Investigations of the transition from field electron emission to plasma discharges (glow discharges and micro-arcs) with extended use of the Fowler-Nordheim plot

(Abstract ID: 110)

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-> **Posters with abstract <u>ID 110</u>, 111 and 116**

OUTLINE:

1. Introduction

2. Electron field emission with micro-arc discharges

3. Transitions from electron field emission to plasma discharges

- Types of stable plasma discharges: glow and micro-arc discharges
- Smooth transition (electron field emission → glow discharge)
- Sudden transition (electron field emission → micro-arc discharge)
- Graphical evaluation method

4. Extended use of the Fowler Nordheim plot for energetic evaluation

5. Plasma-physical approach

6. Conclusion and outlook

1. Historical Introduction

Otto von Guericke and his electrostatically experiment

Fig. 1. Otto von Guericke and his electrostatically experiment with charged sulphur ball and bird's feather. In the year 1672 he had a correspondence with Gottfried Wilhelm Leibniz (9 letters). One topic was a discussion about observed discharge effects (spark discharges) [1].

[1] O. v. Guericke, G. W. Leibniz, "Leibniz und Gericke im Diskurs – Die Exerpte aus den Experimenta Nova und der Briefwechsel" (Latin and German); Editors: B. Heinicke, W. Knapp, P. Rubini, P. Streitenberger, DE GRUYTER, Berlin (2018).

1. Introductions Field emission measurement with I_E > 1 mA (DC)

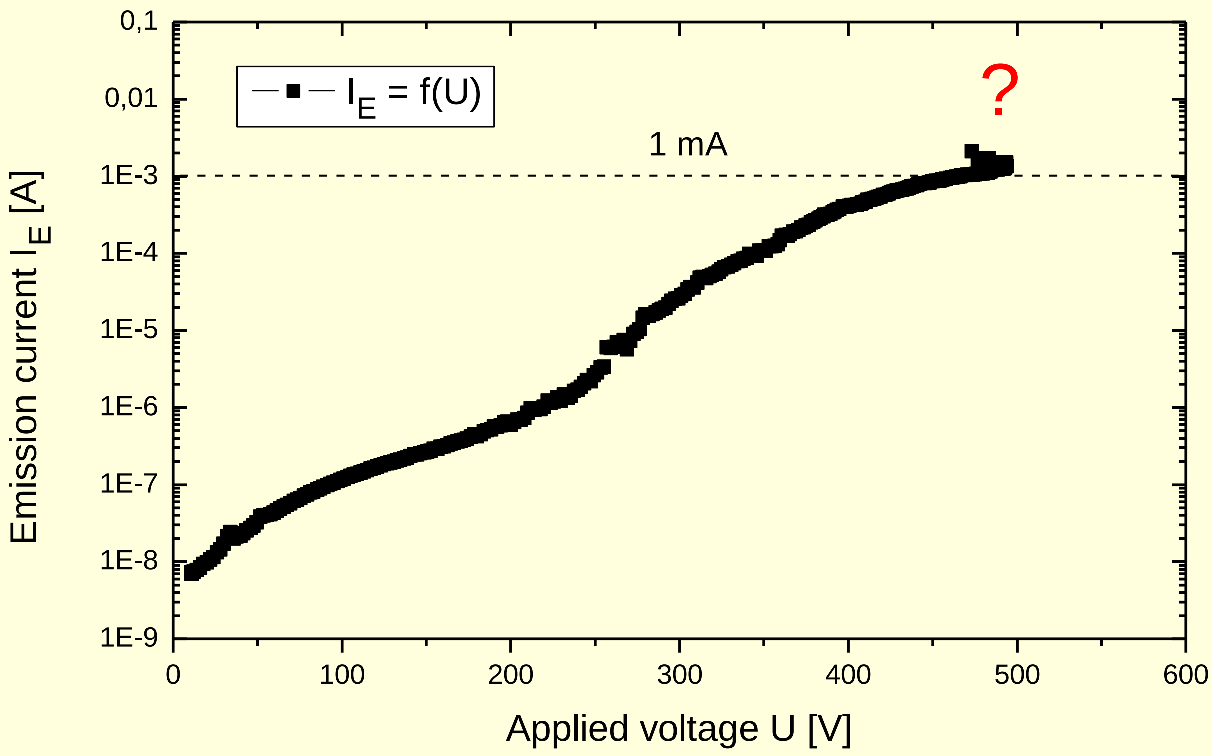
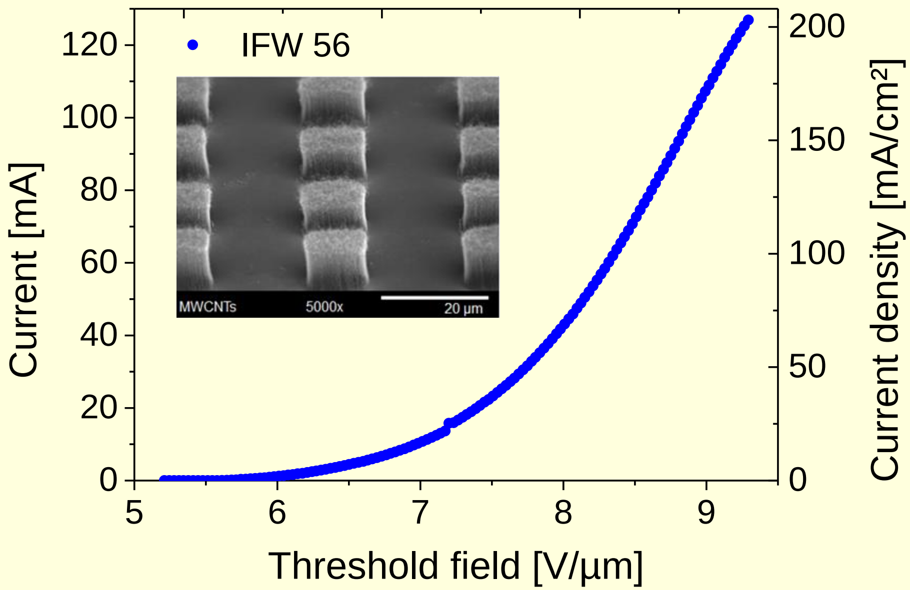


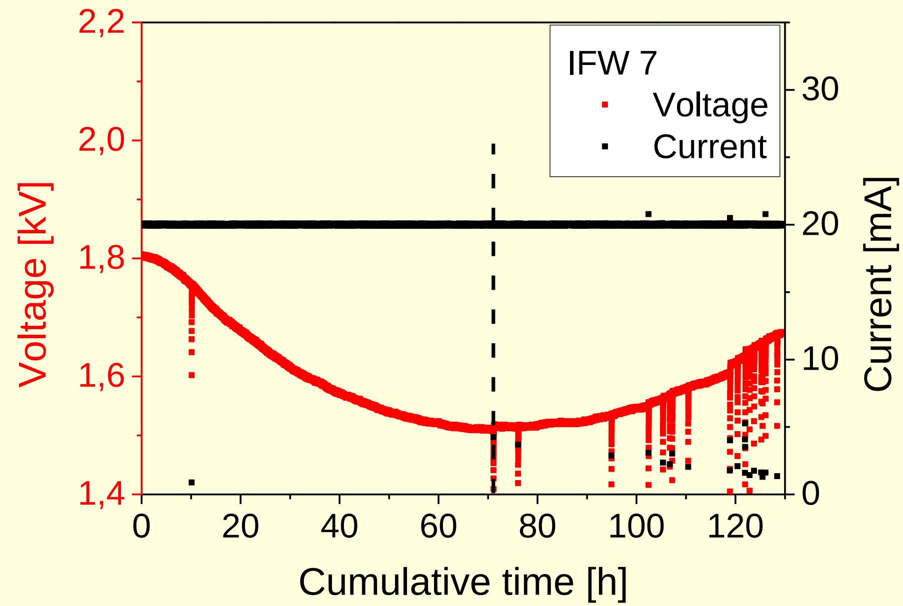
Fig. 1. Field-emission characterization: I_E = f(U) diagram with a voltage reduction for currents > 1.5 mA [1].

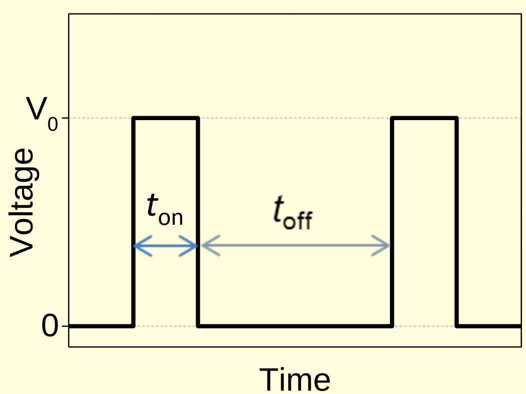
[1] W. Knapp, "Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for extended use of vacuum components as very large FE cathode arrays." Poster contribution IVNC 2017.

2. Electron field emission with micro-arc discharges

Longterm FE stability measurement with breakdowns (vacuum micro-arcs)



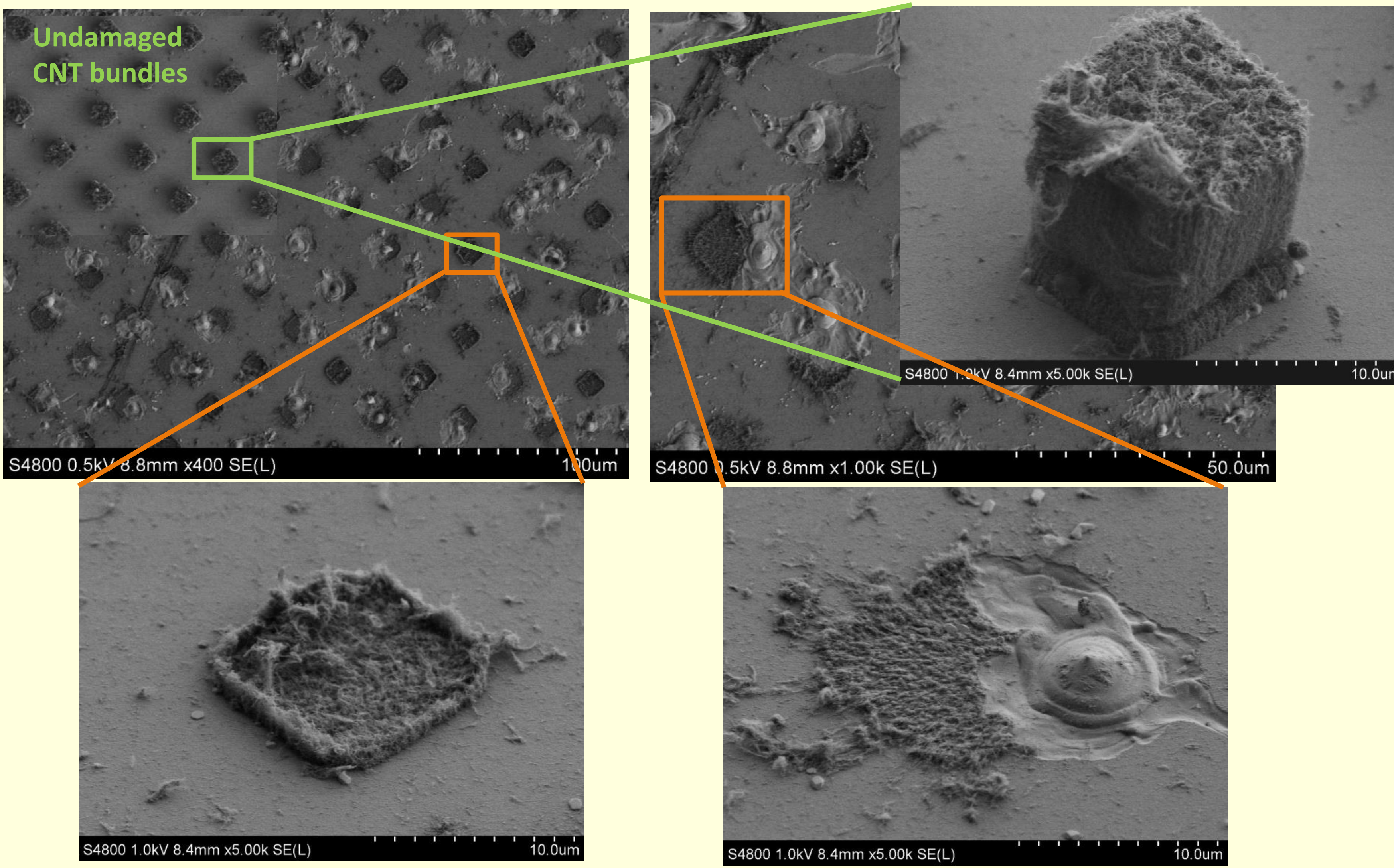




- Stability measurements with 20 mA pulsed current
- 10 ms pulse-on time, 50% duty cycle ($t_{on}/(t_{on+toff}) = t_{on}/T = 0.5$)
- Emission stable for 70 hours, voltage decreasing => no degradation
- Degradation started at *t* = 70h, number of arcs increased

