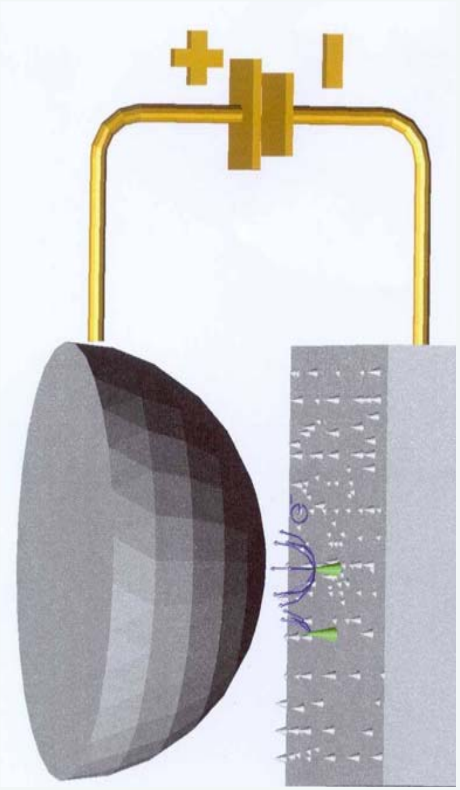
DC Spark Test System for CLIC



Trond Ramsvik

TS / MME

27 January 06

Outline

- *Introduction*
  - *Motivation, Origin of Breakdown*
- *Experimental Setup*
- *Local Field*
- *Spark Conditioning (Mo, W, Cu)*
    - *General*
    - *Breakdown Field ↔ Material*
    - *Breakdown Field ↔ Residual Gas*
    - *Breakdown Field ↔ Surface Treatments*
  - *Comparison with results from RF*
- *Spark Conditioning (Ti)*
- *Future projects / Wishes*
- *Conclusions*

Introduction: Why DC spark experiments?

With a simple DC spark-test system, the properties of various materials can be studied at high electric fields in an easy and controlled way.

➡ **Goal: To find materials that withstand the highest field without breakdown and have low level of deterioration even when breakdown events occur.**

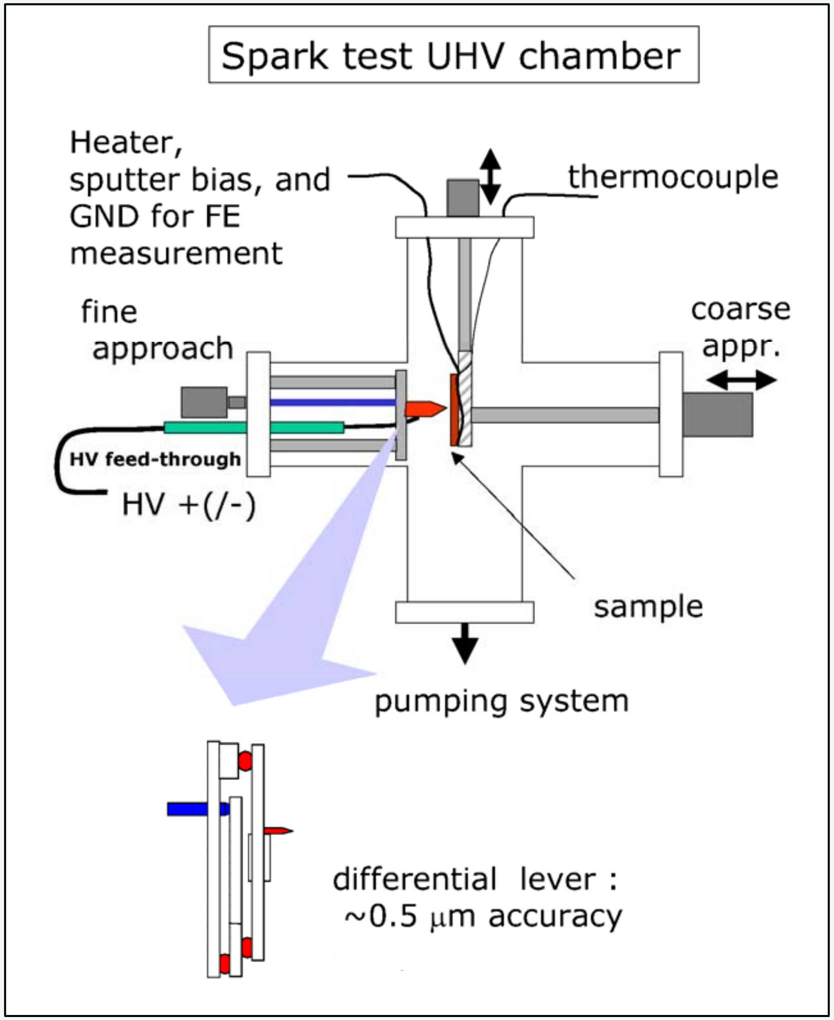
Introduction: Origin of Breakdown

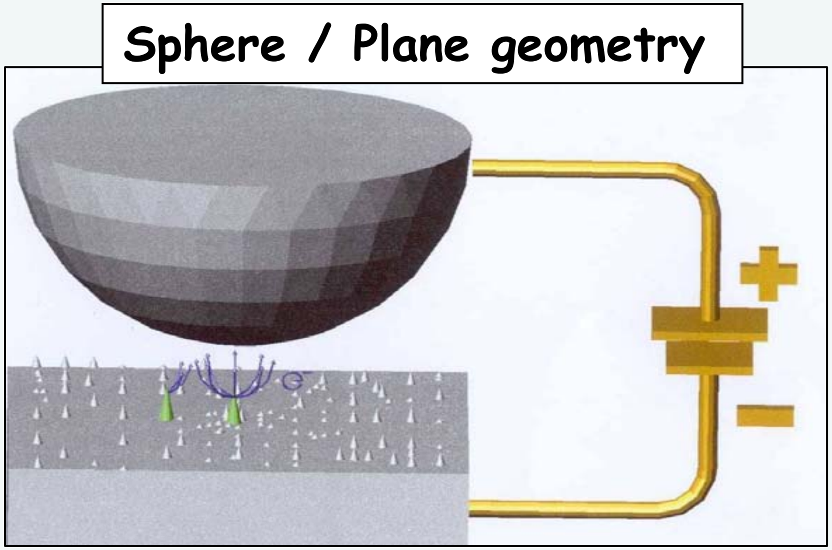
- ***The physics of breakdown is still not perfectly understood***

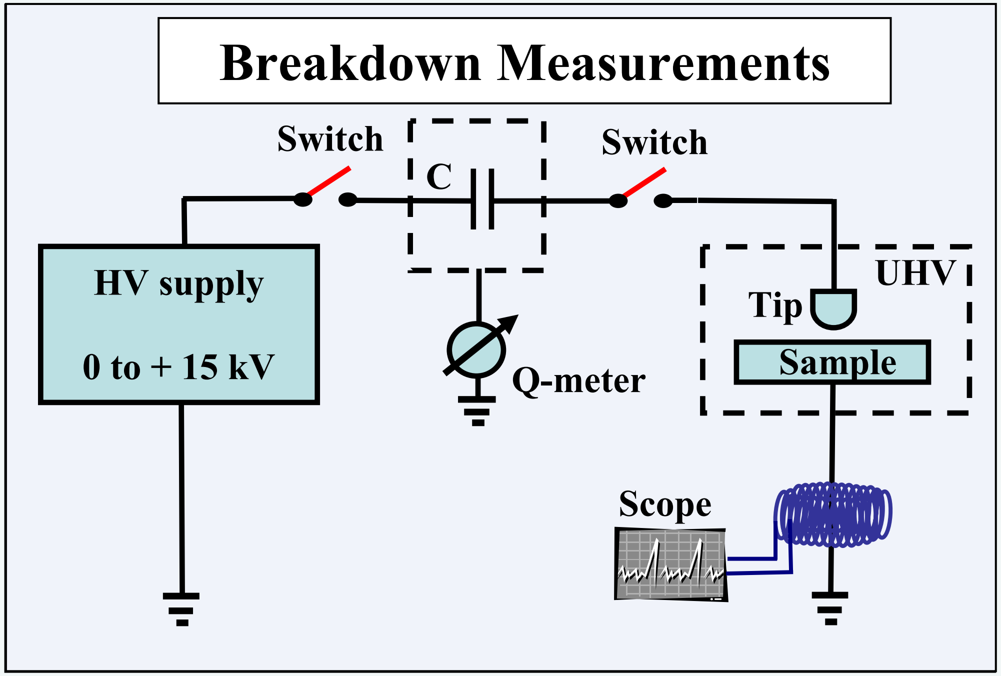
- ***Commonly accepted that breakdown at small gaps (d ≤ 0.5 mm) is initiated by an electron field emission based mechanism from one or a few microprotrusions****

- ***Process towards breakdown. Suggested Models:***
  - *"Anode-initiated"*
    - electron bombardment of anode
      - release of gas and/or anode material through intense localized heating or electron stimulated desorption (ESD)
      - Avalanche ionization of the released species
  - *"Cathode-initiated"*
    - The microprotrusion on the cathode becomes unstable
      - fracture of the surface due to the tensile stress produced by the electric field
      - ohmic heating from high field emission current density
  - *Exchange*
    - Avalanche of mutual secondary emission of ions, electrons between the electrodes

Experimental Setup



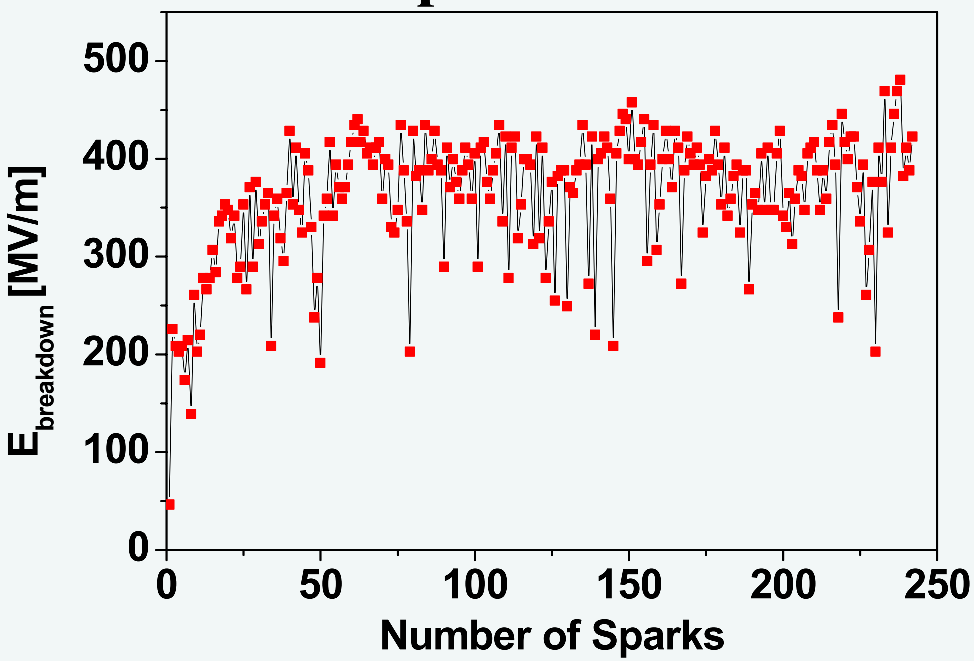




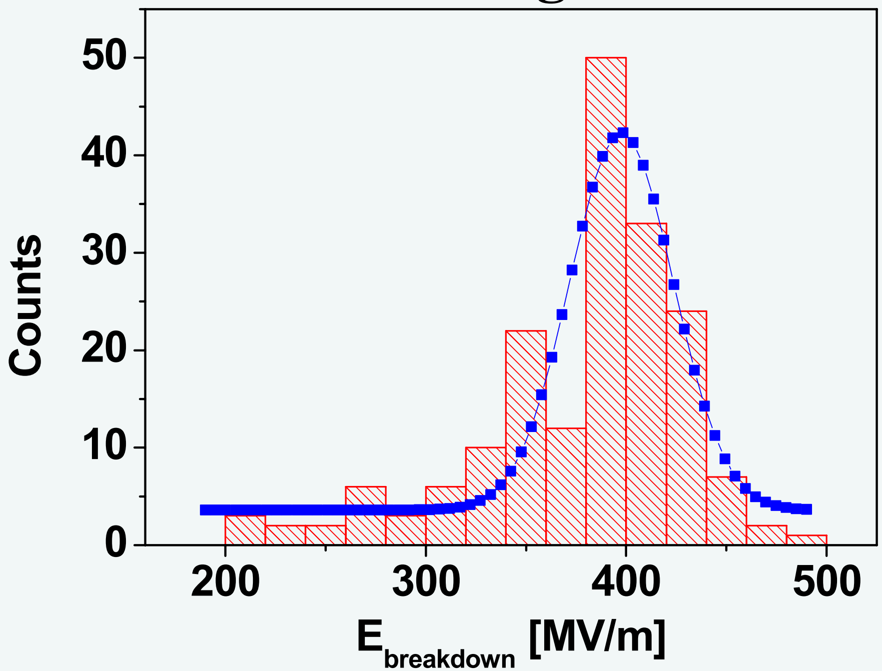
Automatic Spark Conditioning

Molybdenum (Mo) – Tip and Sample

Spark Scan



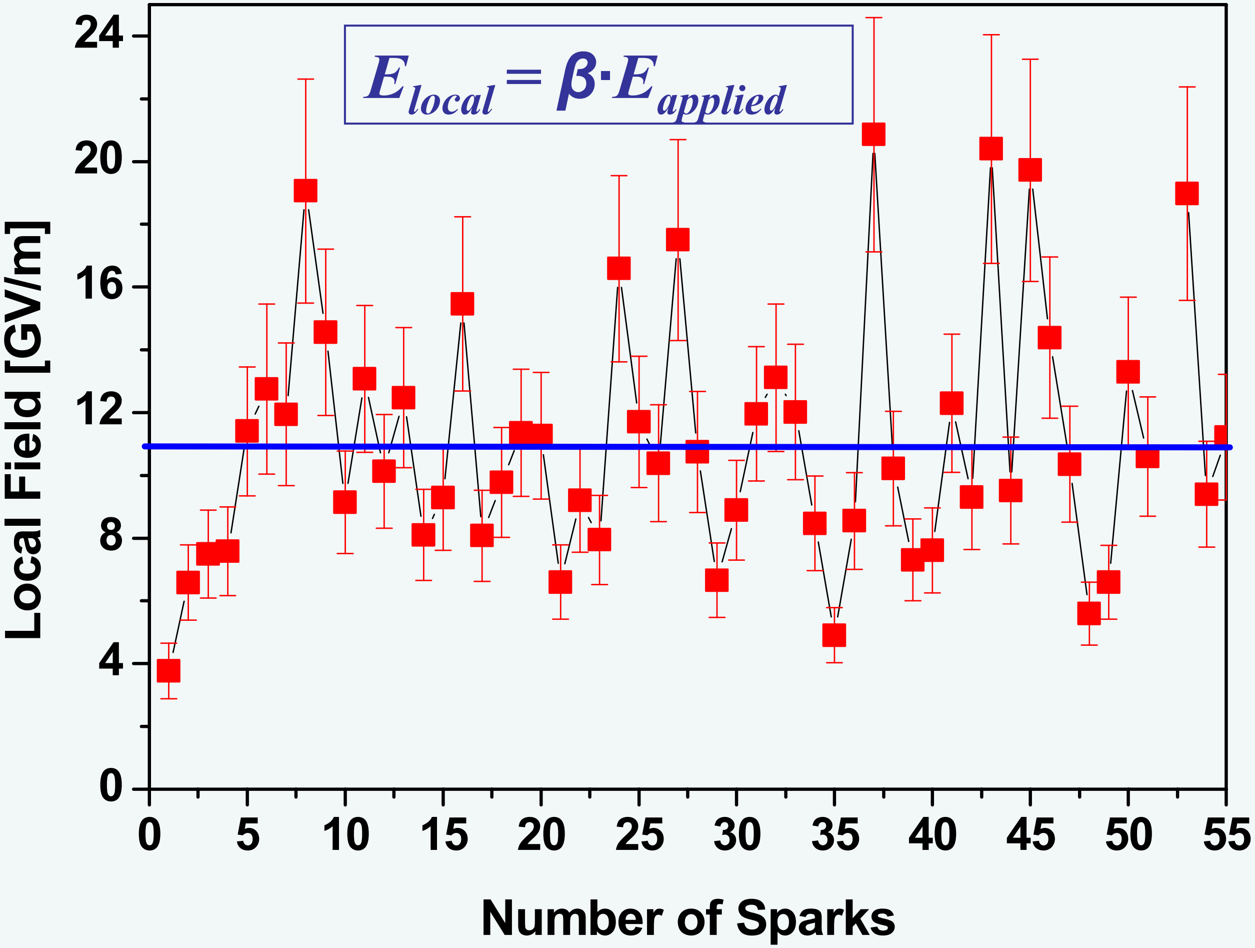
Histogram



$$E_{breakdown}^{sat} \cong (398 \pm 4)\ MV/m\ at \sim 4 \times 10^{-8}\ mbar$$

Local Field

Field evaporation ↔ Tensile Strength



Measured tensile strength of Mo*:

750 MPa

$$\sigma = \frac{\varepsilon_0 E^2}{2}$$

$E_{local} \approx 11$ ***GV/m***
(max 21 GV/m)

⇩

$\sigma_{tensile} \approx$ ***<u>520 MPa</u>***
(max ~1950 MPa)

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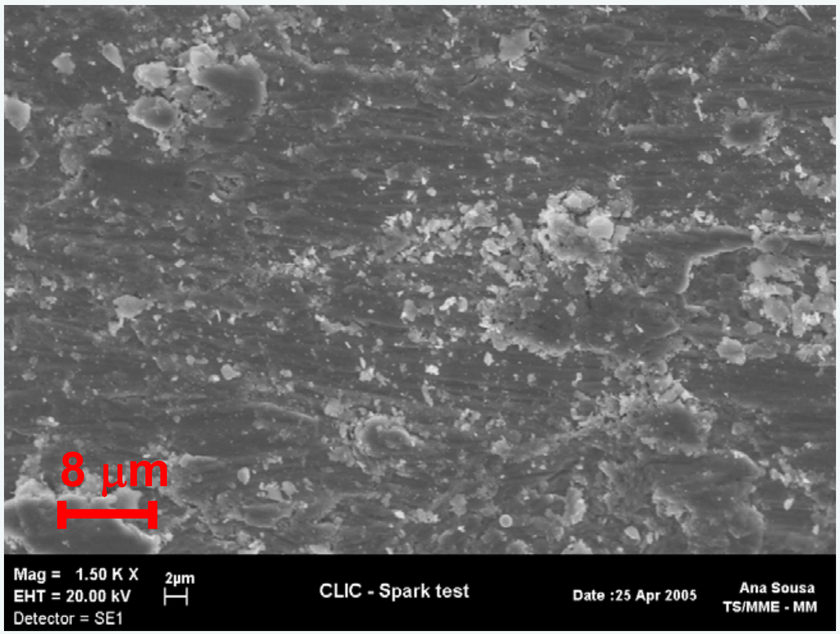
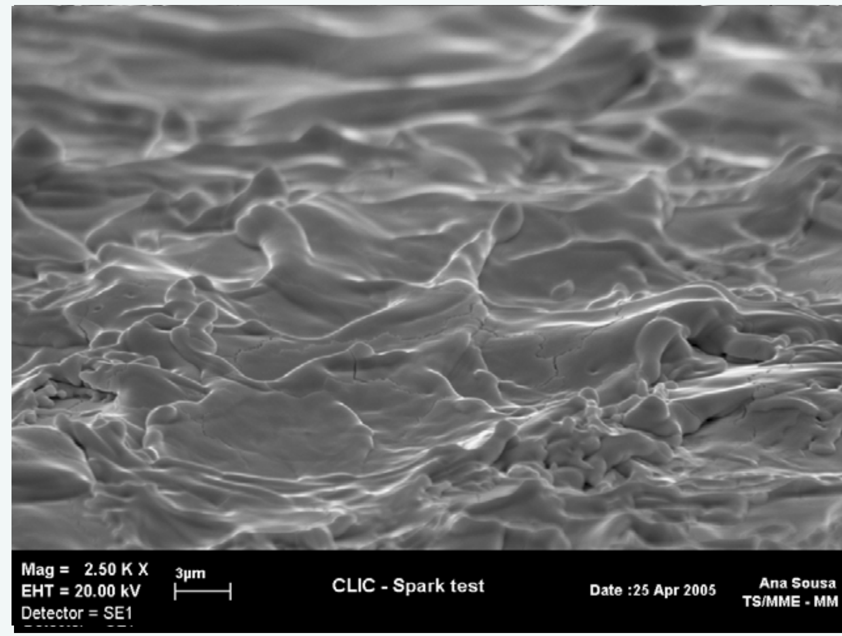
Scanning Electron Microscopy

Molybdenum surface after ~ 1600 sparks
Average energy per spark: 0.8 J

Outside spot



Inside spot



Local Melting smoothes out the surface

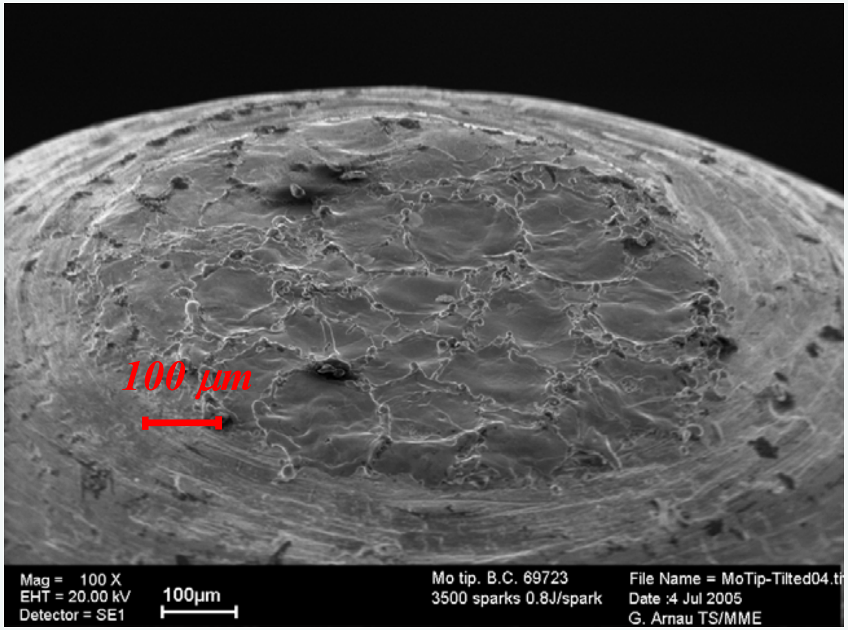
→ *Number of micro-protrusions strongly reduced*

