CONTROLLED MICRO-ARC TREATMENTS IN VACUUM ELECTRON SOURCES WITH CNT CATHODES FOR LONG-TERM EMISSION STABILITY

Dr.-Ing. Wolfram Knapp

E-mail: dr.who.knapp@t-online.de

Knapptron GmbH - Vakuumelektronik, Privatweg 3, D-39291 Möser

formerly

Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, D-39106 Magdeburg, Germany

Abt. Vakuumphysik und -technik

Outline of my lecture:

1. Motivation
2. Vacuum electron sources with CNT cathodes
3. Experimental setup
4. Standard measurements of FE characteristics
5. Characterization of discharges (breakdowns)
6. **Controlled micro-arc treatments for long-term electron emission stability**
7. **Options for increasing the emission current**
8. Summary and outlook

1. Motivation

1.1. General Motivation:

Development of long-term stable electron sources with **field emission cathodes** for a wide range of vacuum electronic applications

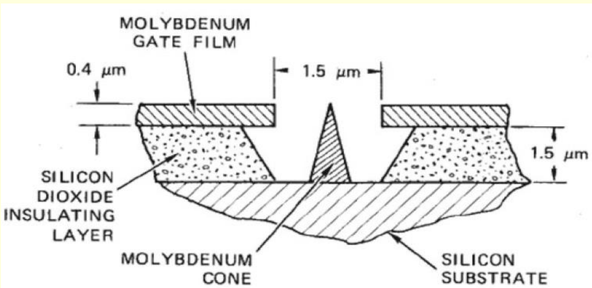
1.2. Special Motivation:

Development of long-term stable **mini X-Ray sources**, e.g. for multi-source static computer tomography (CT) without mechanical rotation of the X-Ray tubes

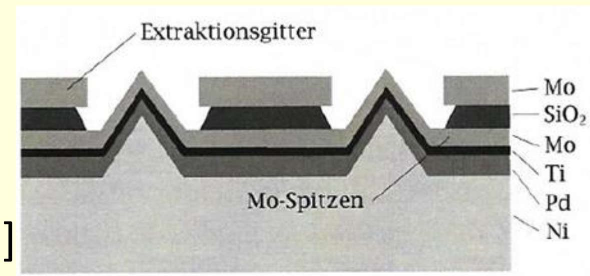
1.1. General Motivation

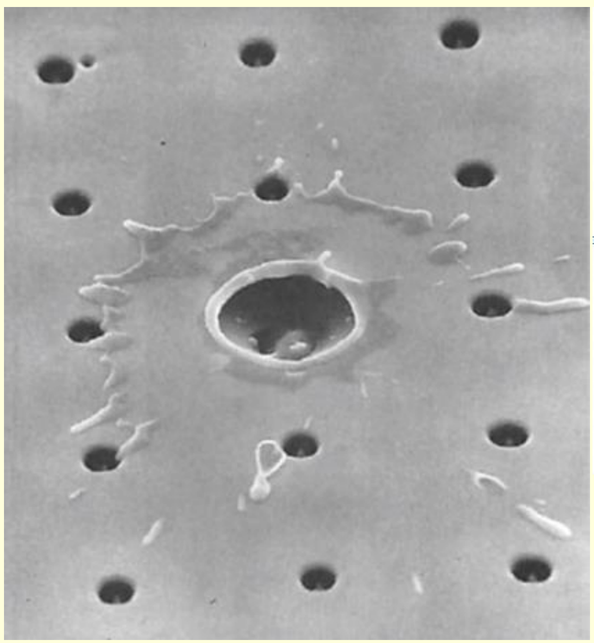
Main problem regarding long-term stability:
Destruction of the field emitter cathodes during discharges,
e.g. large-area Field Emission Arrays (FEAs) with Spindt-type cathodes

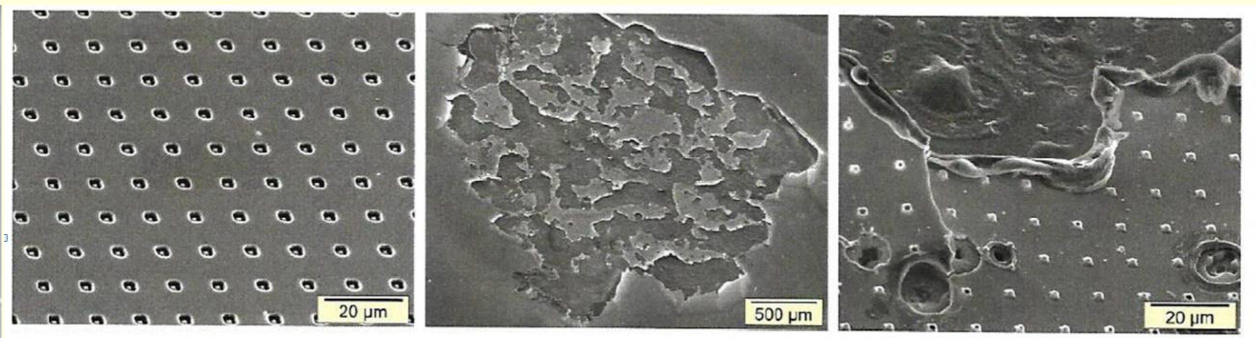
[1]



[2]







(a) Intaktes FEA (b) Defektes FEA (Übersicht) (c) Defektes FEA (vergrößert)

Abbildung 6.1: Elektronenmikroskopische Aufnahmen der PSI FEA unter einem 45°-Blickwinkel.

[1] G. Gaertner, W. Knapp, R.G. Forbes: Modern Development s in Vacuum Electron Sources. Topics in Applied Physics, Vol. 135, Springer Nature Switzerland AG, 2020, p. 551 and 557.

[2] Marcel , Lotz: Entwicklung feldemitterbasierter Ionisationsmanometer für den Einsatz in kryogenen Vakuumsystemen. Johann Wolfgang Goethe-Universität Frankfurt, FB Physik (D30), Frankfurt am Main, 2018, S. 69.

1.2. Special Motivation

State of the art for **Static CT**: Nanovision 2020

RSNA 2020|Multi-source Static CT Technology: CompoundEye 24 Micro CT

2020.12.04

[1] http://en.**nanovision**.com.cn/

2020.12.04

RSNA 2020|Multi-source Static CT Technology: CompoundEye 24 Micro CT

1.2. Special Motivation

State of the art for **Static CT**: MIT 2018

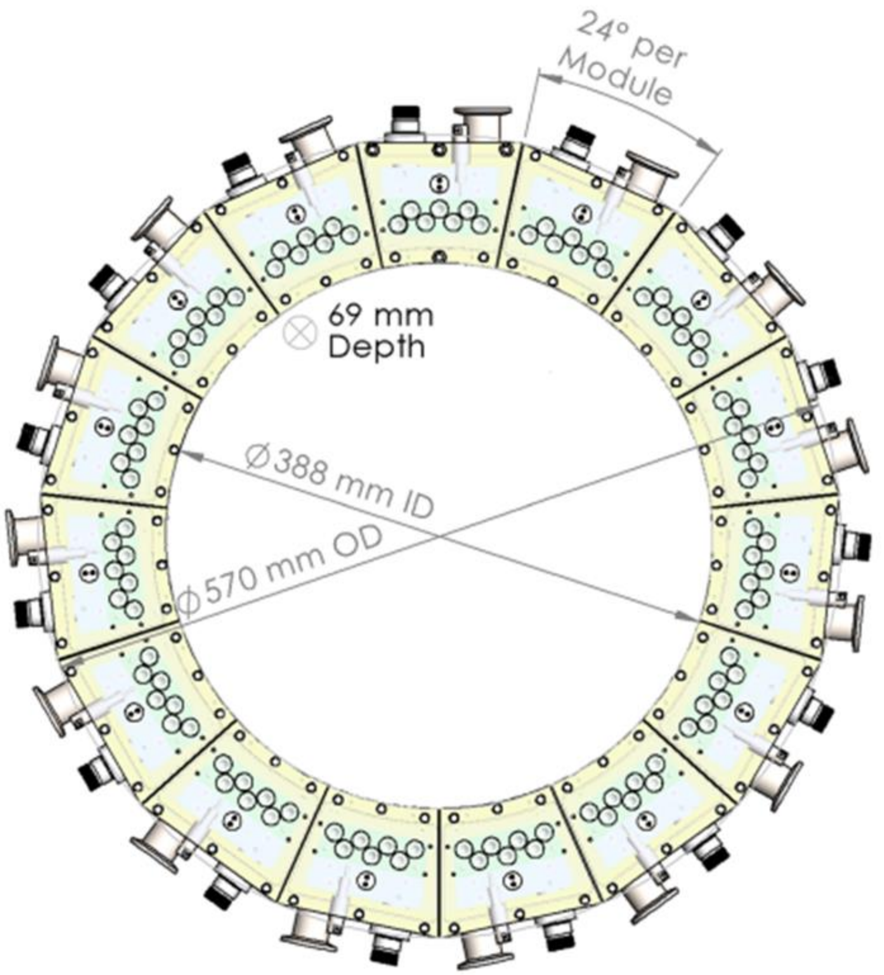
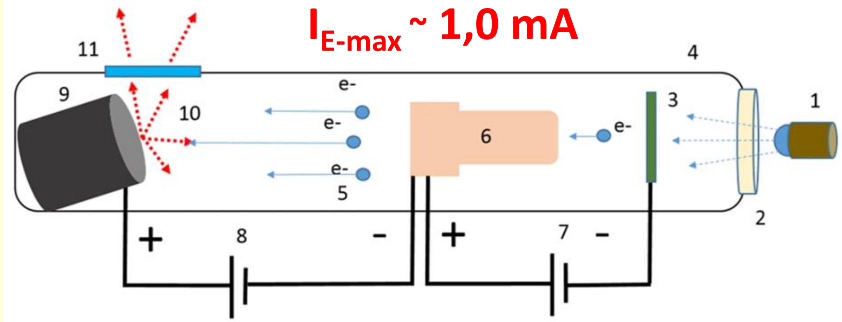


Figure 5. CAD diagram of full ring of modules, with dimensions.

