emitted have enough energy to produce always breakdown.

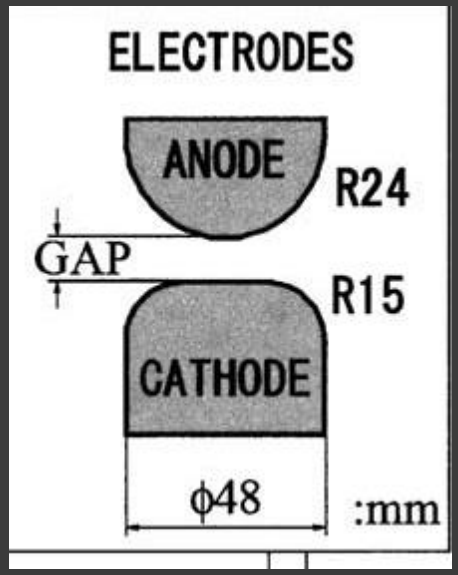
The BIRD model

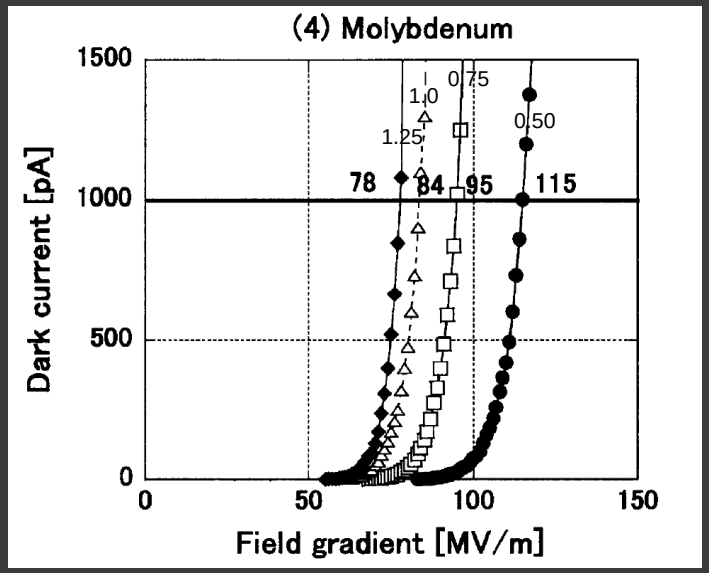
- Experimentally, time to burst ranges between 1-100 s.
- With the following layer parameters: $\varepsilon_r = 10; E_d = 10\left[\frac{MV}{m}\right]; E_0 = 10\left[\frac{MV}{m}\right]$) we have burst for *2<β<10.* For β>10, bursts occur istantaneously.
- For β=5, the k_1 value is $10^{-19}<k_1<10^{-22}$.
- For FN, the k_1 value is $k_1 = \frac{k_{1FN}}{\Phi} \sim 3.5 \cdot 10^{-7} \left[\frac{A}{V^2}\right]$

?

The FN equation modified

A detailed analysis has been carried out on measurement of Dark Current made by Furuta et al.





- Material: molibdenum
- Test made at different gaps (in mm)

Furuta et al: "Reduction of field emission dark current for high-field gradient electron gun by using a molybdenum cathode and titanium anode", Nuclear Instruments and Methods in Physics Research A 538 (2005) 33–44