Scanning Electron Microscopy - Mo

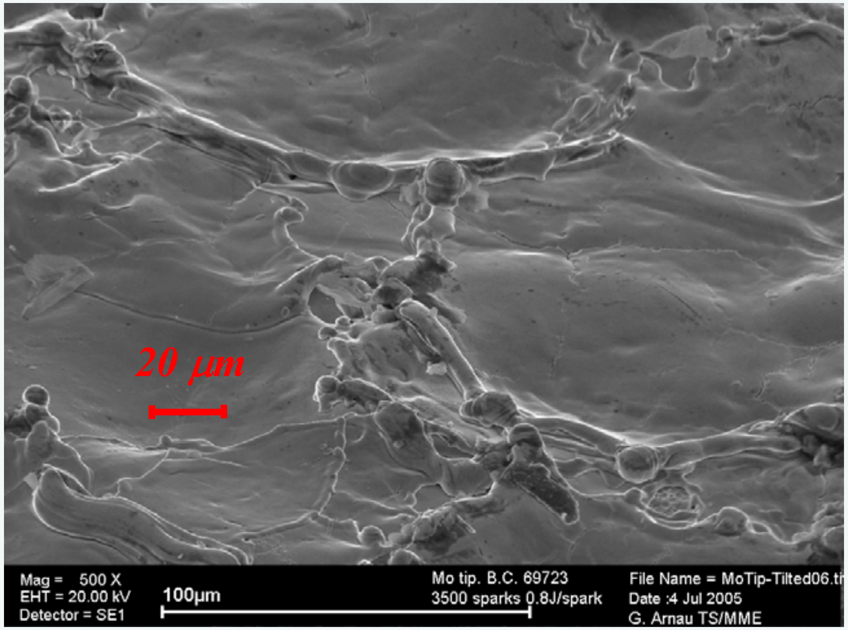
Molybdenum tip after ~ 3500 sparks

Average energy per spark: 0.8 J

Mag. = 100x, Tilted 70°

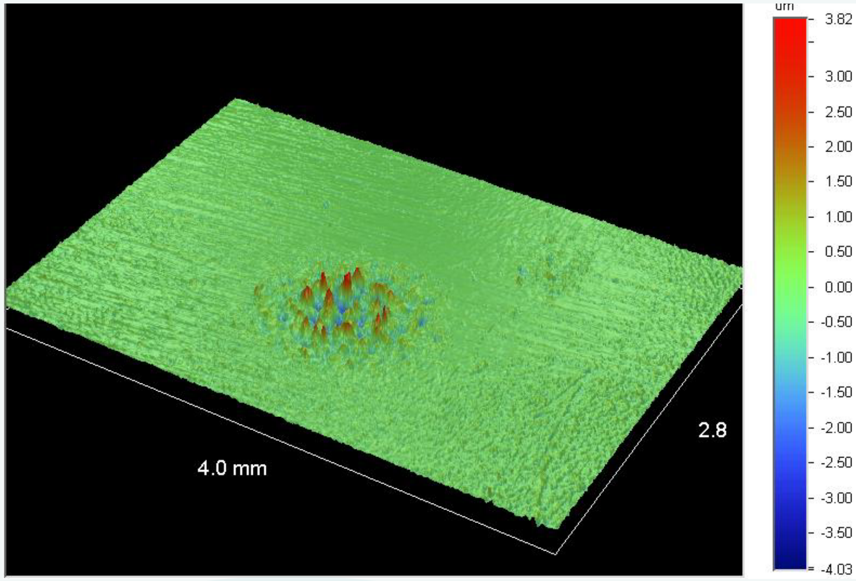


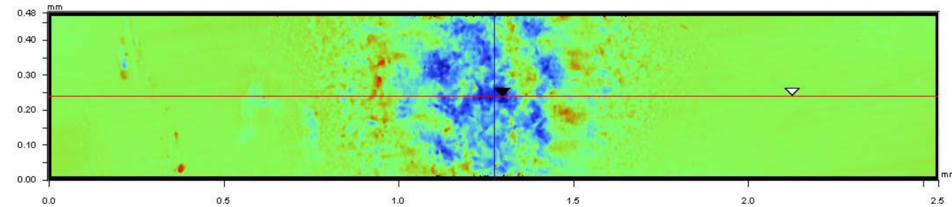
Mag. = 500x, Tilted 70°

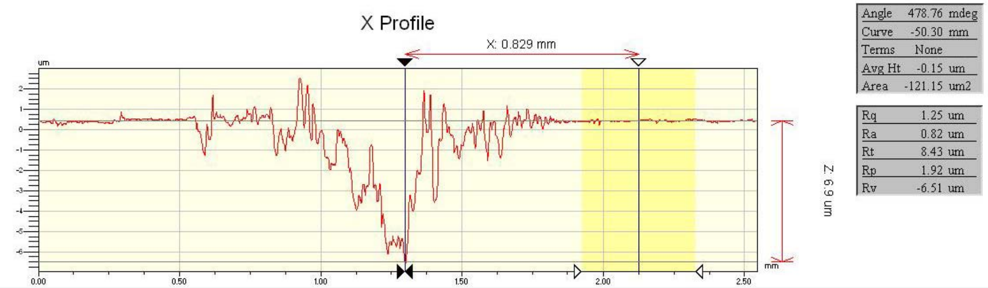


Diameter of affected tip: ***~0.82 mm***
Diameter of affected sample: ***~1.75 mm***

Depth Profile - Mo







Net Missing Volume:

474914,5 μm^3

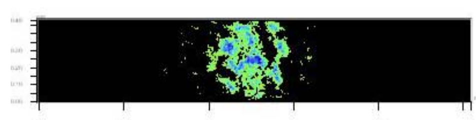
297 μm^3/spark

~3 ng/spark

@ 0.8 J/spark

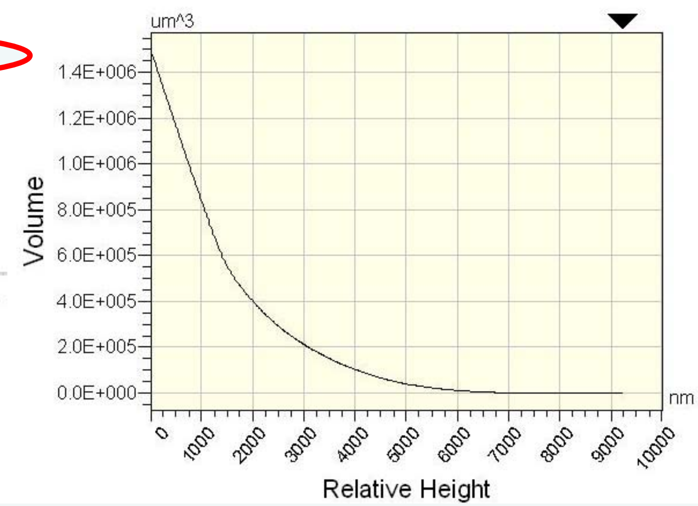
Volume Calculations

Volume Options	Normal
Natural Volume	1498440.75 um3
Normal Volume	1.40 um3
Negative Volume	559077.94 um3
Positive Volume	84163.45 um3
Net Missing Volume	474914.50 um3
Total Displaced Volume	643241.38 um3



Thresh: 3.44 um 37.25% of P-V
Pts Below: 96.71% of Total
Vol: 1.59e+005 um3 10.58% of Total

Volume



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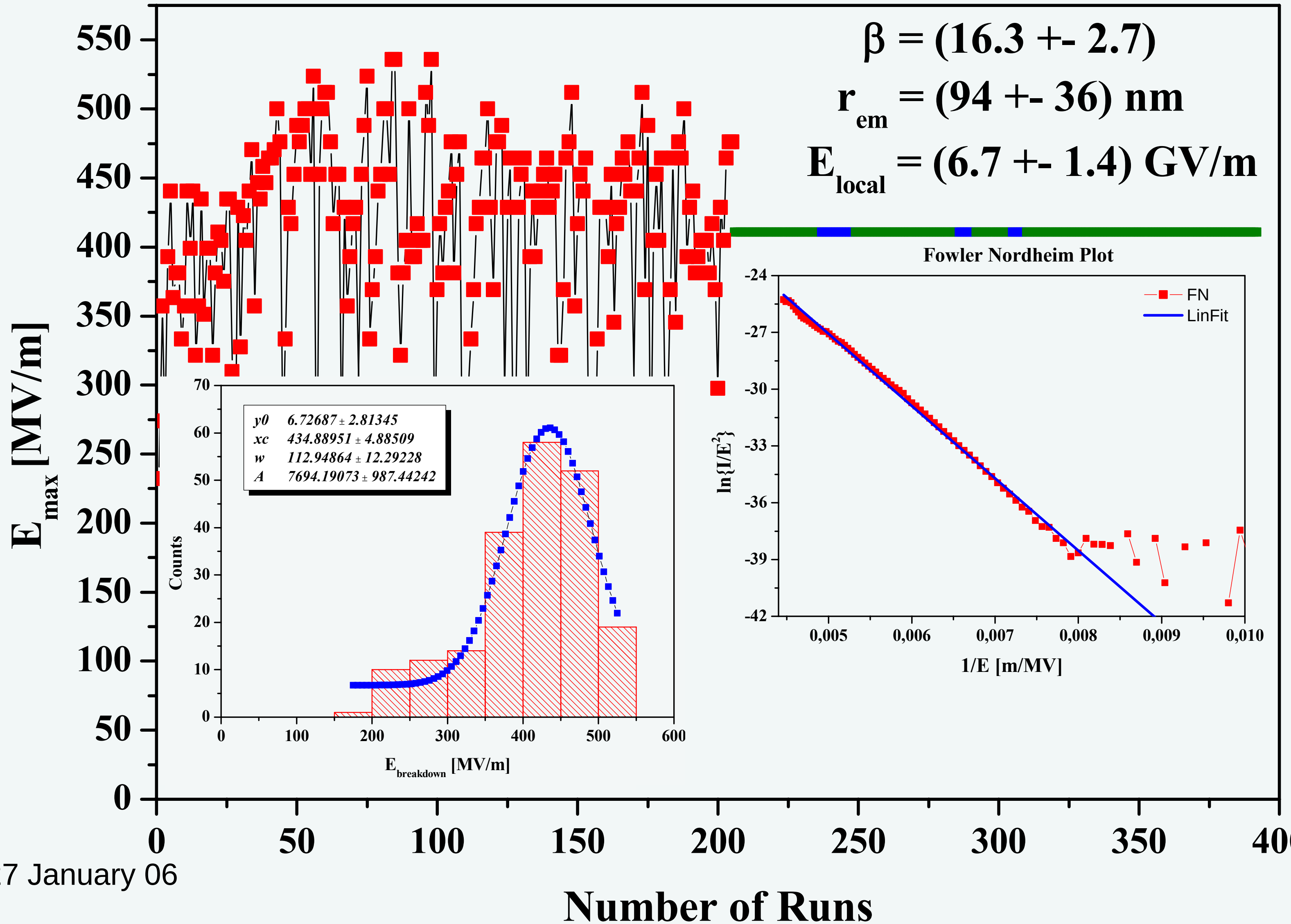
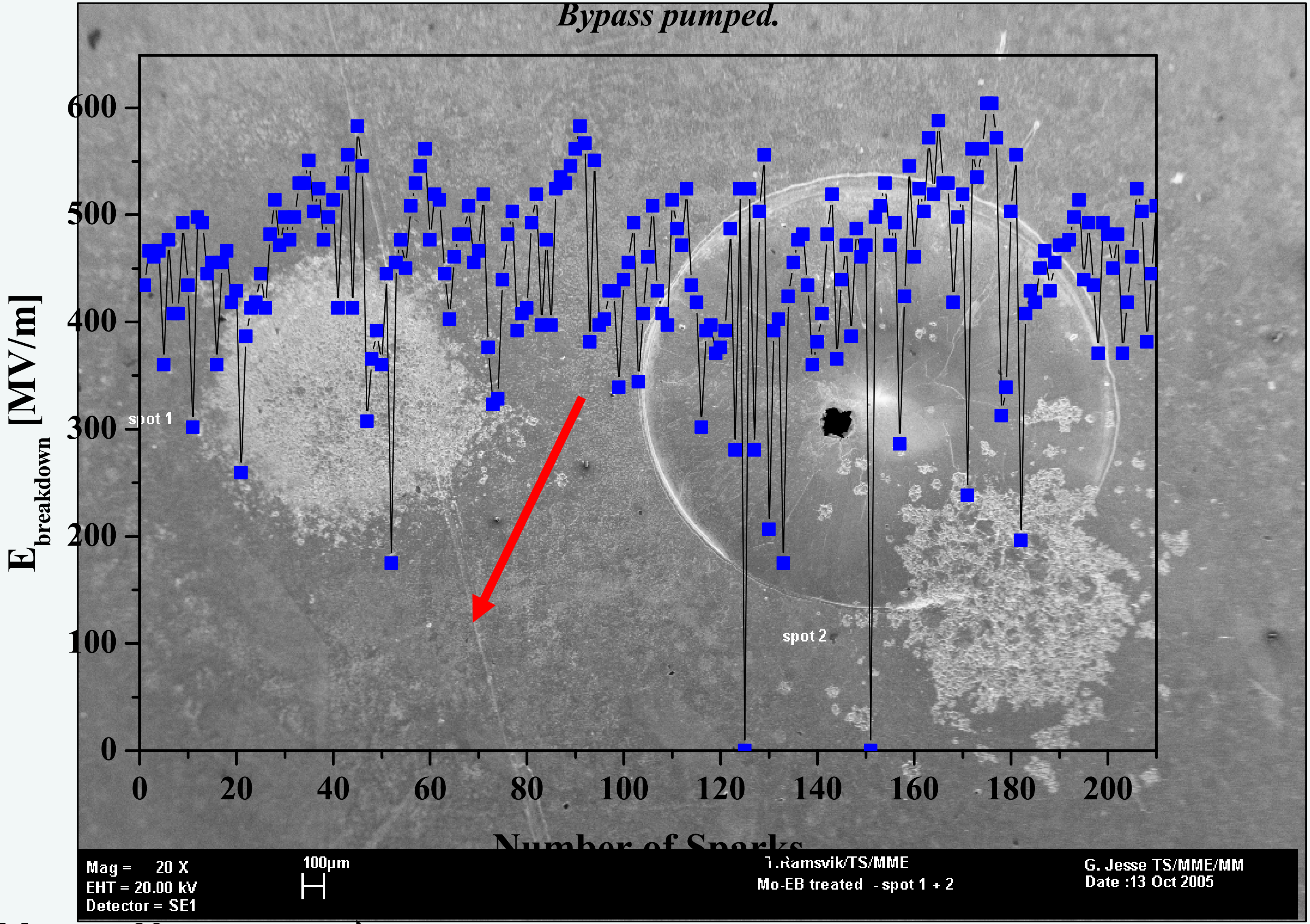
Operation Field of Conditioned Mo

Saturation Field = 435 MV/m **Operation Field = 410 MV/m**



Mo: e-beam treated – 150 keV

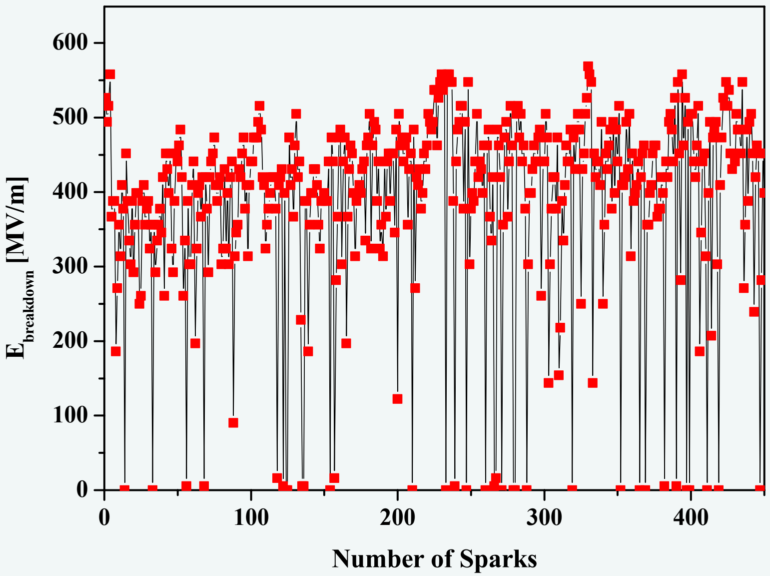


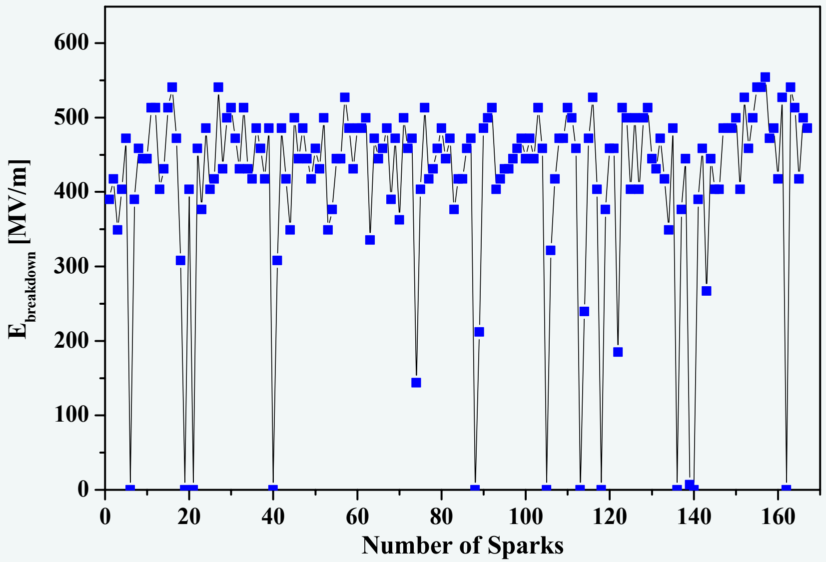
Immediate conditioning!!

Mo - heated with e-beam

not re-crystallized

~ 4 hours in air between heating and mounting in spark system



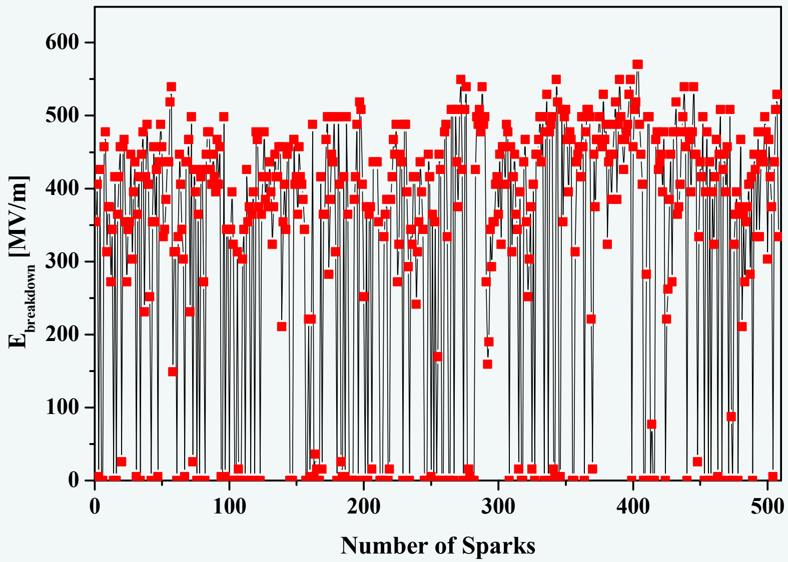


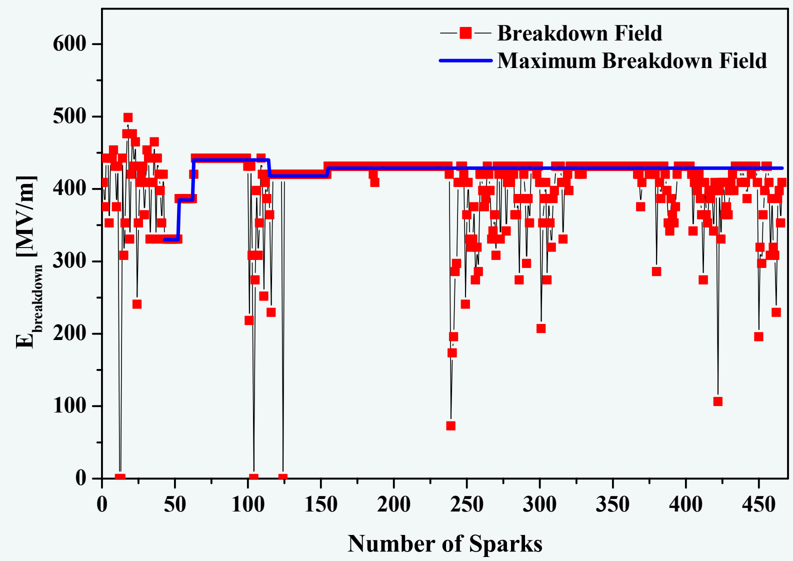
Initial Breakdown Field:
~ 350 MV/m

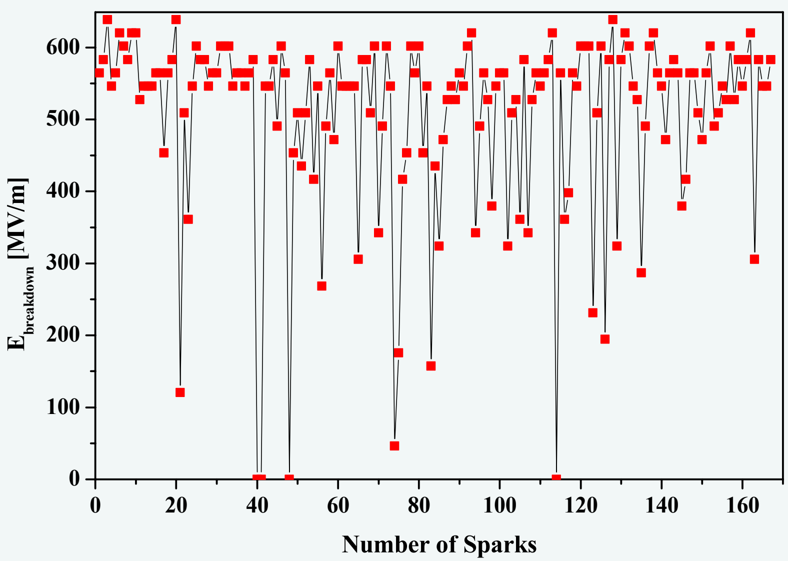
Conditioning with "normal" speed to ~450 MV/m

Conditioning almost immediately to ~450 MV/m

Mo - heated with e-beam





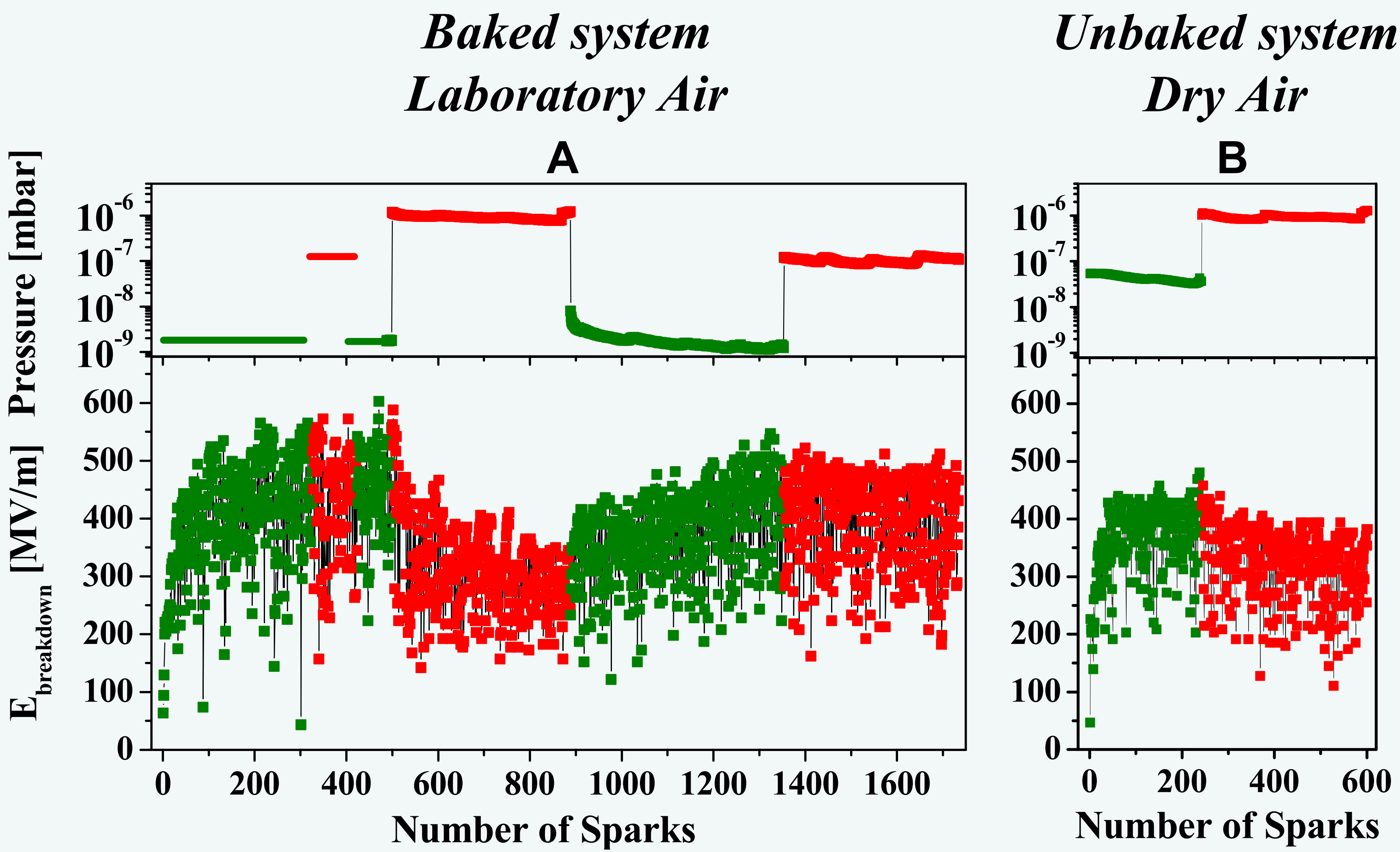


heavily re-crystallized 5.5 kV / 60 mA

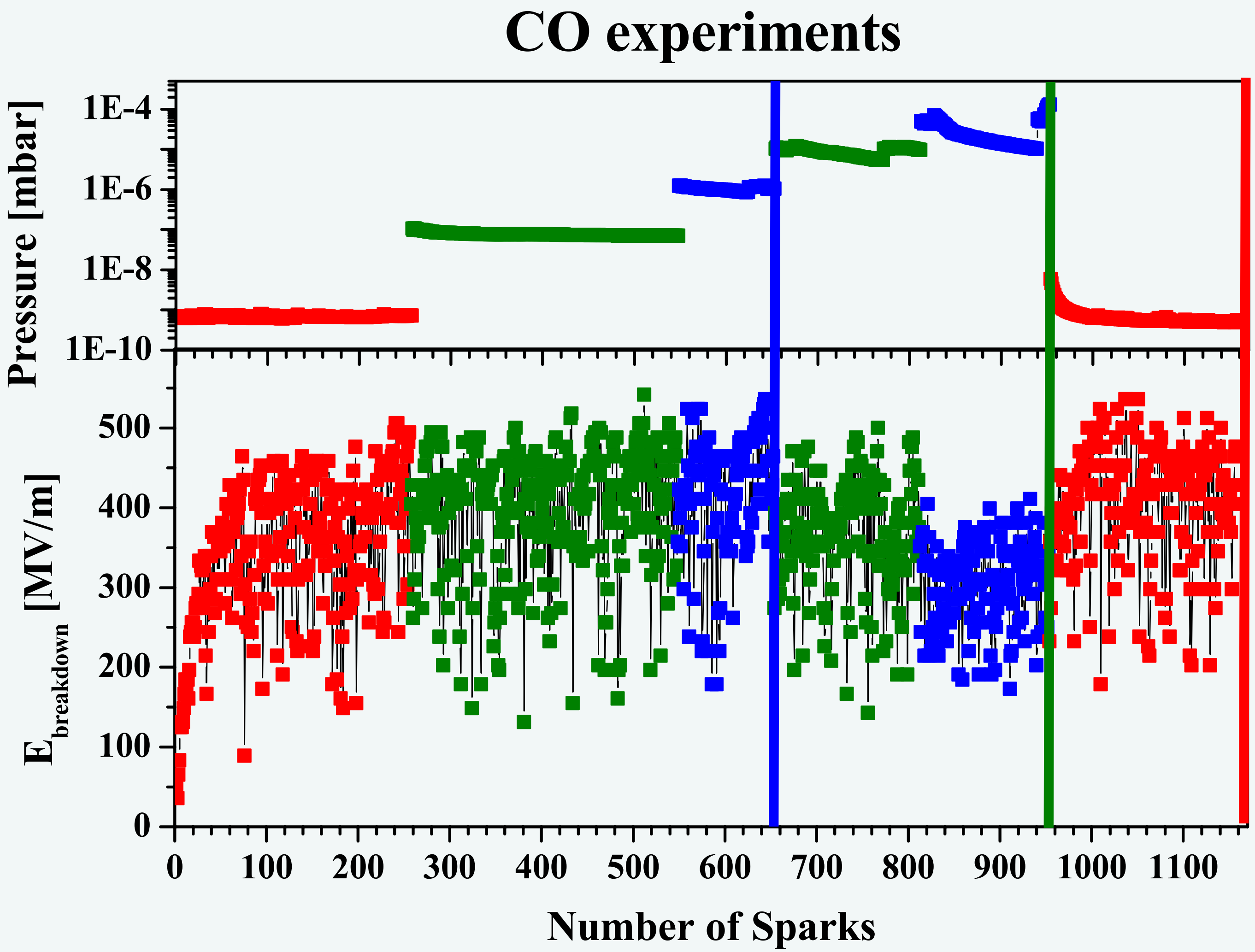
~ 4 hours in air between heating and mounting in spark system