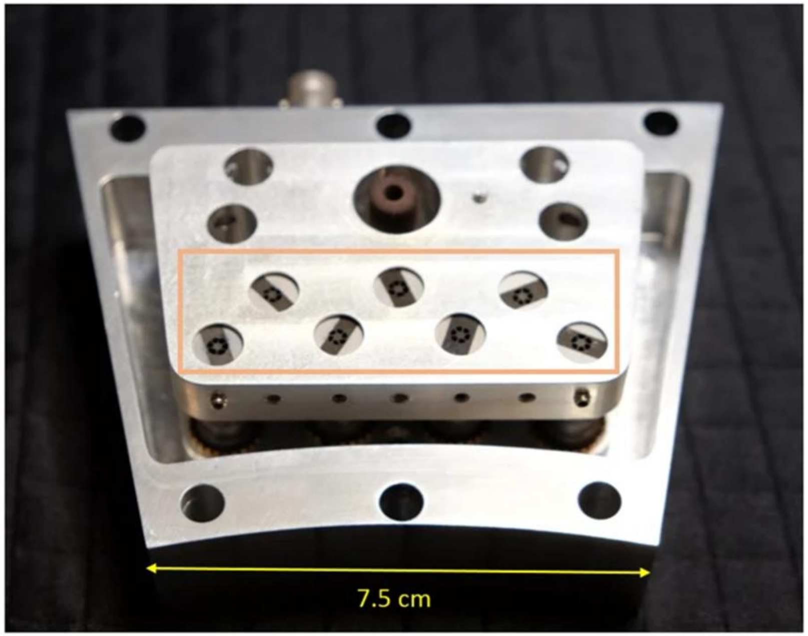
15 Module (15 x 24°=360°) x 7 X-Ray Tubes = **105 X-Ray Tubes**

[1] https://www.nature.com/articles/s41598-018-32505-z

$I_{E\text{-}max}$ ~ **1,0 mA**



Schematic of the miniature x-ray source. A pulsable UV LED (1) emits UV photons which pass through a quartz window (2) into the vacuum manifold (4) and interact with a photoemissive magnesium film (3). This interaction produces electrons which are amplified by a Channeltron device (6), which is supplied with a 3 kV bias voltage (7). The amplified electrons (5) are accelerated through a large electric field provided by an external high voltage source (8), and impact on an angled tungsten target (9). This interaction (10) produces x-ray photons which leave the vacuum manifold through a beryllium window (11).



Internal view of the module, with the exit ports of the Channeltrons highlighted.

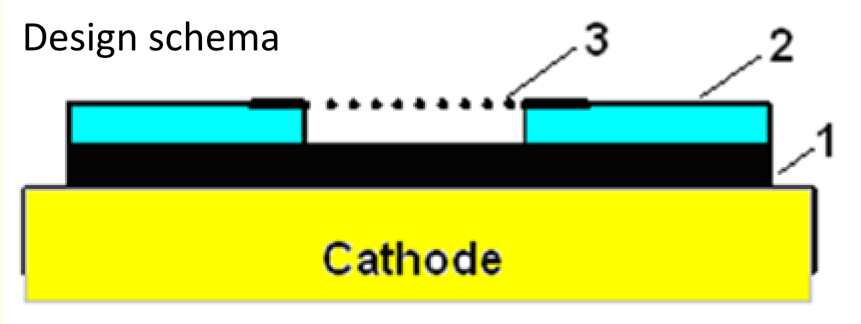
1.2. Special Motivation

State of the art for mini X-Ray tubes

D.J. Caruso, M. Dinsmore – TWX, LLC, S. Cornaby, S. Liddiard, C. Jensen – Moxtek, Inc.
Miniature X-Ray Sources and the Effects of Spot Size on System Performance. https://moxtek.com/wp-content/uploads/pdfs/

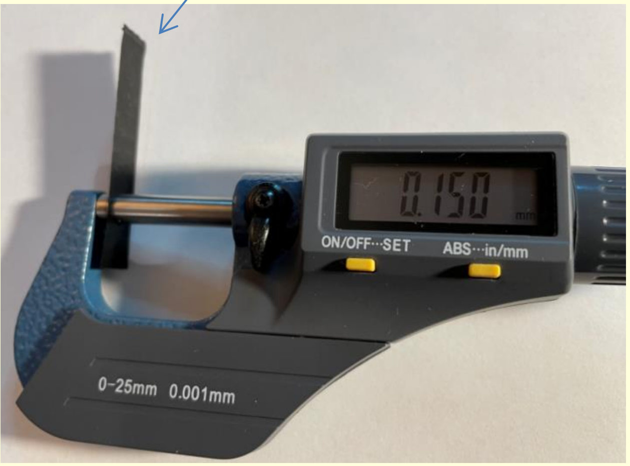
2. Vacuum electron sources with CNT cathodes

Electron sources design of prototypes (robust design)

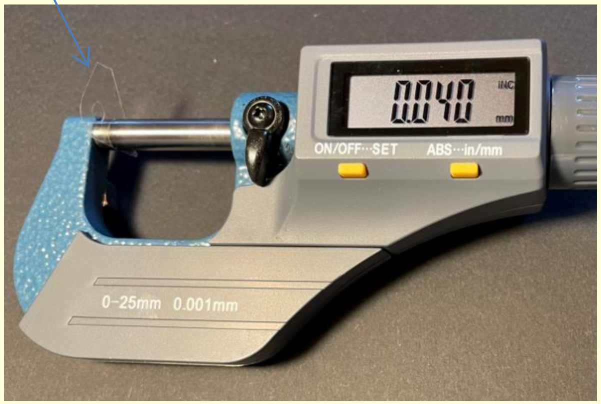


Legende: **1** - CNT FE Cathode, **2** – Spacer (Mica), **3** - Micro Grid (Stainless Steel)

ES with I_E > 5 ... 10 mA



d_{CNT} = ~150 µm



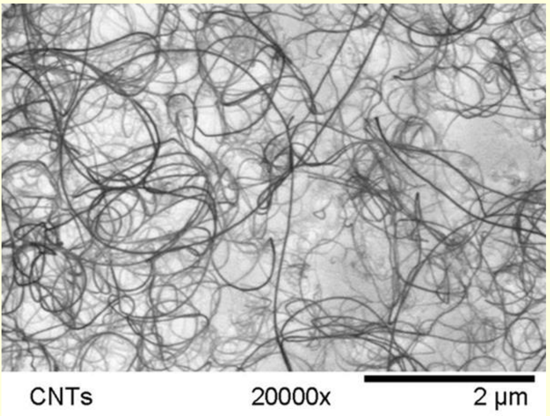
d_{Spacer} = 40 ... 60 µm

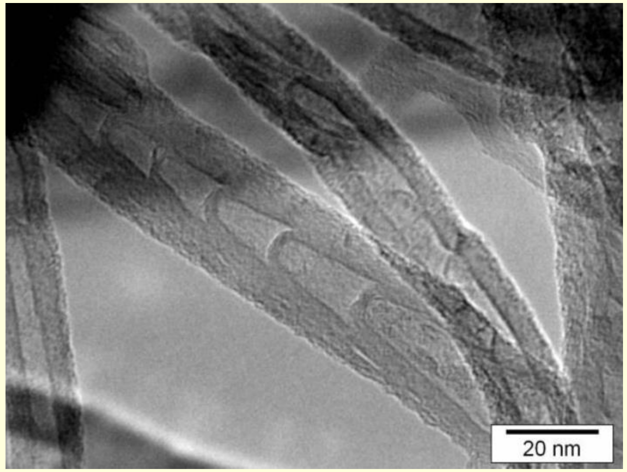
Knapp, Wolfram: Controlled micro-arc treatments in vacuum electron sources with CNT cathodes for long-term emission stability.
Lecture L2.3-4, 8th ITG International Vacuum Electronics Workshop (IVEW) 2022, September 2-3, Physikzentrum Bad Honnef, Germany

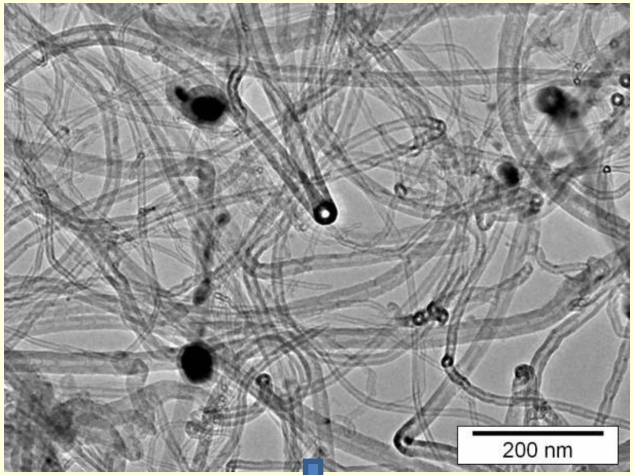
2. Vacuum electron sources with CNT cathodes

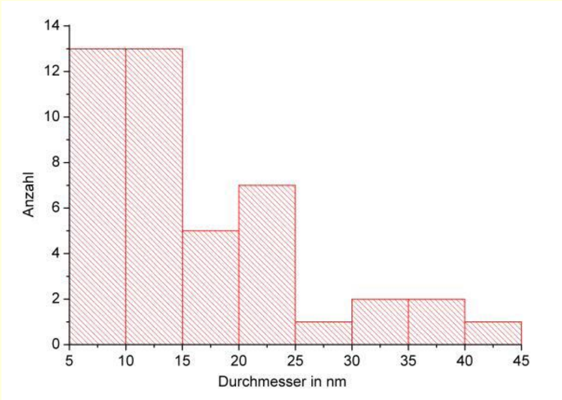
CNT field emitter cathode material: multiwall CNT (MWCNT)