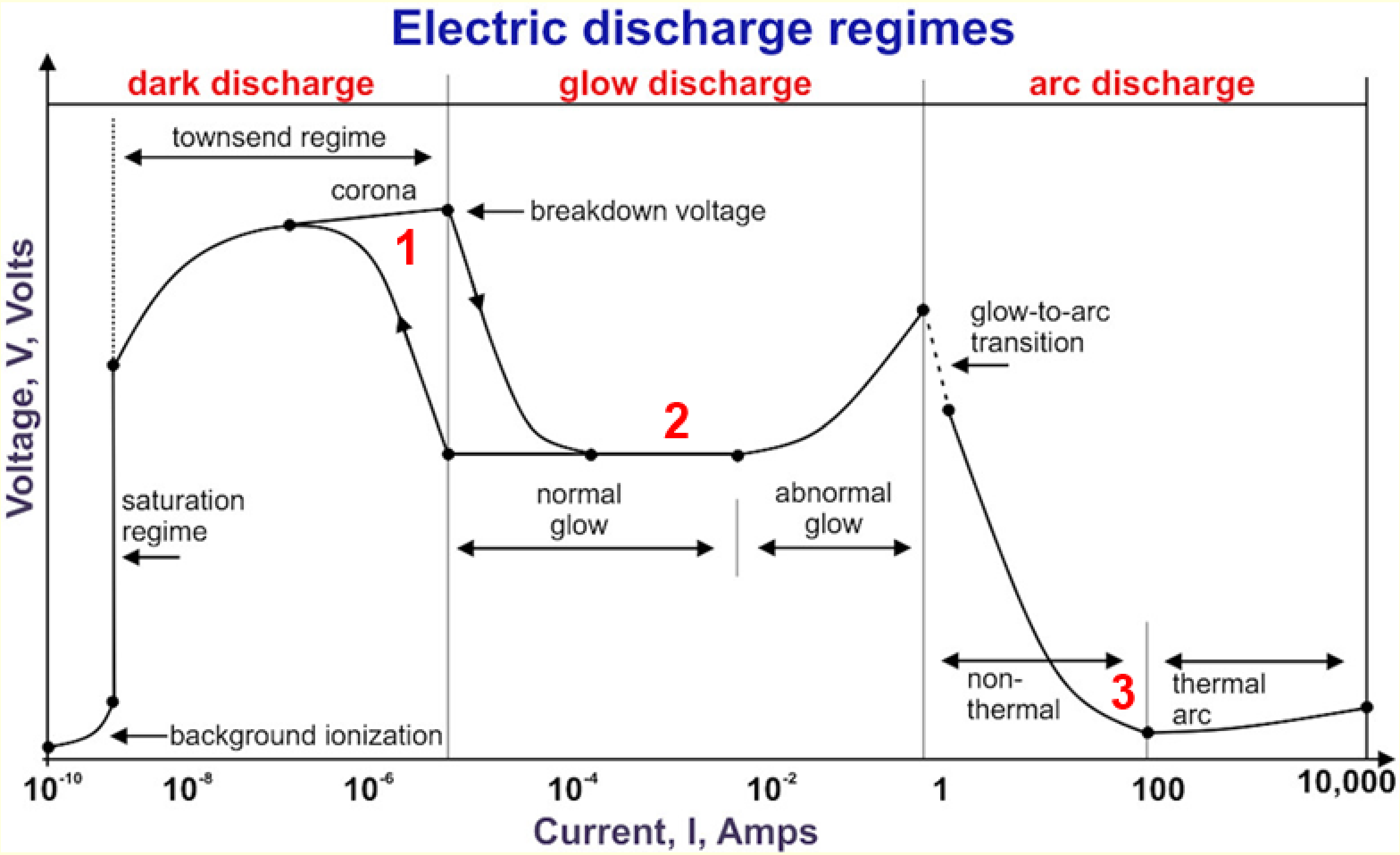
2. Electron field emission with micro-arc discharges

Demages of CNT emitters



[1] D. Wenger, W. Knapp, B. Hensel, S. Tedde, „Transition of Electron Field Emission to Normal Glow Discharge“, IEEE Transaction on Electron Devices 61 (11), p. 3864 (2014).

3. Transitions from FE to plasma discharges 3 types of stable plasma discharges



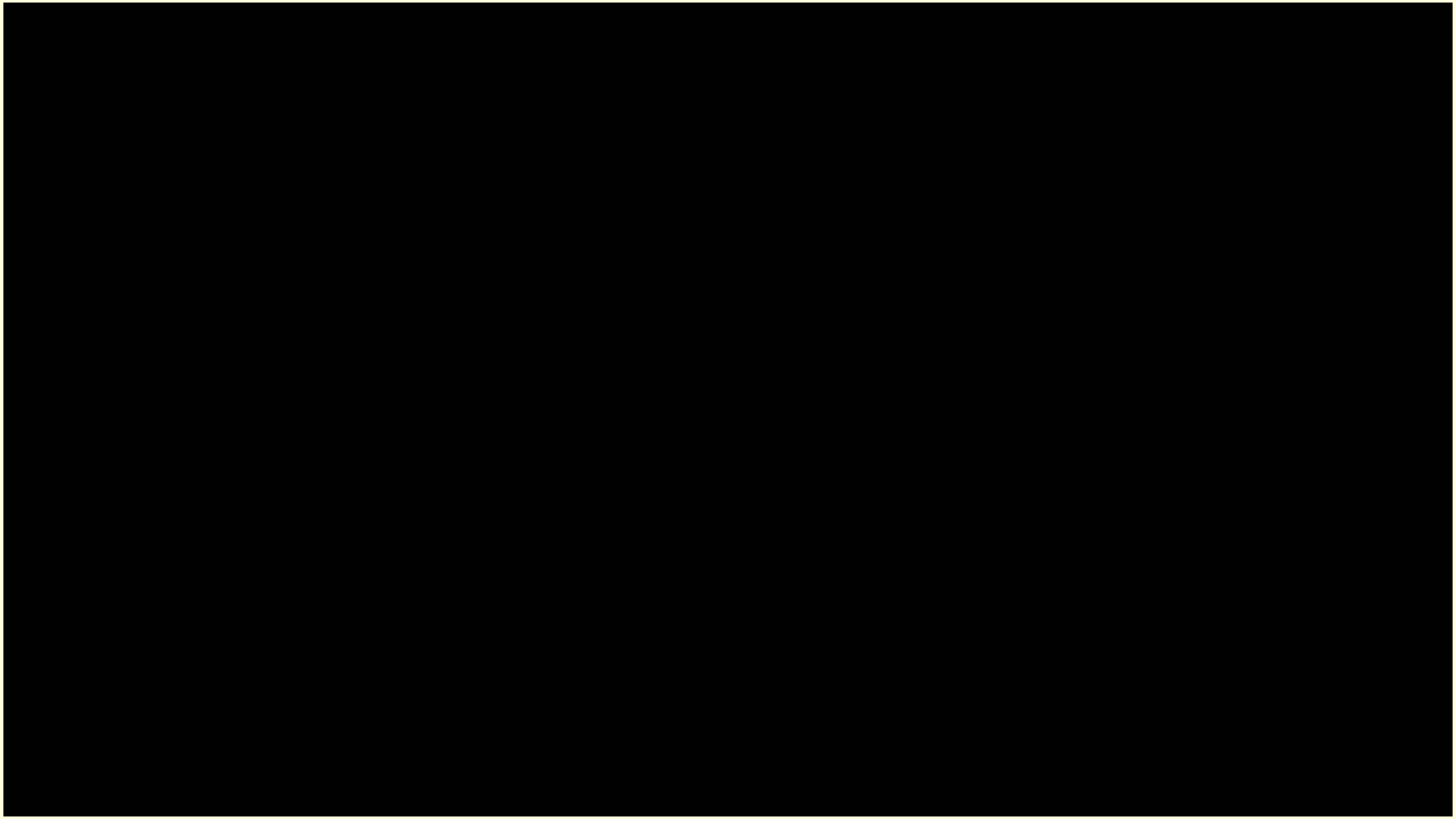
1. corona discharge **2. normal glow discharge** **3. arc discharge**

(I < 1 A: micro-arc discharge)

[1] https://www.plasma-universe.com/Electric_glow_discharge

3. Transitions from FE to plasma discharges (video):

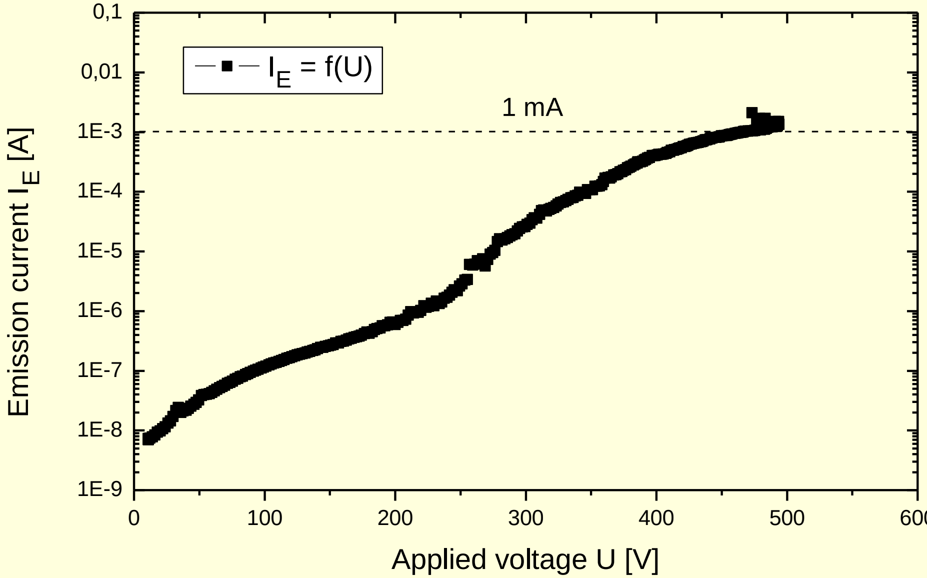
Types of stable plasma discharges: corona, glow and micro-arc discharges (2)



3. Transitions from FE to plasma discharges (video):

Types of stable plasma discharges: corona, glow and micro-arc discharges (1)

3. Transitions from FE to stable plasma discharges:
Example for DC operation with smooth transition



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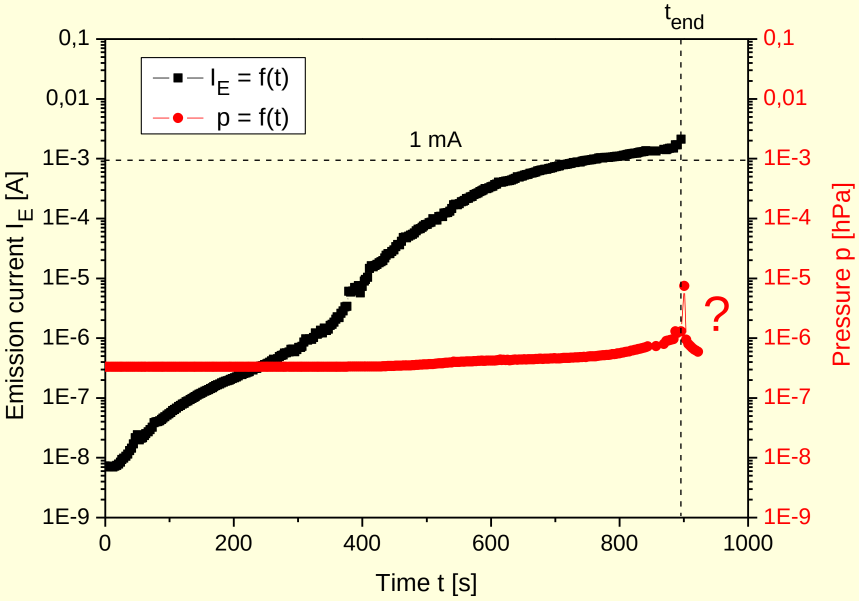
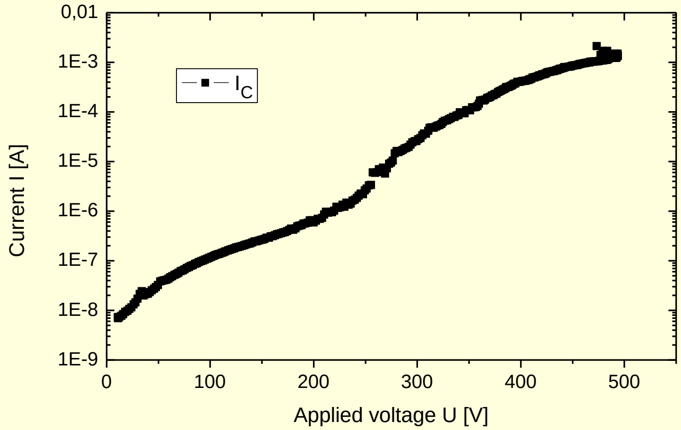


Fig. 2. Field-emission characterization: **I_E = f(t) diagram** with corresponding vacuum pressure curve p = f(t).

[1] W. Knapp, "Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for extended use of vacuum components as very large FE cathode arrays." Poster contribution IVNC 2017.

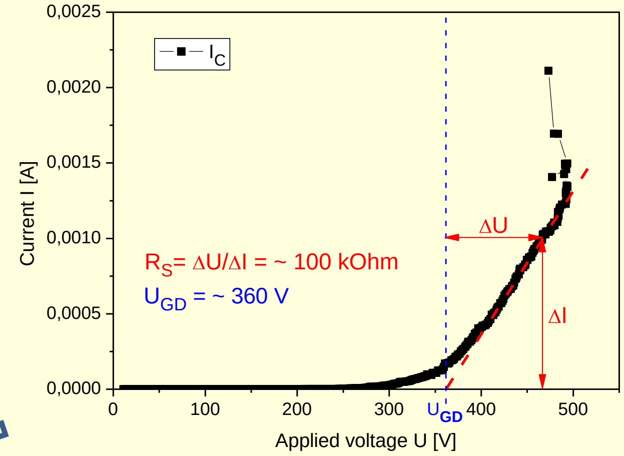
3. Transitions from FE to plasma discharges Graphical evaluation method: 4 steps

1st step: IU semi-logarithmic diagram (FE diagram)

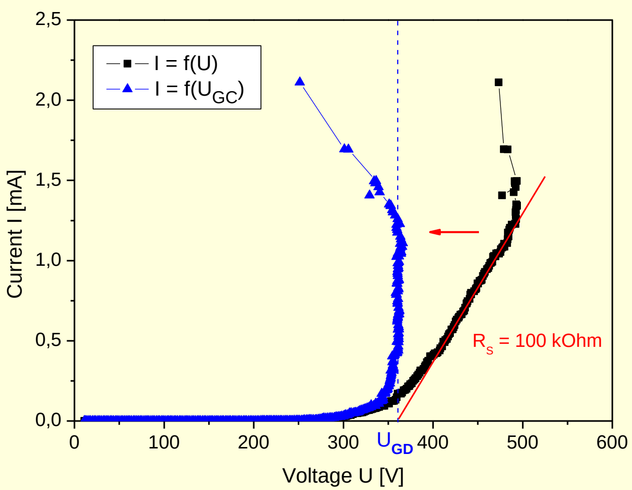


1st example:
smooth transition

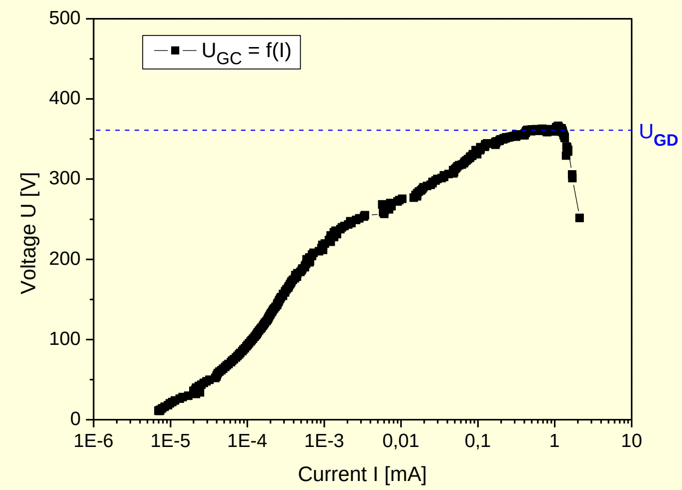
2nd step: IU linear diagram with linearity test for U_{GD} and R_S



3rd step: IU linear diagram with V_{RS} correction



4th step: UI diagram (plasma physics)



3. Transitions from FE to plasma discharges

Smooth transition from field emission to glow discharge!