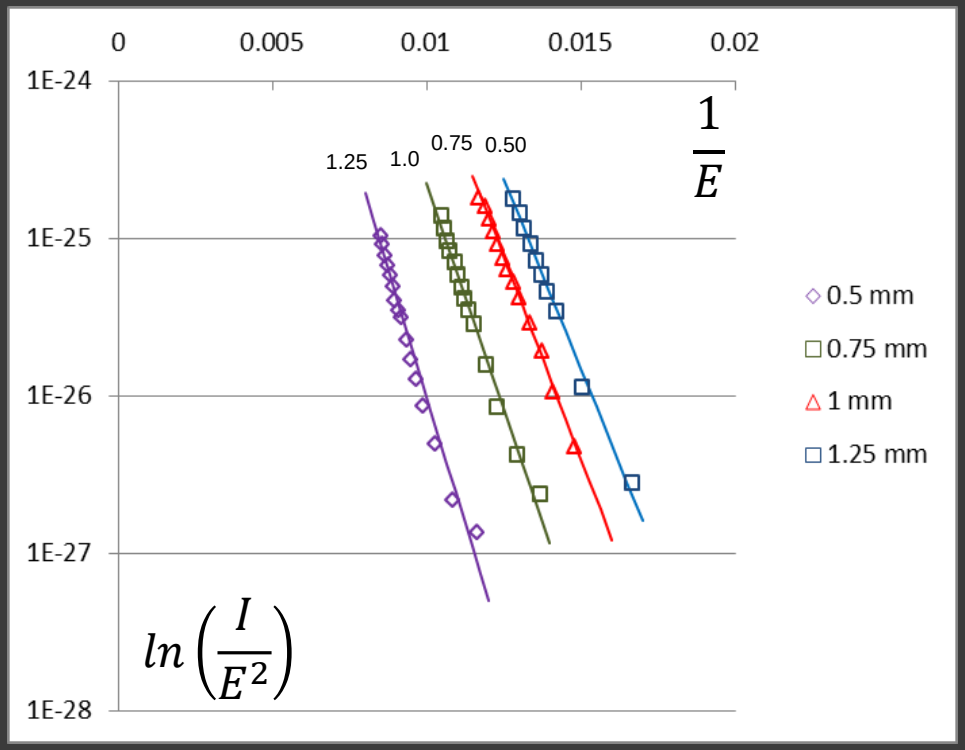
The FN equation modified

FN plots

$$E = \frac{V}{d}$$

$$ln\left(\frac{I}{E^2}\right) = \ln(q) - m \cdot \frac{1}{E}$$

$$q = S \cdot k_1 \cdot \beta^2 \cdot \frac{1}{\Phi};\ m = \frac{k_2 \cdot \Phi^{\frac{3}{2}}}{\beta}$$



Φ=4.655 eV
k_1=1.54 10^{-6} [A·eV/V^2]
k_2=6.86 10^9 [V/m/eV$^{1.5}$]

d [mm]	β	S [10^{-12} mm^2]
0.50	46	40
0.75	52	123
1.00	58	186
1.25	62	191

The FN equation modified

Remarks.

1. β is a consequence of the status of the cathode surface. It is hard to identify the physical reason of a β dependence upon the gap length.

2. The emitting surface has a diameter ranging from 6 to 14 nm. It would mean that ONLY ONE protrusion ($r \approx 5$ nm and $h \approx 250$ nm; $\beta=50$) emits all the current. Not credible.

The FN equation modified

Proposal for remark #1.

- The gap increase corresponds to voltage increase, so electrons with higher energy hitting the anode would cause a current increase due to:
  - Enhanced anode outgassing => interelectrode gas ionization
  - Enhanced emission of Xrays/ions from the anode => stimulation of electron emission at the cathode.

Dependence upon voltage introduced

The FN equation modified

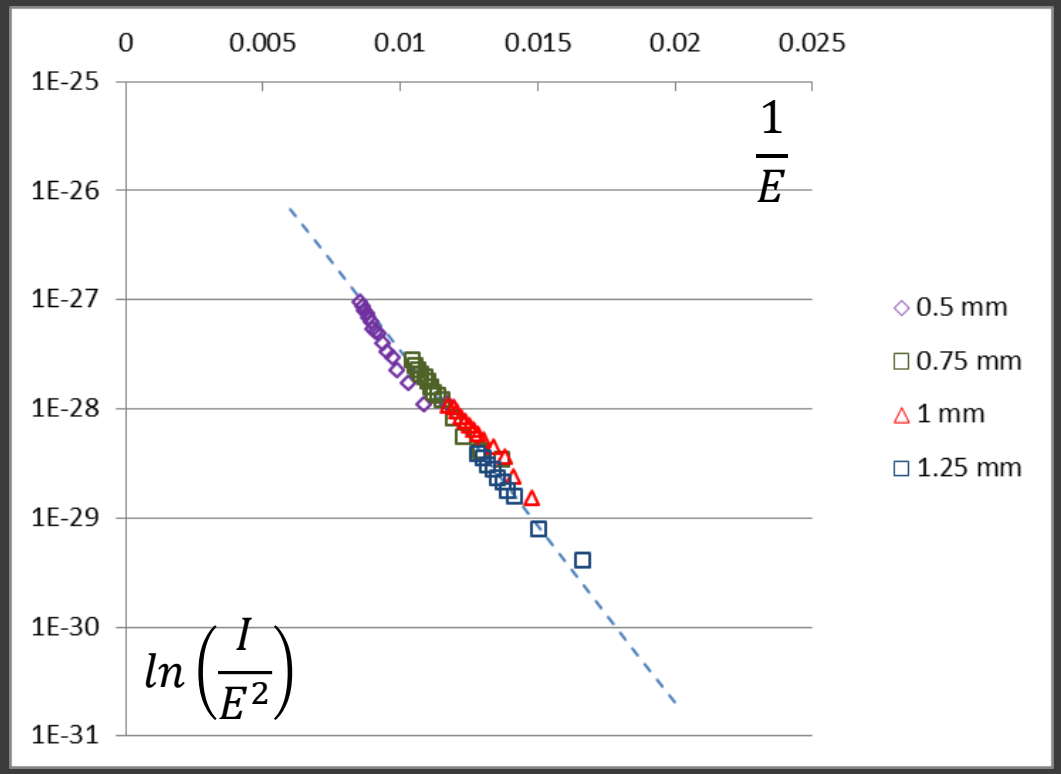
$$ln\left(\frac{I_e}{E^2}\right) = \ln\left(q_v \cdot f_1(V) \cdot f_2(V)\right) - \frac{m_v}{f_2(V)^{\frac{3}{2}}} \cdot \frac{1}{E}$$