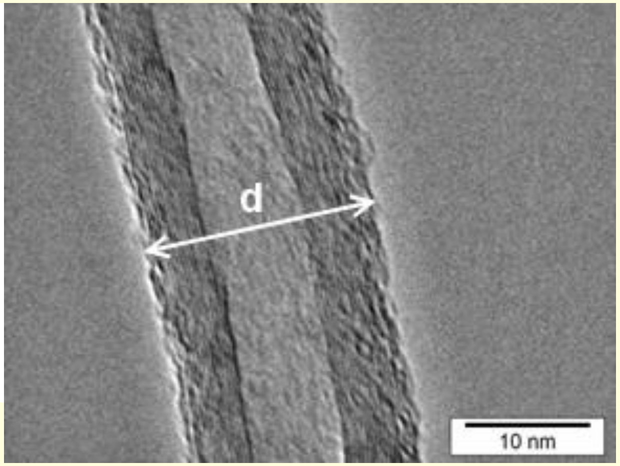
→ 3D structure with excellent field enhancement (γ > 2000)

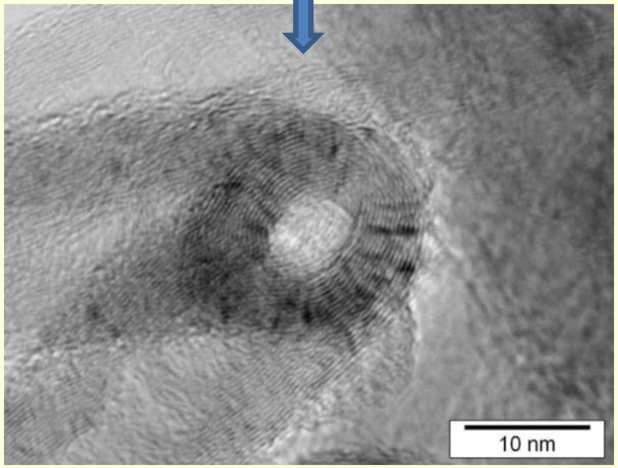








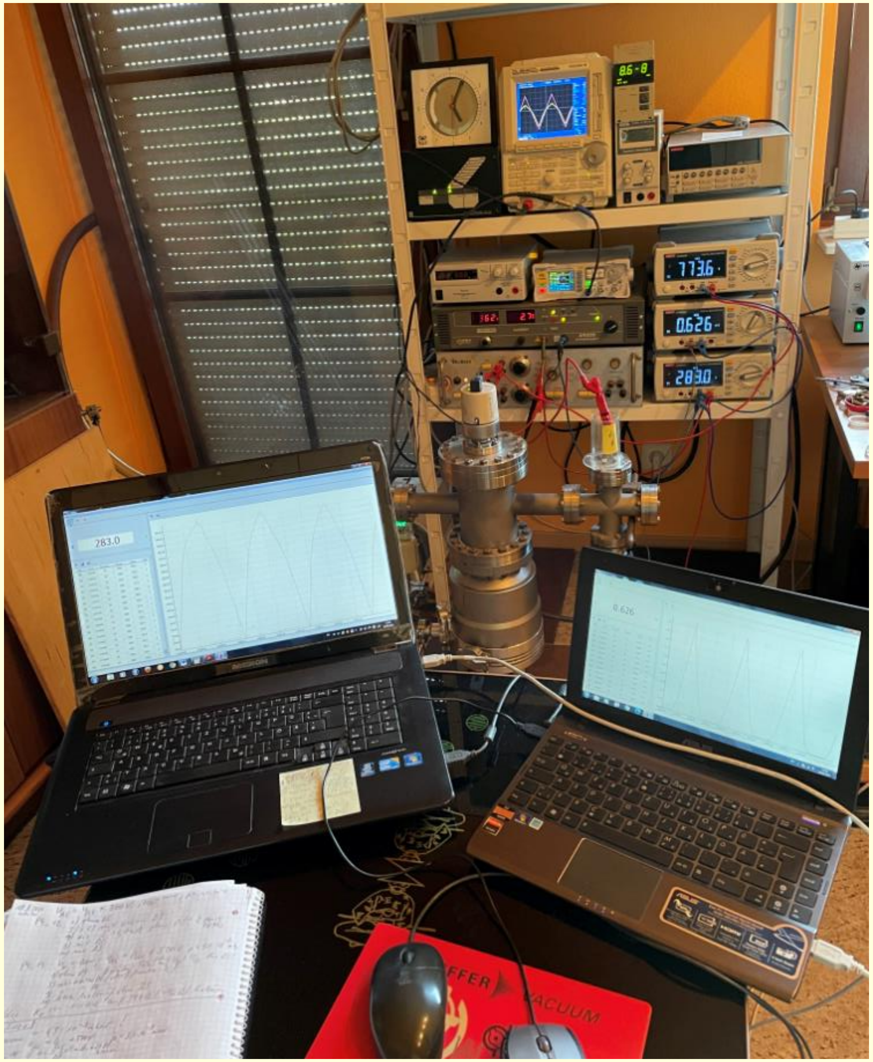


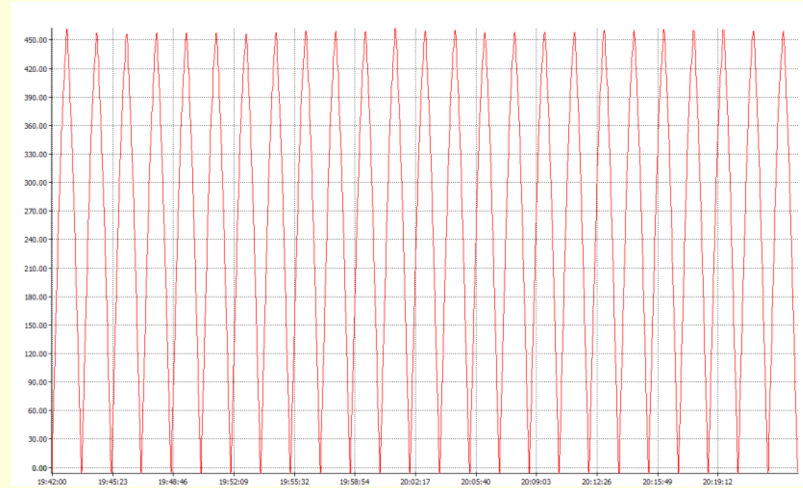


[1] P. Veit: TEM- und EDX-Analyse von Kohlenstoffnanotubematerialien, Report 6.4.2009, Otto-von-Guericke-Universität Magdeburg/FNW/IEP (knapp01.doc)

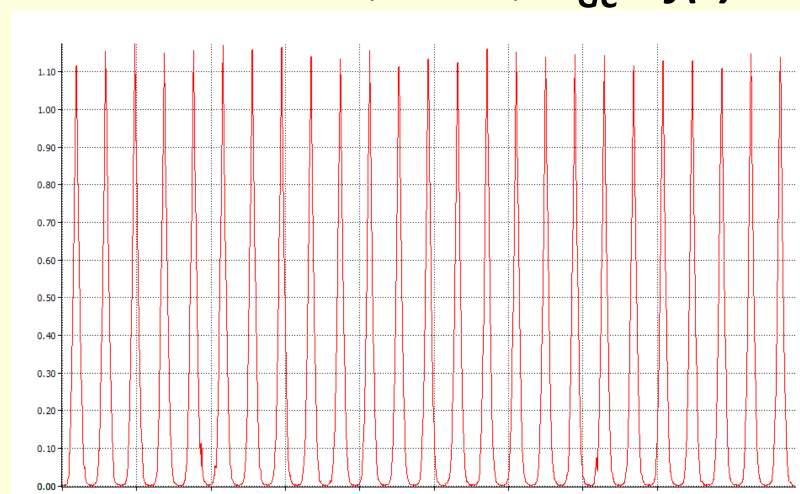
3. Experimental setup

General view of the measuring device with monitoring of 25 field emission (FE) characteristic curve measurements