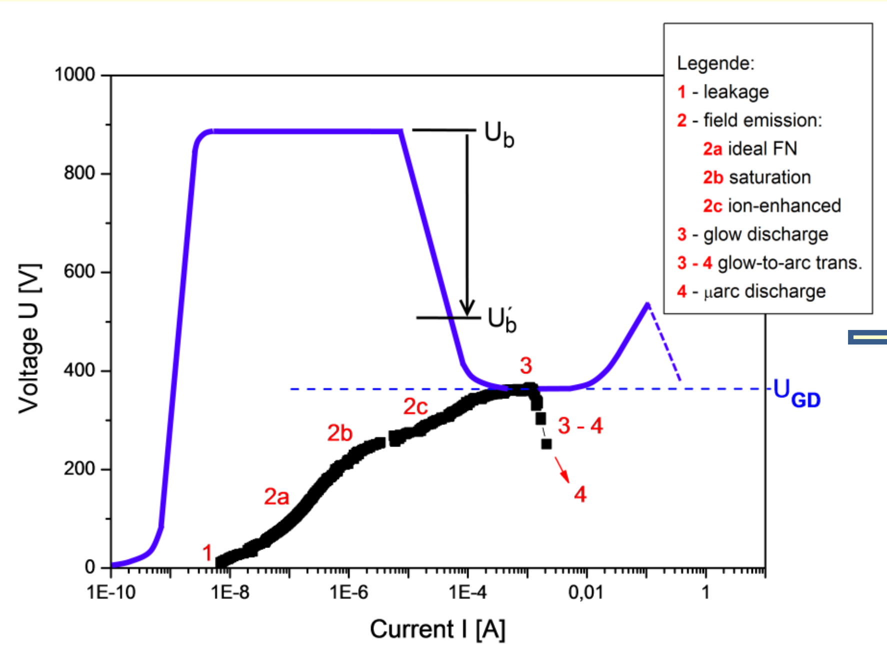


Fig. 1. U-I characteristic with smooth transition and corresponding schema of gas discharge

1. Breakdown voltage U_b:

$$U_b = F_c \cdot d \qquad (1)$$

(F_c - critical field, d – distance of electrodes)

2. Reduced breakdown voltage U_b' (with FE):

$$U_b' = U_b / \beta \qquad (2)$$

(β – tip field enhancement factor of FE cathode)

$U_b' > U_{GD} \rightarrow$ **breakdown (sudden transition)**

$U_b' < U_{GD} \rightarrow$ **smooth transition**

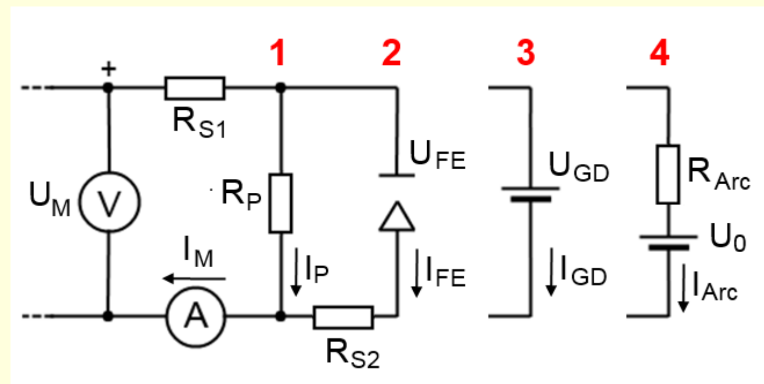
Fig. 2. Equivalent circuit diagram for different stationary conditions:

1 - leakage (e.g. insulation resistance),

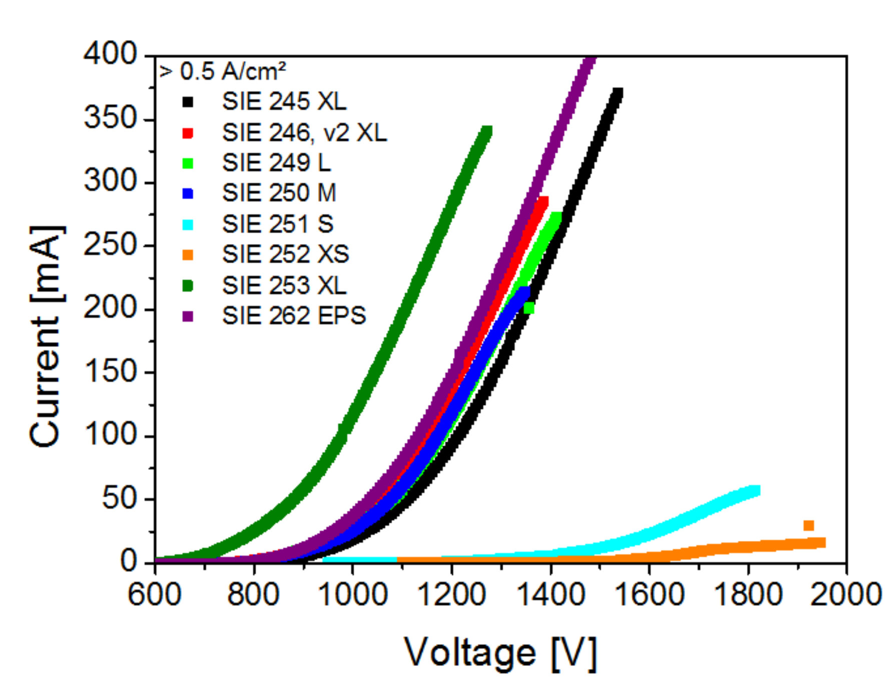
2 - field electron emission,

3 - normal glow discharge with constant voltage characteristic,

4 - micro-arc discharge (for currents I > 1A).



3. Transitions from FE to plasma discharges   Field emission measurement



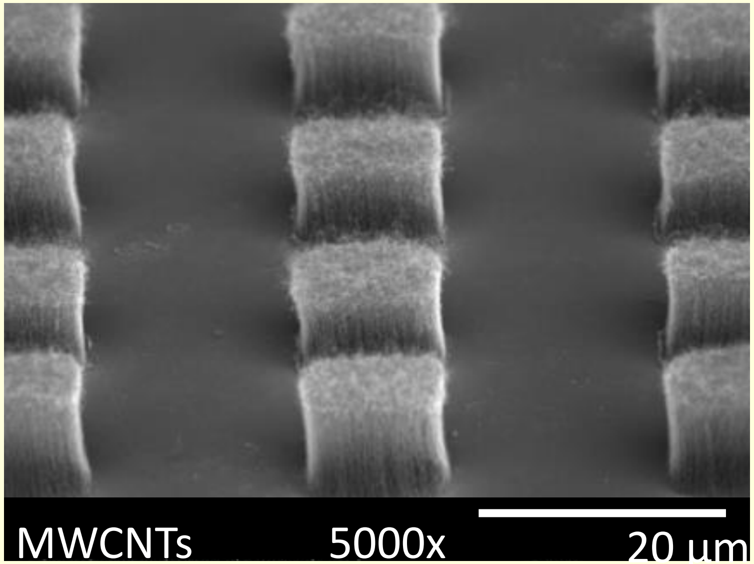
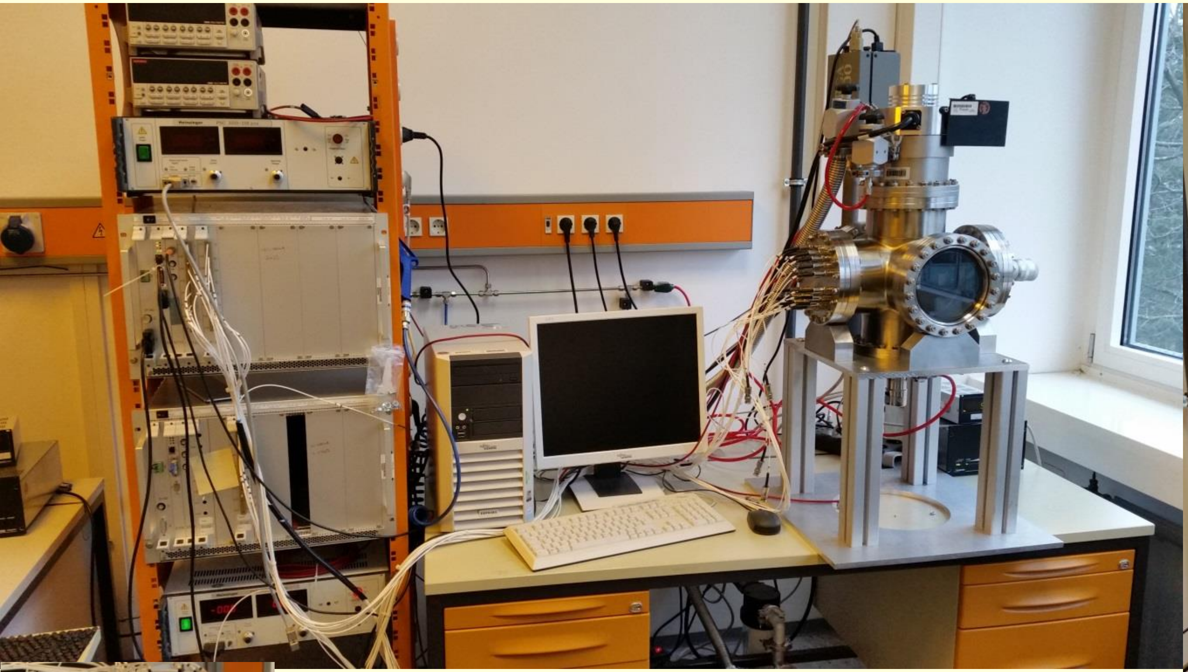
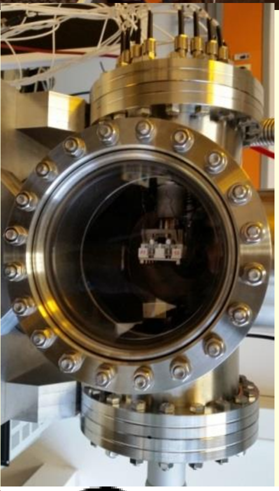


Fig. 1 FE characteristic I = f(U) of large array CNT emitter cathodes and measured values Tab. 1 (photo of sample SIE 262 in I-U diagram [left]).

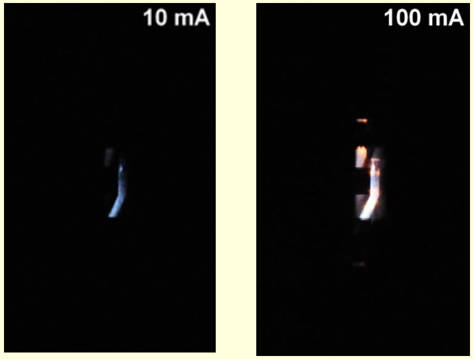
Sample ID	Substrate	Area [mm²]	Maximum current [mA]	Maximum current density [A/cm²]	Threshold field for 10 / 100 mA/cm² [V/µm]	
SIE 245	Silicon	51	371	0.73	9.0	11.1
SIE 246	Silicon	51	285	0.56	8.4	10.5
SIE 249	Silicon	28.3 (51)	273	0.97	8.2	10.0
SIE 250	Silicon	12.6 (51)	215	1.70	7.8	9.3
SIE 251	Silicon	3.1 (51)	57	1.85	9.9	13.0
SIE 252	Silicon	0.8 (51)	16	2.00	--	13.7
SIE 253	Silicon	51	341	0.67	6.9	8.8
SIE 262	Stainless steel	63	402	0.64	8.6	10.6