University of Geneva 26.10.2005

Gas Experiments - Air/Mo



Gas Experiments – CO/Mo

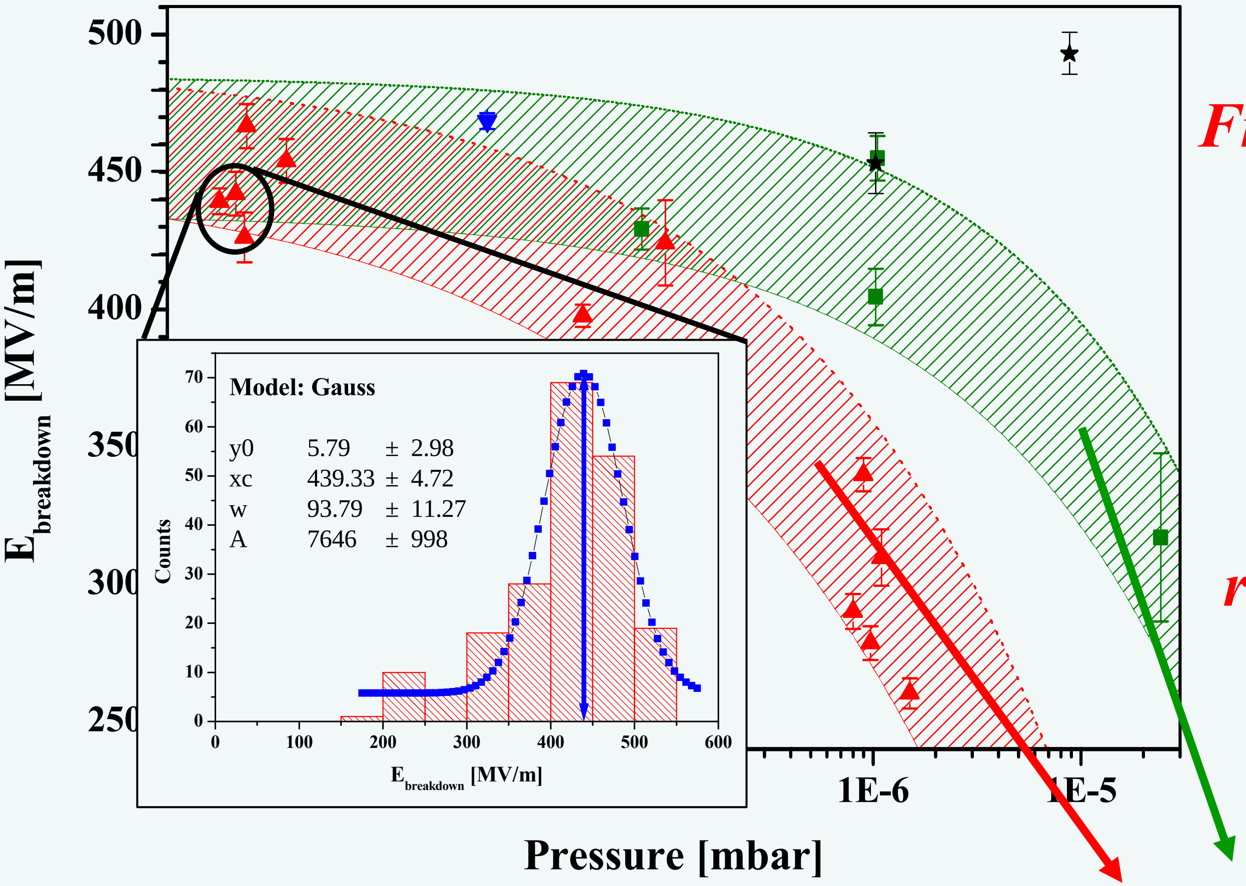


No change in breakdown-field below 10^{-6} mbar

"Abrupt" decrease above 10^{-5} mbar

Recovery of breakdown field

Gas Experiments - (Air-CO)/Mo



From ~10^{-9} to ~ 10^{-6} mbar of air

The saturated breakdown field is reduced by ~140 MV/m

$$E^{0\ mbar,\ CO}_{breakdown} = (465 \pm 30)\ MV/m$$

$$k_{CO} = (12425 \pm 1008)\ MV/m\ (mbar)^{-1}$$

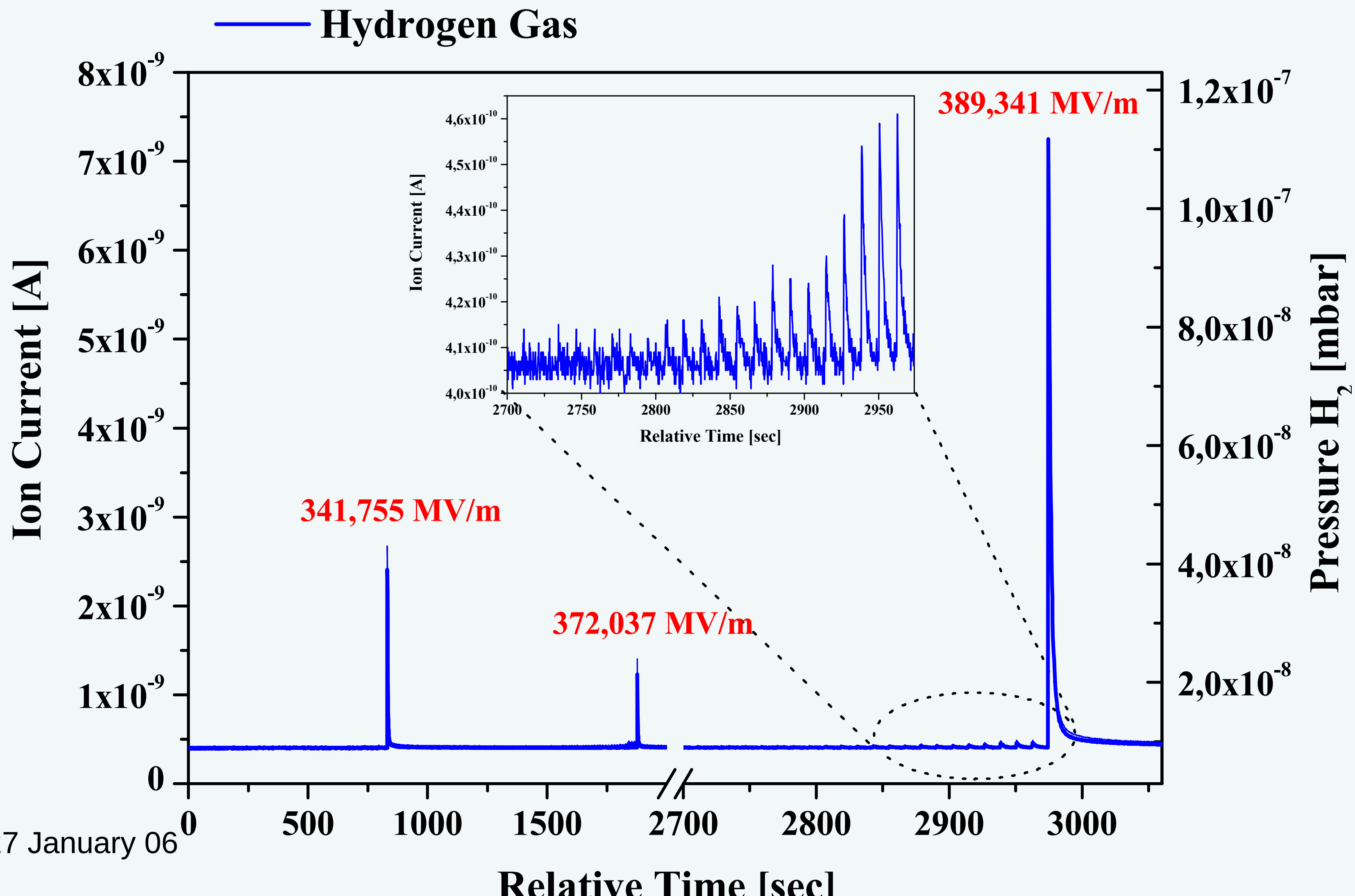
$$n_{CO} = (0.42 \pm 0.02)$$

$$E_{breakdown} = E^{0\ mbar}_{breakdown} - k \cdot \{P\}^n$$

Mass Spectroscopy - Mo

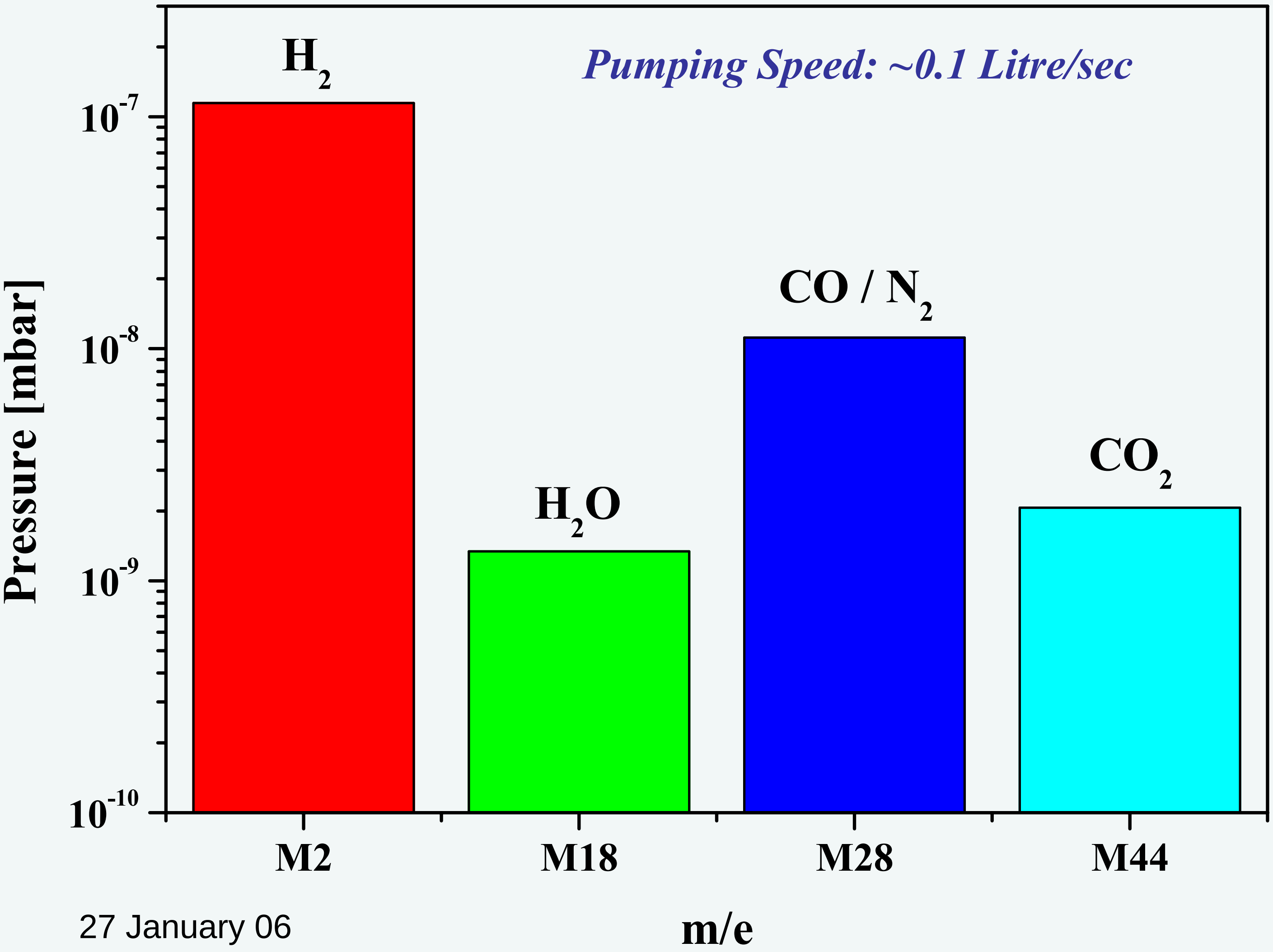
Example: Release of Hydrogen Gas

Pumping Speed: ~0.1 Litre/sec



Mass Spectroscopy - Mo

Release of gas due to spark

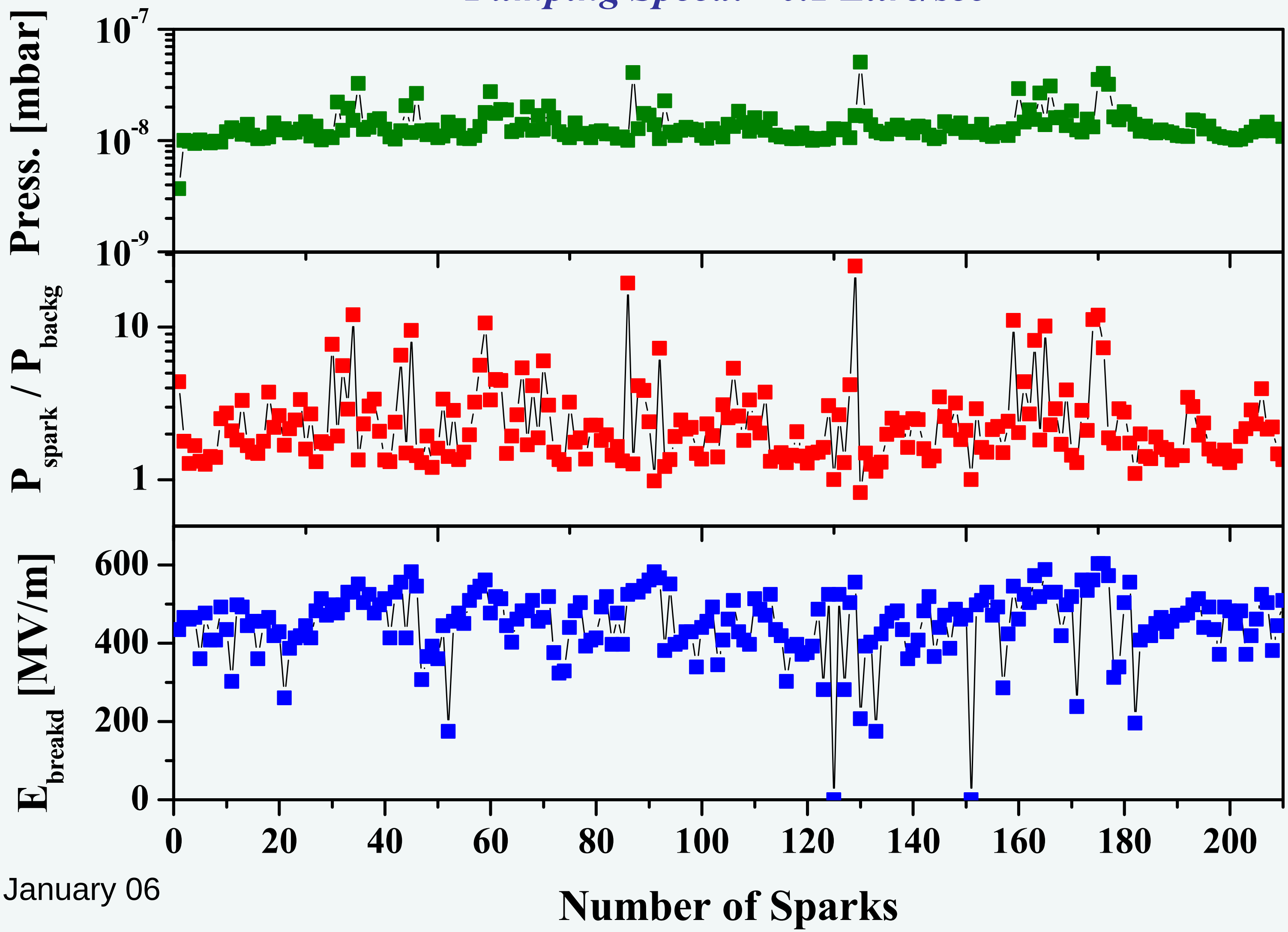


Hydrogen gas most abundant specie

Spark Conditioning vs. Pressure Rise

E-beam treated Molybdenum

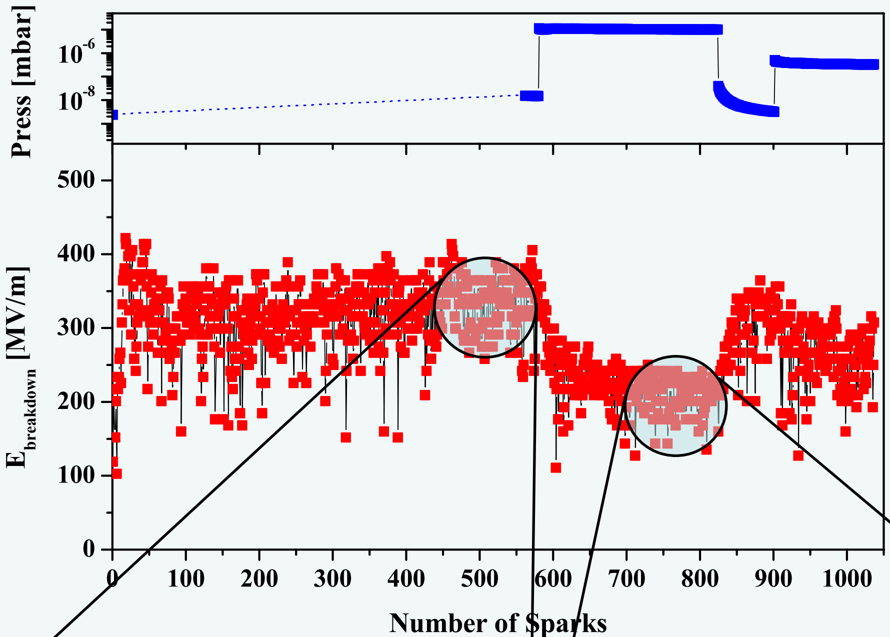
Pumping Speed: ~0.1 Litre/sec

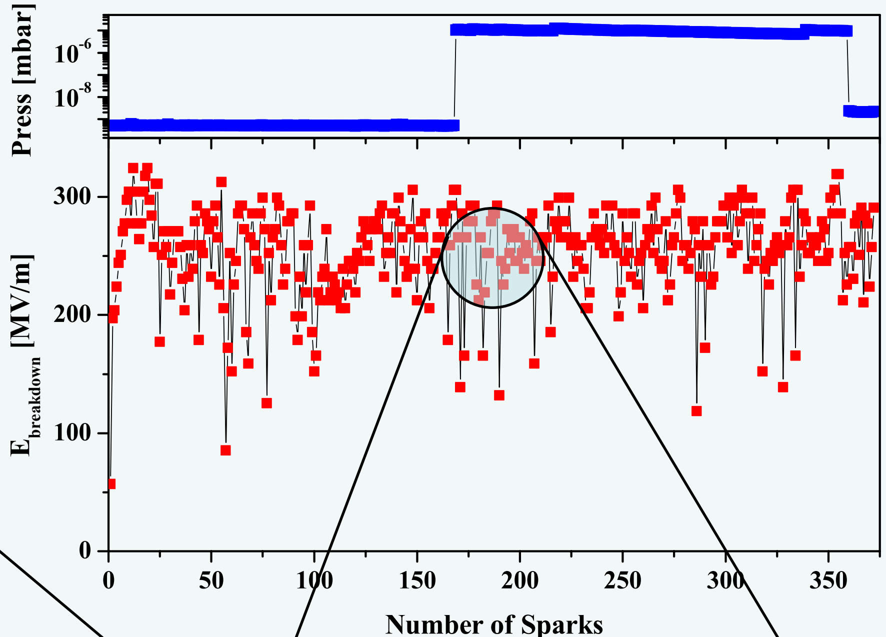


Gas Experiments - W

Laboratory Air

CO





(333,4 ± 5,1) MV/m

(219,0 ± 1,2) MV/m

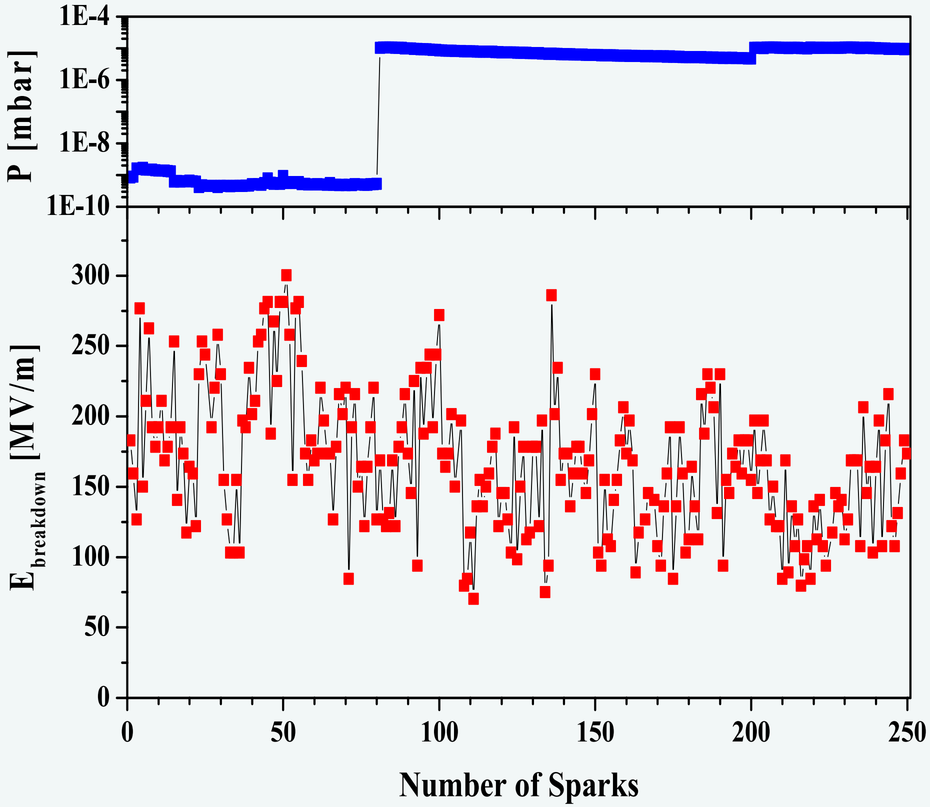
(261,9 ± 1,3) MV/m

$E_{breakdown}$ reduced by <u>34 %</u> at $1 \cdot 10^{-5}$ mbar Air

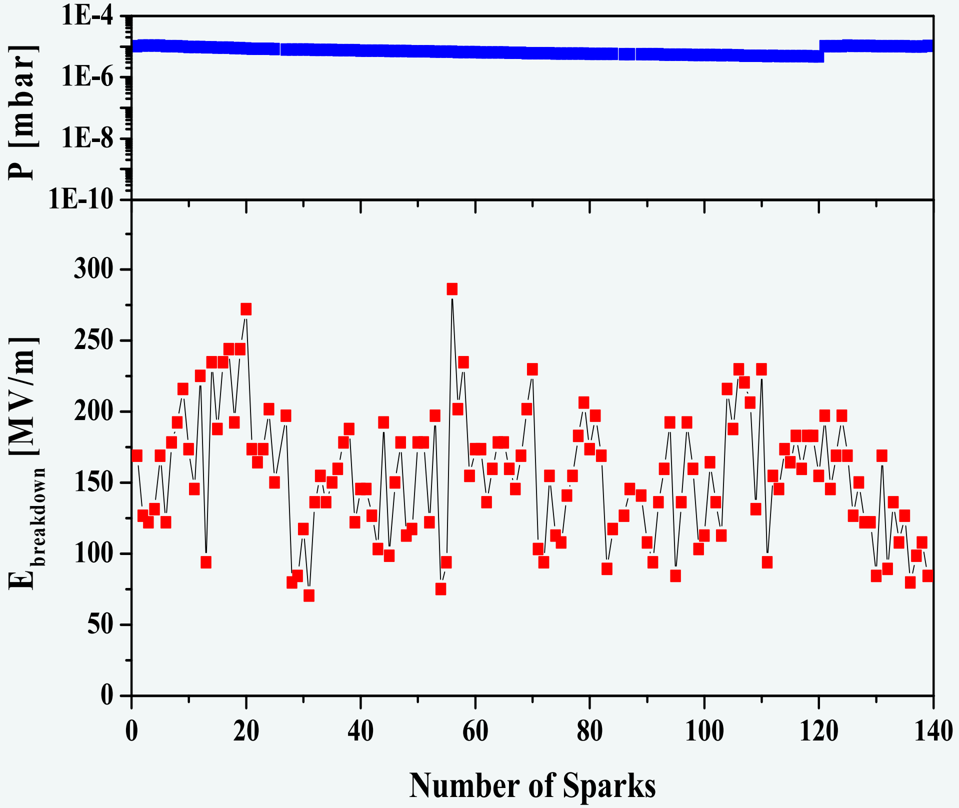
No reduction of $E_{breakdown}$ at $1 \cdot 10^{-5}$ mbar CO