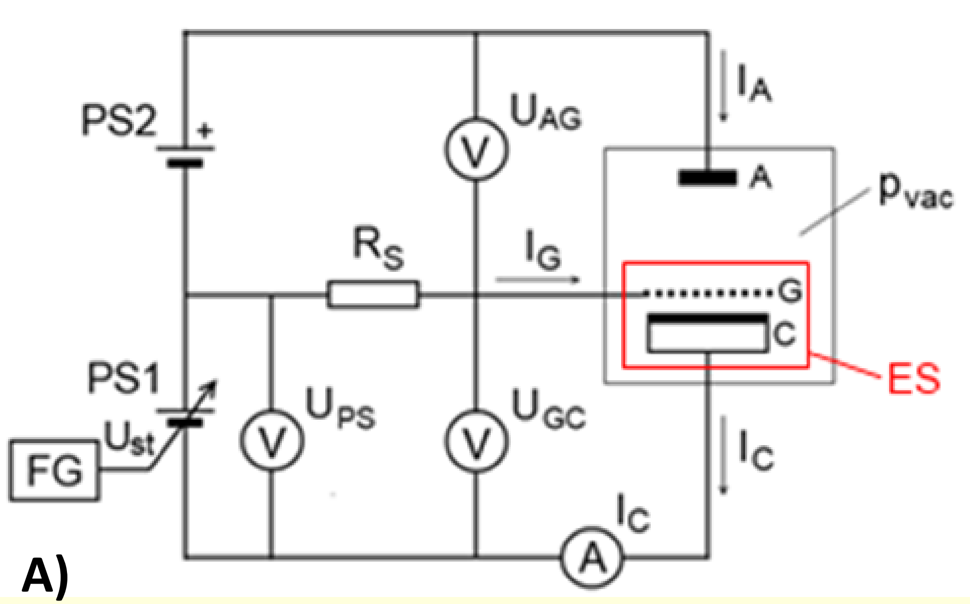


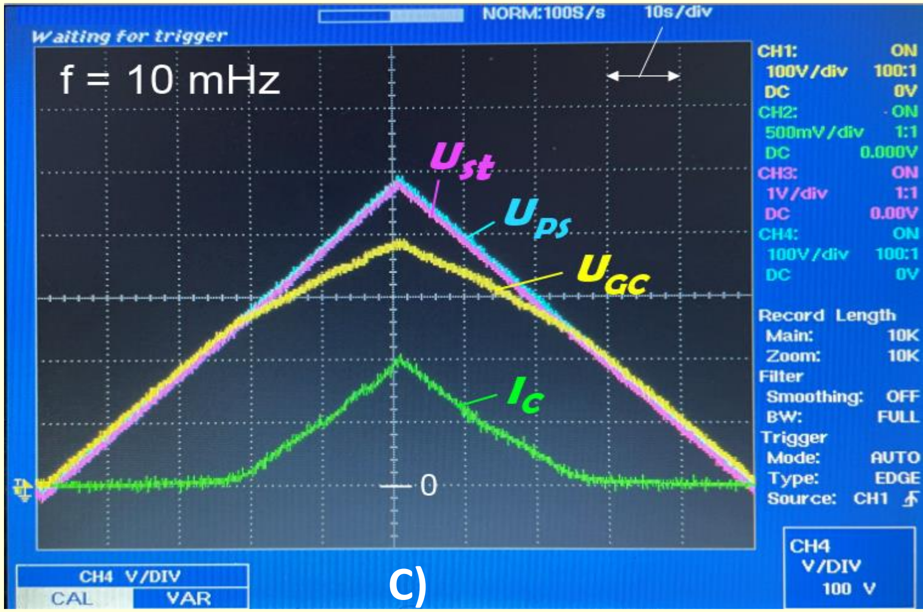
Measurement P4-18 (Probe P4): ***U_{GC} = f(t)***



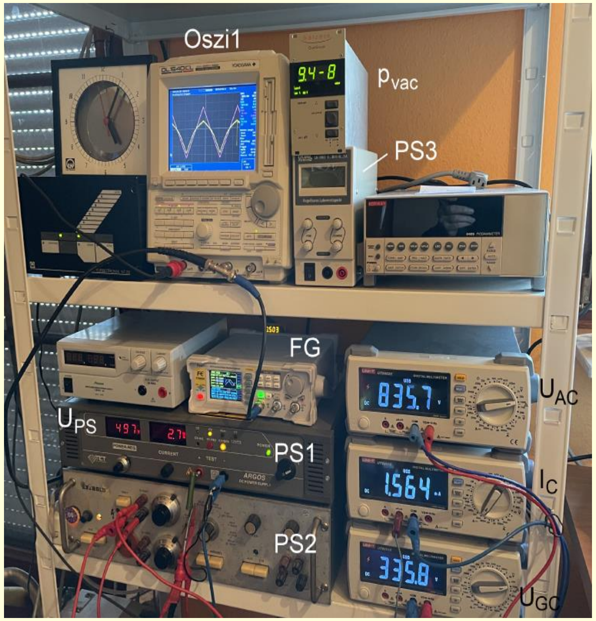
Measurement P4-18 (Probe P4): ***I_C = f(t)***

3. Experimental setup





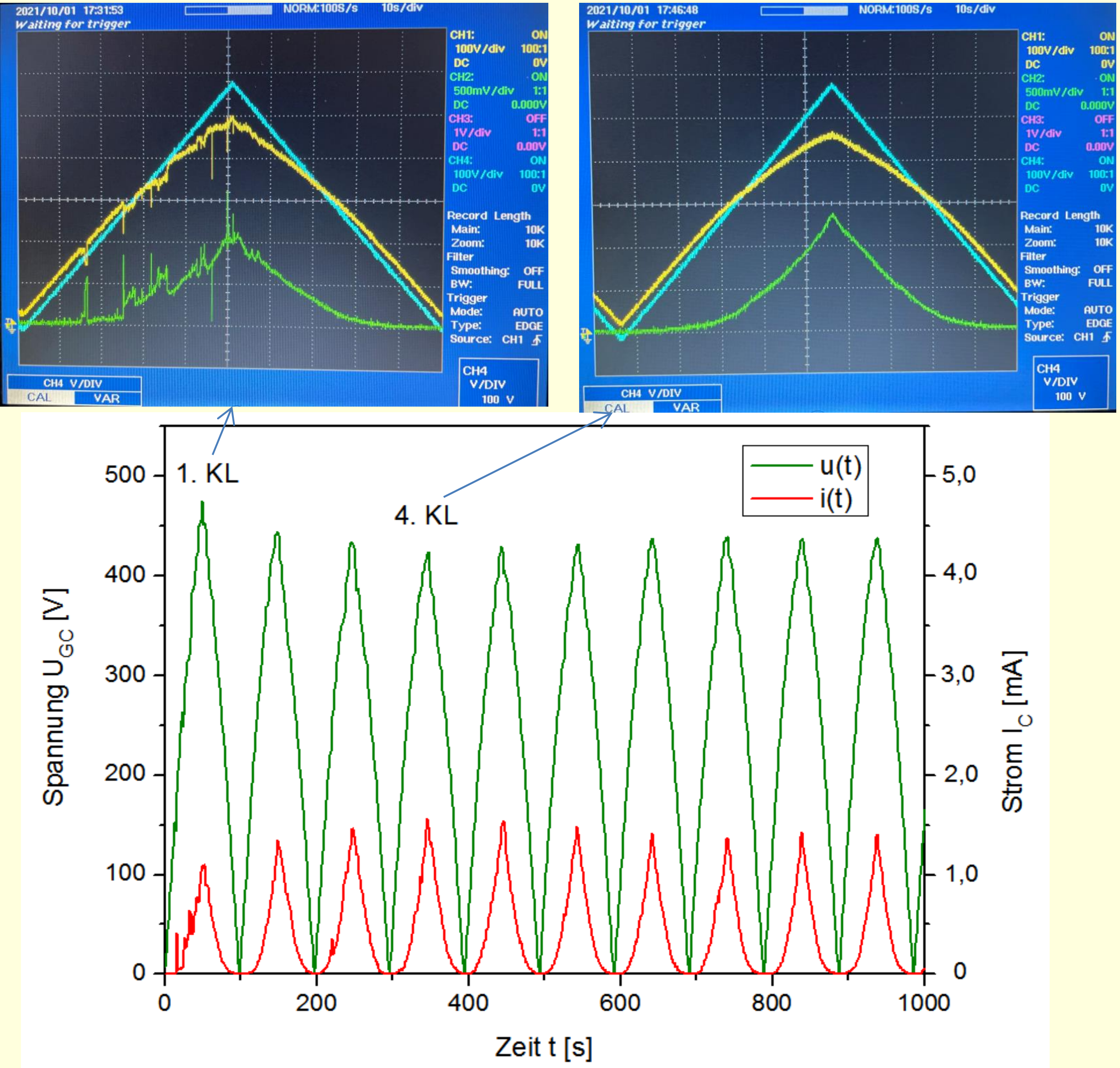
B)



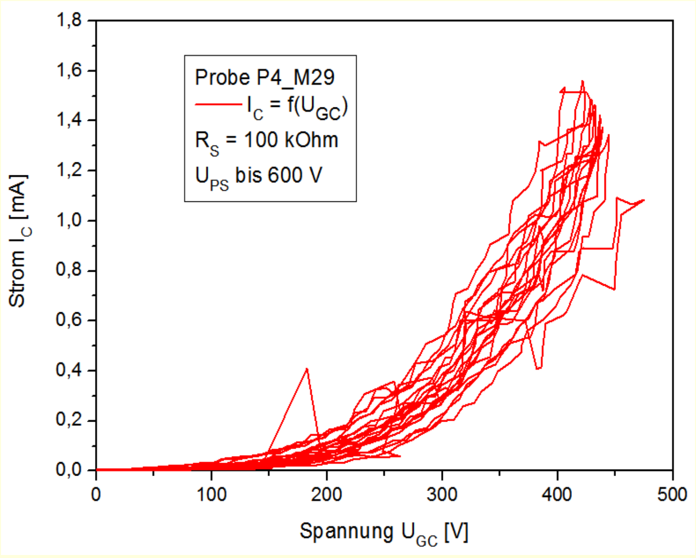
A) Circuit diagram for FE characterization of electron sources with CNT field-emission cathodes,
B) Photo view to the measurement setup of the circuit diagram in **A)** [with permission of KnapptronLab],
C) Oscillogram of a complete FE characteristic curve measurement (up and down measurement in 100 s) with the drive voltage $\boldsymbol{U_{st}}$, programmed voltage of the power supply unit $\boldsymbol{U_{PS1}}$, extraction voltage at the electron source $\boldsymbol{U_{GC}}$ and emission current $\boldsymbol{I_C}$.