3. Transitions from FE to stable plasma discharges: Optical observation



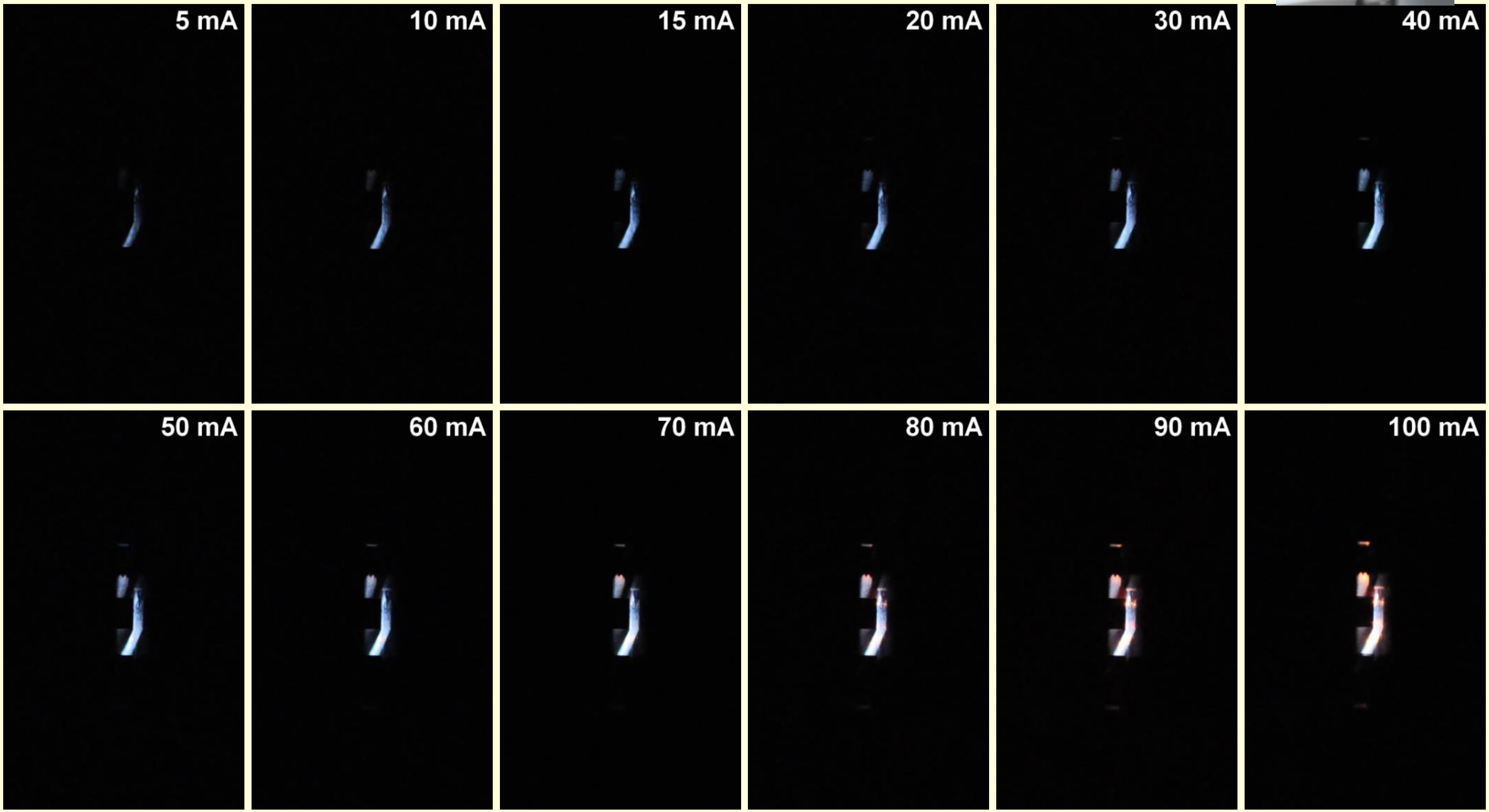


glow-to-arc transition



Figures:
Observation of glow discharges during FE measurements

glow-to-arc transition



3. Transitions from FE to plasma discharges:

Example for pulse operation with smooth transition from FE to GD

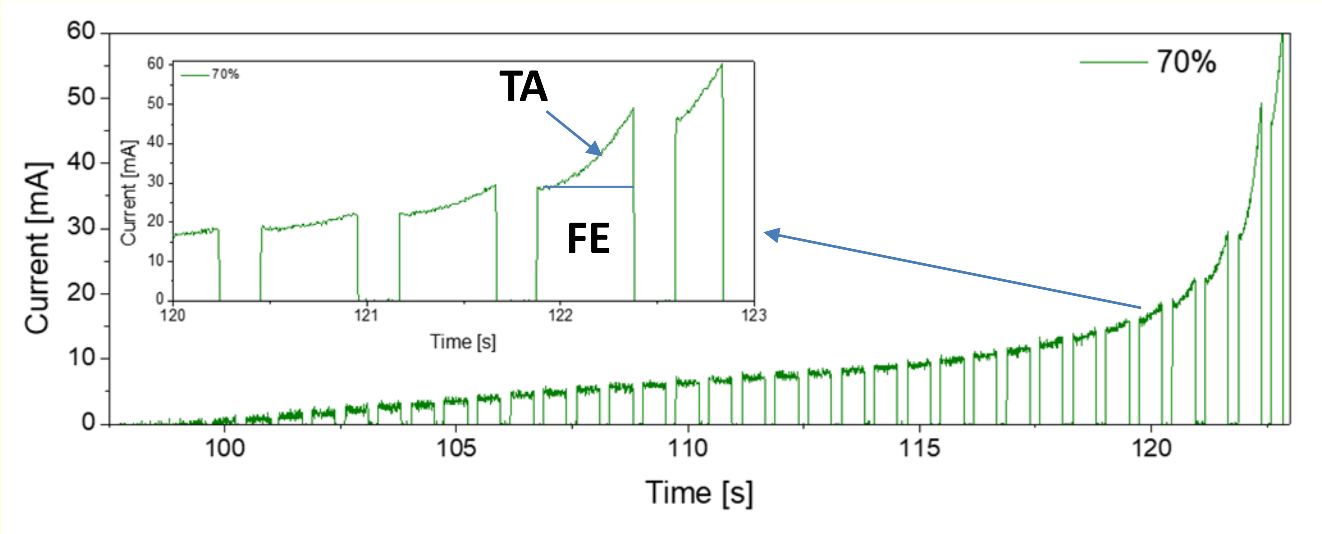


Fig. 1. Analysis of high-current FN measurement with pulse mode operating and smooth FE-to-GD transition.
FE – Field Emission, rectangle pulse form current, current curve is an exponential functions (cf. FN equation),
TA - Townsend avalanche, exponential functions with low time constant

-> resulting cathode current: $I_C = I_{FE} + I_{TA}$

(X-axis in Fig. 1.: Time t ~ extraction voltage U_{ext} [voltage ramp]),

[1] W. Knapp, "Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for extended use of vacuum components as very large FE cathode arrays." Poster contribution IVNC 2017.

3. Transitions from FE to plasma discharges (in a micro electron source)

Sudden transition from field emission to micro-arc discharge

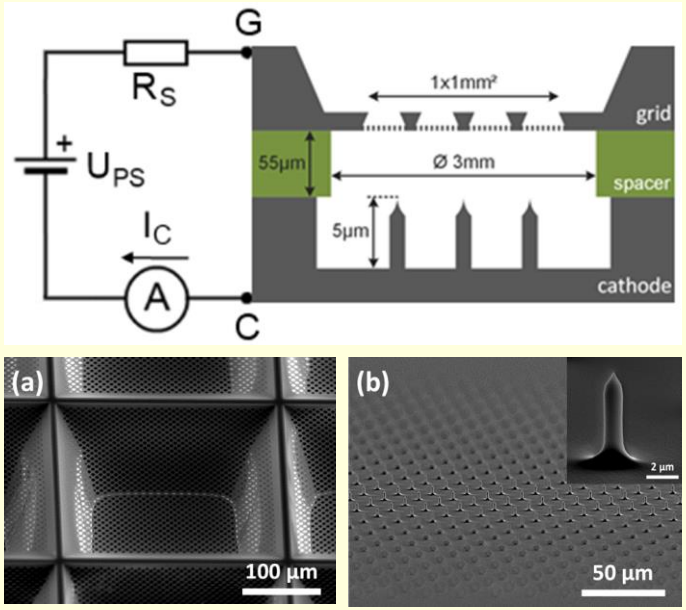


Fig. 1. Electrical measuring circuit and non-scaled scheme of micro electron source with SEM images:
(a) cathode-side view of micro-grid detail and (b) Si-tips array cathode, inside: geometry of single Si-tip field emitter [1, 2].

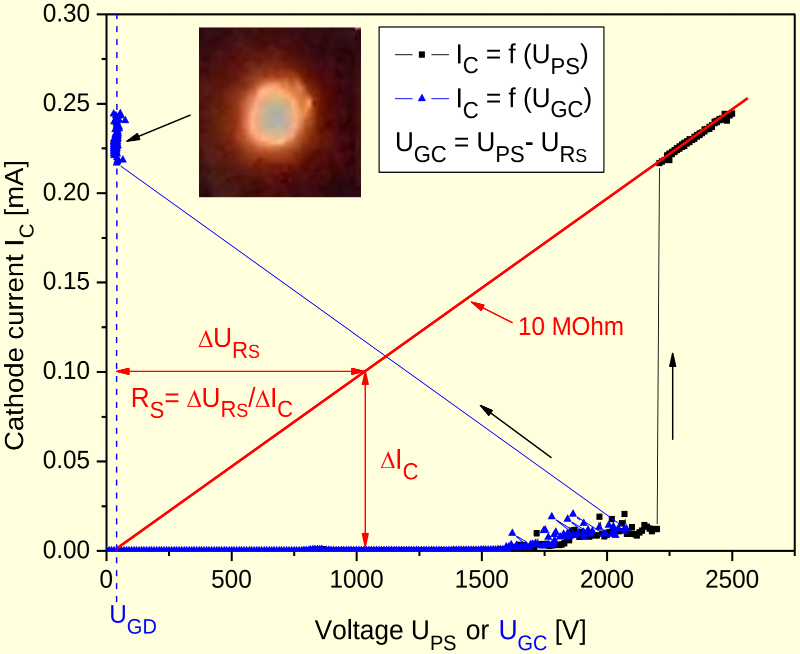


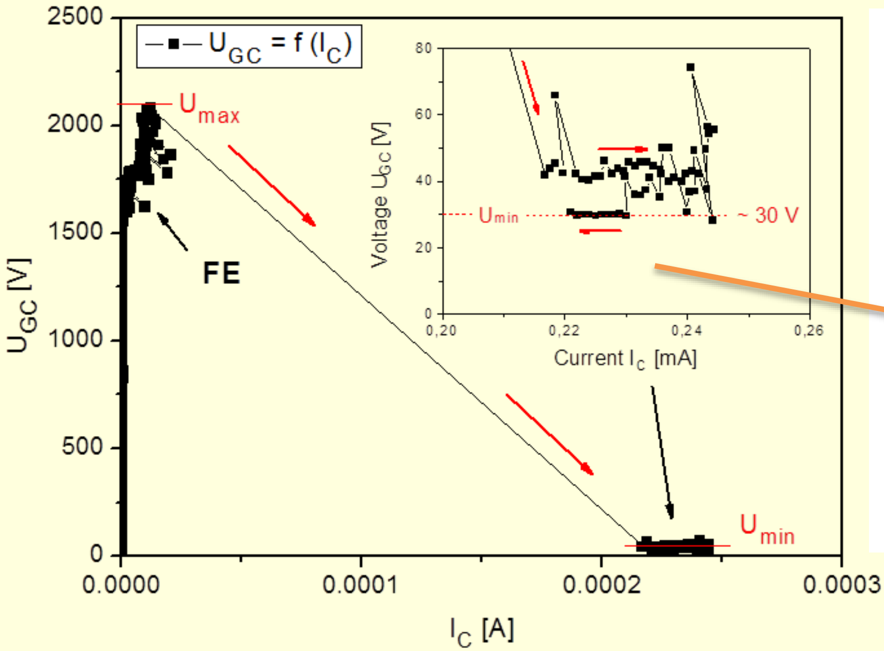
Fig. 2. Transition from field electron emission (FE) to stable plasma discharge, e.g. micro-arc discharge (µArc): Linear diagram of measured characteristic and linearity test after transition with R_{serial} = 10 MOhm.

[1] R. Schreiner, C. Langer, C. Prommesberger, R. Ławrowski, F. Dams, M. Bachmann, F. Düsberg, M. Hofmann, A. Pahlke, P. Serbun, S. Mingels, G. Müller, "Semiconductor field emission electron sources using a modular system concept for applications in sensors and X-ray sources", Technical Digest, 2015 28th IVNC, 13-17 July 2015, Guangzhou, China.

[2] W. Knapp, C. Langer, C. Prommesberger, M. Lindner, R. Schreiner, "Investigations of the transition from field electron emission to stable plasma discharge in a micro electron source at vacuum pressure." Poster contribution, IVNC 2017.

3. Transitions from FE to plasma discharges

Sudden transition from field emission to micro-arc discharge



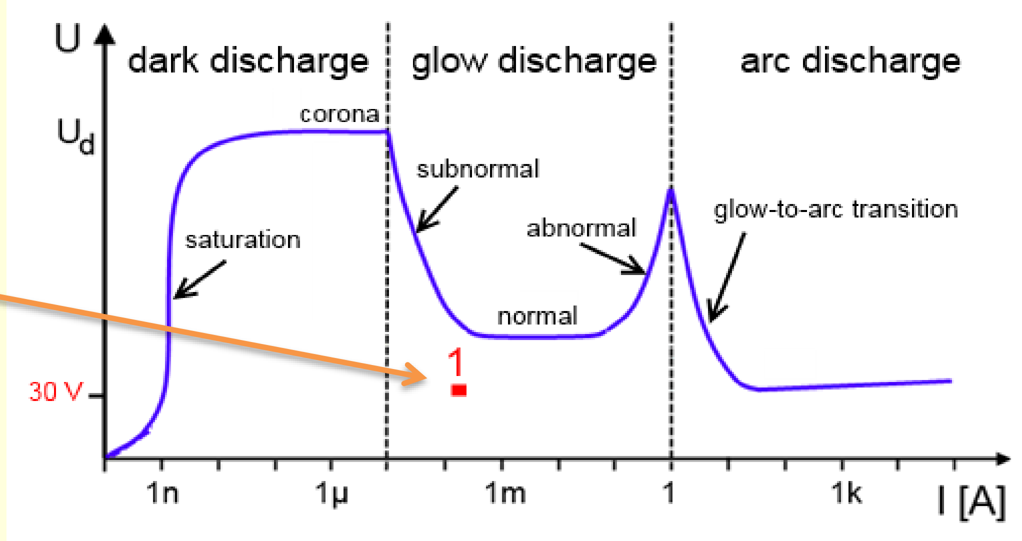


Fig. 1. Example of sudden transition (voltage breakdown) from field electron emission (FE) to stable plasma discharge, e.g. micro-arc discharge (µArc), with swapping the diagram axes from field-emission I = f (U) to plasma characteristics U = f(I) [1].

Fig. 2. U-I Scheme of plasma discharges with measurement **1** of Fig. 1 (the simplified scheme based on the image in [2]).

[1] W. Knapp, C. Langer, C. Prommesberger, M. Lindner, R. Schreiner, "Investigations of the transition from field electron emission to stable plasma discharge in a micro electron source at vacuum pressure." Poster contribution, IVNC 2017.

[2] J. Reece Roth, „Industrial Plasma Engineering: Volume 2 - Applications to Nonthermal Plasma Processing", CRC Press, 2001, ISBN 0750305452, p. 39 (or: https://www.plasma-universe.com/Electric_glow_discharge).

4. Extended use of Fowler Nordheim plot

Standard use: calculation of field enhancement factor ß

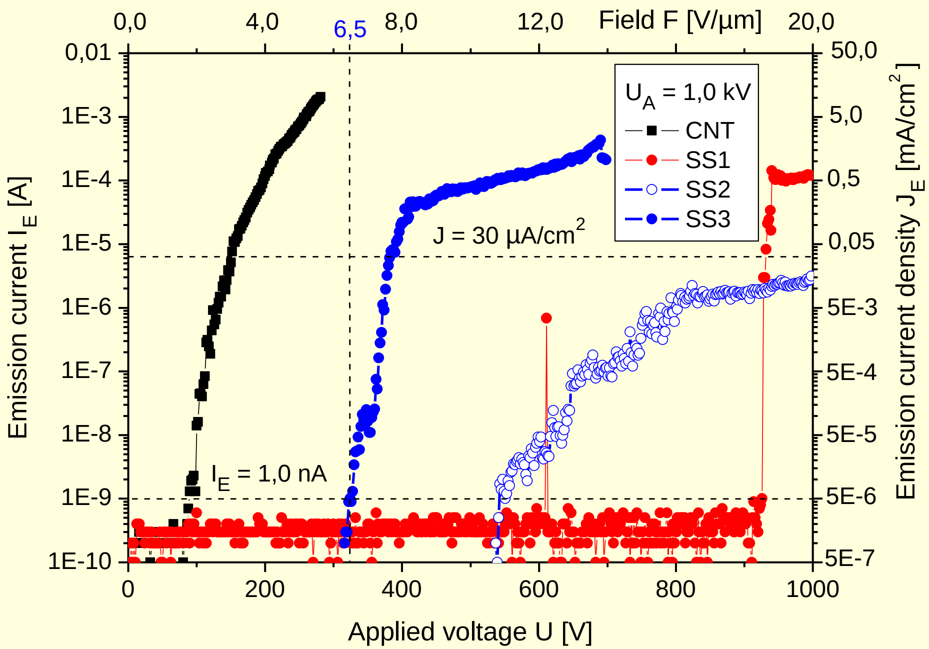


Fig. 1 Field-emission (FE) characterization of three stainless steel samples SS1, SS2 and SS3, and CNT Buckypaper with the same area for comparing [1]. For sample SS3 the current density value J = 30 µA/cm² lies significantly below the saturation characteristic.