Gas Experiments – Cu

Laboratory Air



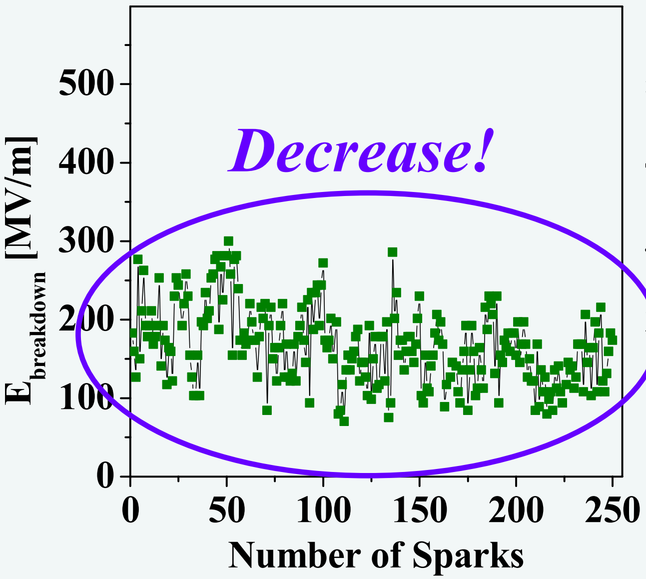
CO



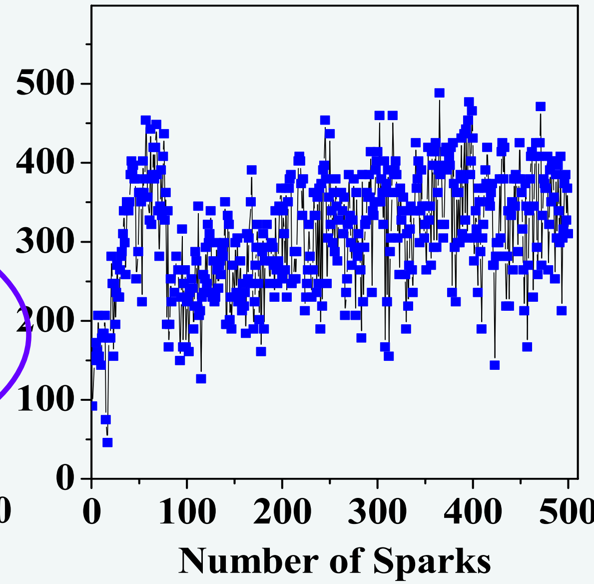
No significant effect of exposure to Air and CO

Comparison Cu - W - Mo

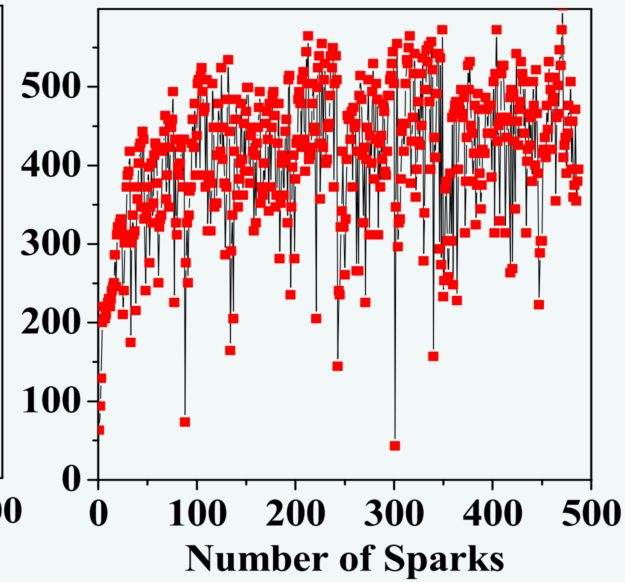
Copper



Tungsten



Molybdenum

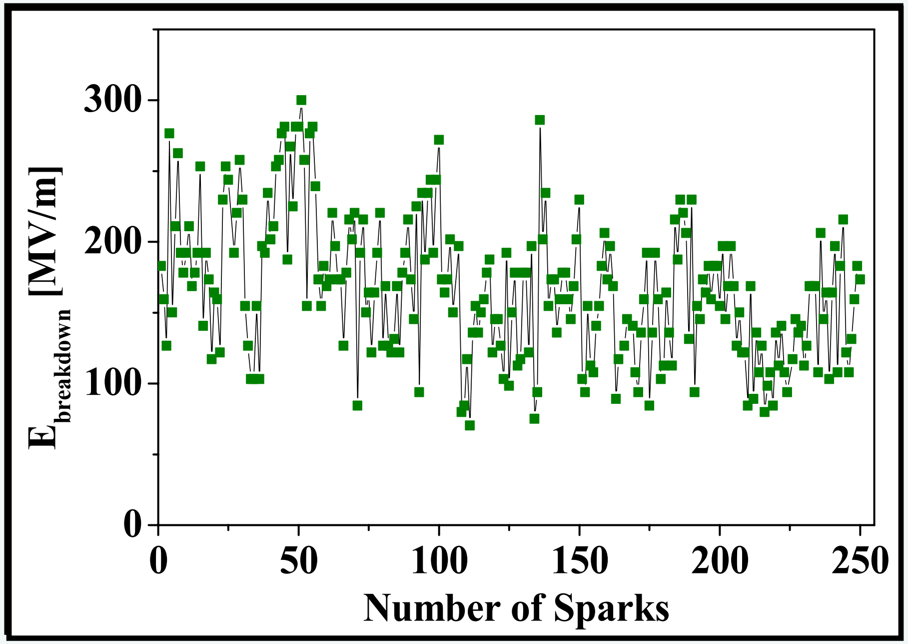


Cu: $E^{sat}_{breakdown} \cong (159 \pm 3)$ MV/m at $\sim 7 \times 10^{-10}$ mbar

W: $E^{sat}_{breakdown} \cong (349 \pm 6)$ MV/m at $\sim 2 \times 10^{-08}$ mbar

Mo: $E^{sat}_{breakdown} \cong (431 \pm 7)$ MV/m at $\sim 2 \times 10^{-09}$ mbar

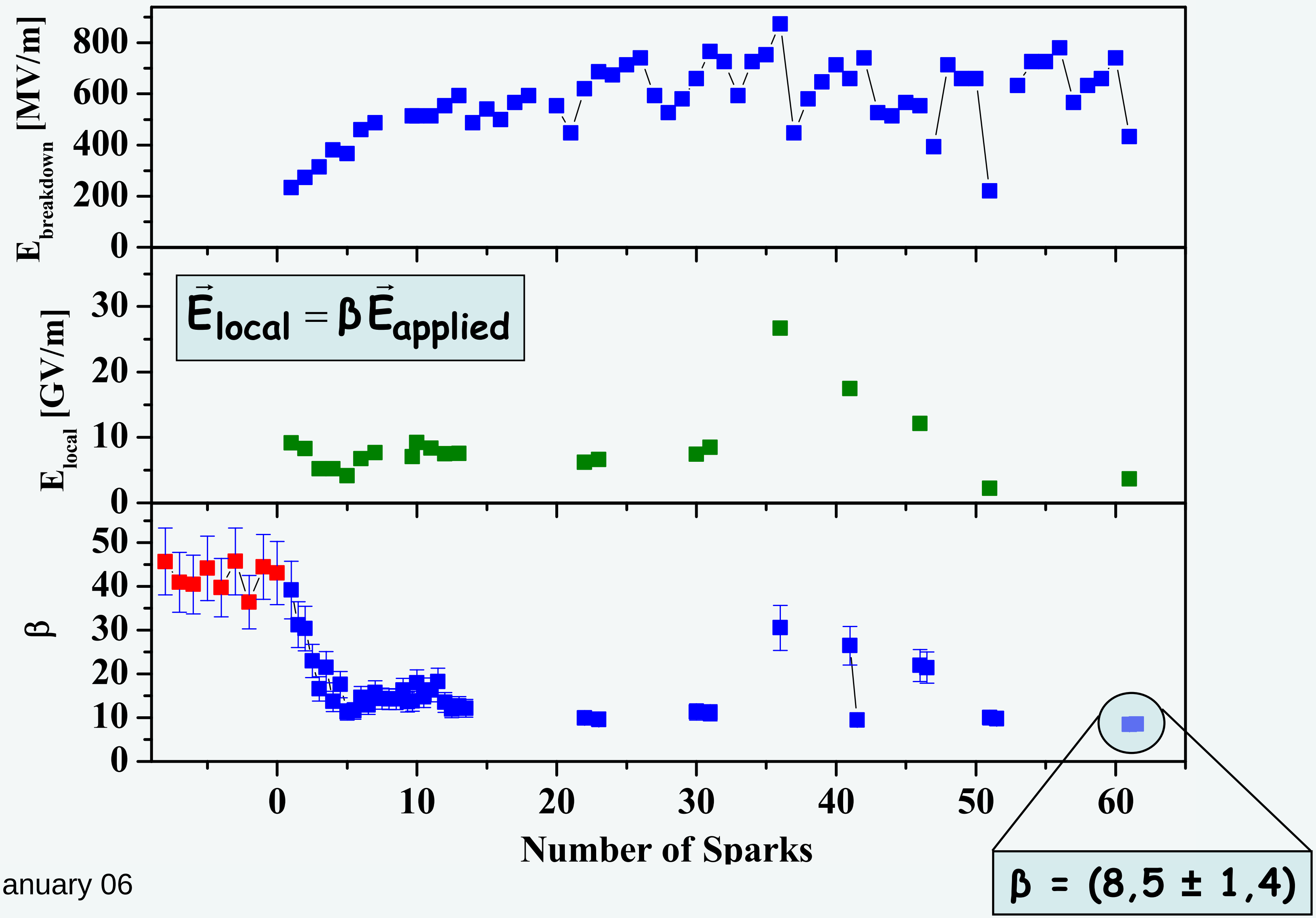
Comparisons - 30 GHz measurements



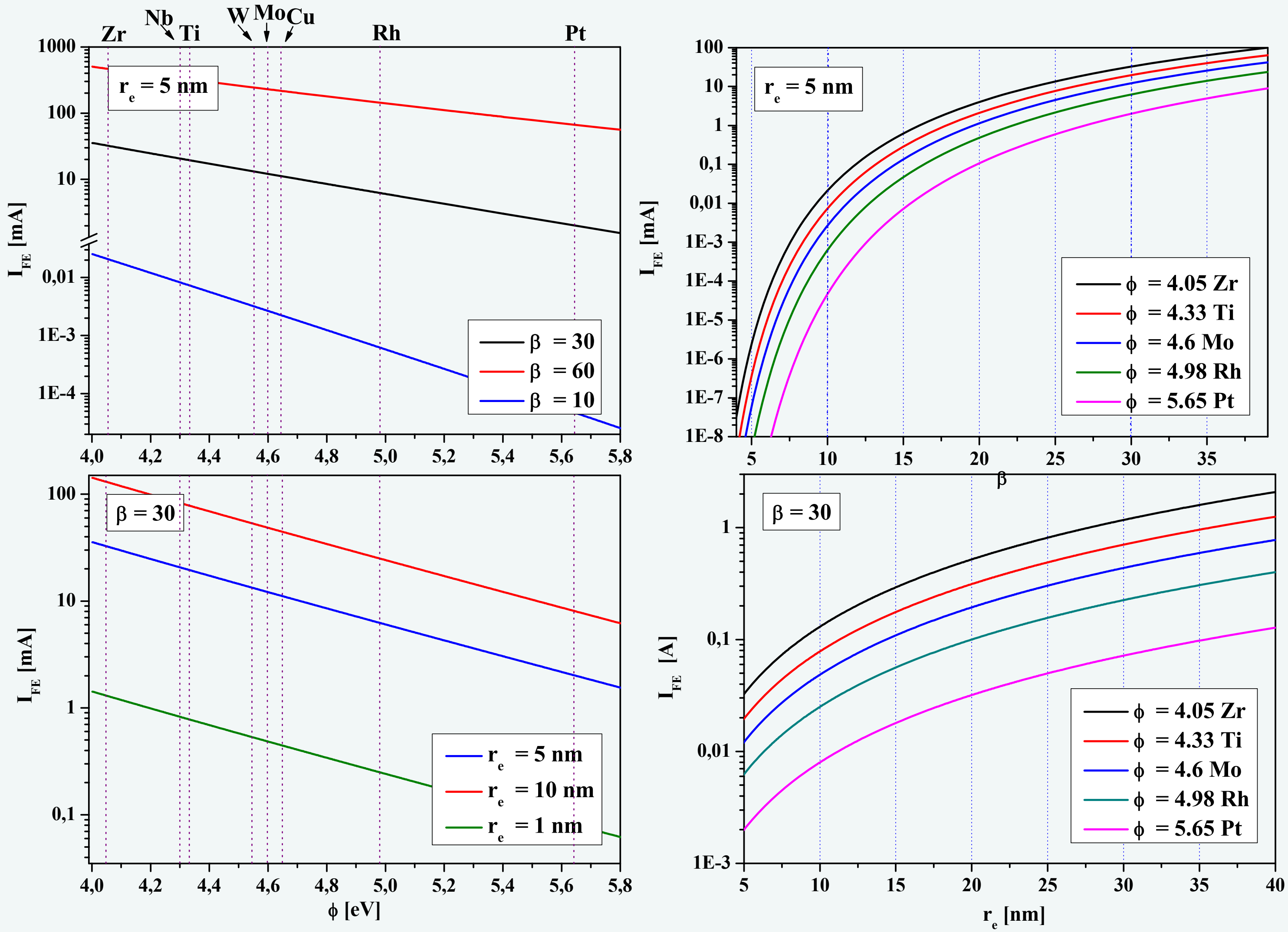
	E^{sat}_{breakd} (DC) [MV/m]	Max. surface field in RF [MV/m]
Cu	160	241
W	349	329
Mo	430	420

- ***DC and RF breakdown measurements give similar breakdown fields for Mo and W***
- ***Superior behavior of both Mo and W with respect to Cu.***

Titanium Anode and Cathode



Dependence of I_{FE}



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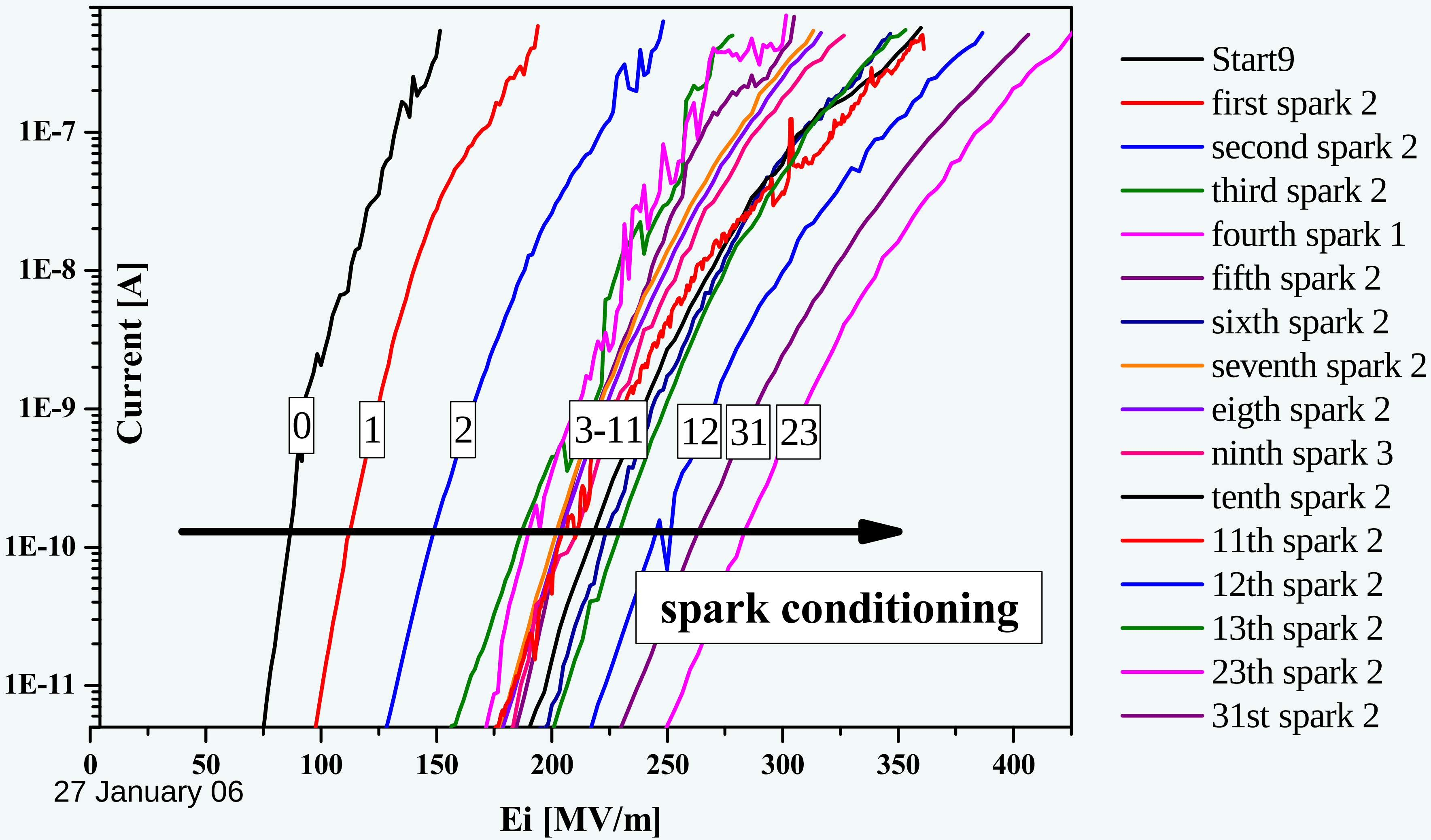
$$\frac{I_{FN}}{E^2}\frac{6.494\cdot 10^5}{\left(A_e\beta^2\right)} = \frac{10^{4.52\varphi^{-1/2}}}{\varphi}\cdot\exp\left[-\frac{2.84\cdot 10^9\varphi^{1.5}}{\beta E}\right]$$

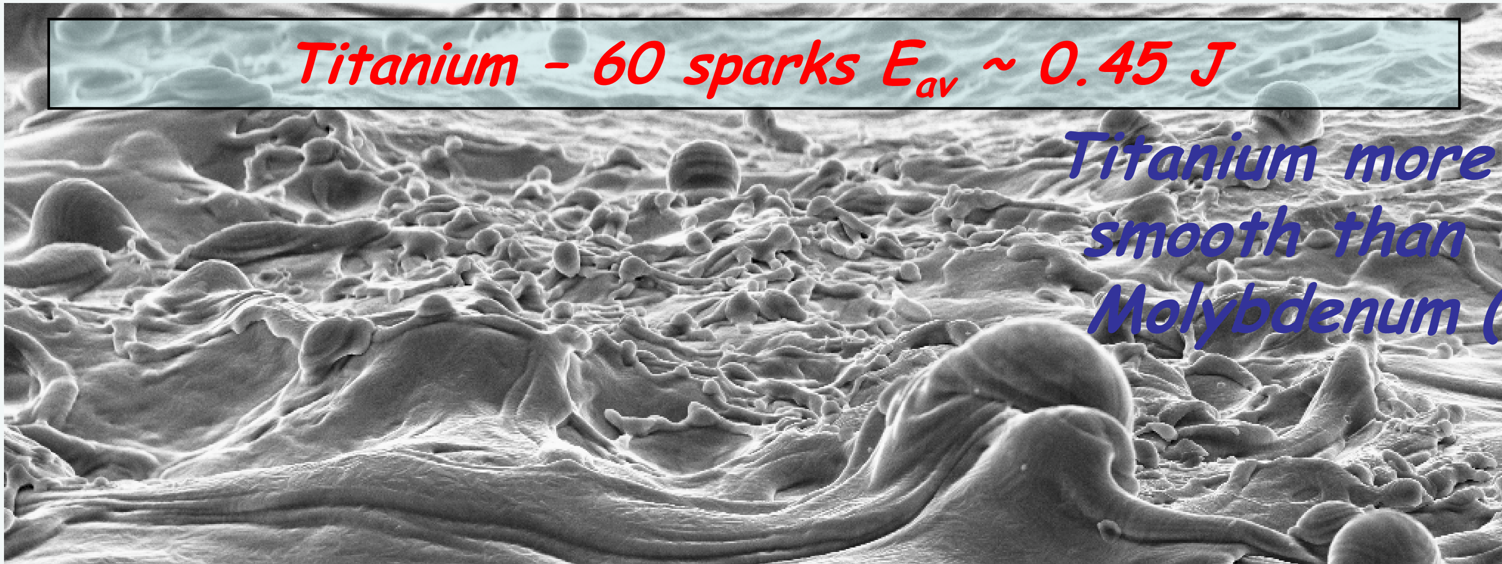
E = 300 MV/m

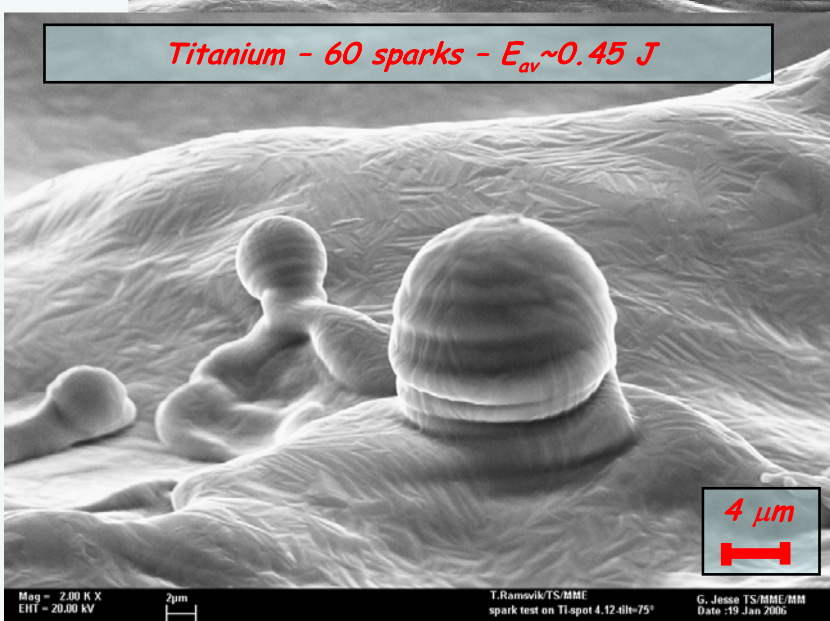
Titanium - I_{FE} variation

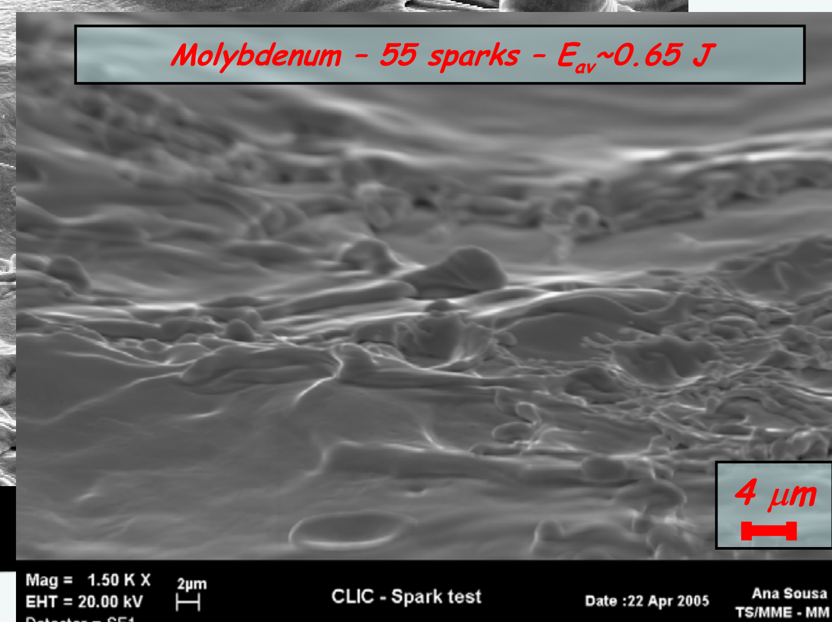
Increase of the threshold for field emission also increase the breakdown field
W. T. Diamond: J. Vac. Sci. Technol. A 16(2) (1998) 707.