4. Standard measurements of FE characteristics

Repeat FE measurements of CNT cathode after 13 days at atmosphere

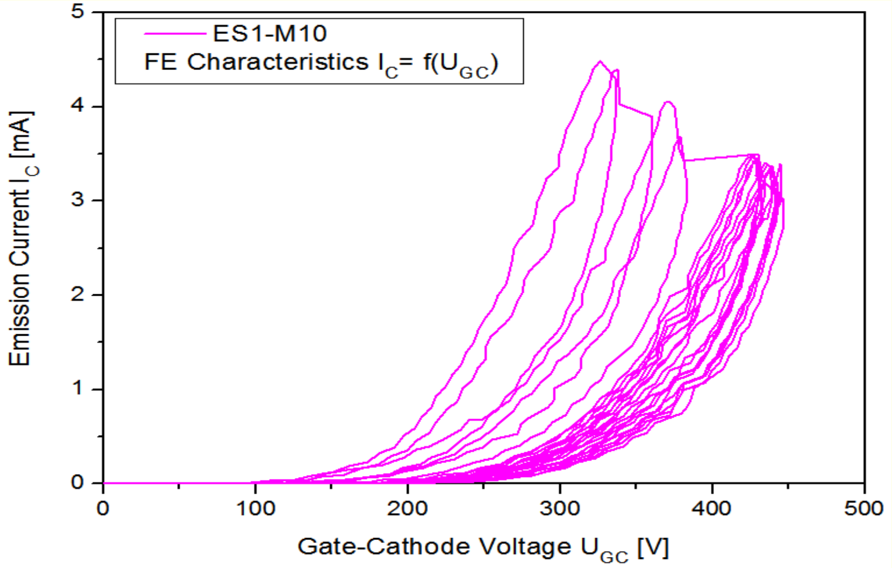


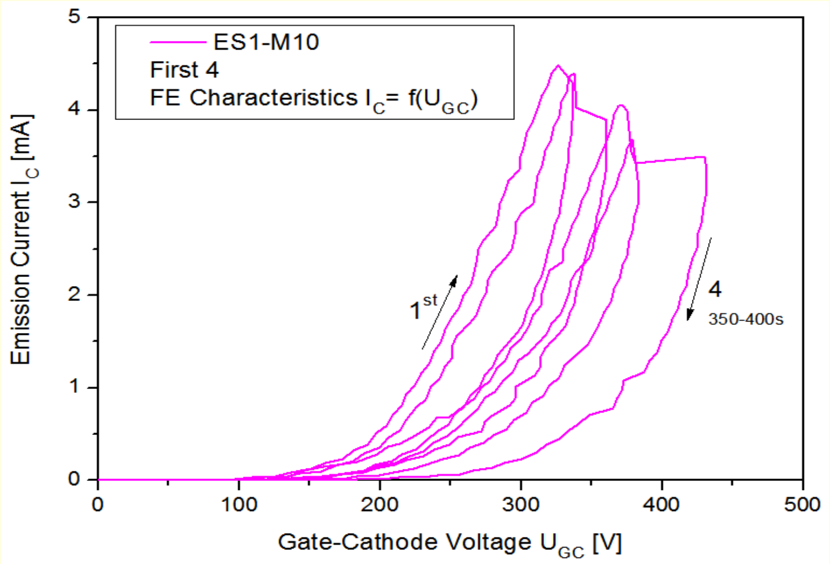
Note:
- In FE measurements, the first measurements are more strongly associated with other effects, e.g. caused by outgassing, if no special pretreatment has been performed.
- But, the first measurements are a simple pretreatment, so for the analysis of field emission, a later measurement is more accurate.



4. Standard measurements of FE characteristics

Example: Pretreatment includes the first 4 FE characteristic curve measurements (Pretreatment time approx. 400 seconds)



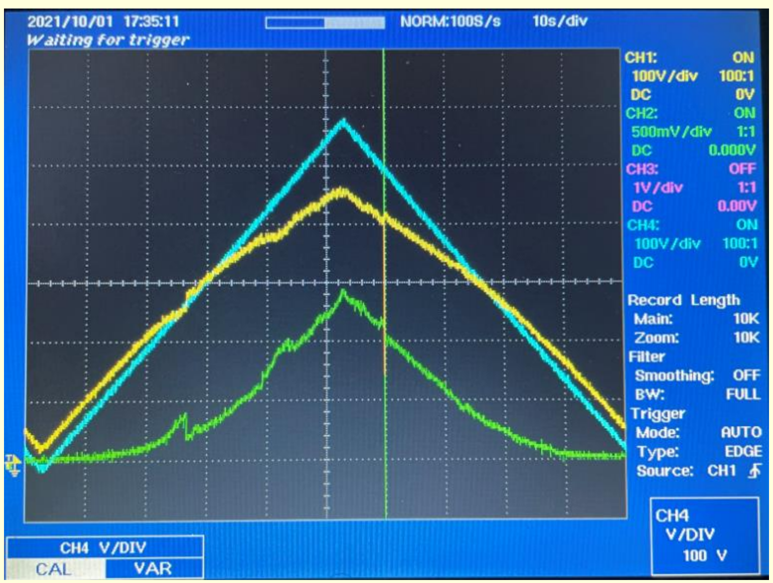


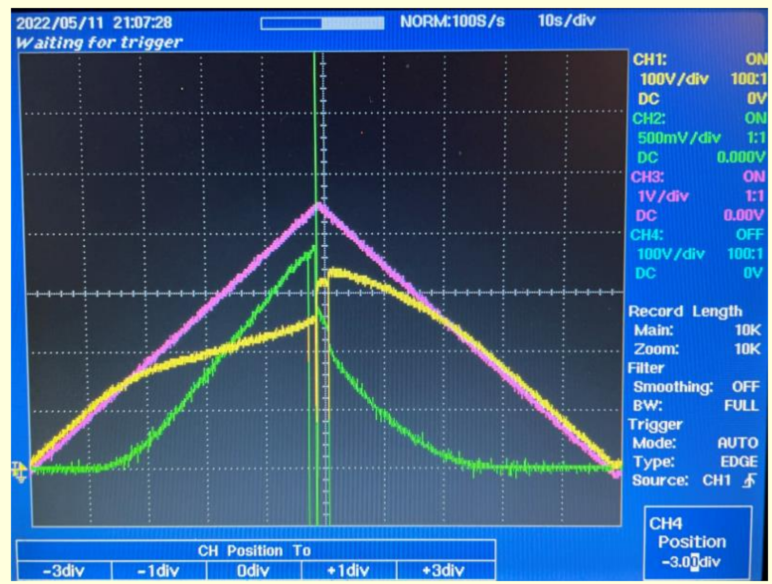
Note:

- In FE measurements, the first measurements are more strongly associated with other effects, e.g. caused by outgassing, if no special pretreatment has been performed.
- But, the first measurements are a simple pretreatment, so for the analysis of field emission, a later measurement is more accurate.

5. Characterization of discharges (breakdowns)

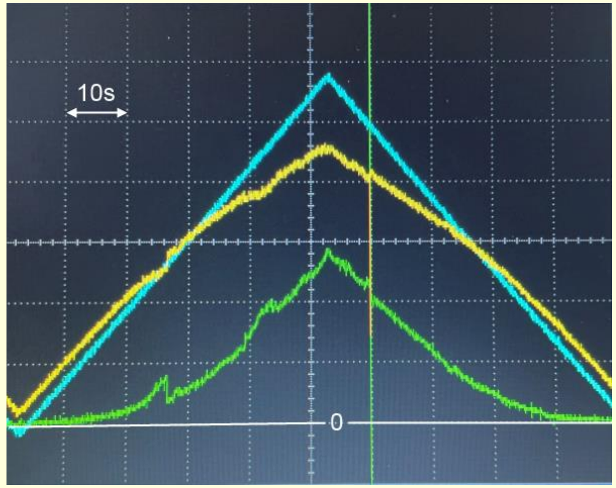
Observation of typical discharges during characteristic curve measurements

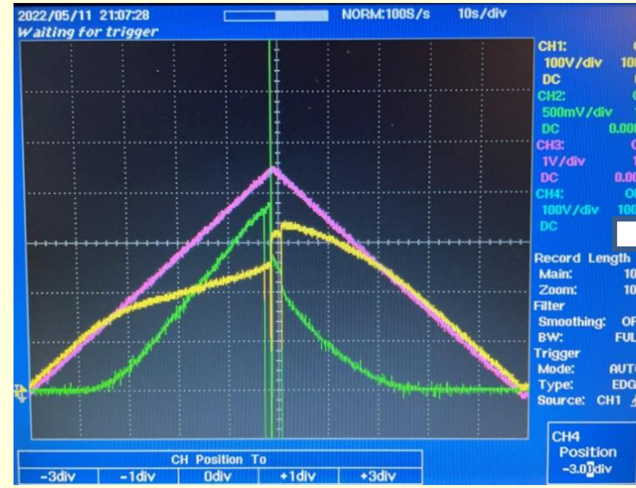




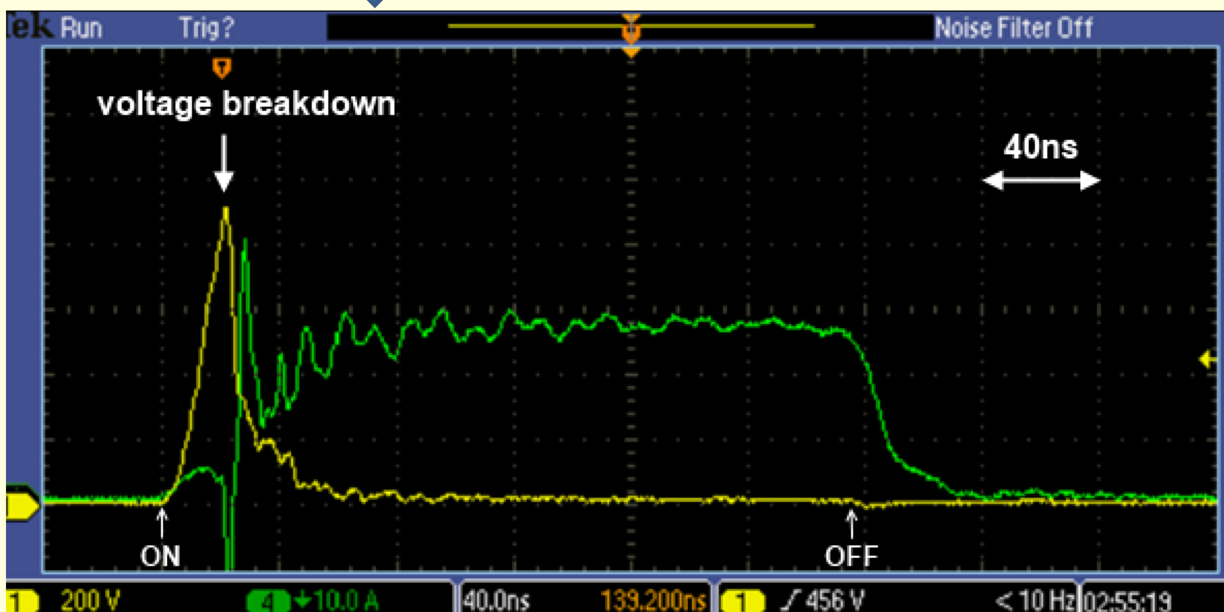
5. Characterization of discharges (breakdowns)

Why do the discharges have positive and negative current peaks (green curves)?