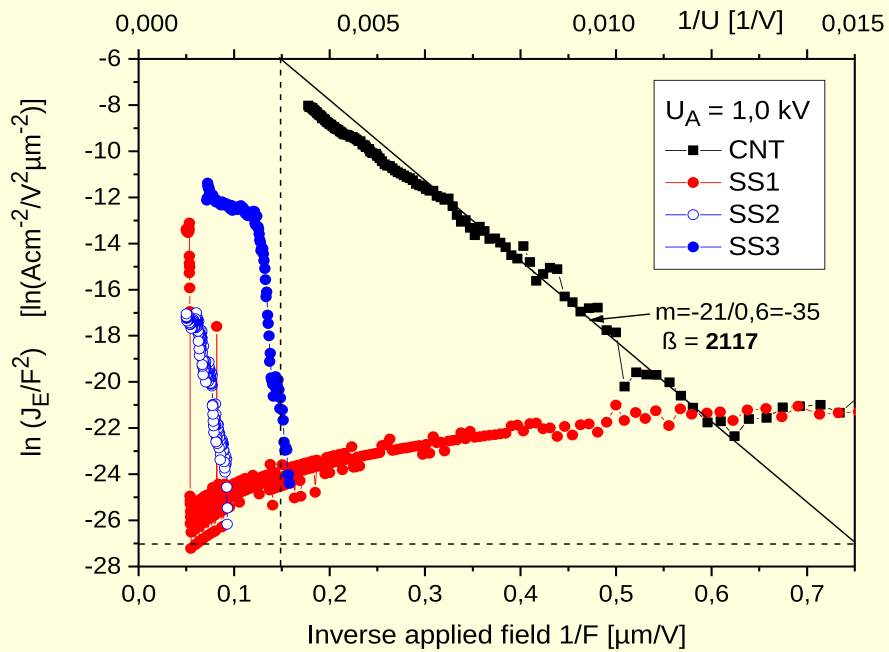


Fig. 2 Fowler-Nordheim plot (FN plot) of FE measurements in Fig. 1. and with graphic presentation of slope m for $ß_{CNT}$ calculation [2]:

$$ß_{CNT} = -\,(B \cdot \Phi^{3/2})\ /\ m$$

[1] W. Knapp, D. Schleussner, “Field-emission characteristics of carbon buckypaper”, JVST B 21 557-561 (2003).

[2] W. Knapp “Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for extended use of vacuum components as very large FE cathode rrays.” Poster, IVNC 2017.

4. Extended use of Fowler Nordheim plot Energetic evaluation of charge transfers

For novel investigations of the transition from field emission to stable plasma discharges an extended use of FN plot is proposed.

For this the inverse voltage (x-axis of the FN plot) is extended with factor 1 (= I·t / I·t):

$$\mathbf{1/U} = I \cdot t / U \cdot I \cdot t = \mathbf{Q/E} \qquad (1),$$

where U is the voltage, I the current, t the time,
Q the sum of all transported charges and
E the energy required for this.

The ordinate of Fowler-Nordheim plot will be unchanged.

The relation Q/E is a possible option for energetic evaluation.

The **operation compass** is important for basic orientation.

The direction Q/E maximum (red arrow or x-axis: 1/U) is the direction of energetically optimal charge transfer.

It can be seen that the micro-arc discharge has a charge transfer with the least energy input.

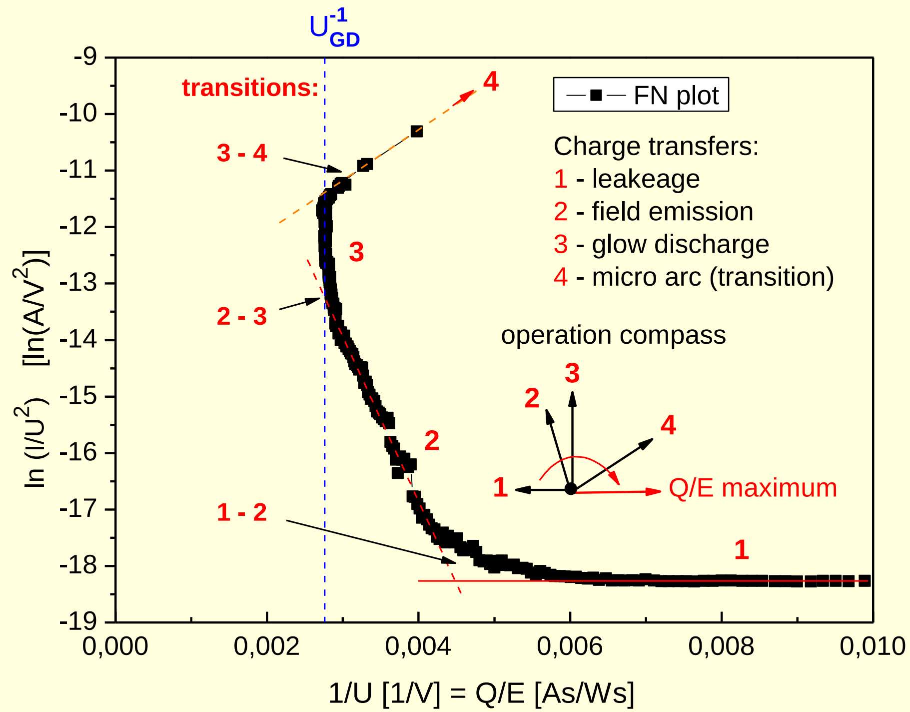
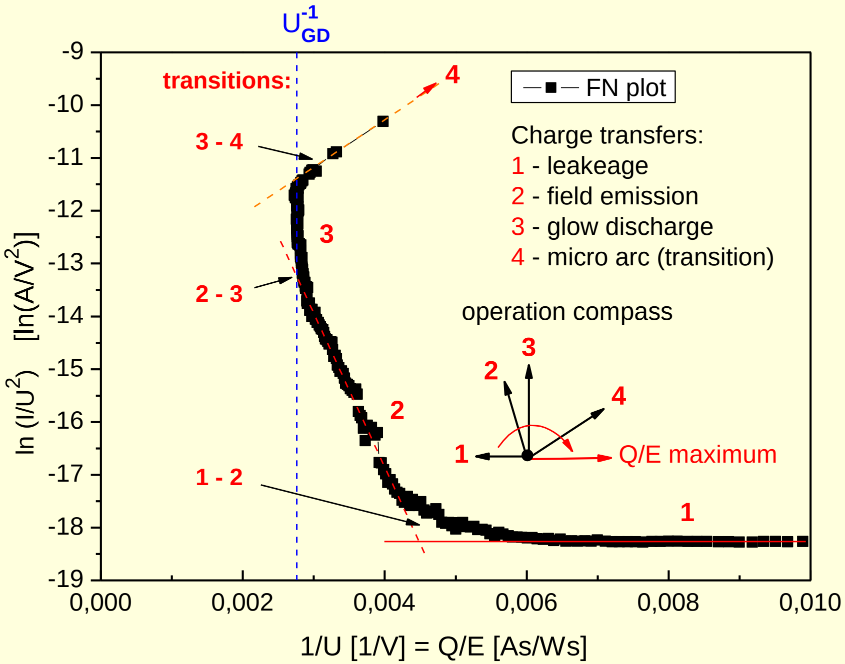


Fig. 1. FN plot of presented measurement SS3 [1] with smooth transitions. U_{GD} is the constant voltage of normal glow discharge.

[1] W. Knapp “Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for extended use of vacuum components as very large FE cathode rrays.” Poster, IVNC 2017.

4. Extended use of Fowler Nordheim plot Energetic evaluation of charge transfers

R_S = 100 kΩ, FE-cathode: stainless steel SS3 [1]



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R_S = 10 MΩ, FE-cathode: array of Si-tips [2]

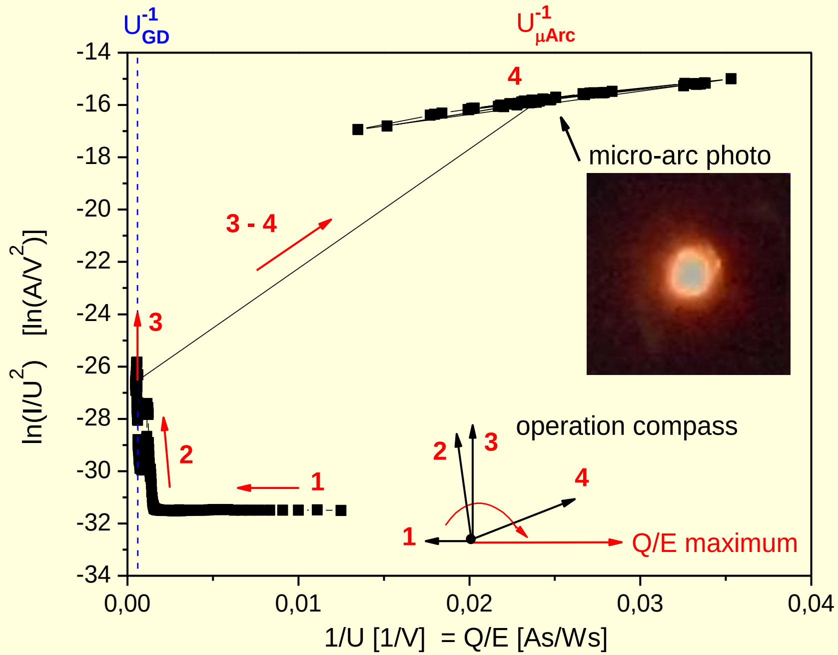

Fig. 2. FN plot for energetic evaluation of the transition from field electron emission to plasma discharges, as presented and detailed explained in [2, 3], with: **1** – leakage current, **2** – field emission, **3** – normal glow discharge, **3 - 4** – glow-to-arc transition, **4** – micro-arc discharge.

[1] W. Knapp "Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for extended use of vacuum components as very large FE cathode rrays." Poster, IVNC 2017.

[2] W. Knapp, C. Langer, C. Prommesberger, M. Lindner, R. Schreiner, "Investigations of the transition from field electron emission to stable plasma discharge in a micro electron source at vacuum pressure." Poster contribution, IVNC 2017.

[3] D. Wenger, W. Knapp, B. Hensel, S. T. Tedde, „Transition of Electron Field Emission to Normal Glow Discharge", IEEE Transaction on Electron Devices 61 (11), p. 3864 (2014).

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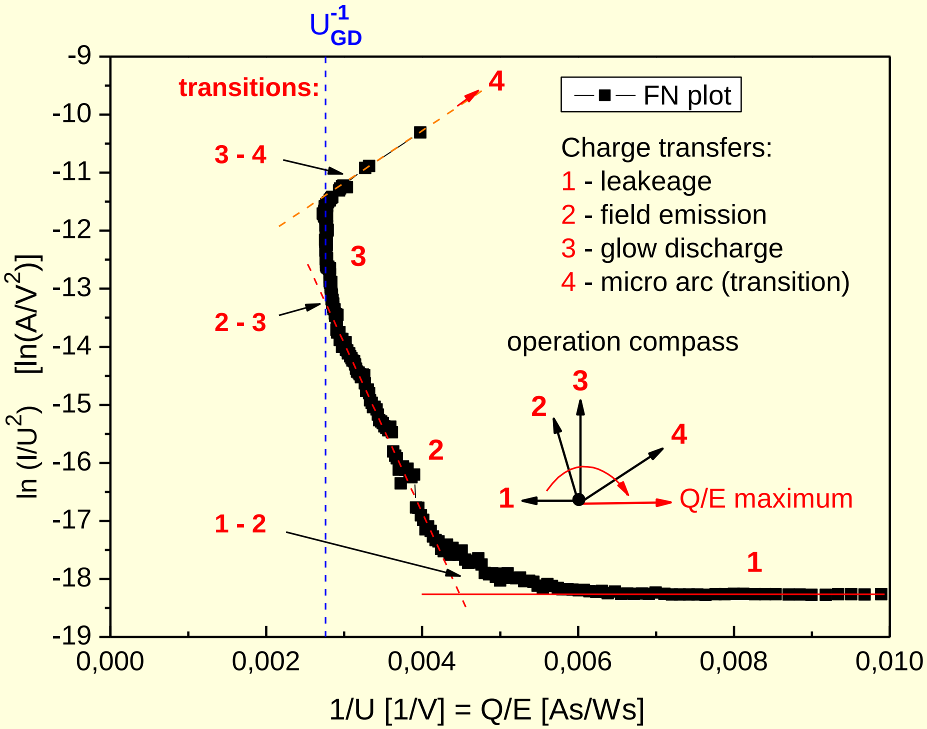

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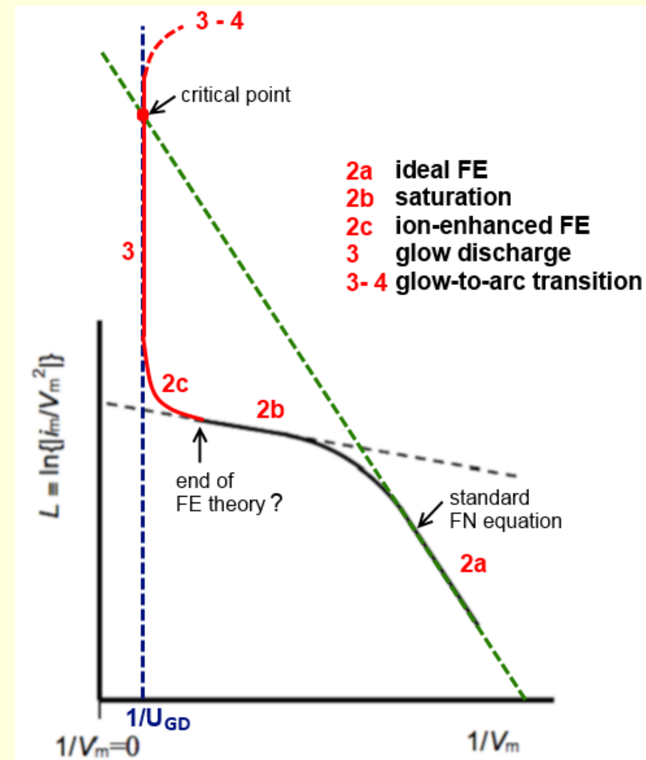


Fig. 2. Scheme of extended FN plot with smooth transition from field emission to glow discharge (based on Fig. in slide 117/132 [2]).