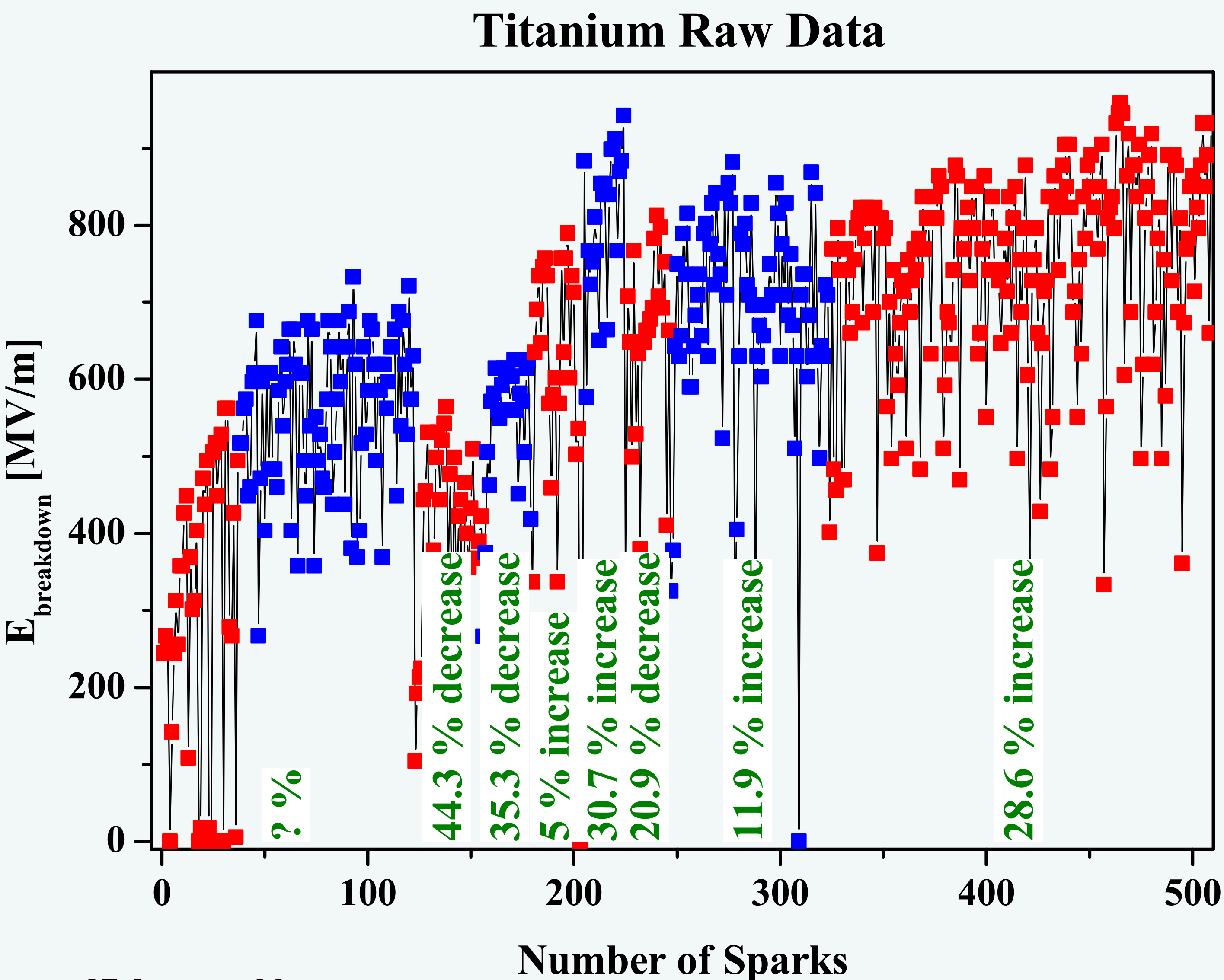
Titanium cathode - SEM study





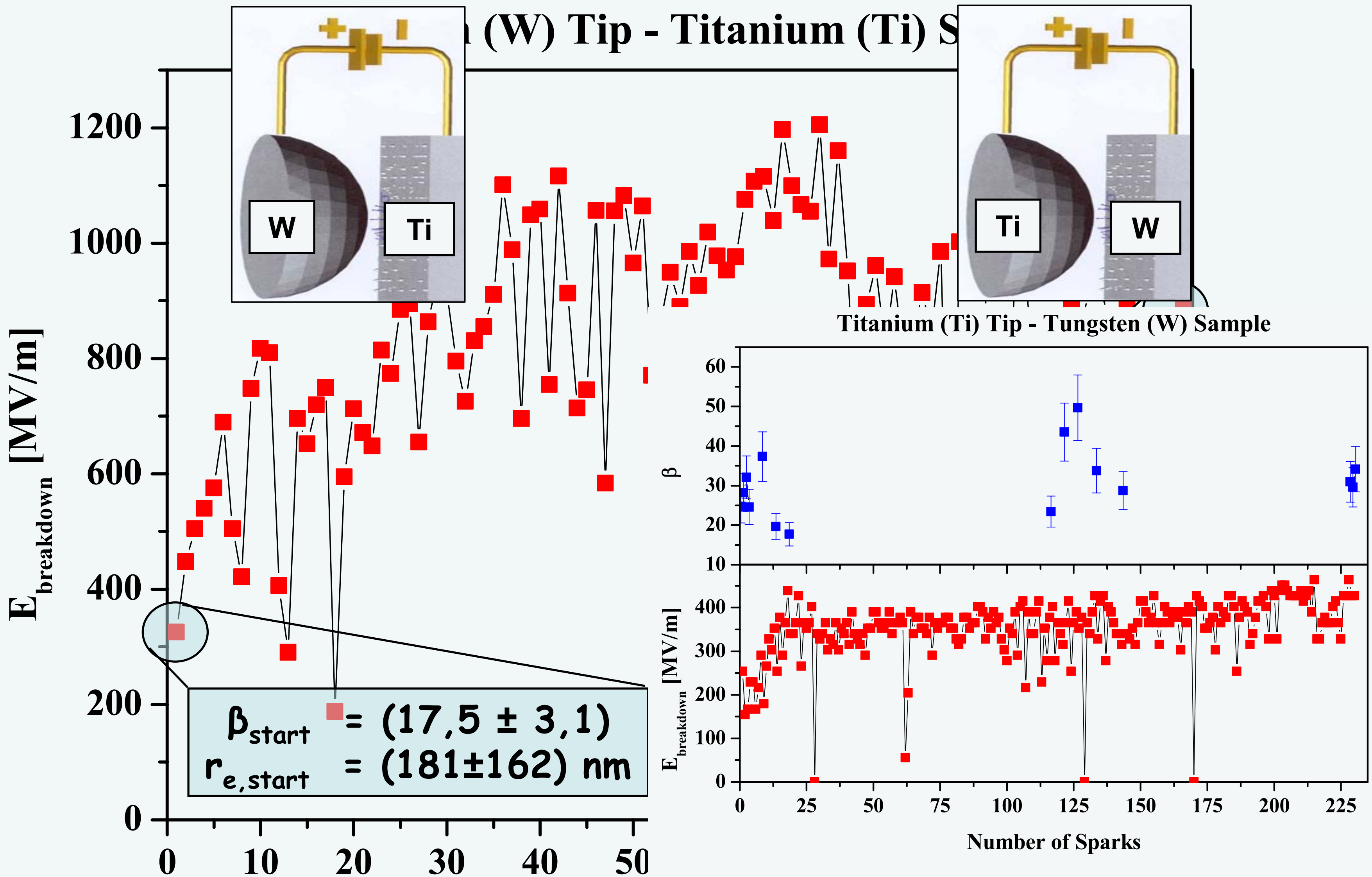


Titanium Anode and Cathode



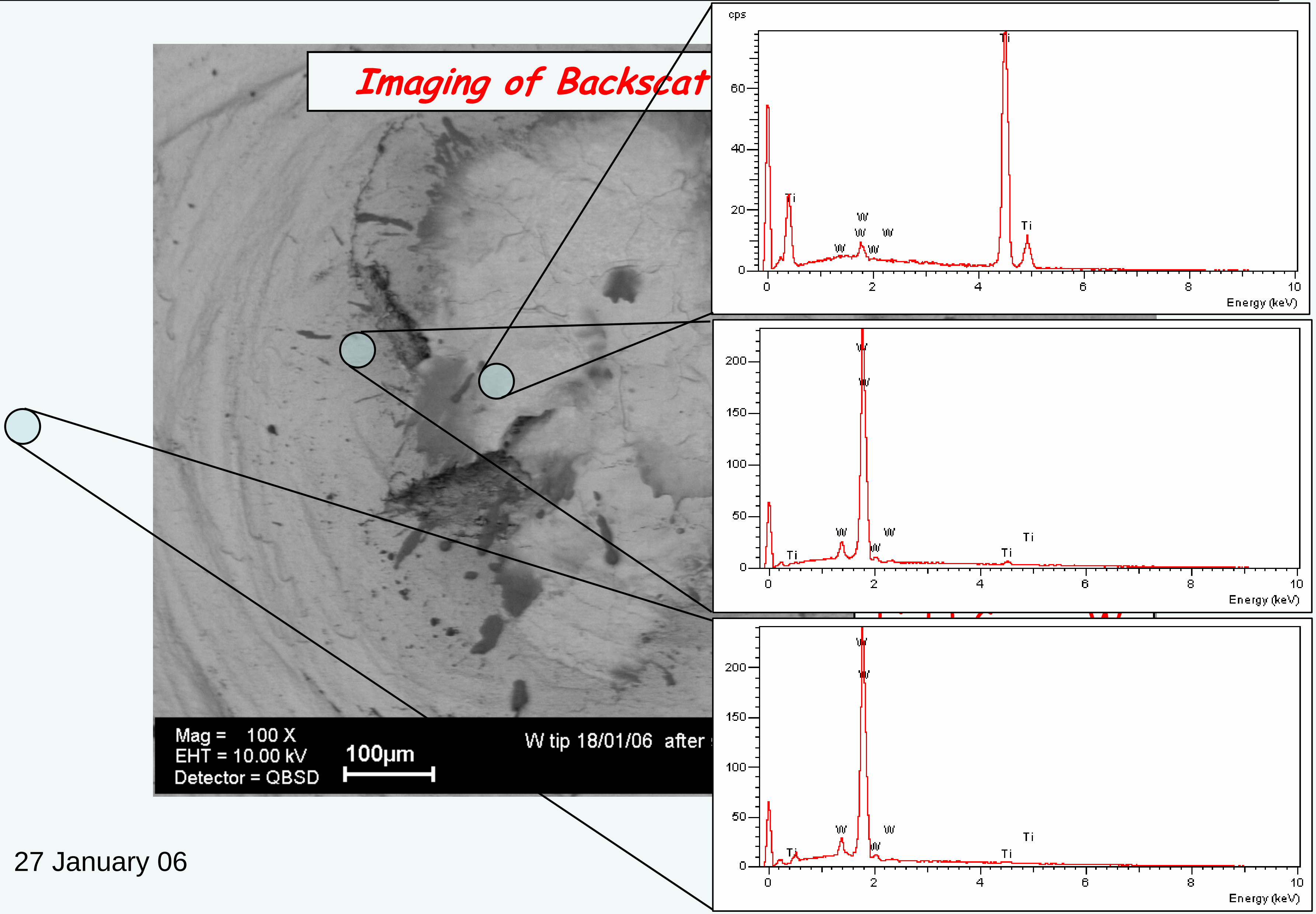
Significant erosion of Ti material at the moment of spark

W ↔ Ti / anode ↔ cathode



Cathode initiated processes dominating

W anode - Ti cathode SEM/EDX



Introduction: Choice of materials

Seminar: 10 June 2005

Criteria:	Titanium:
• *low vapor pressure @ 1000 K*	• *High*
• *high tensile strength*	• *Low*
• *high melting point*	• *Average*
• *high thermal conductivity*	• *Low*
• *high electrical conductivity*	• *Low*

⇨ *Molybdenum & Tungsten*

Future Projects

Continue the study of various materials

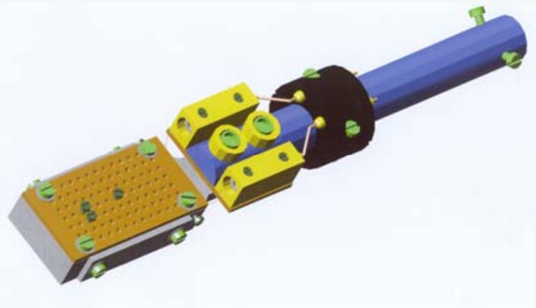
- TiVAl
  - higher tensile strength than pure Titanium
  - → maintain low beta, and avoid severe erosion ?
- Glidcop, CuZr
  - higher resistance to fatigue than pure Copper
- Mo-Re alloys
  - study the effect of increased tensile strength, while maintaining similar properties as Mo
- Chromium
- Sputter Cleaned Molybdenum
  - study the effect of molybdenum oxide on the surface
- (others)

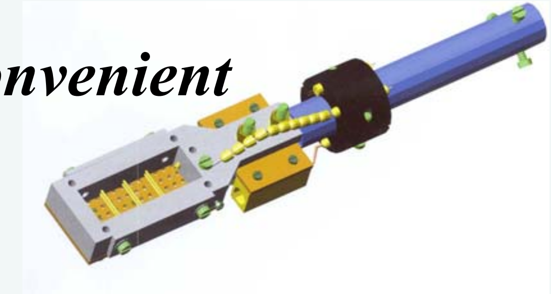
Regulate the energy over the gap junction

In-situ annealing and sputtering of samples

Wish list (2006)

- New spark system?:
  - *facilitate higher throughput of materials and preparation techniques*
  - *Improvements in the experimental setup*
    - *XYZ movements*
    - *E-beam heating → ~ 1000°C*
      - *"In-situ" treatments*
    - *several samples*
    - *variation of energy over gap more convenient*





Estimated Cost for materials:
~ 33 kCHF

- Technical Student for DC spark system?

Conclusions

- ***Ex-situ surface heating of Molybdenum influences significantly the conditioning speed***
- ***There is a residual gas effect on the breakdown field for Molybdenum and Tungsten***
- ***Titanium shows a higher breakdown field than Molybdenum and Tungsten due to low enhancement factor***
  - ***Erosion during breakdown makes this alternative problematic***
- ***Cathode initiated processes are the dominating sources for electrical breakdowns***

Contributors

- *Sergio Calatroni*
- *Gonzalo Arnau Izquierdo*
- *Ahmed Cherif*
- *Gudrun Jesse*
- *Morten Kildemo*
- *Holger Neupert*
- *Alessandra Reginelli*
- *Ana Sousa E Silva*
- *Mauro Taborelli*
- *Walter Wuensch*

Transition to Field Emission:

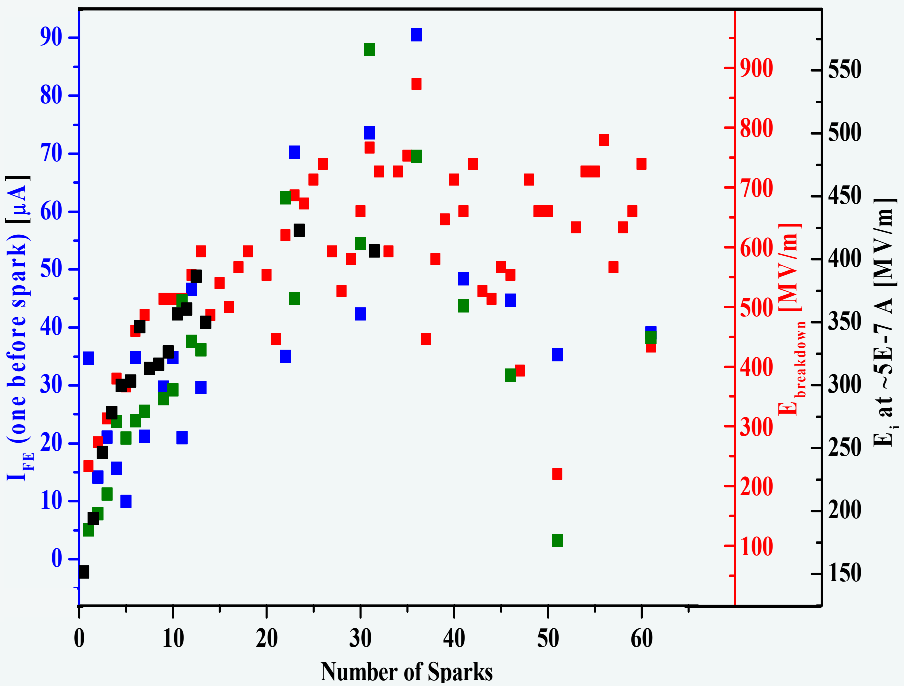
W. T. Diamond: J. Vac. Sci. Technol. A 16(2) (1998) 707.

- Work function changes at the cathode
  - Adsorption of foreign species / oxidation
  - Transfer of microparticles from the anode and stripping of small areas of the cathode
- Mechanical changes produced by the strong electrical forces on the electrode surfaces
- ~~Gas desorption from the anode with sufficient density to s[illegible]e discharge~~
  - ~~Higher voltage → higher gas desorption~~

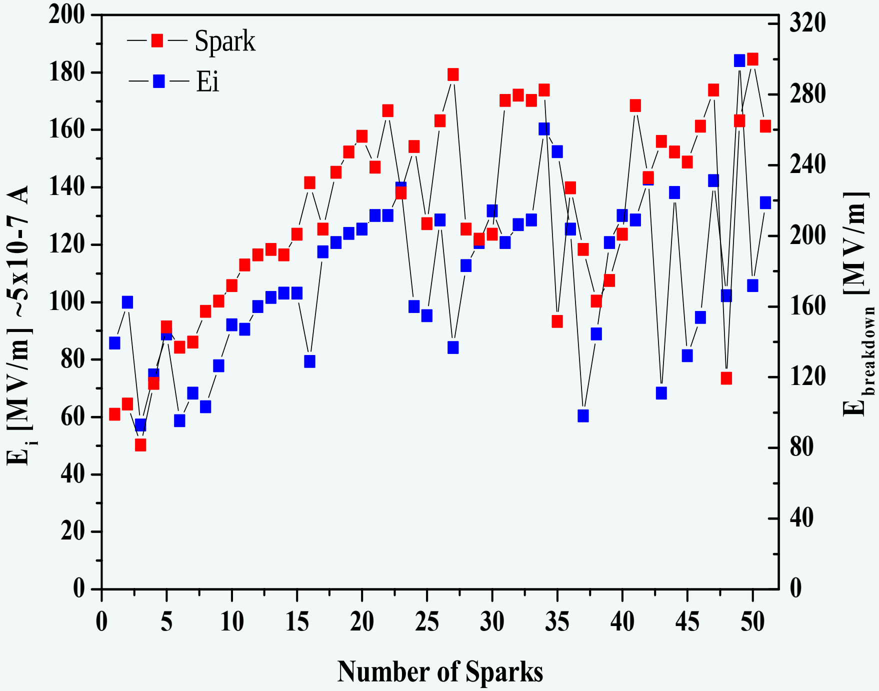
Important at large gaps

Comparison E_{break}-I_{FE}

Titanium

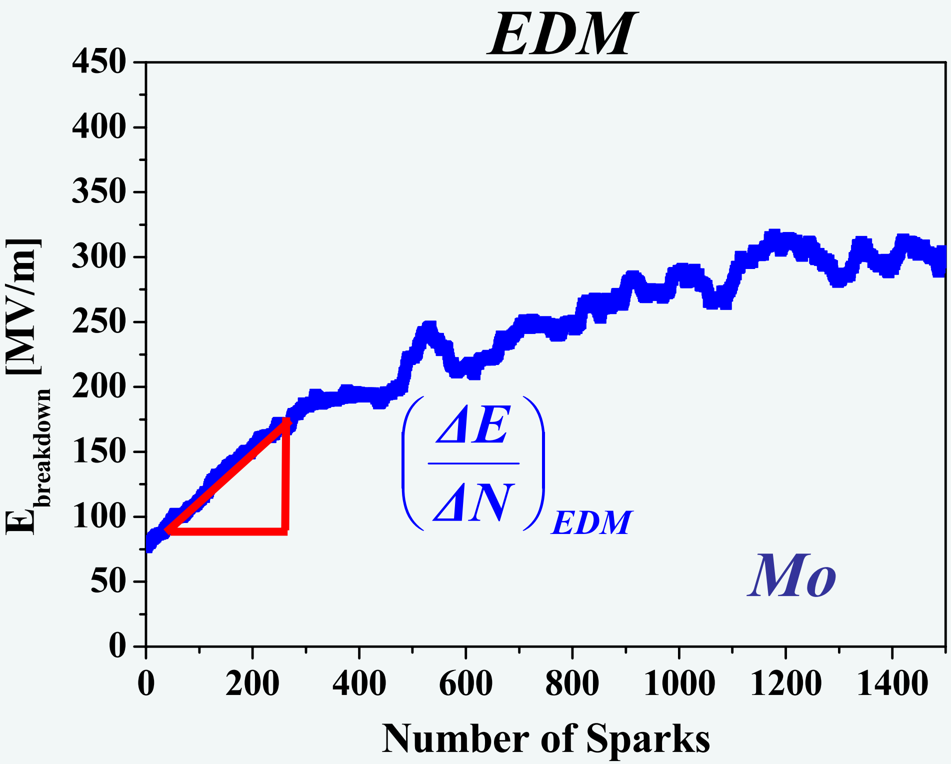


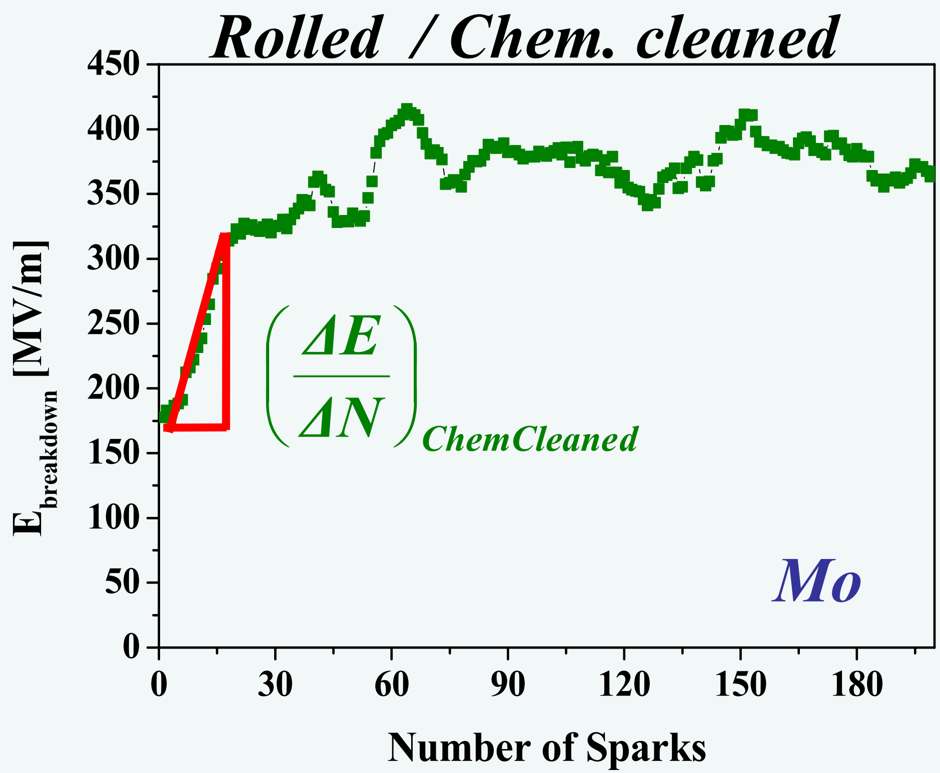
Molybdenum



I_{FE} and Breakdown Field closely related

Electro Discharge Machined (EDM)





$$\left(\frac{\Delta E}{\Delta N}\right)_{EDM} \approx 0{,}4 \ \frac{MV/m}{spark}$$