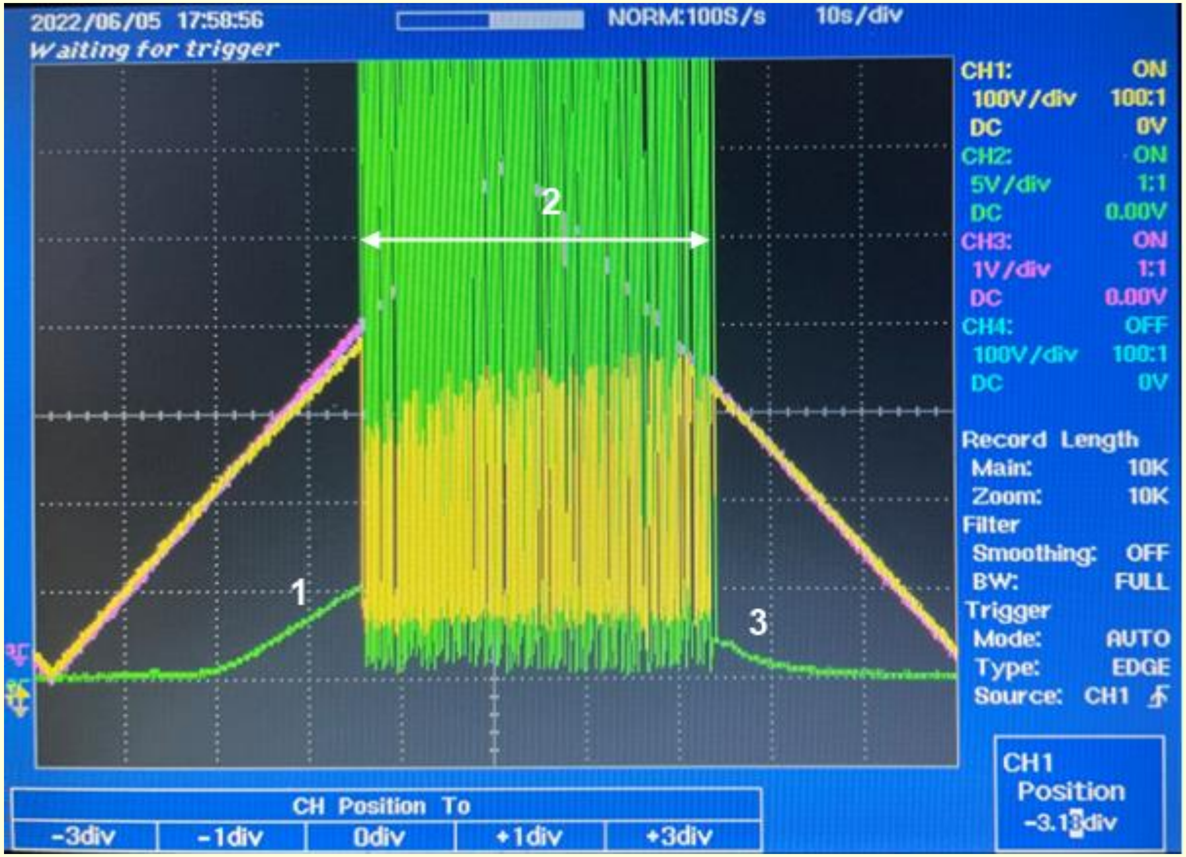


Discharge measurement with high time resolution gives the answer:
Initial plasma oscillation after voltage breakdown with transition to quasi-stationary plasma (pulse: t_p ~ 235 ns) [1].



[1] https://www.eagleharbortech.com/wp-content/uploads/2020/05/EHT-prod-brochures-NSP-line-V12-web.pdf

6. Controlled micro-arc treatments for stability



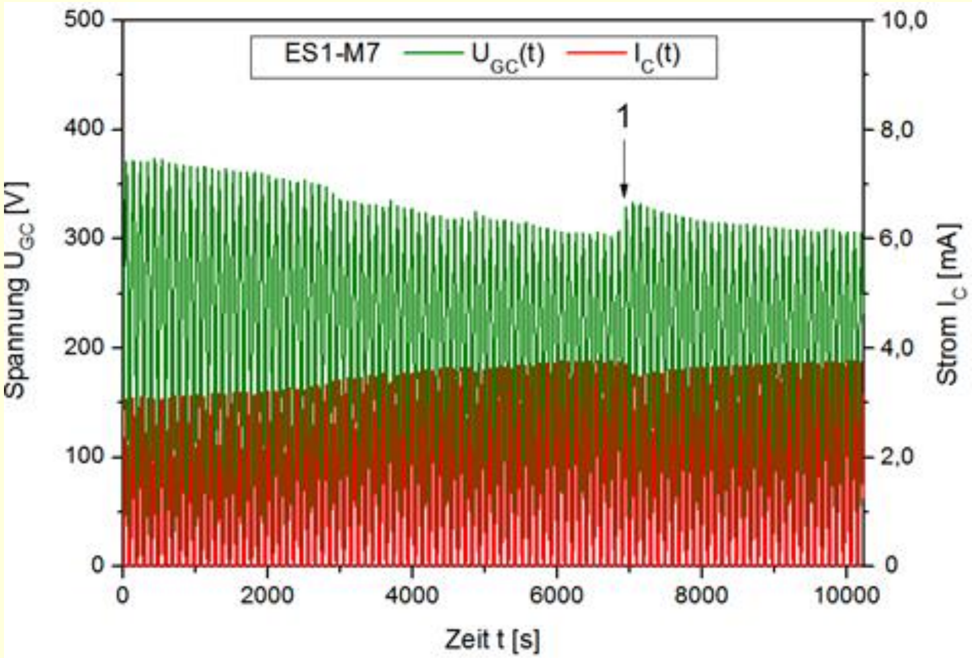
Controlled micro-arc treatment (**2**) with ~ 40 seconds duration and with FE characteristic before (**1**) and after micro-arc treatment (**3**) [measurement ES1-M19].

<u>Control of the micro-arc treatment via the elektrical parameters (p_{vac} = const.):</u>

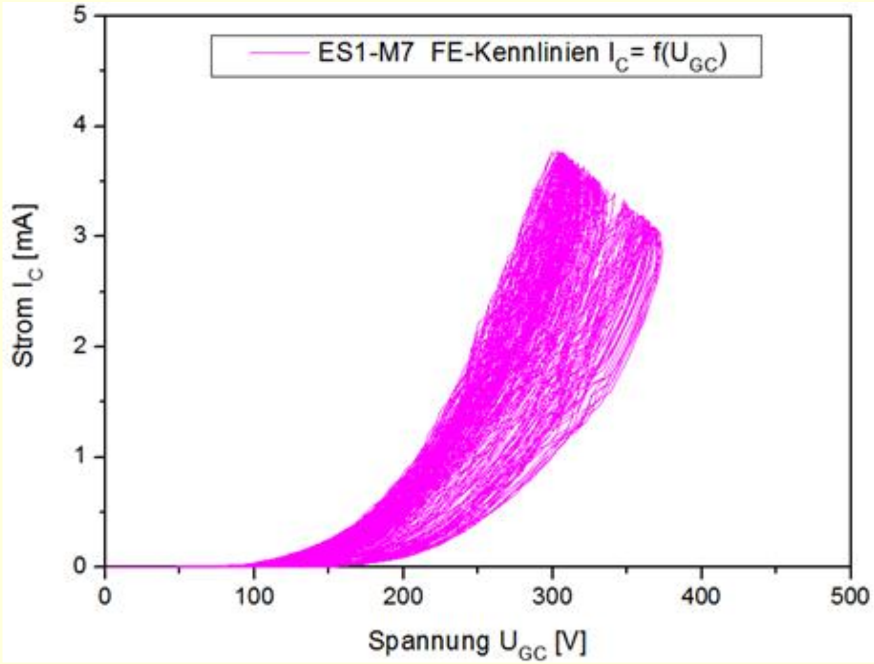
1. Series resistor R_S = 4,7kΩ (for all other FE characteristic measurements R_S = 100kΩ!),
   ⟹ higher extraction voltage U_{GC} and also field strength E_{GC} (when d_{GC} = constant).
2. Limitation of the PS1 short-circuit current $I_{C\text{-}max}$ = 24 mA (here with oscillations).

6. Controlled micro-arc treatments for stability

Long-term test after micro-arc treatment for conditioning (burn-in)



A)



B)

Fig. 1 **Long-term test** of the electron source ES1 (M7 with $U_{PS\text{-}max}$ = 700V, R_S = 100 kΩ):
A) $U_{GC}(t)$ and $I_C(t)$ time courses over the period of approx. **100 field emission characteristic curve measurements** (measuring time t > 10.000s ~ 3h),
B) FE characteristic diagram $I_C = f(U_{GC})$ with tolerance range in long-term test.
Note: the tolerance range is the result of all elements and devices in the measuring circuit!