Critical point: "Ideal" FE and GD have identical electrical parameters (U and I)! -> A differentiation is difficult.

[1] W. Knapp "Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for extended use of vacuum components as very large FE cathode arrays." Poster, IVNC 2017.

[2] R. Forbes "INTRODUCTION TO FIELD ELECTRON EMISSION AND ITS THEORY (TUTORIAL LECTURE)" IVNC2013, Roanoake, July 2013.

5. Plasma-physical approach

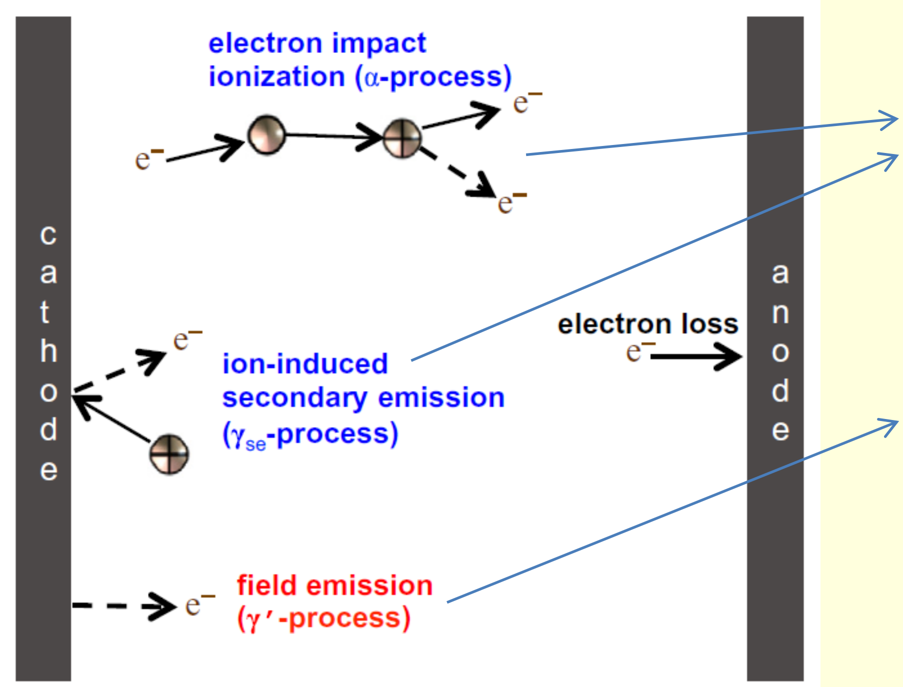


Figure 2. Schematic of charge generation processes in a standard DC discharge. Electron impact ionization (α-process) generates electrons in the volume while secondary emission (γ-process) generates electrons at the cathode. Field emission is the process of direct electron tunneling into the gas due to the high electric fields that are generated at the microscale.

Townsend avalanche criterion for pure secondary electron emission:

$$\gamma_{se} \cdot \left(e^{\alpha \cdot d} - 1\right) = 1$$

Fowler Nordheim equation for pure field electron emission:

$$J_{FE} = \frac{I_{FE}}{A} = a\frac{E^2}{\varphi} exp\left(-b\frac{\varphi^{3/2}}{E}\right)$$

Townsend avalanche criterion for secondary and field electron emission:

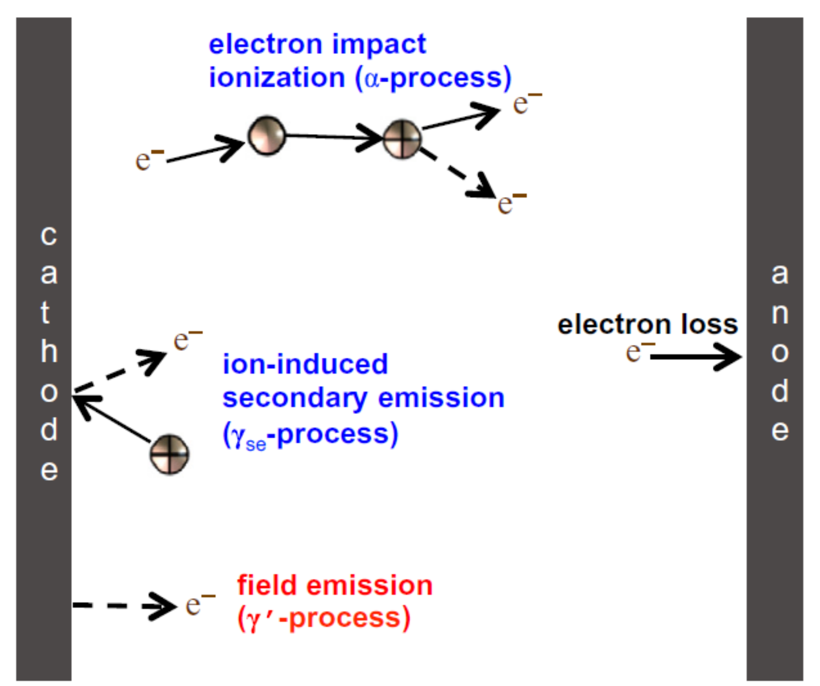
$$\left(\gamma_{se} + \gamma^{I}\right) \cdot \left(e^{\alpha \cdot d} - 1\right) = 1$$

Note: $I_{FE} = 1.6\, nA \cong 10^{10} \frac{e^-}{second}$!

→ **Field electron emission is an excellent ignition support for discharges.**

[1] D.B. Go, A. Venkattraman: Microscale gas breakdown: ion-enhanced field emission and the modified Paschen´s curve (Topical Review), J. of Phys. D: Appl. Physics 47 (2014) 503001.

5. Plasma-physical approach with vacuum-physical comments



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→ **Kinetical energy**, e. g. for an electron:

$$eU = \frac{1}{2} m_e \cdot v^2 \quad \text{with } U \leq U_{ac}$$

→ **3 sources of gas molecules [= *f(T)*]:**

1. gas desorption from electrode surfaces: $10^{14} \ldots 10^{15}$ molecules / cm^2 !
2. outgassing from electrodes
3. evaporation of electrode material

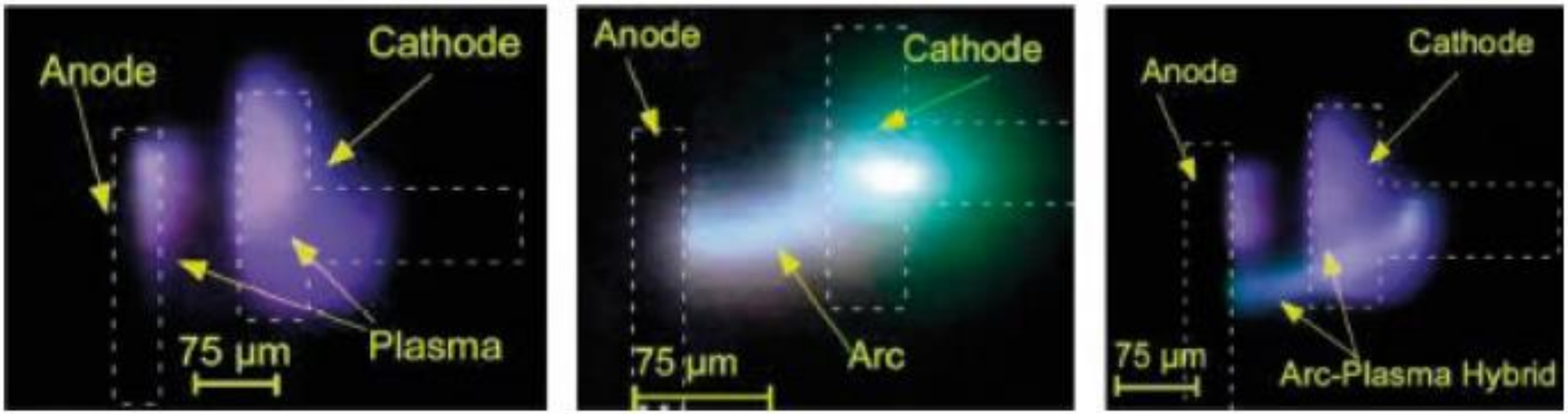
→ **ionization and ion collection** of gas molecules in the electron beam

→ **transition** from electron emission to stable plasma discharge ($n_e \sim n_i$)

[1] D.B. Go, A. Venkattraman: Microscale gas breakdown: ion-enhanced field emission and the modified Paschen´s curve (Topical Review), J. of Phys. D: Appl. Physics 47 (2014) 503001.

5. Plasma-physical approach: Breakdowns with different R-limitations

R_{serial} = 100 kΩ	R_{serial} = 80 Ω	R_{serial} = 22 kΩ
glow discharge	**micro-arc discharge**	**hybrid: glow & arc discharge**

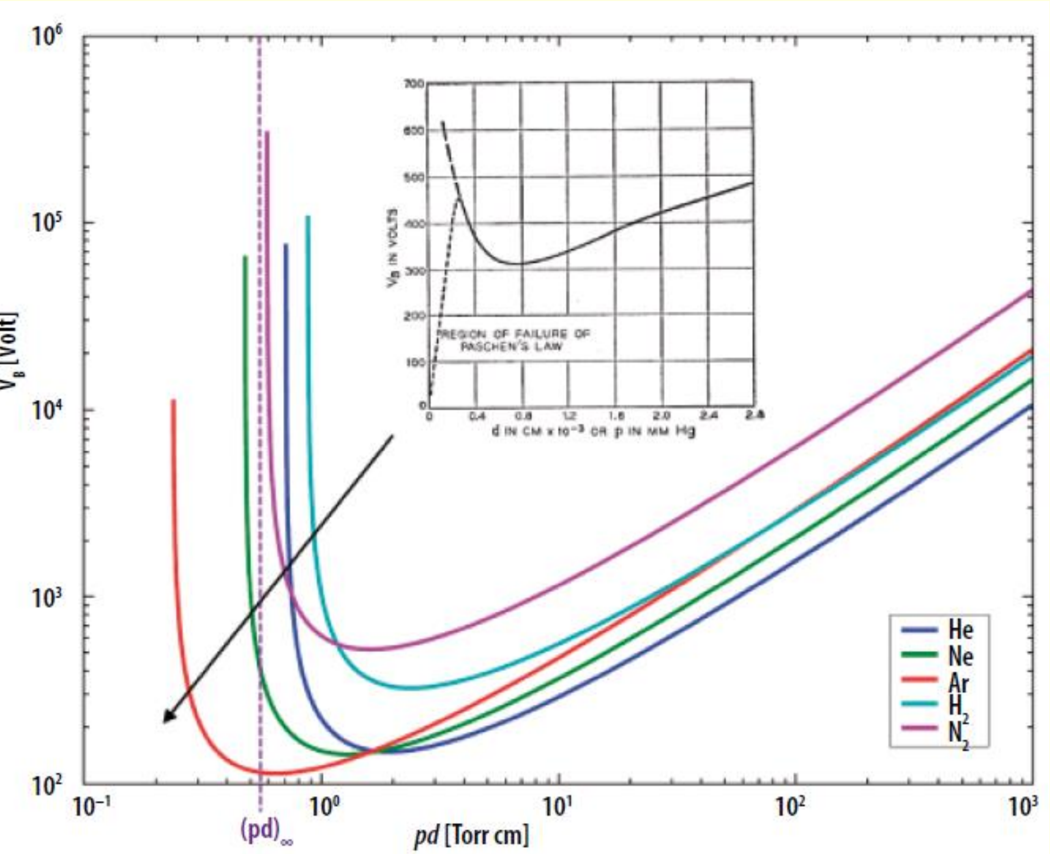


Glimmentladung (Plasma) | Mikrolichtbogen (Arc) | Hybrid: Glimmentladung + Mikrolichtbogen

[12] *B. Mitra, Y. B. Gianchanfani*: Micro arc-plasma hybrids for detection of vapors at atmospheric pressure, Sensors 2005 IEEE, Irvine, CA, Oct. 30–Nov. 3 (2005).

[1] W. Knapp, “Vakuummikro- und Vakuumnanoelektronik mit Feldemission – Besonderheiten der Spannungsfestigkeit bei Abständen unter 10 µm“ (in German), Vakuum in Forschung und Praxis (ViP), Vol. 28, Nr. 6 (Nov. 2016) 42-48.

5. Plasma-physical approach: Breakdowns in small electrode gaps < 10 µm



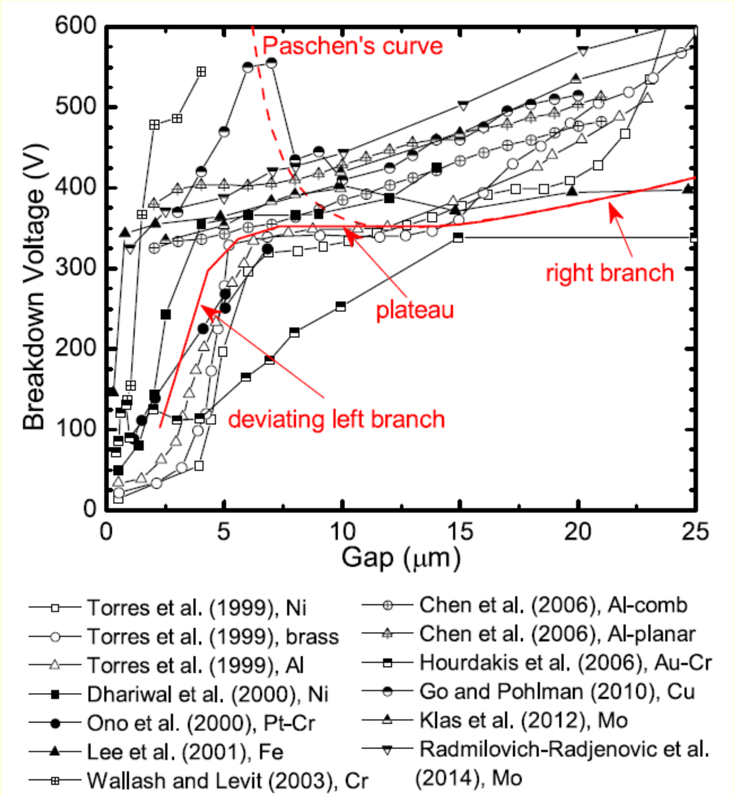


Figure 5. Breakdown voltage as function of the electrode distance in air at atmospheric pressure. The dash line is Paschen's curve for air (assuming $\gamma_{se} = 0.005$) and the solid line is a schematic illustration of the modified Paschen's curve. Data were extracted from [5, 25, 27, 28, 30, 33, 34, 38, 42 and 45], respectively.