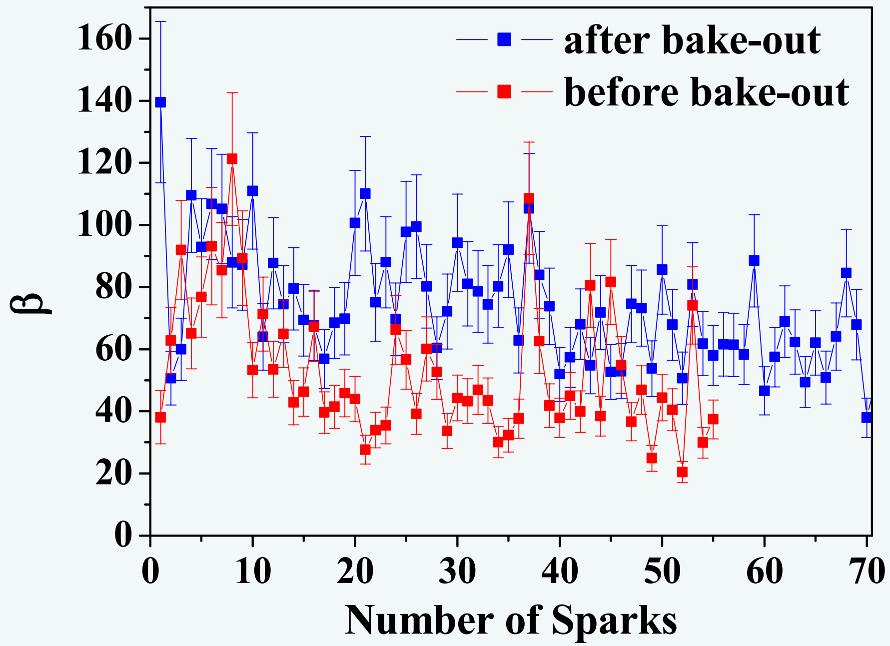
$$\left(\frac{\Delta E}{\Delta N}\right)_{ChemCleaned} \approx 8 \ \frac{MV/m}{spark}$$

$$\frac{\left(\Delta E / \Delta N\right)_{CC}}{\left(\Delta E / \Delta N\right)_{EDM}} \approx 20$$

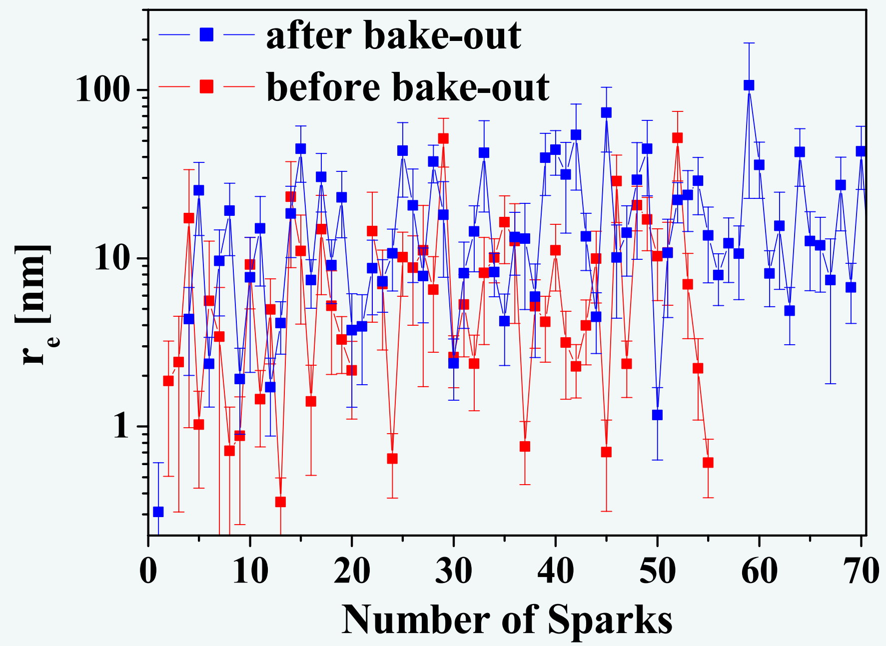
Results from Fowler - Nordheim plots

Molybdenum Tip and Sample

Enhancement Factor (β)



Emission Radius (r_e) [nm]

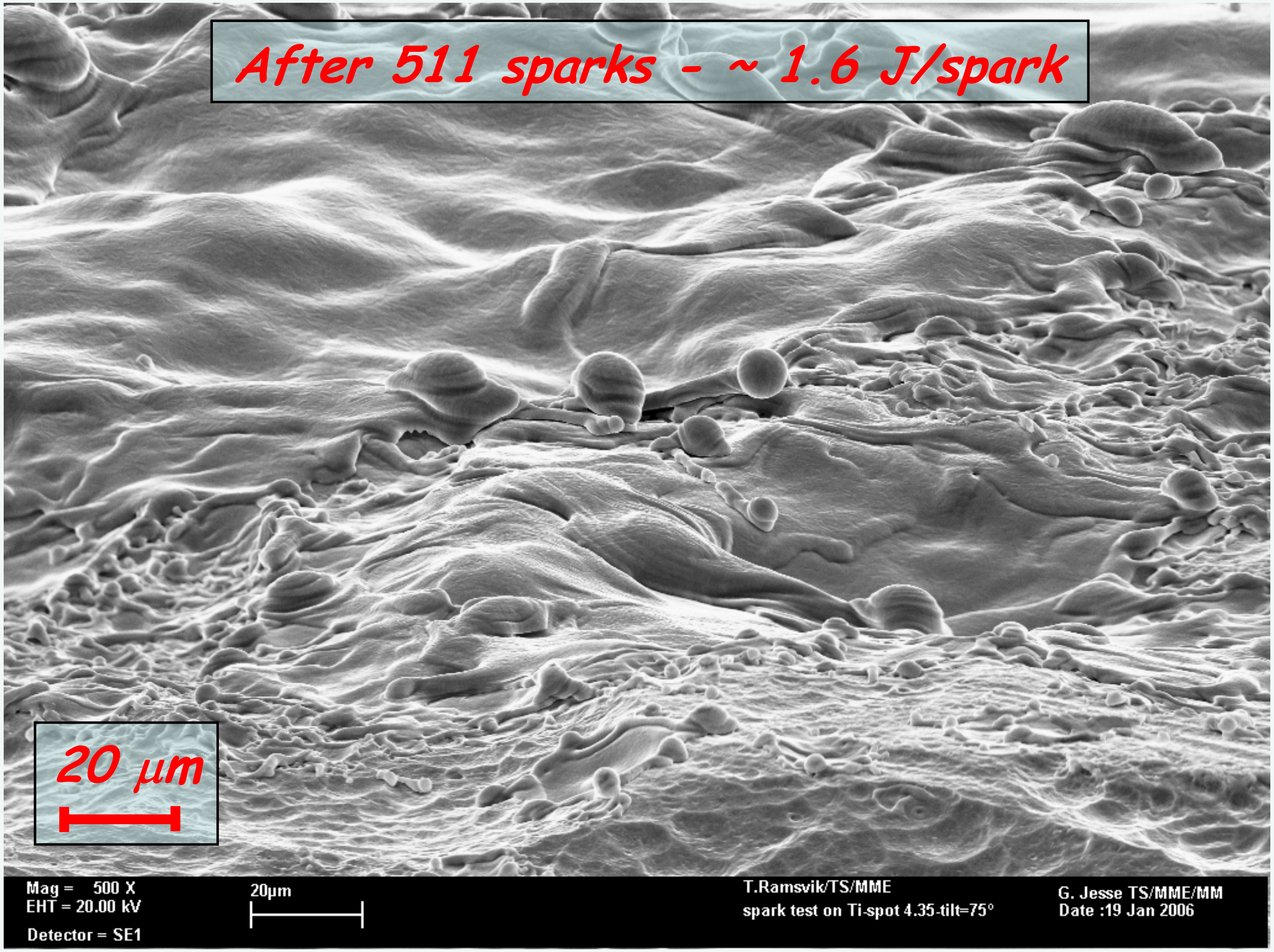


Before bake-out: $\beta \sim (40 \pm 10)$ $r_e \sim (2 \rightarrow 11)$ nm

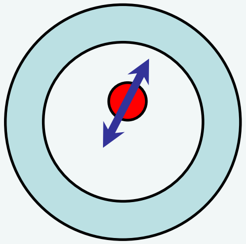
After bake-out: $\beta \sim (60 \pm 10)$ $r_e \sim (5 \rightarrow 40)$ nm

High uncertainty

Titanium cathode - SEM study



Movement of electrons in RF



$$M\frac{d^2z}{dt^2} = qE_0 \cos\omega t$$

Phase of RF field

$$z = z_0 + \frac{qE_0}{M\omega^2}\left(\cos\varphi - \cos\omega t\right) - \frac{qE_0}{M\omega}\left(t - \frac{\varphi}{\omega}\right)\sin\varphi$$

$\omega = 2\pi \cdot 33\times10^9\ s^{-1}$

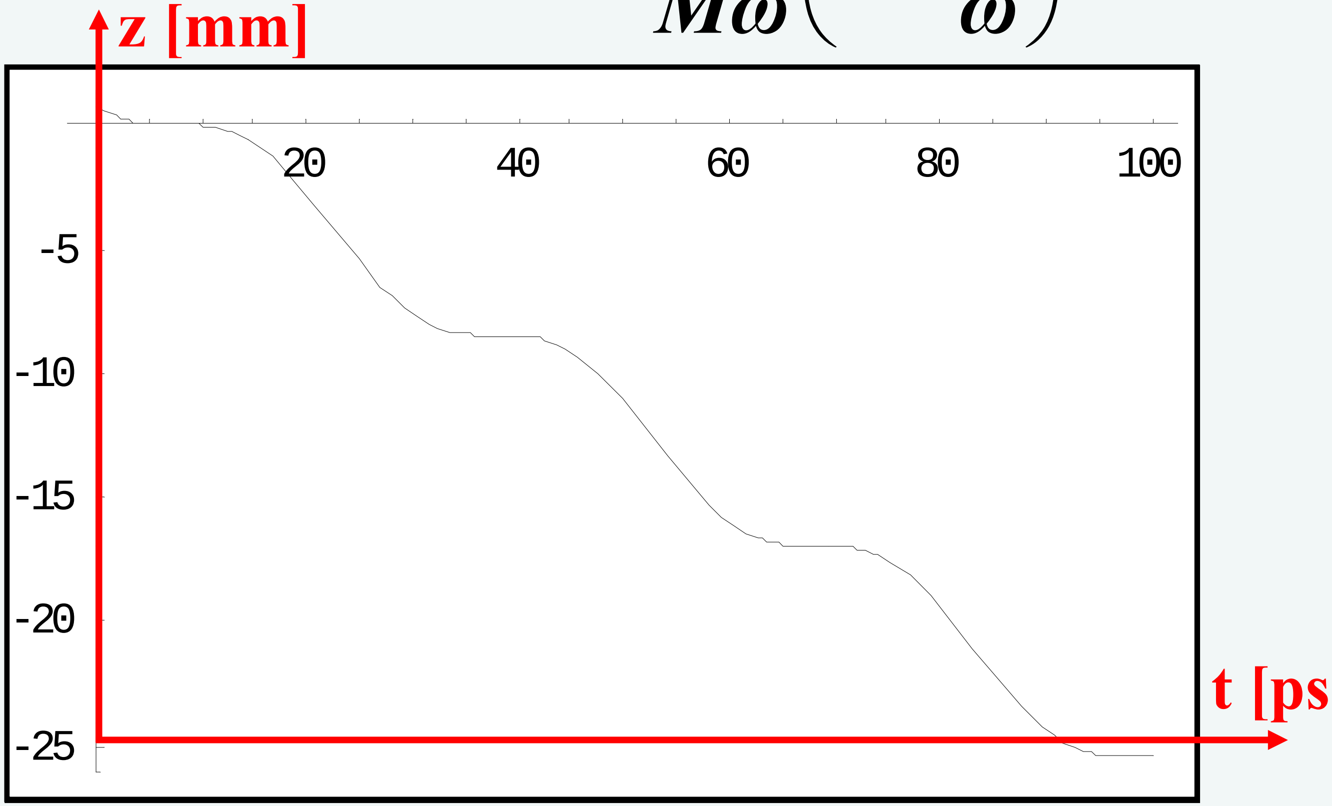
$q = 1.6\times10^{-19}$ C

$E_0 = 330\times10^6$ MV/m

$M_e = 9.1\times10^{-31}$ kg

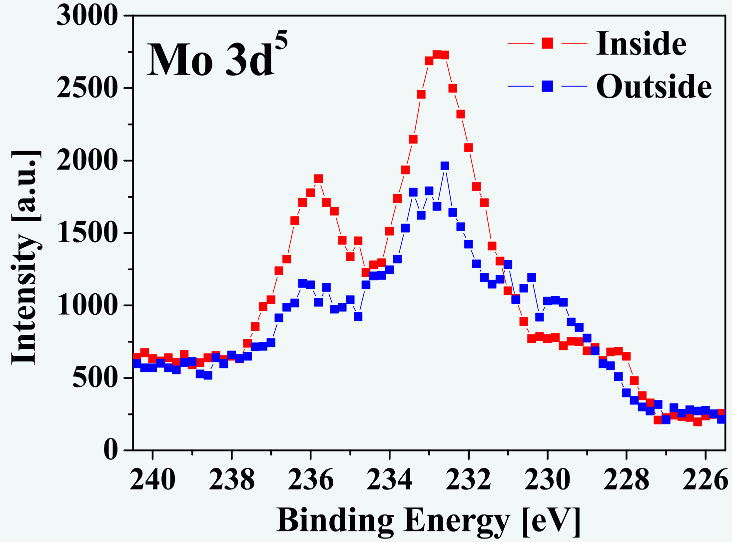
$\varphi = \pi/2$

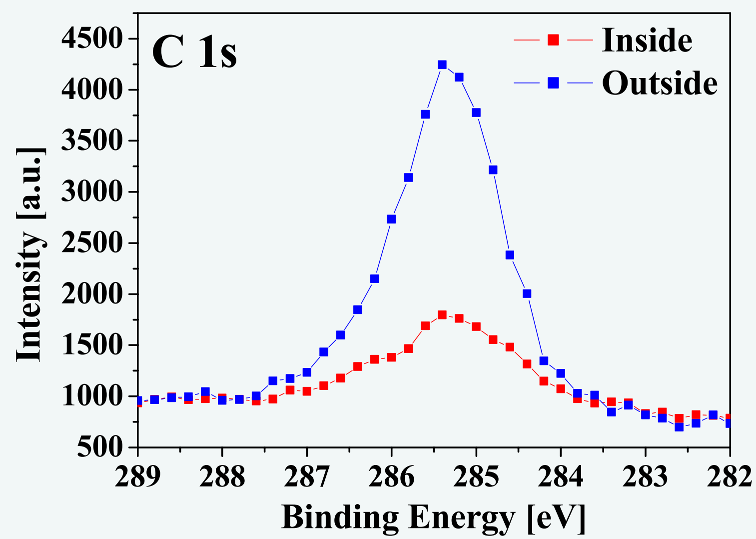
$z_0 = 0$

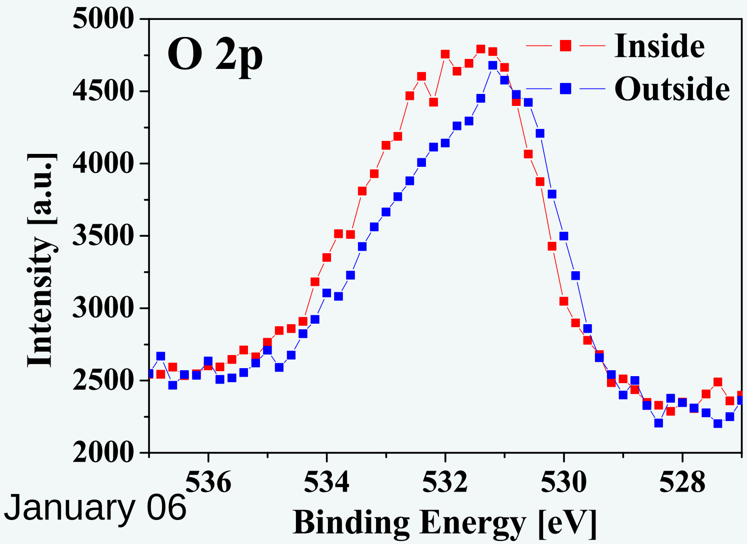


XPS

After ~1600 sparks and exposed to air





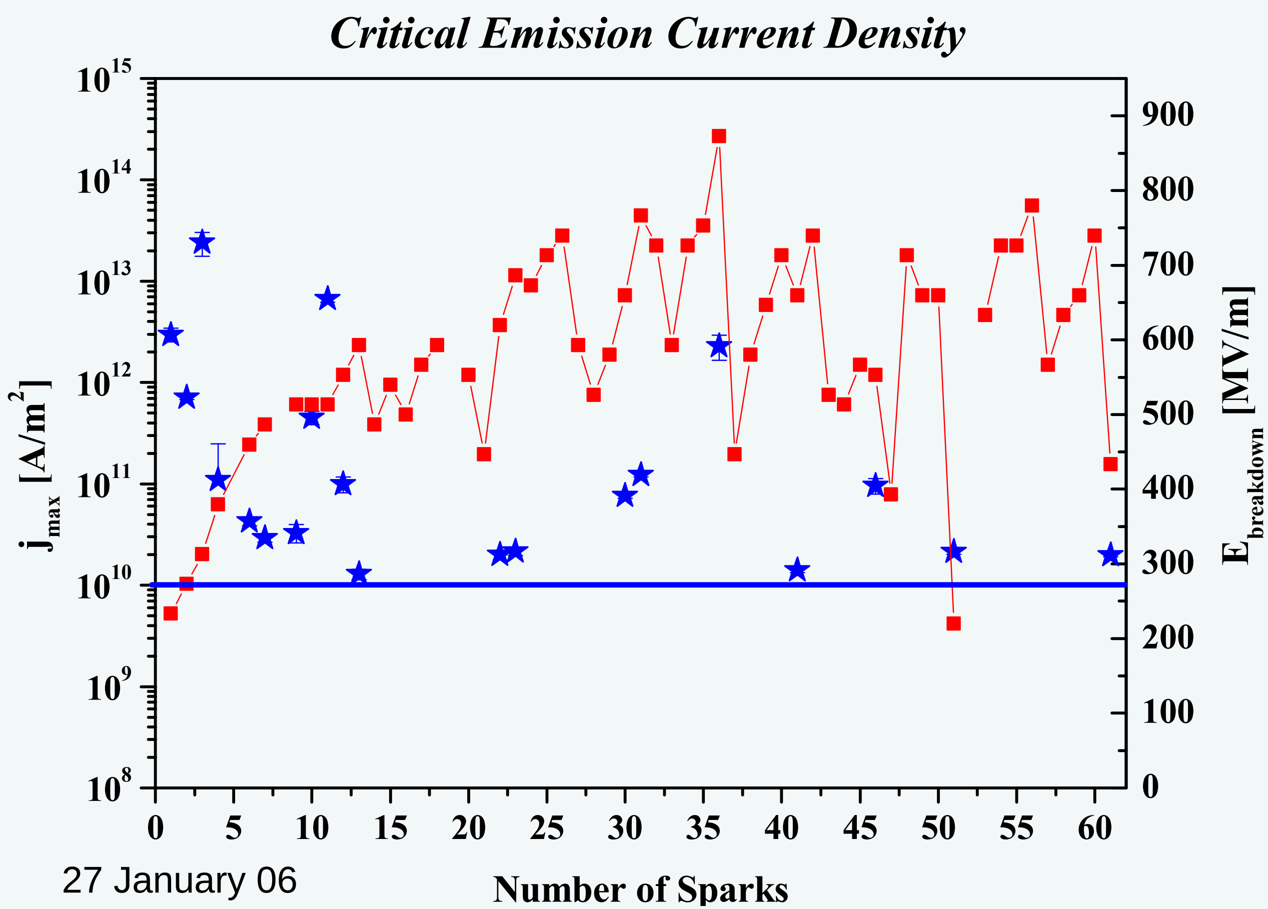


- ***Carbon reduced***
- ***Oxygen unchanged***
- ***Molybdenum Oxide peaks stronger***

Alessandra Reginelli TS/MME

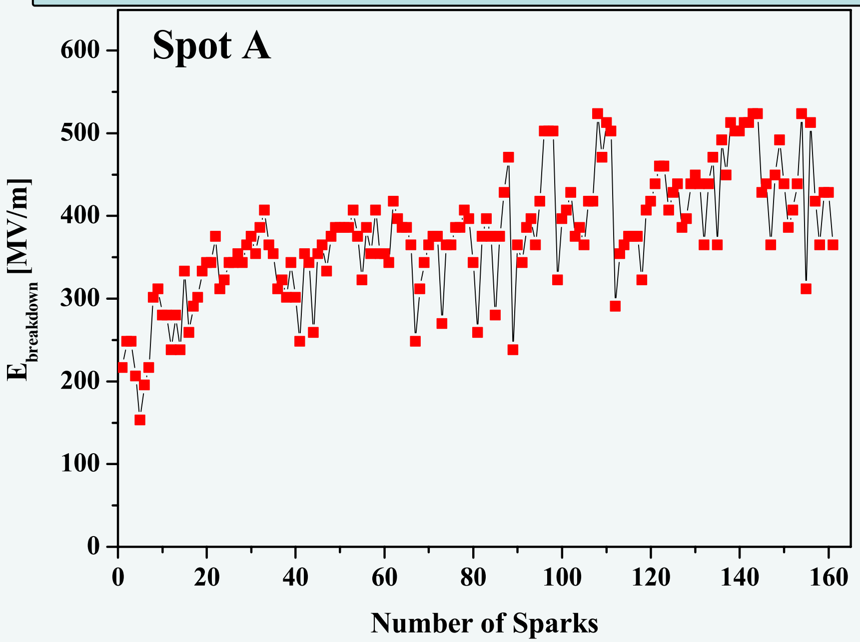
Titanium Anode and Cathode

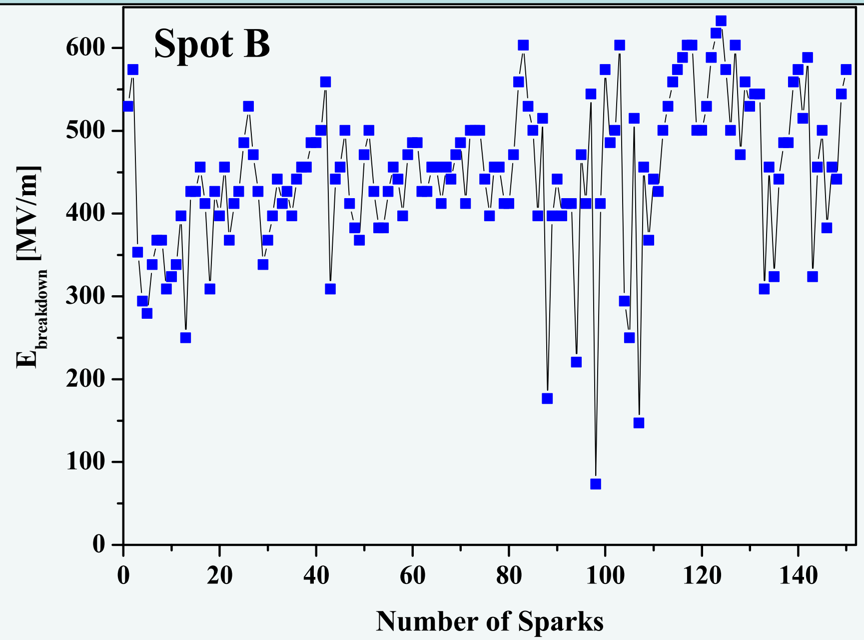
E. W. Muller (1937): **There is a critical emission current density of about $1 \cdot 10^{10}$ A/m^2 at which the emitting surface becomes thermally unstable, cathode material is vaporized and breakdown is consequently initiated.**



E. W. Muller, Z. Physik, 106, 541. (1937)

Mo - 950°C for 2 h in furnace



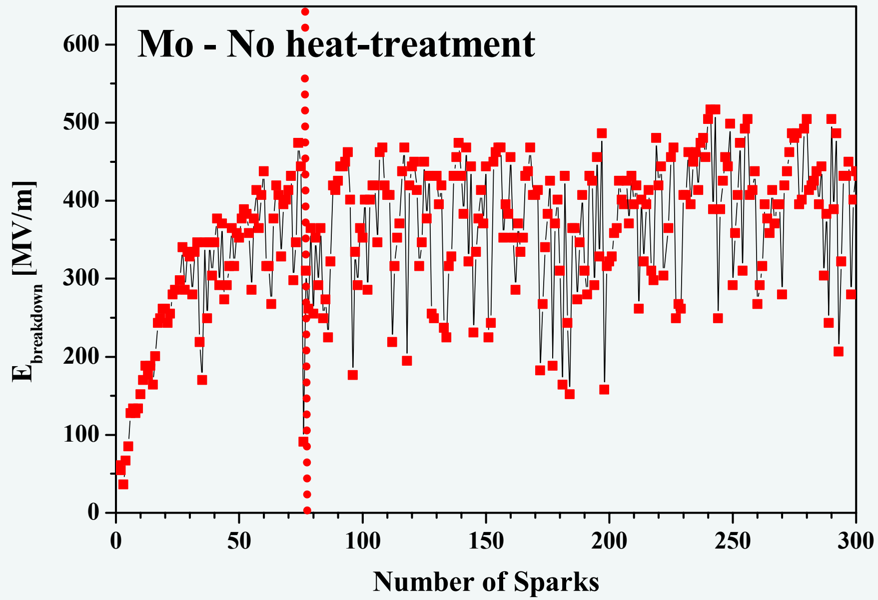


Conditioning Speed

Increased !