7. Options for increasing the emission current

Field Emission driven Explosive Electron Emission (EEE)

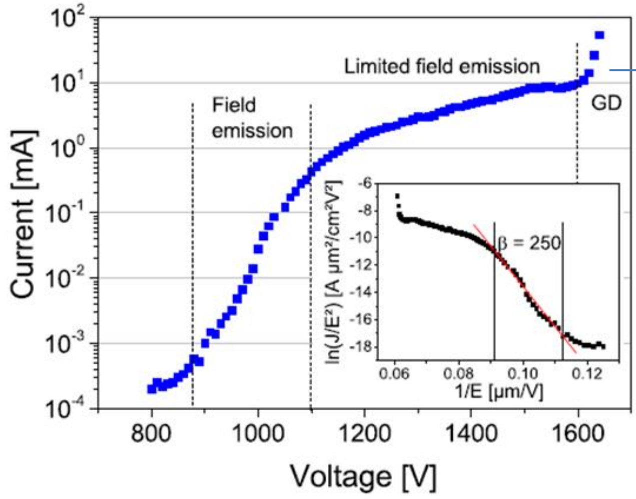
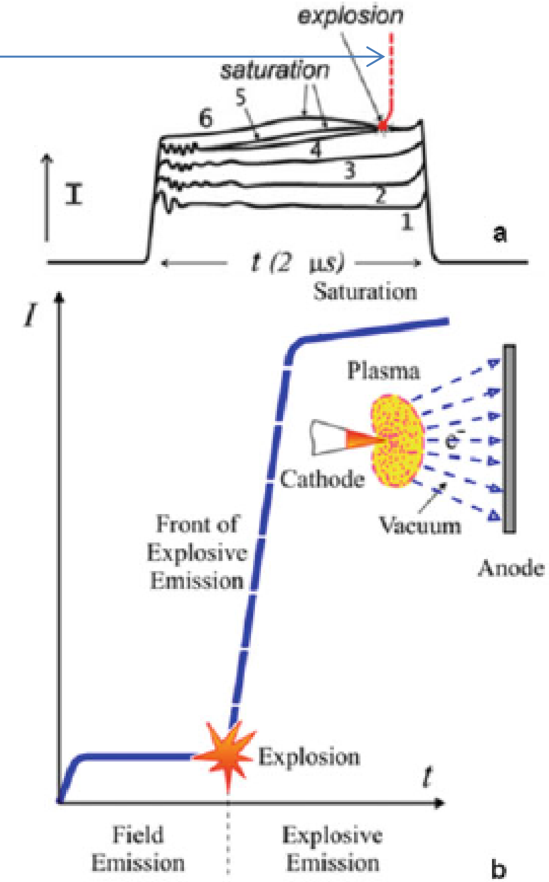
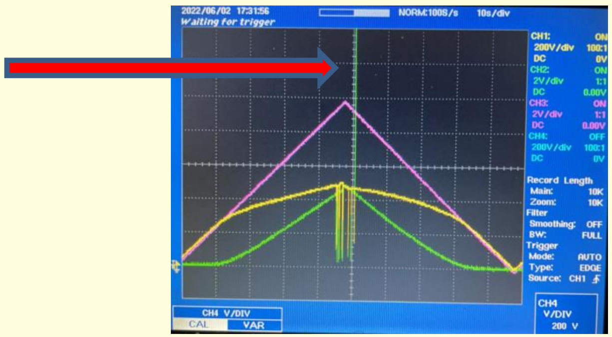


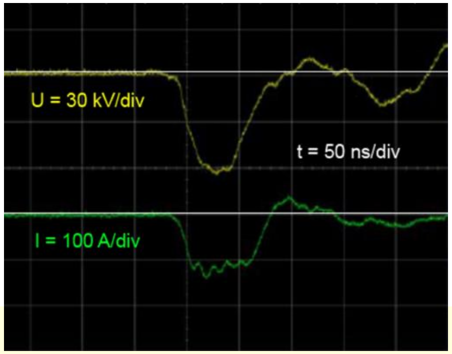
Fig. 2. I–V characteristics in dc mode. Three different emission areas are visible: FN-type FE, limited FE, and vacuum breakdown (GD). The field enhancement factor $\beta = 250$ is calculated from the FN plot (inset).

Fig. 11.1 a Behavior of a field emission current before an explosion, for a single pointed tungsten emitter. Curves 1, 2, 3, 4, 5 and 6 are oscillograms of the FEE current as the voltage is increased; "saturation" is the transition to the saturation stage; "explosion" is the transition point to the EEE (the build-up of electron current at the instant of the explosion is shown by a dashed line). **b** Scheme (model) of the transition from field emission to explosive emission for a single point emitter



I_{EEE}





[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).

[2] G. Gaertner, W. Knapp, R.G. Forbes: Modern Development s in Vacuum Electron Sources. Topics in Applied Physics, Vol. 135, Springer Nature Switzerla nd AG, 2020, see Chapter 11: Georgiy N. Fursey: Explosive Electron Emission of Carbon-Based Cathodes and Application.

7. Options for increasing the emission current

Field Emission driven Explosive Electron Emission (EEE)

Plasma-physical approach:

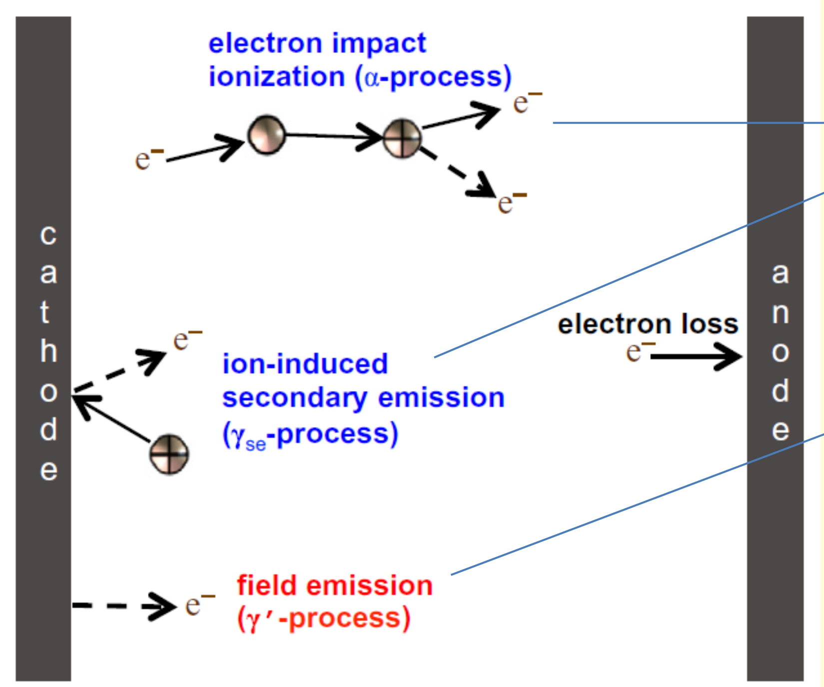


Figure 2. Schematic of charge generation processes in a standard DC discharge. Electron impact ionization (α-process) generates electrons in the volume while secondary emission (γ-process) generates electrons at the cathode. Field emission is the process of direct electron tunneling into the gas due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

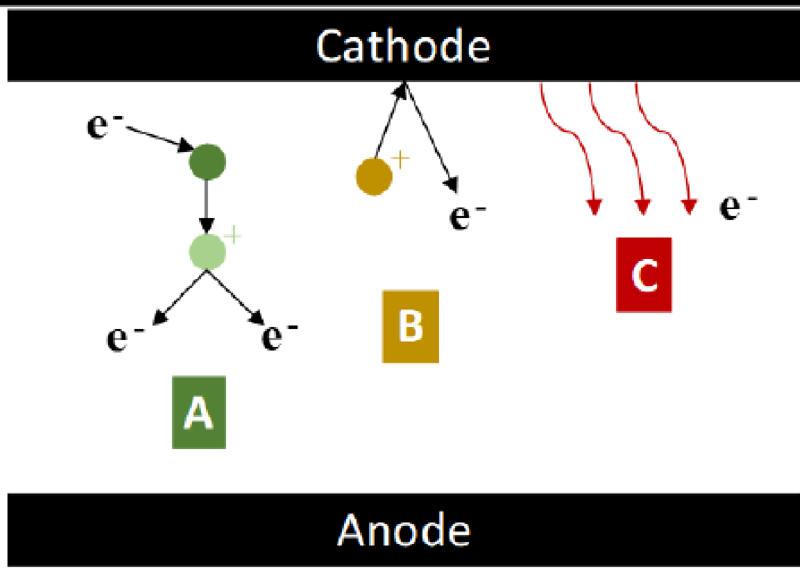
[1] D.B. Go, A. Venkattraman: Microscale gas breakdown: ion-enhanced field emission and the modified Paschen´s curve (Topical Review), J. of Phys. D: Appl. Physics 47 (2014) 503001.

7. Options for increasing the emission current

Field Emission driven Explosive Electron Emission (EEE)

Plasma-physical approach:

Microscale Gas Breakdown



A: Impact ionization & collisional process – Townsend Avalanche. B: Ion-induced secondary emission; C: Field emission.