$f_1(V) = (1 + \alpha_1 \cdot V^{\gamma})$ accounts for the dark current enhancement due to gas ionization. (Furuta proposed dependence upon electric field).

$f_2(V) = (1 + \alpha_2 \cdot V)$ accounts for the stimulation of electron emission from the cathode. Not considered in this fit.

The FN equation modified

With the new fit, the dependence of β upon gap disappears



$$\alpha_1 = 1.4 \cdot 10^{-11}[V^{-1}]$$
$$\gamma = 7.3$$

$$q_v = 6.0 \cdot 10^{-25}$$
$$m_v = 7.5 \cdot 10^{8}$$

Again, with classical FN coefficients, non realistic emitting surface results

The FN equation modified

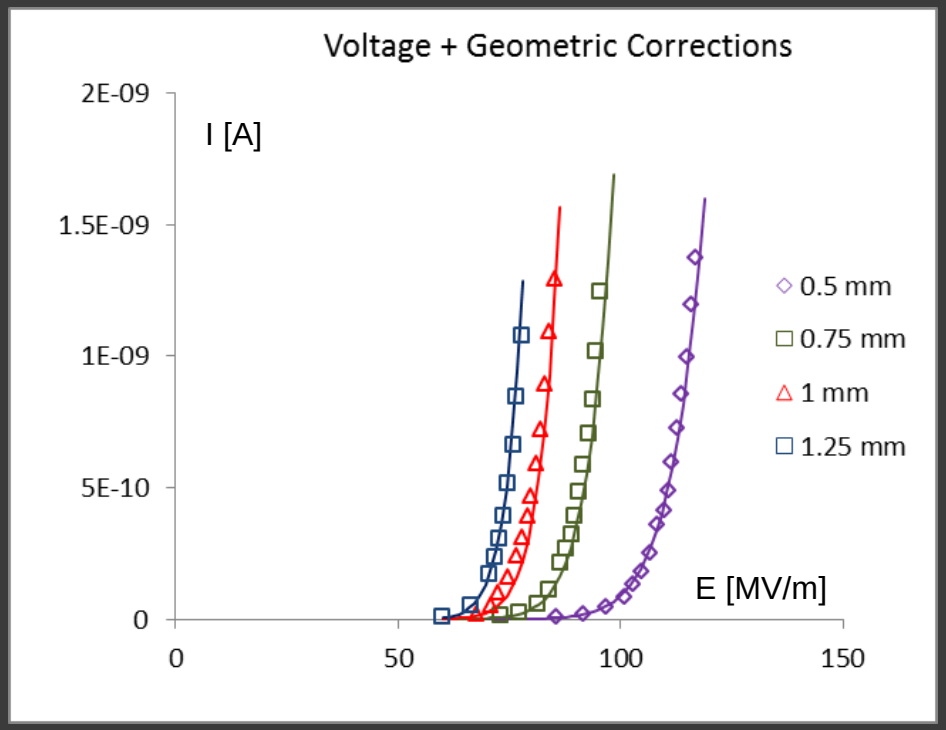
Proposal for remark #2.

- The sensible hypothesis is that all the surface participate to the FN current emission.

- An estimate of the emitting surface is done by integrating the current density along the cathode surface, using the local electric field; the parameter q_g fits the data:

$$I(E) = \int q_g \cdot f_1(V) \cdot f_2(V) \cdot E(s)^2 \cdot e^{-\frac{m_g}{f_2(V)^{1.5} \cdot E(s)}} \cdot dS$$