[1] D.B. Go, A. Venkattraman: Microscale gas breakdown: ion-enhanced field emission and the modified Paschen´s curve (Topical Review), J. of Phys. D: Appl. Physics 47 (2014) 503001.

5. Plasma-physical approach: Breakdowns in small electrode gaps < 10 µm

223301-5 Bilici *et al.* J. Appl. Phys. 119, 223301 (2016)

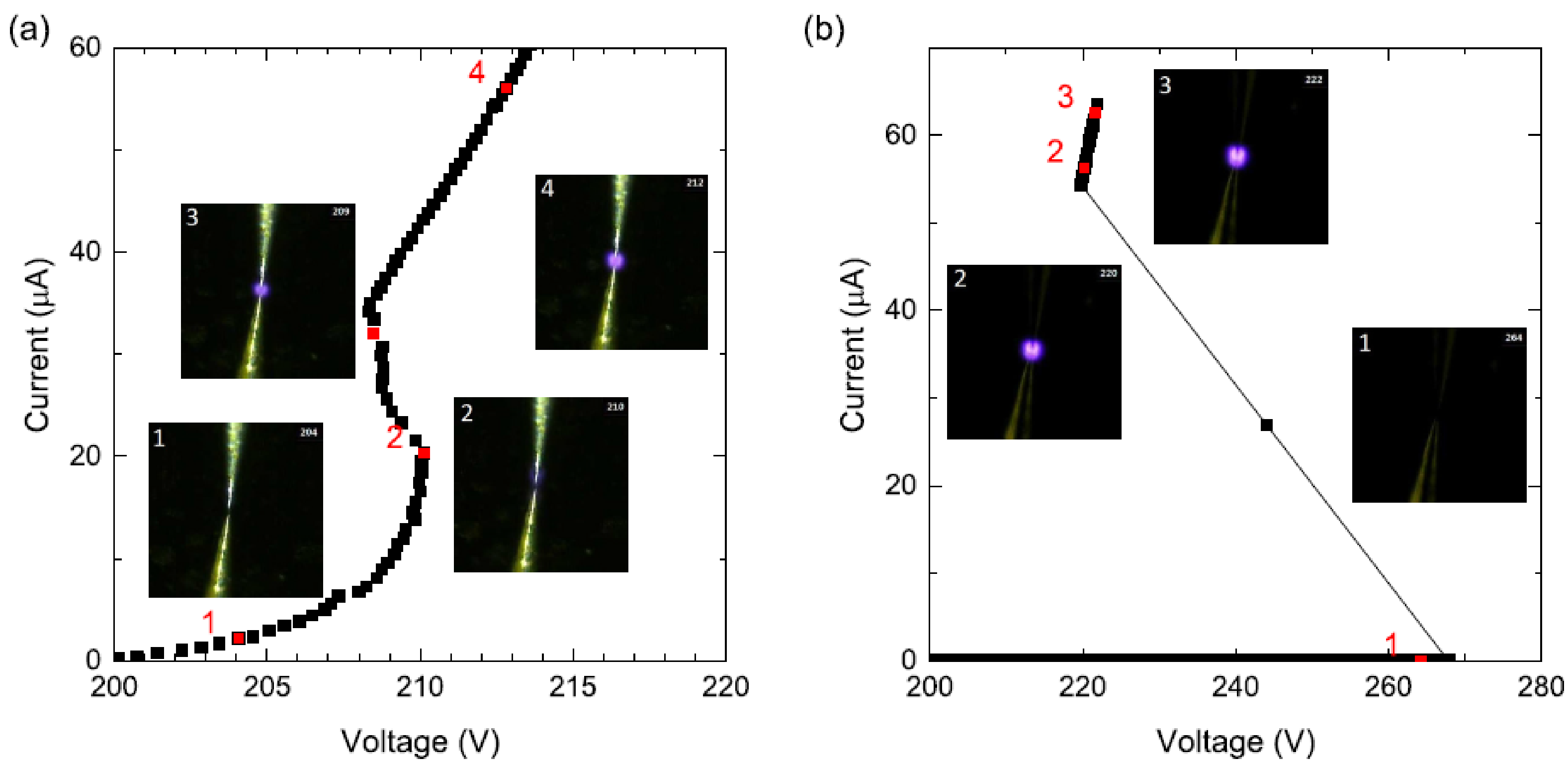


FIG. 3. Representative current–voltage measurements for (a) 1 μm and (b) 10 μm tip-to-plane electrode gaps, and corresponding images extracted from videos of gas breakdown. (Multimedia view) [URL: http://dx.doi.org/10.1063/1.4953648.1] [URL: http://dx.doi.org/10.1063/1.4953648.2]

[2] M. A. Bilici, J. R. Haase, C. R. Boyle, D. B. Go, R.M. Sankaran, "The smooth transition from field emission to self-sustained plasma in microscale electrode gaps at atmospheric pressure", J. Appl. Phys. 119 223301 (2016).

5. Plasma-physical approach: Breakdowns in small electrode gaps < 10 µm

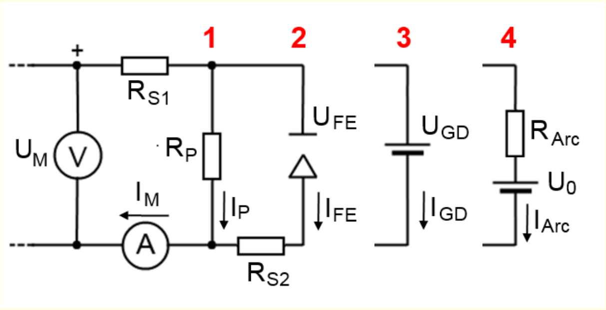


Fig. 1. Equivalent circuit diagram for different stationary conditions:

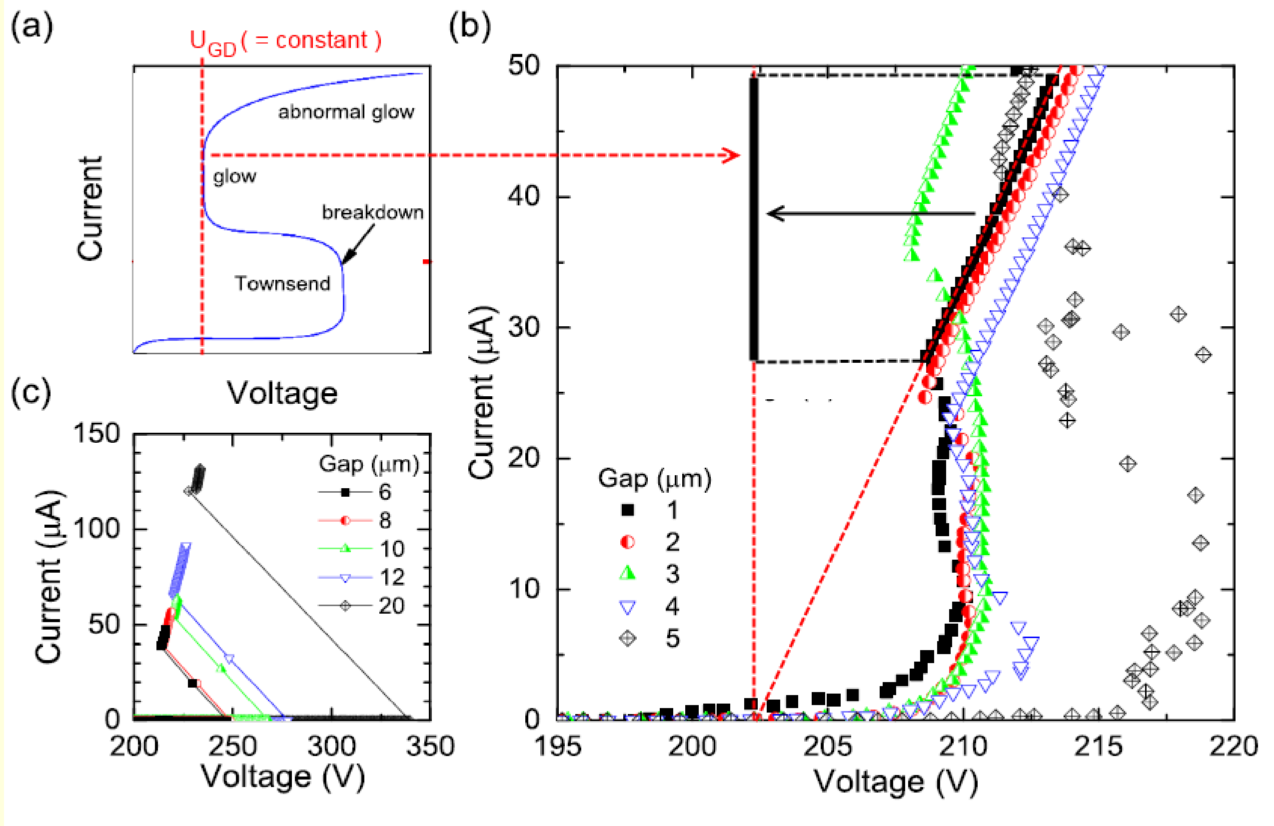
1- leakage (e.g. insulation resistance),

2 - field electron emission,

3 - normal glow discharge with constant voltage characteristic,

4 - micro-arc discharge. For $I_{\mu Arc}$ << 10A:

$$U_{\mu Arc} = U_0 + R_{\mu Arc} \cdot I_{\mu Arc} \cong U_0$$



Note: Direct R_{serial} (R_{S1}) measurement is possible because **normal glow discharge** has a constant voltage characteristic, cf. **3** in Fig. 1.

[2] M. A. Bilici, J. R. Haase, C. R. Boyle, D. B. Go, R.M. Sankaran, "The smooth transition from field emission to self-sustained plasma in microscale electrode gaps at atmospheric pressure", J. Appl. Phys. 119 223301 (2016).

6. Conclusion and outlook

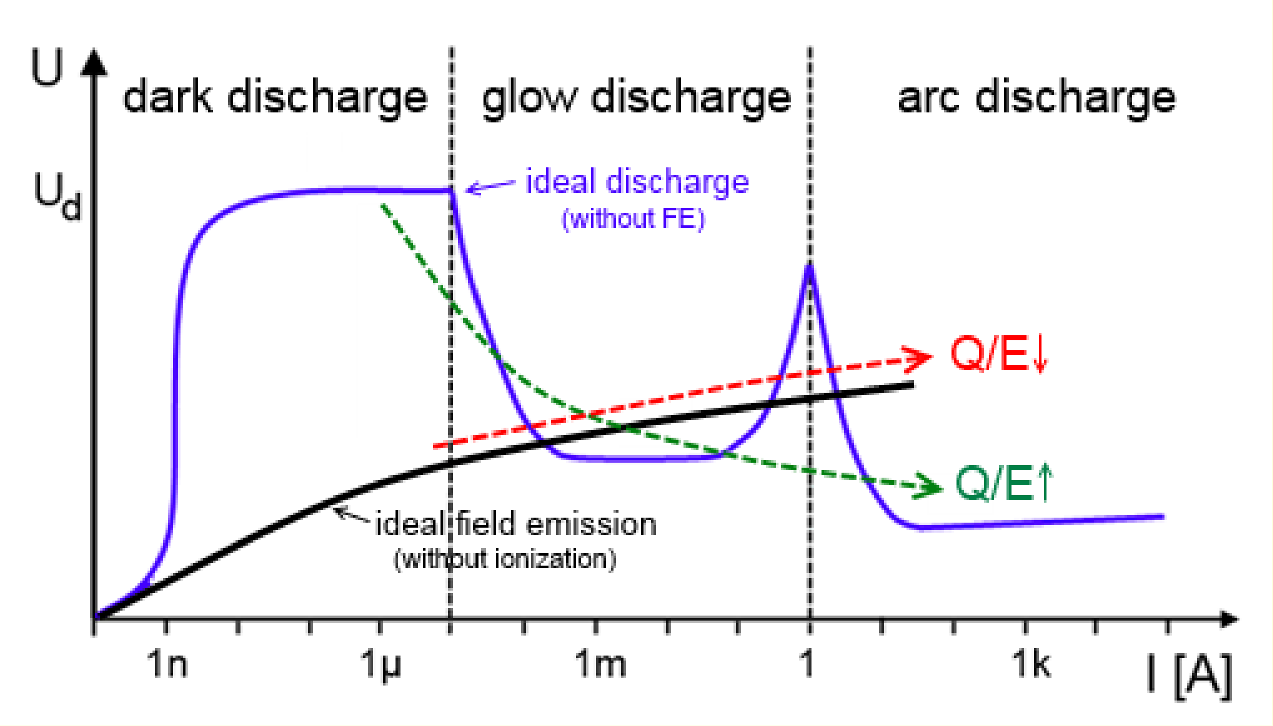


Fig. 1. Trends of efficiency of charge transfers

[1] W. Knapp, "Energetic evaluation of the transition from field electron emission to plasma discharges with extended use of the Fowler- Nordheim plot.", constributed talk IVNC 2017, Regensburg July 10 – 14, 2017, TECHNICAL DIGEST, p. 34.