Modify Townsend avalanche criterion to include ion enhancement from positive space charge due to field emission

$$\boxed{(\gamma_{SE} + \gamma')[\exp(\alpha d) - 1] = 1}$$

This positive space charge will also increase the electric field by an amount $E^+ \ll E$ **!**

$$j'_{FN} = C_{FN}(E + E^+)^2 \exp[-D_{FN}/(E + E^+)]$$

Couple with Poisson's equation

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon_0}$$

where ρ is the charge density and ε_0 is the permittivity of free space. At breakdown:

$$F_{br} = \frac{2E^2 v_d \varepsilon_0}{D_{FN} d j_{FN}} \frac{\{1 - \gamma_{SE}[\exp(\alpha d) - 1]\}}{[\exp(\alpha d) - 1]} = \frac{\exp(x_0)\,(1 + 2\bar{E}x_0)}{x_0}$$

$$x_0 = \frac{-1 + \sqrt{1 + 8\bar{E}}}{4\bar{E}} \approx 1$$

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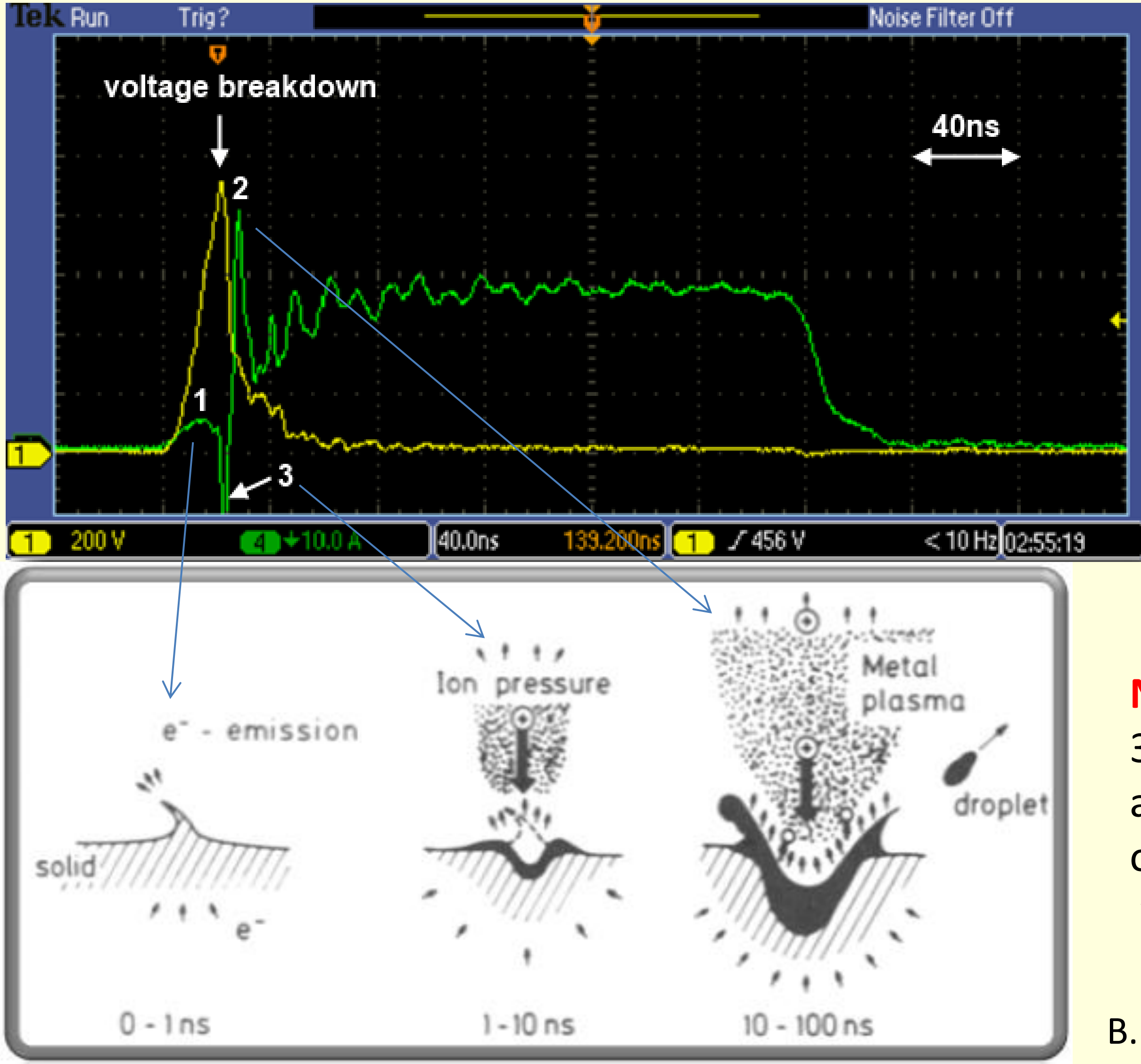
A. L. Garner, A. M. Loveless, J. N. Dahal, and A. Venkattraman, IEEE Trans. Plasma Sci. **48**, 808-824 (2020).

7. Options for increasing the emission current

Field Emission driven Explosive Electron Emission (EEE)



<u>Two pulse techniques are possible:</u>

1) **1st pulse**
Short time FE pulse
$t_{e^{-}-pulse} < 10\, ns$

2) **2nd pulse**
1st pulse-amplitude of plasma oszillation
$10\, ns < t_{e^{-}-pulse} < 30\, ns?$

Note:
3) Between both pulses can be a strong ion bombardment of the cathode!
$t_{i^{+}-pulse} \approx 3 \ldots 4\, ns$

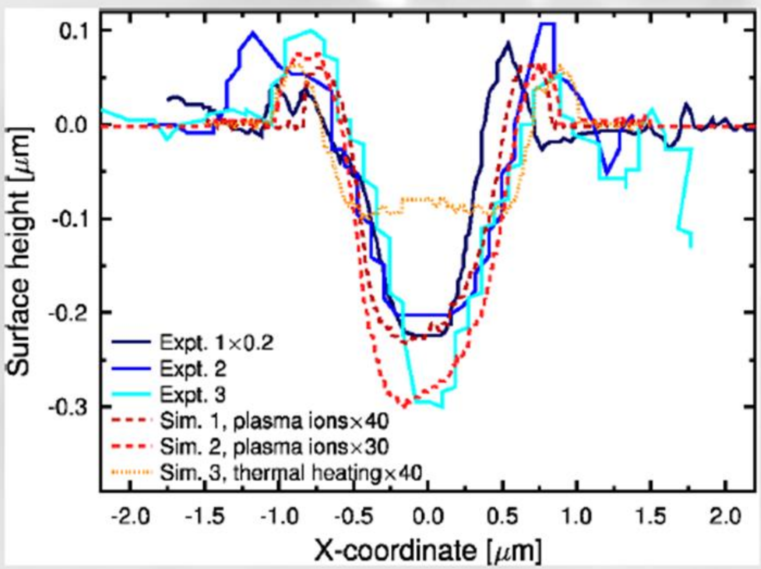
B. Jüttner, 1979, R. Behrisch 1988

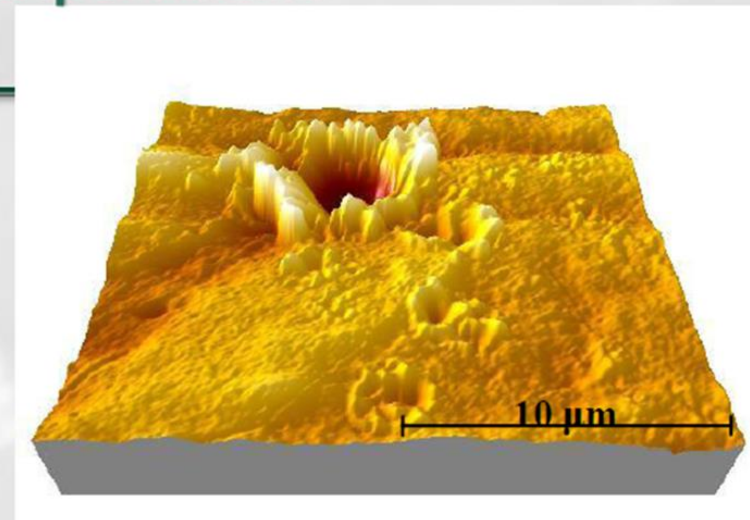
7. Options for increasing the emission current

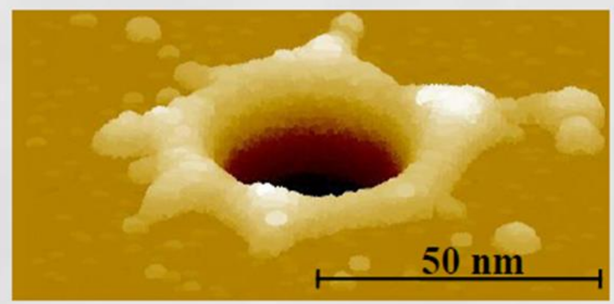
Investigations of cathode-side breakdown damage at the Uni. Helsinki:

Comparison to experiment

- **Self-similarity:** Crater depth to width ratio remains constant over several orders of magnitude, and is the same for experiment and simulation







H. Timko, F. Djurabekova et al., Mechanism of surface modification from the arc plasma–surface interaction in Cu, Phys. Rev. B 81, 184109 (2010).

8. Summary and outlook

- **Prototype electron sources with CNT field emission cathode can be used for applications up to about 10 mA DC.**
- **CNT field emitter are pre-aged (burn-in) by controlled micro-arc treatments.**
- **The control is performed via the vacuum pressure and electrical parameters.**
- **The most important goal is to achieve a long-term stable electron field emission for a wide range of vacuum electronic applications.**
- **For higher emission currents > 1A the pulse technique has advantages, assuming the field emitter can withstand ion bombardments.**
- **When applying high voltage pulses, the pulse time should be less than 10 ns. Then the transition to Explosive Electron Emission (EEE) takes place.**
- **CNT field emitters are very well suited as cold cathodes for mini X-ay tubes.**
- **This makes them ideal for use in static (non-mechanical rotation) computed tomography scanners, which will be equipped with hundreds of mini X-Ray tubes and very fast electronic CT scanning depending on the detectors.**

Thank you very much for your attention!

The speaker as Otto von Guericke during the 30th IVNC 2017 in Regensburg/Walhalla