The FN equation modified



The interpolation yields

$q_g = 4.7 \cdot 10^{-20}$

$m_g = 7.5 \cdot 10^{8}$

Being $q_v = q_g S = 6.0\ 10^{-25}$

The 'effective' emitting area results

$$S_{eff} = \frac{q_v}{q_g} = 13\ mm^2\ (\boldsymbol{d_{eff} = 4.1\ mm})$$

To check the result, it has been calculated diameter from the effective surface evaluation: $S = \frac{\int J_e(E)dS}{J_{e-max}}$ for the four cases:

d_{eff} @	0.5 mm	0.75 mm	1.0 mm	1.25 mm
60 kV	**2.59**	**3.17**	**3.66**	**4.10**
120 kV	**3.46**	**4.24**	**4.90**	**5.48**

$$\langle \boldsymbol{d_{eff}} \rangle = \boldsymbol{4.0\ mm}$$

The FN equation modified

From these result, the estimate of the FN emission constant is given by

$$k_1 = \frac{k_{1FN}}{\Phi} = \frac{q_g}{\beta^2} = 2 \cdot 10^{-21} \div 5 \cdot 10^{-24} \quad (5 < \beta < 100)$$

This range overlaps with the estimate done using the time between burst. ($10^{-19} \div 10^{-22}$)

BASIC QUESTION

Can dielectric layer have k_1 constant so different from that calculated for metals ?

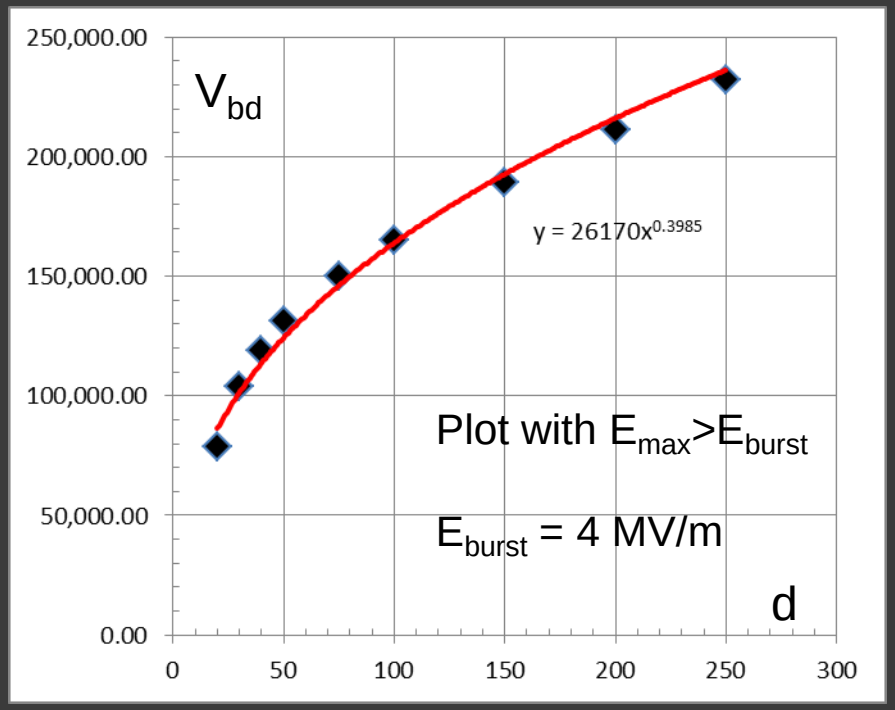
Relation with the Breakdown

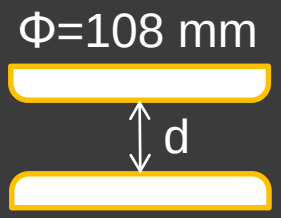
- The Breakdown is caused by the burst that is enough energetic to produce at the Anode outgassing and/or X radiation triggering cascade process.

- The burst acts as the Cranberg/Slivkov particle: these burst in fact can be formed by electrons but also by charged material expelled from the layer in consequence of its local breakdown. Total voltage effect is included ($E_k \cdot V \cdot {E_A}^{\alpha} > W_b$)

Relation with the Breakdown

- The driver of the breakdown is the electric field at the cathode. $E > E_{min} = \frac{2\varepsilon_r}{\varepsilon_r+1} E_d$ to produce bursts. Geometric effect appears when plotting the breakdown voltage against the distance: it mimics the total voltage effects.





Rogowsky profiles

Conclusions

- BIRD model is presently a bit more than a conjecture. An extensive data analysis is planned at our test lab HVPTF on the bursts occurrence.

- Validation in other field is also going on. E.g., we have obtained encouraging results in simulating the time-to-breakdown in thin capacitor films forming DRAMs (Time Dependent Dielectric Breakdown TDDB)

- BIRD model works provided the FN emission from dielectric layer is several order of magnitude less than the value for metals. We have not the necessary expertise prove or reject this assumption so…….

Advices and suggestions are very welcome !

and

thank you for your attention !