6. Conclusion and outlook

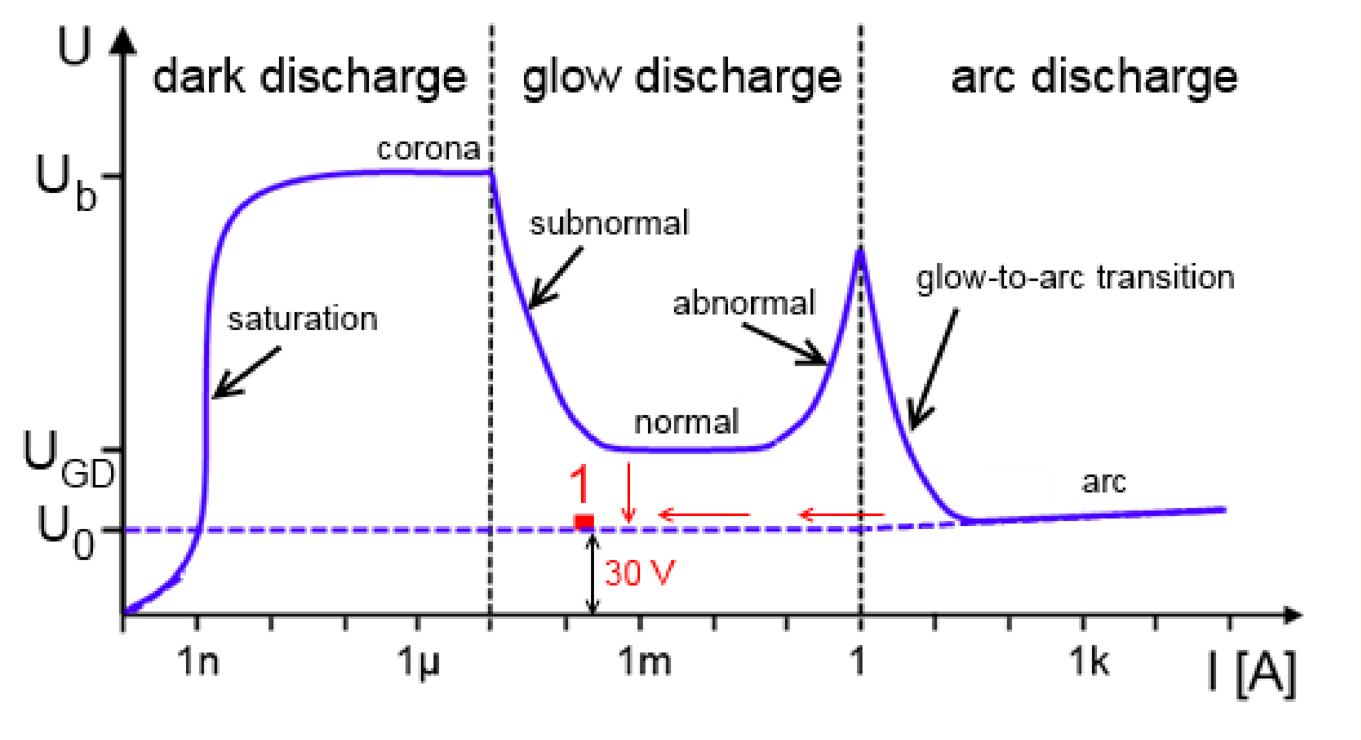


Fig. 1. Field-emission enhanced stable vacuum micro-arc discharge in the range of about 200 µA.

[2] W. Knapp, C. Langer, C. Prommesberger, M. Lindner, R. Schreiner, "Investigations of the transition from field electron emission to stable plasma discharge in a micro electron source at vacuum pressure." Poster contribution, IVNC 2017, Regensburg July 10 – 14, 2017, TECHNICAL DIGEST, p. 166
.

6. Outlook: Electron field emission with micro-arc discharges:
-> Early detection with special ionization gauge!

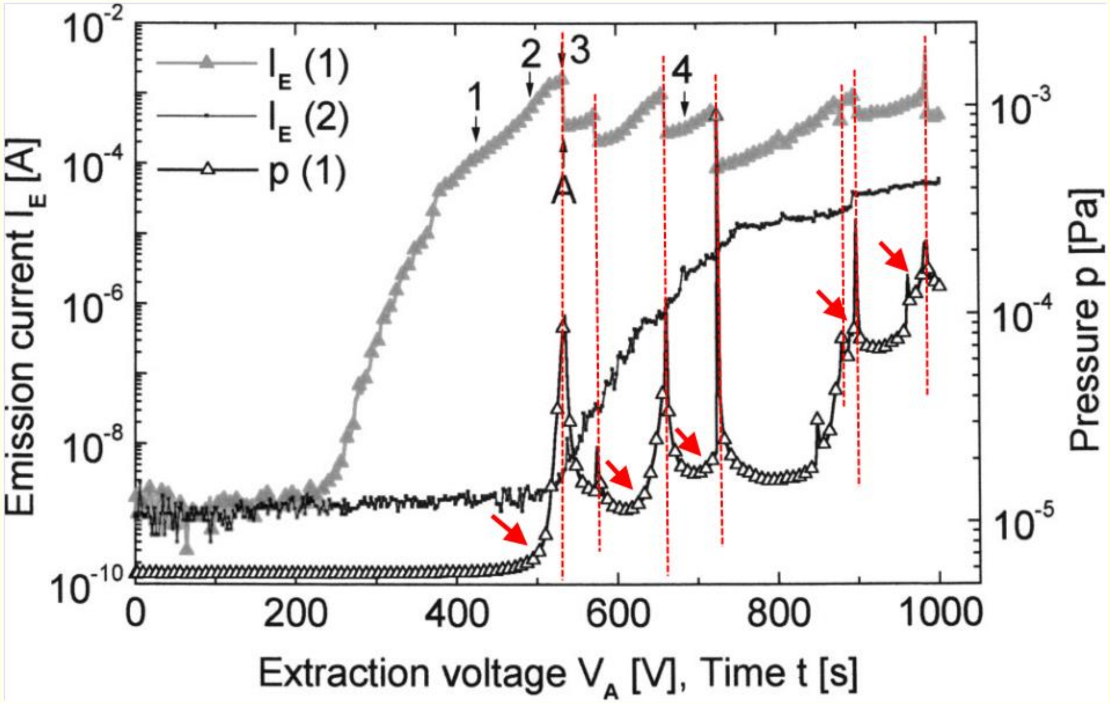


Fig. 1. Stress tests with micro-discharges (emitter–anode distance: 100 µm): current-voltage curve of first I_E (1) and second I_E (2) measurement with corresponding total pressure p (1), and video images (see Fig. 2.). Mark A: first micro-discharge (FIG. 7. in [1]).

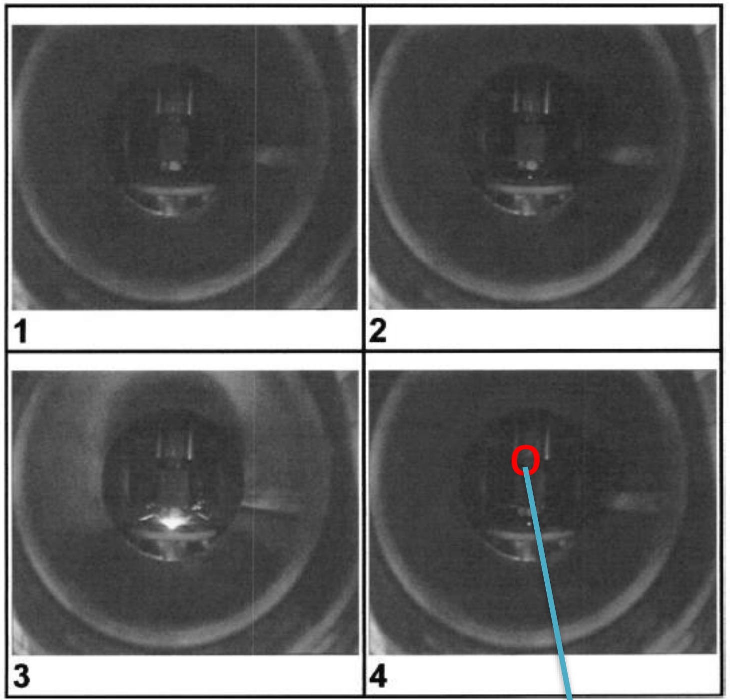


Fig. 2. Video images of field-emission zone during stress test with micro-discharges (FIG. 8. in [1]).

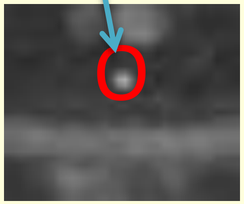


Fig. 3. Magnification of image **4** with corona luminescent.

[1] W. Knapp, D. Schleussner, "Field-emission characteristics of carbon buckypaper", JVST B 21 557-561 (2003).

6. Outlook FE with low current density

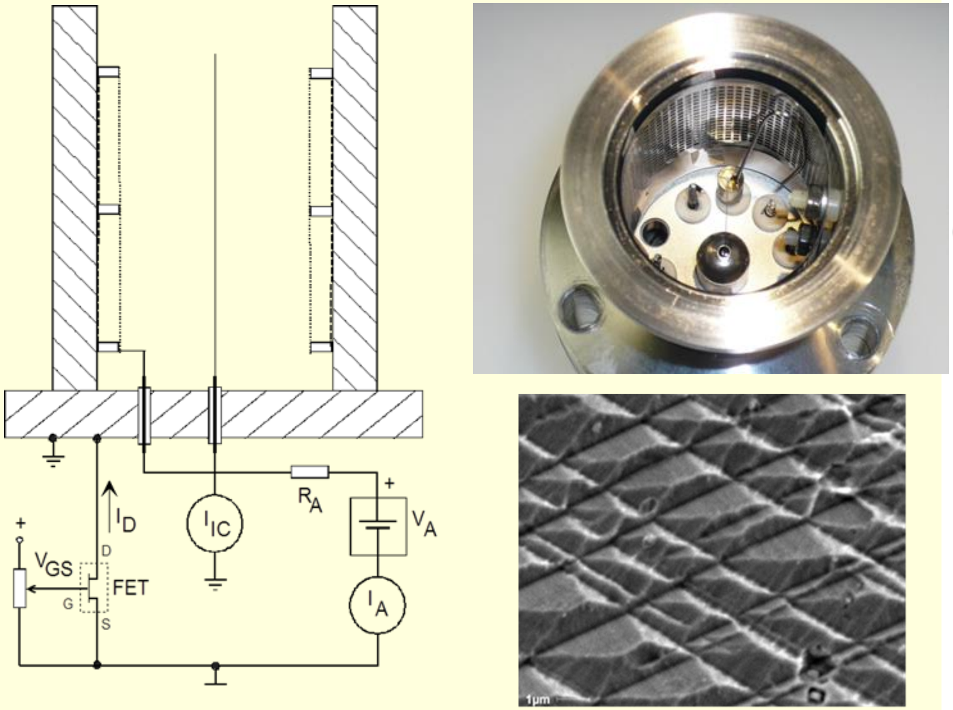


Fig. 1. Schematic circuit and ionization gauge construction for testing with novel large-area stainless steel field-emission cathode [1].

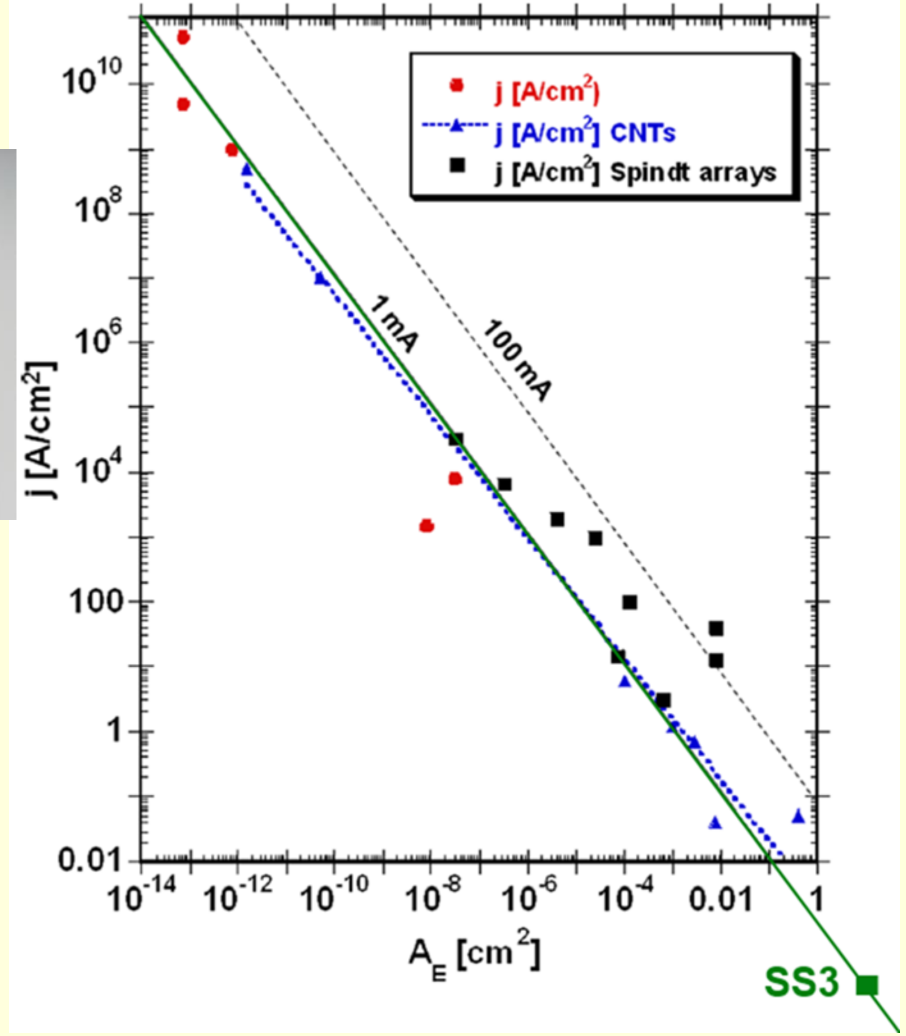


Fig. 2. Plot of cold field-emission current density vs emitter area (including passive parts) based on literature data for CNTs, W tips, and Spindt arrays (FIG. 14 in [1]). Lines of equal currents are shown for 1 mA and 100 mA. The diagram had to be extended for sample SS3 (Fig. 1)

[1] W. Knapp, "Ionization gauge with large-area stainless steel field-emission cathode", Knapptron Lab research report, 2017 (unpublished).

[2] G. Gärtner, "Historical development and future trends in vacuum electronics (review article)", JVST B 30 060801_1-14 (2012).

6. Conclusion and outlook

1. It was shown that transitions from field electron emission to stable plasma discharge are very important for field emission applications in the current range above 0.1 … 1.0 mA.
2. The transitions can be very different, e.g. emission-to-glow transitions are often smooth.
   This can be a major problem for the correct analysis of field-emission characteristics.
3. In order to confirm this transition from field electron emission into a normal glow discharge a graphical evaluation method was developed.
4. In this contribution we report of the first time on an extended use of the Fowler-Nordheim plot for energetic evaluation of charge transfers in vacuum electronics.
5. First results explained clearly, the transitions from field electron emissions to normal glow discharges and/or micro-arc discharges are physically conditioned, especially in the case of higher emission currents and long-term emissions.
6. In the next steps different field emitter cathodes will be investigated regarding their robustness and resistance against glow and micro-arc discharges.
7. Therefore the extended use of the Fowler-Nordheim plot will have an enhanced role in future field emission characterizations.
8. It is recommended to check all field emission measurements in the current range above 0.1 mA. Only in this way is it possible to avoid misunderstandings or even inadequate or incorrect evaluations of field emitters and field-emitter materials.
9. For better understanding:
   a) vacuum pressure measurement
   b) optical observation of cathode – anode distance

Thank you very much for your attention!