Traced of CrO_3 detected

⇨ ***ill-defined sample***

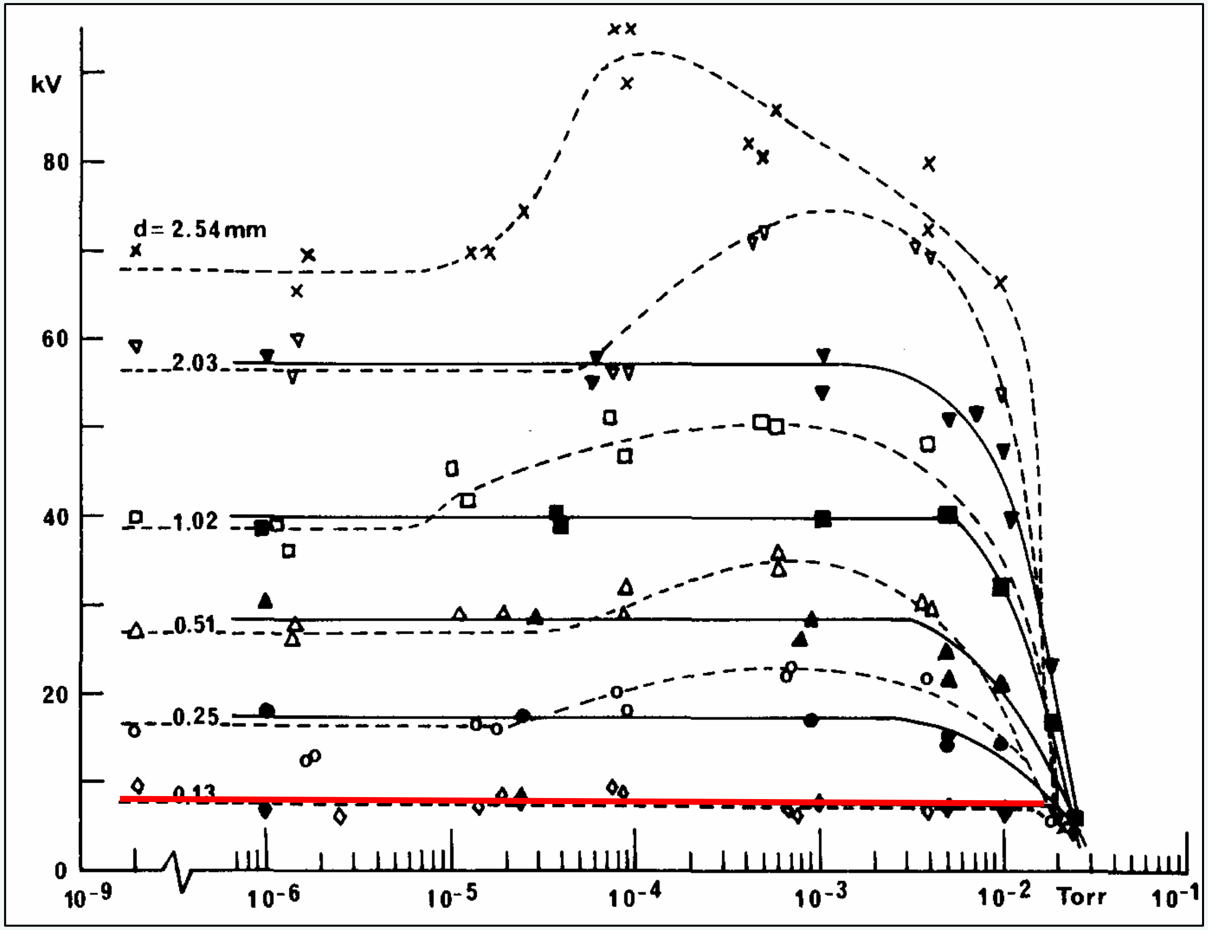


Costs:

- Technical Student for DC spark system (TS/MME?):
- New spark system (CLIC?):
  - UHV system and XYZ manupulator
    - already present
  - Power Supply ~ 16 kCHF (CAEN 20 kV/500 μA)
  - Linear Drive ~ 1.5 kCHF (VG 10 μm resolution)
  - Mechanical micro-positioning device ~ 1.0 kCHF
  - New Switching Electronics ~ 12.0 kCHF
    - 8 pcs 25 kV low current switches ~ 9.7 kCHF
    - 1 pc 30 kV Hammer Switch ~ 1.3 kCHF
    - Switching board ~ 0,5 kCHF
    - Various electronic components and cables ~0.5 kCHF
  - Workshop expenses: 2.0 kCHF (?)

Estimated Cost for materials: ~ 35 kCHF

Gas Experiments

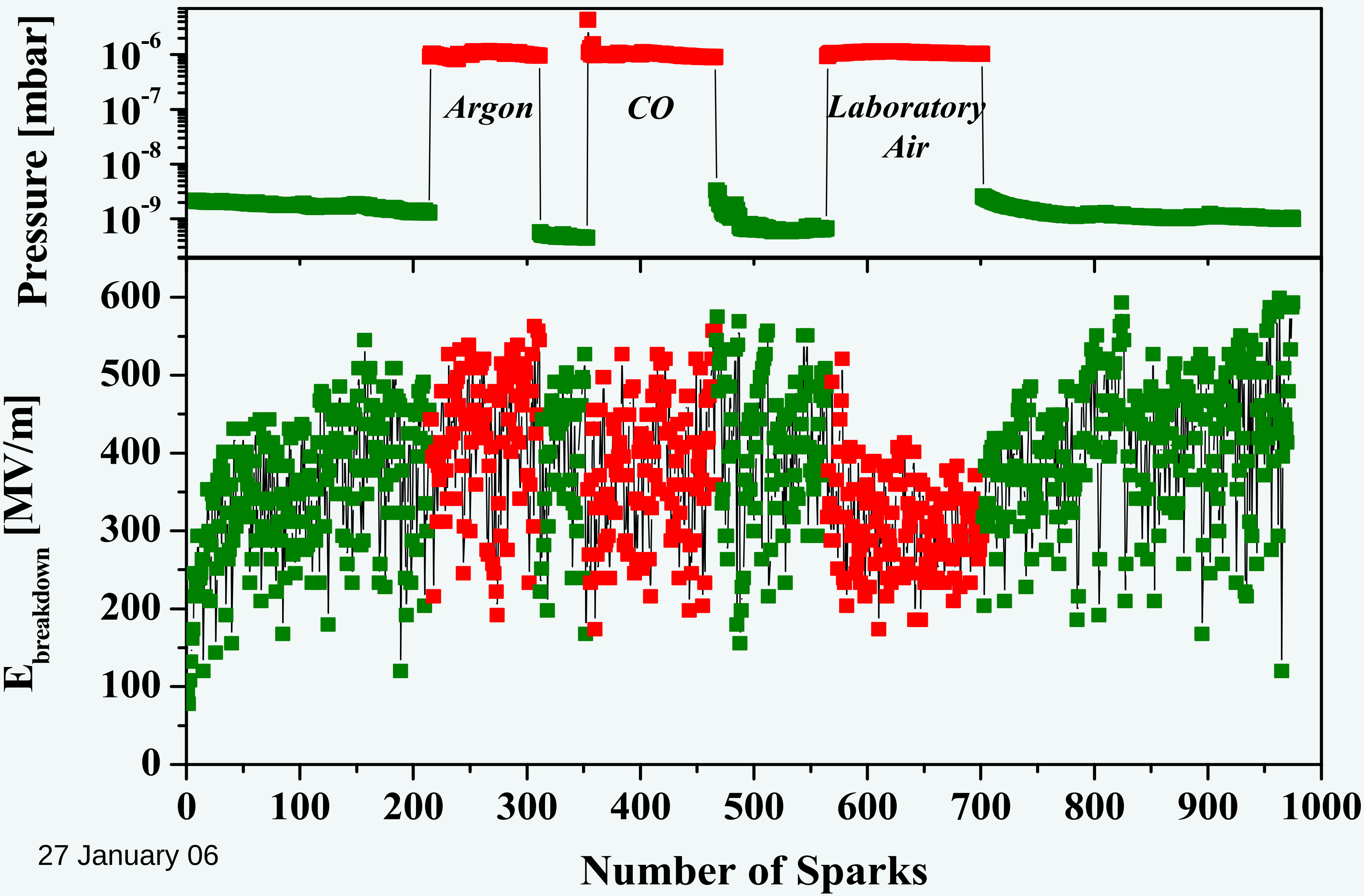


From literature:

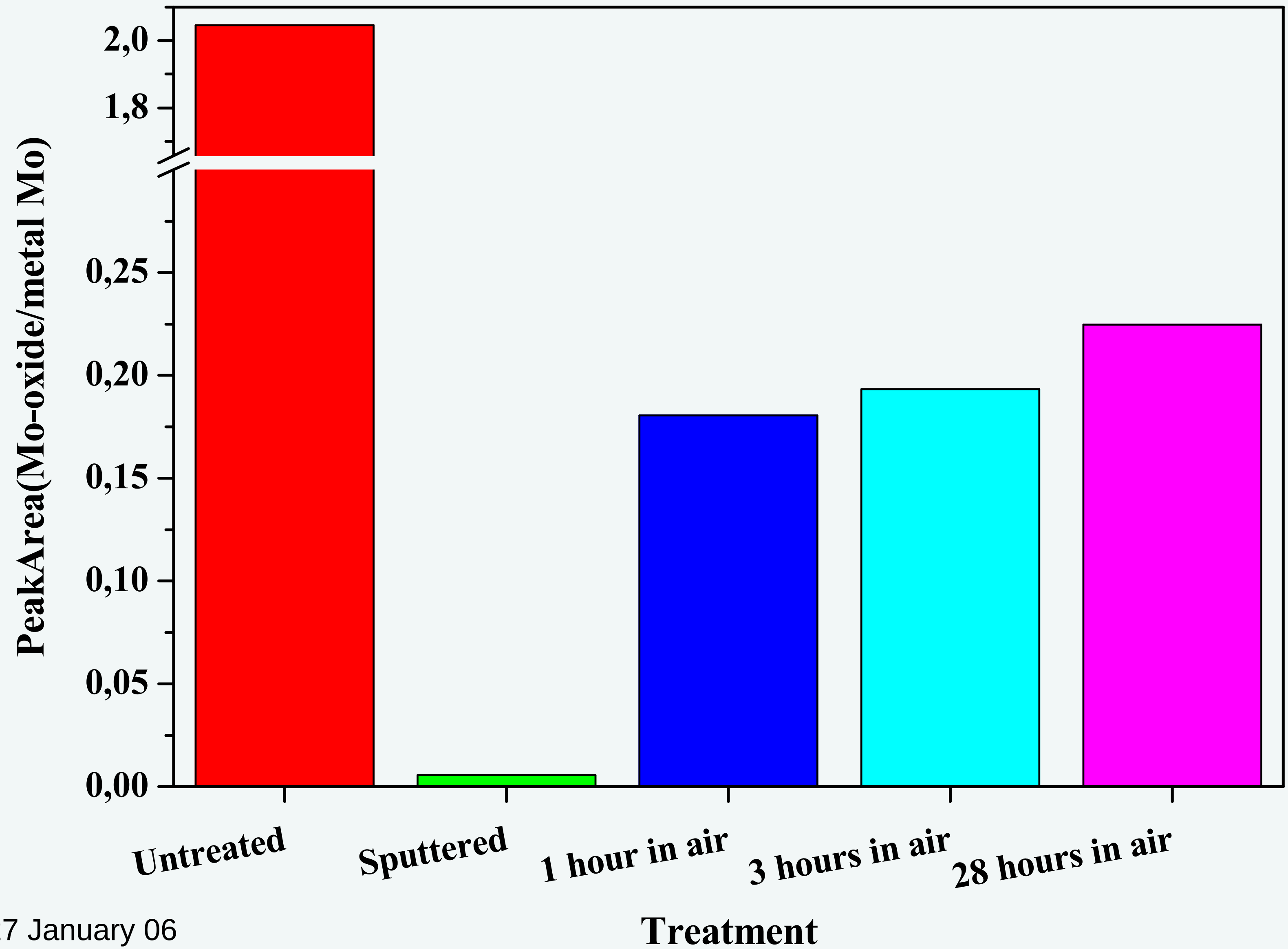
- ***Pressure effect on the breakdown field significant for large gaps***
- ***Breakdown field deteriorates at pressures typically above 10^{-2} mbar***

R. Hackham and L. Altcheh, J. Appl. Phys., 46, 627-36 (1975)

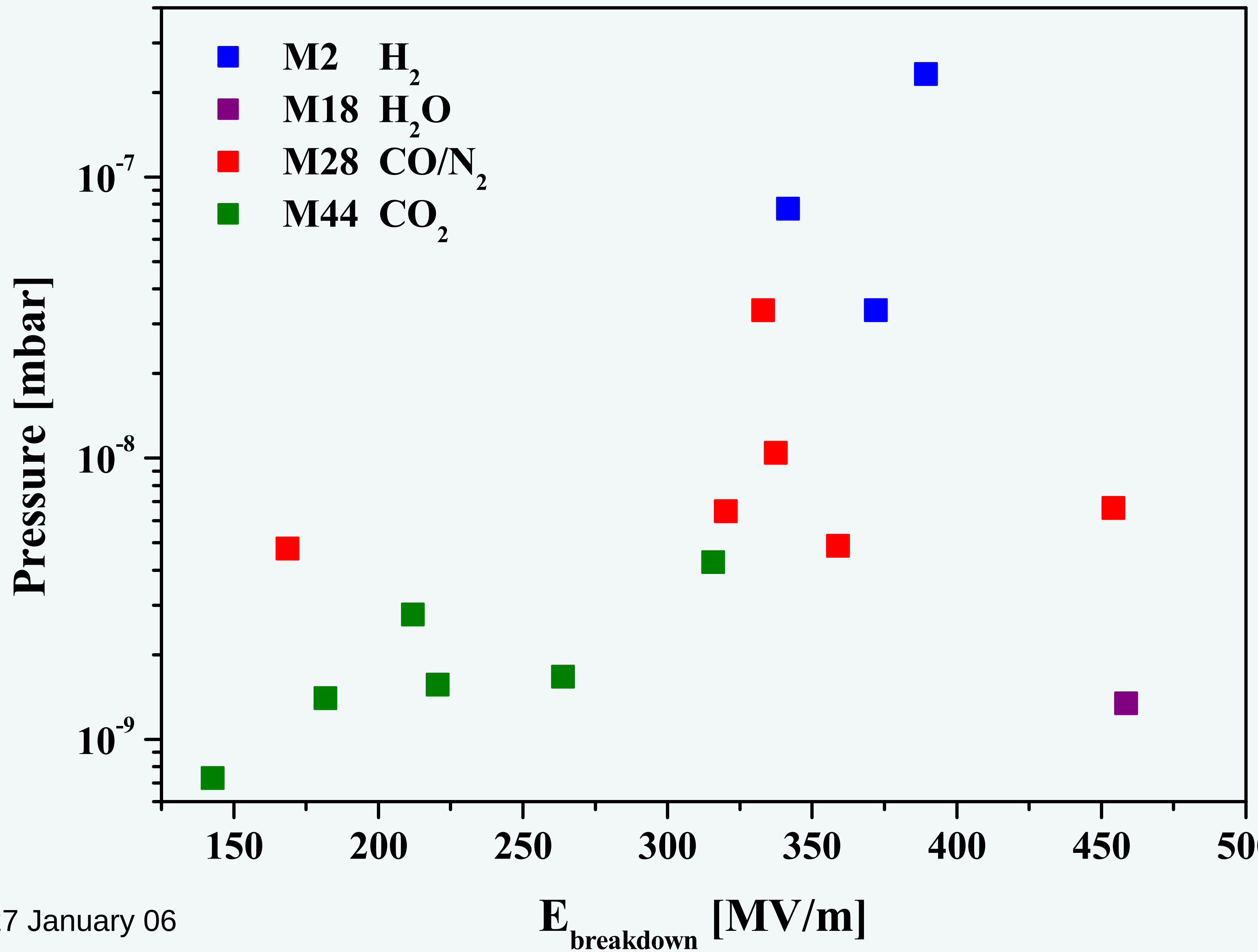
Gas Experiments - Mo



XPS - Sputter Treatment

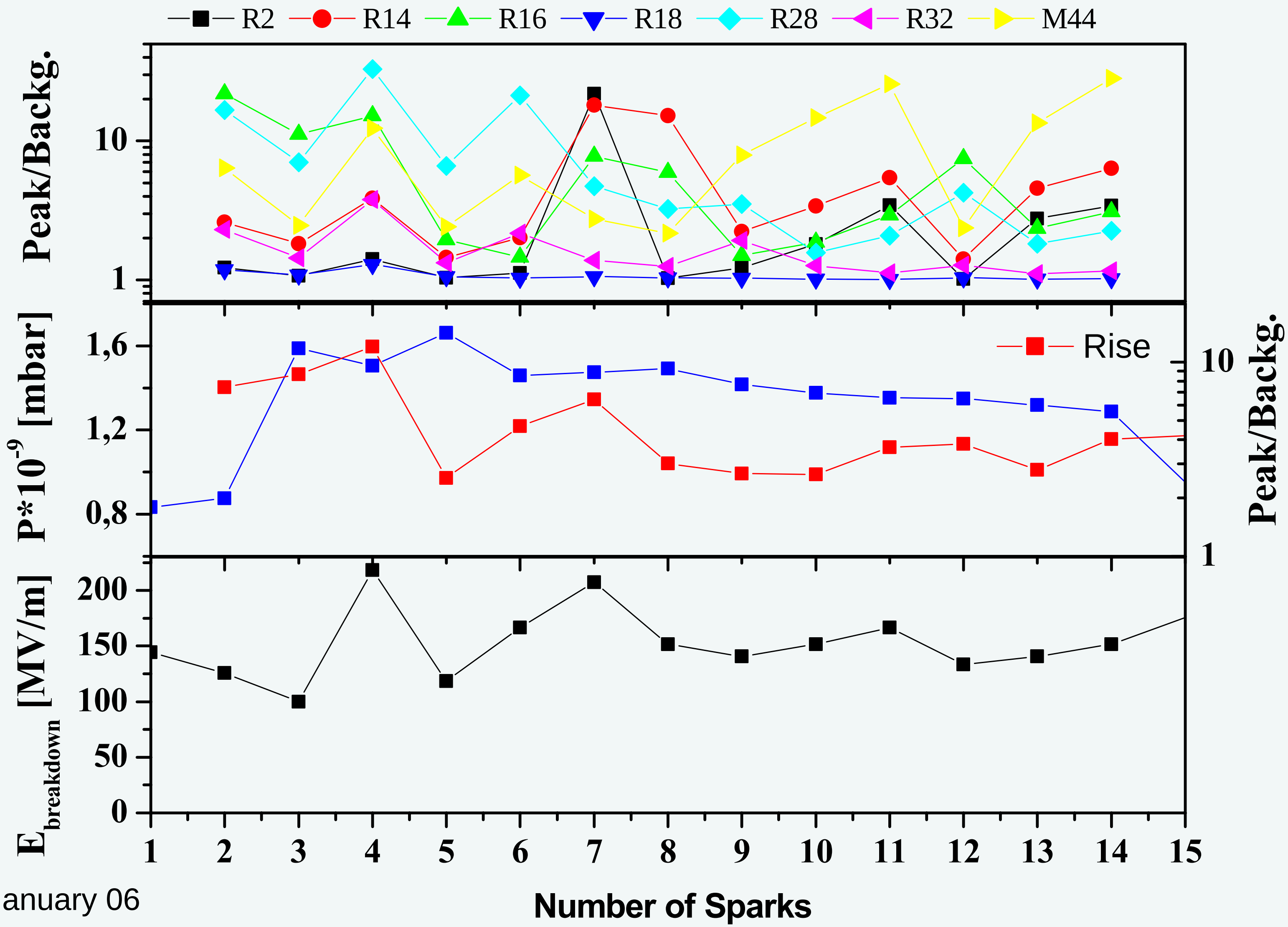


Mass Spectroscopy - Mo



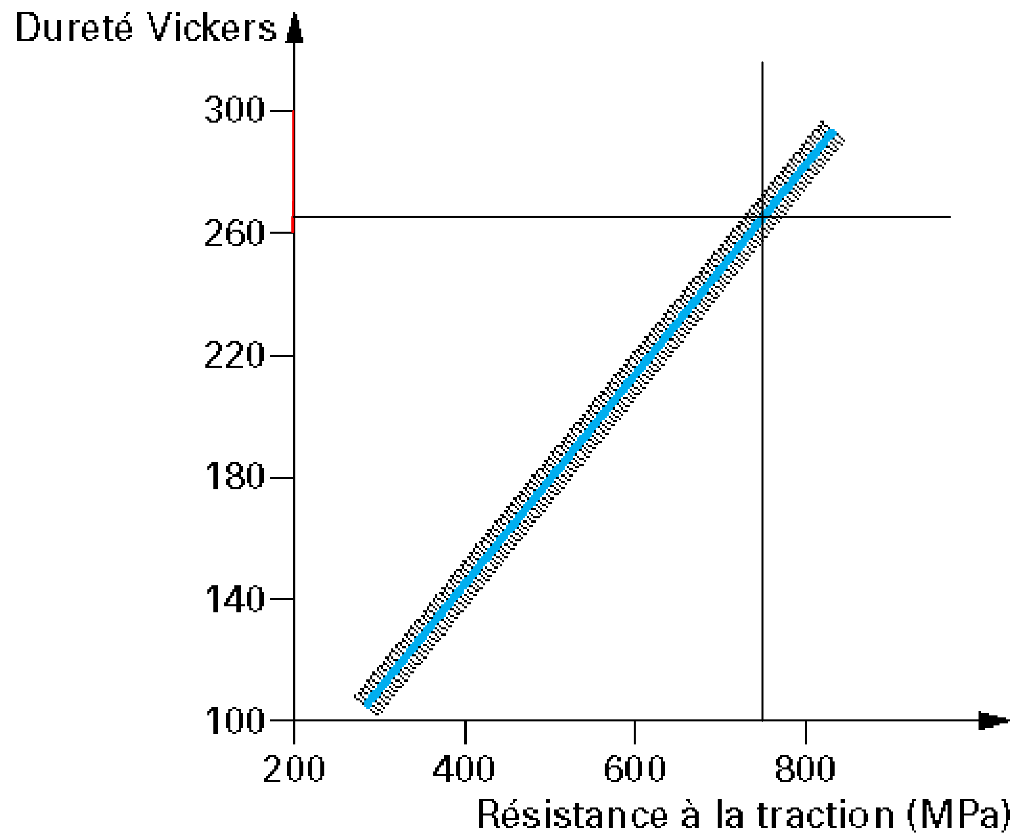
Gas Experiments – Mass Spec.

Cu Tip and Sample

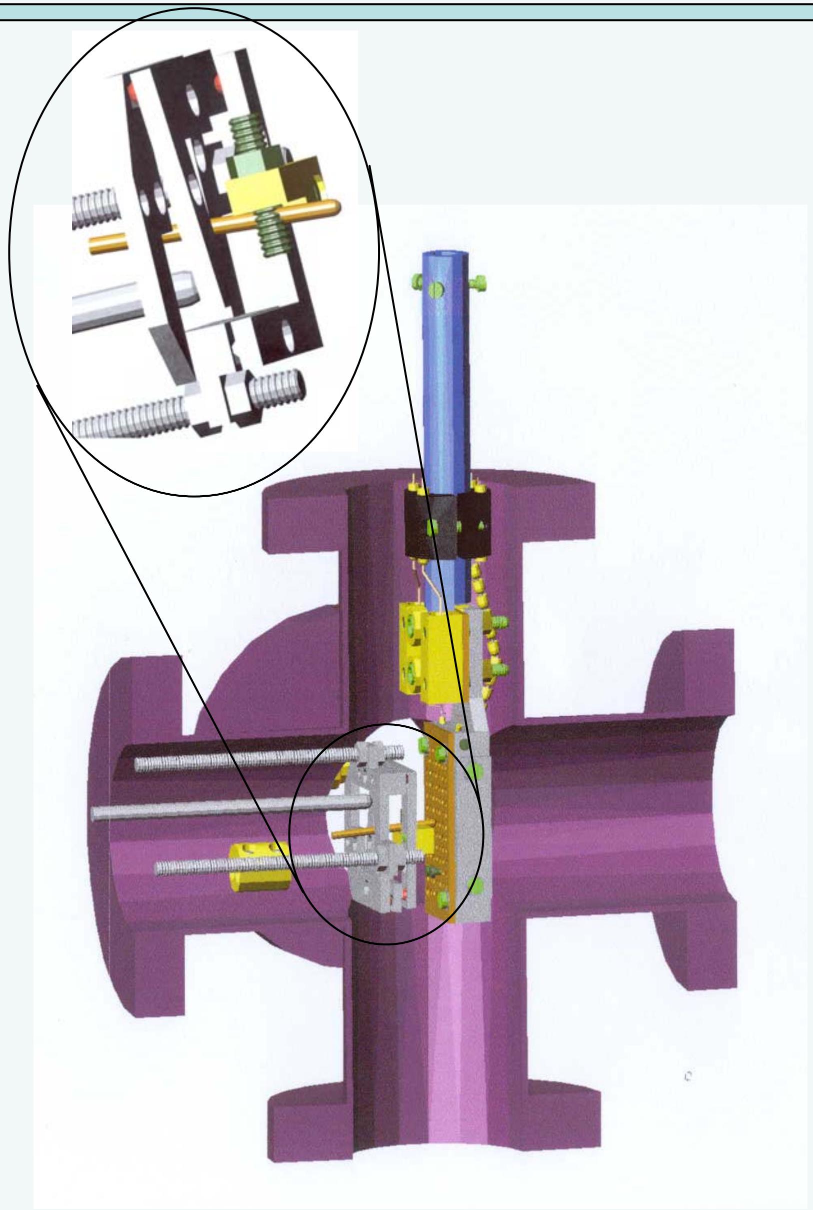


27 January 06

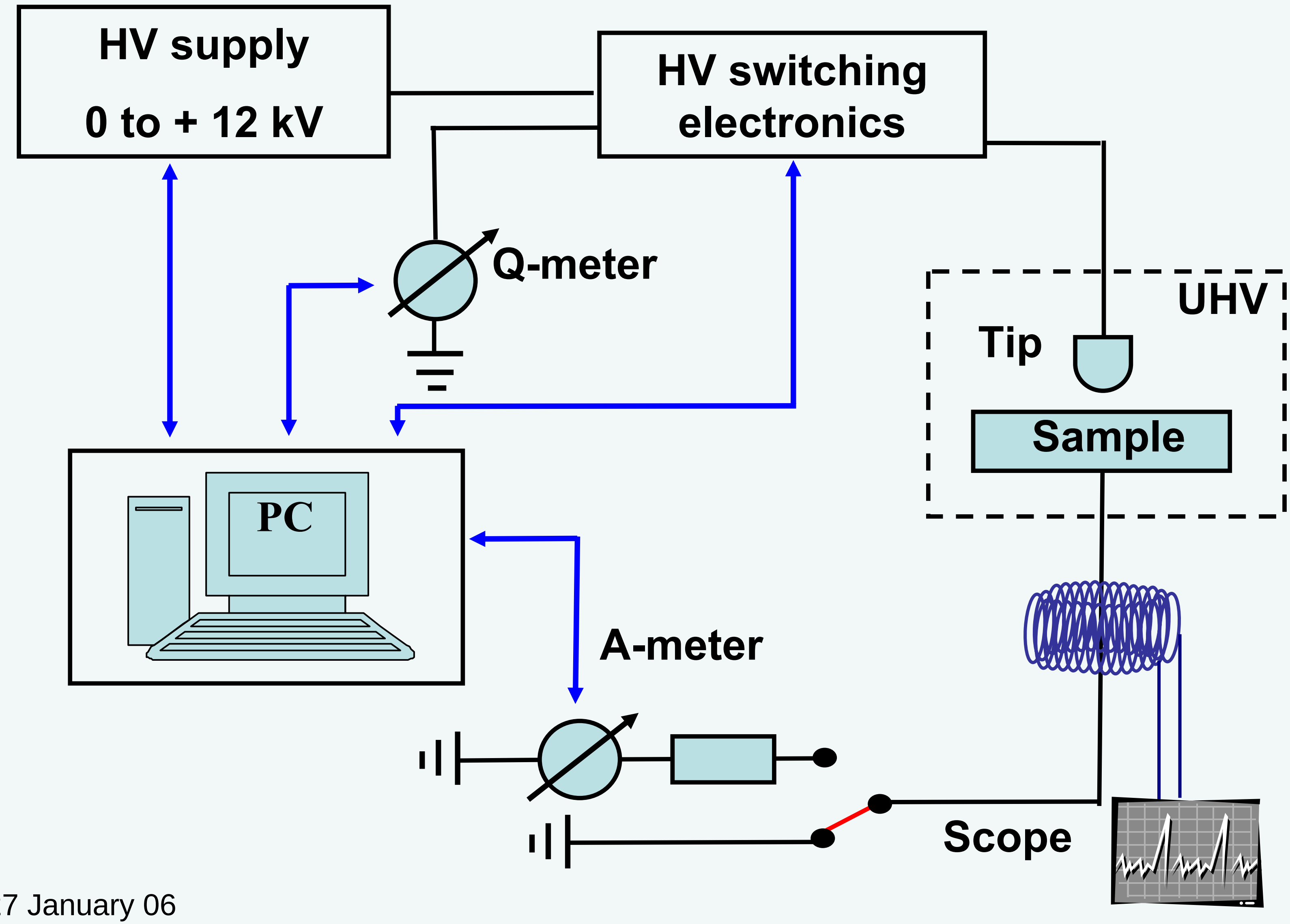
Vickers ↔ Tensile Strength



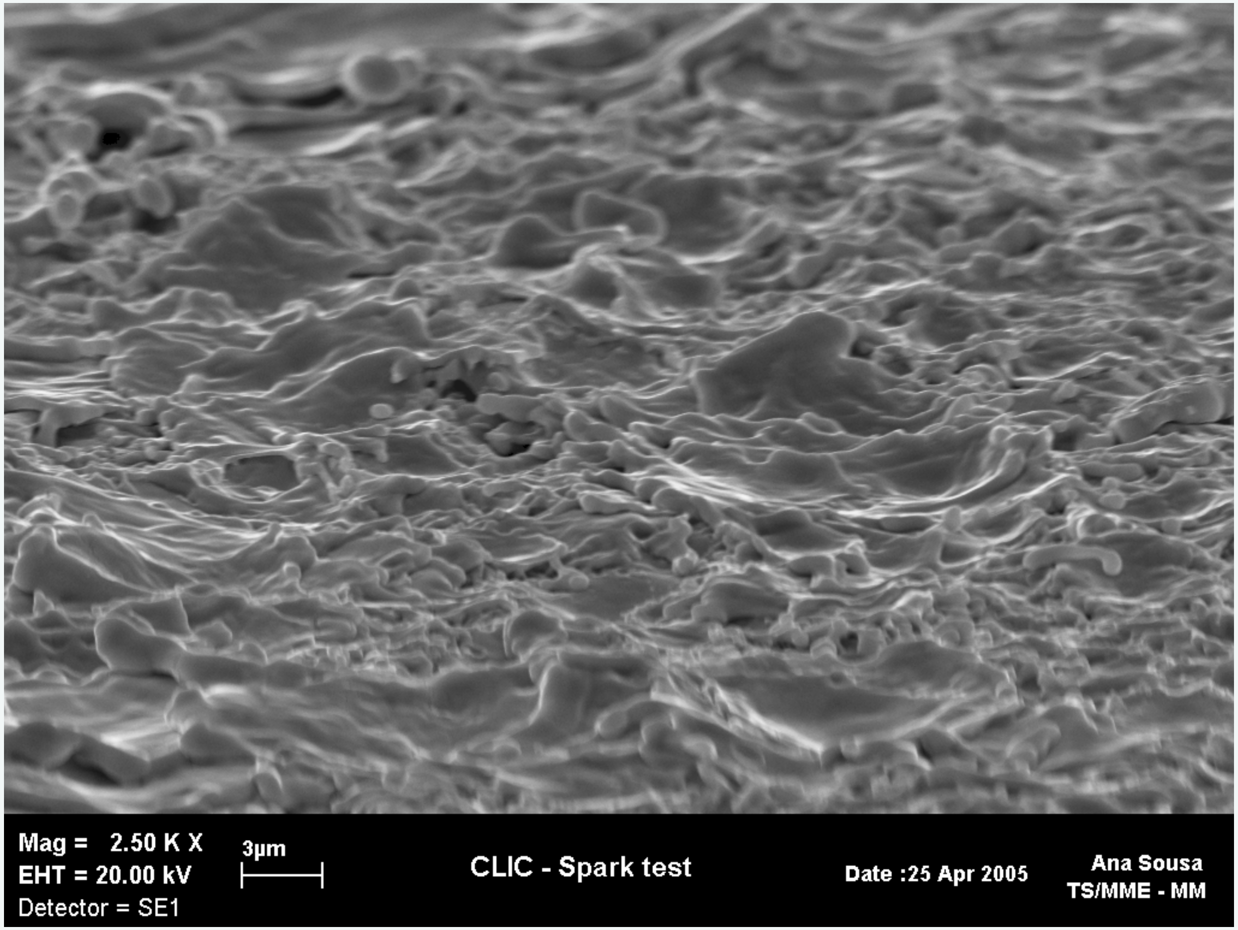
C. Bourgés Monnier, “*Propriétés du molybd è ne et des alliages à base de molybdene*”, Ecole des mines, Paris



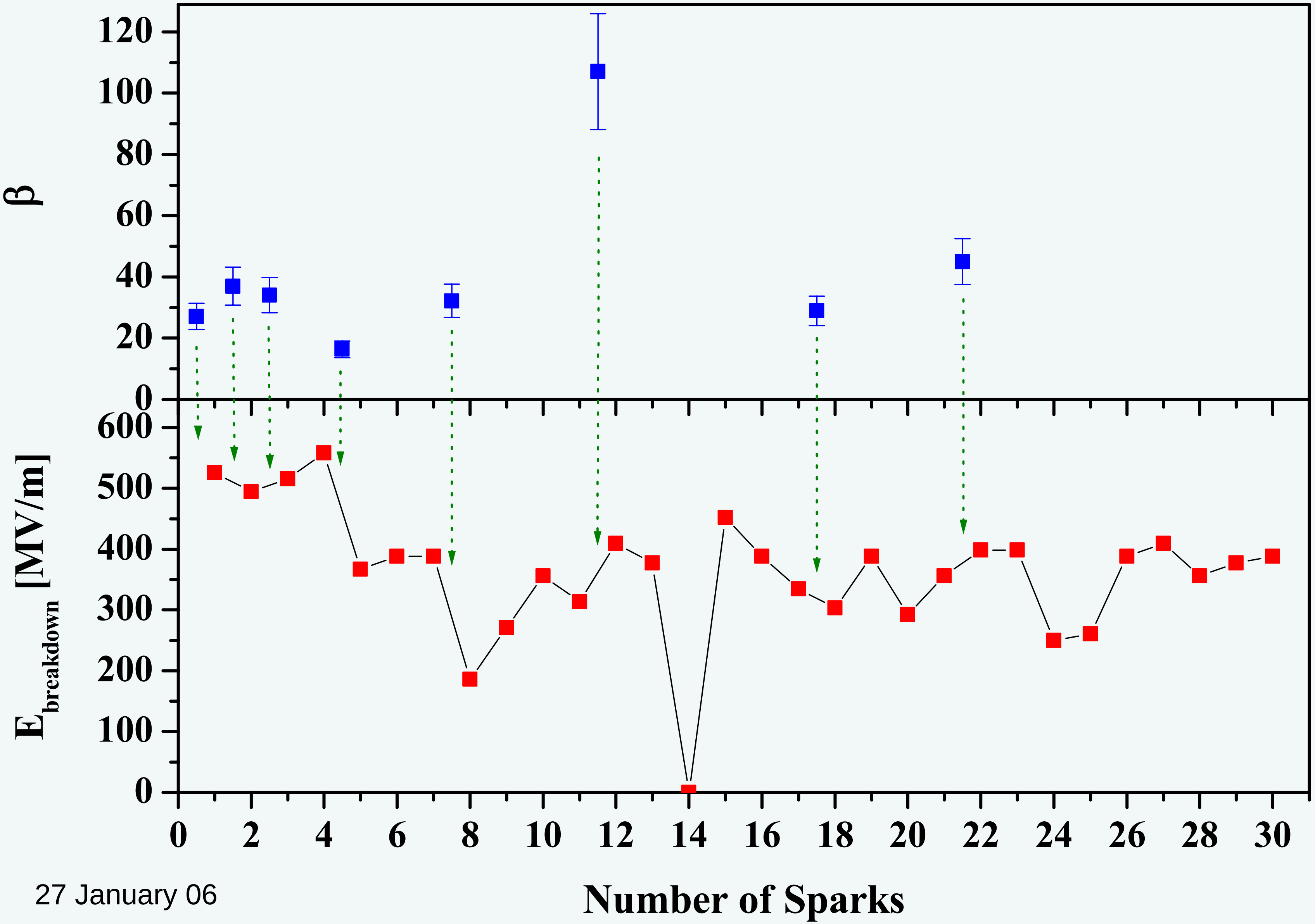
Details of experimental setup



Scanning Electron Microscopy



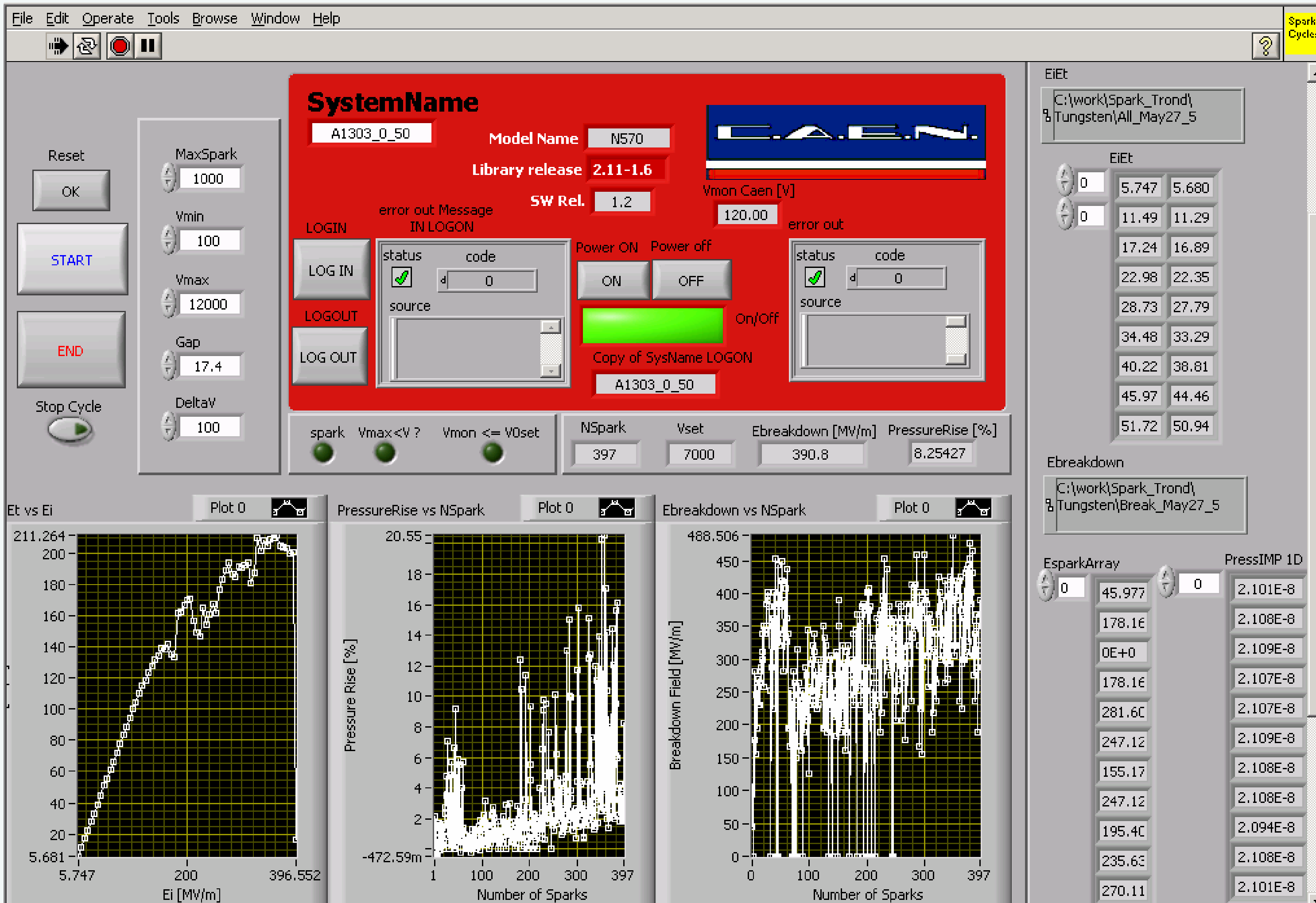
Mo - evap. 25.10.2005 z=4.16 Beta



27 January 06

Automatic Spark Conditioning

Results of Spark Conditioning



27 January 06

Field Evaporation of Mo and W

First-principles study on field evaporation of surface atoms from W(011) and Mo(011) surfaces

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Abstract

The simulations of field-evaporation processes for surface atoms on W(011) and Mo(011) surfaces are implemented using first-principles calculations based on the real-space finite-difference method. The threshold values of the external electric field for evaporation of the surface atoms, which are ~6 V/Å for tungsten and ~5 V/Å for molybdenum, are in agreement with the experimental results. While the threshold value of the electric field and the local-field enhancement around the evaporating atoms agree with those expected from the conclusion of the previous study using structureless jellium, the induced charge around the surface atom has a significant difference from that obtained by the jellium model.

Keywords: Density functional calculations; Molecular dynamics; Field effect; Field evaporation; Metallic surfaces

W: 60 GV/m

Mo: 50 GV/m

Gas Experiment – R. Hackam / L. Altcheh

ac (50 Hz) and dc electrical breakdown of vacuum gaps and with variation of air pressure in the range 10^{-9}–10^{-2} Torr using OFHC copper, nickel, aluminum, and niobium parallel planar electrodes

Reuben Hackam and Leo Altcheh

Electronic and Electrical Engineering Department, The University of Sheffield, Sheffield, S1 3JD, England
(Received 2 May 1974; in final form 6 August 1974)

Breakdown potentials of vacuum gaps are measured over a wide range of air pressure using both direct and alternating (50 Hz) applied voltage and employing four different electrode materials. The air pressure is varied in the range 2×10^{-9}–2.5×10^{-2} Torr for dc and 6×10^{-7}–2.5×10^{-2} Torr for ac applied voltage. OFHC copper, nickel, aluminum, and niobium are used to fabricate the electrodes. It is found that the peak ac breakdown voltage is usually higher than the dc voltage for a fixed electrode separation and a fixed gas pressure. Under certain conditions considerable improvement in the insulating property of the gap can be obtained in semivacuum. The improvement in the breakdown voltage of the gap is considerable and can reach up to 62% in some cases. The higher breakdwon voltage is attributed to the increased work function of the metal-gas adsorbate system.

OFHC copper, nickel, aluminum, and niobium

Gas Experiment – R. Hackam / G. R. G. Raju

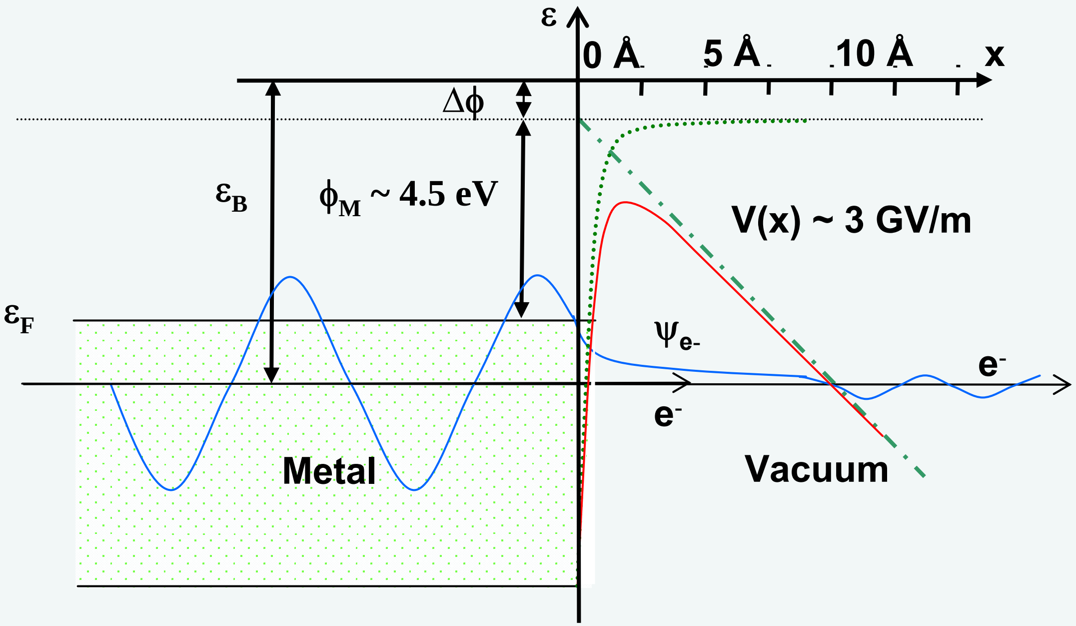
Electrical breakdown of a point-plane gap in high vacuum and with variation of pressure in the range 10^{-7}–10^{-2} Torr of air, nitrogen, helium, sulphur hexafluoride, and argon

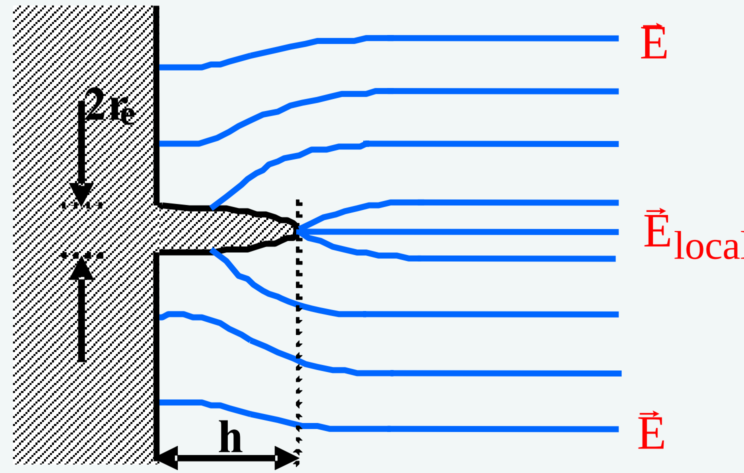
Reuben Hackam and G. R. Govinda Raju

Electronic and Electrical Engineering Department, The University of Sheffield, Sheffield, S1 3JD, England
(Received 18 February 1974; in final form 29 April 1974)

The dc breakdown potential of a point-plane electrode configuration is measured in high vacuum ($\sim 10^{-7}$ Torr) using the positive and the negative voltage polarity of the point electrode as a function of gap separation. Air, nitrogen, helium, sulphur hexafluoride, and argon are used in turn to alter the electrode coverage by adsorption of various gases in high vacuum. It has been found that helium gives the highest breakdown voltage at a given gap length, in high vacuum. It has also been found that very high sparking potential values are obtained using positive-point–negative-plane electrodes (90 kV at 0.3 mm gap length, helium at 3×10^{-7} Torr). The effect of ac (50 Hz) glow discharge conditioning on the dielectric strength of the gap is investigated and found to give considerable improvement in the voltage that the gap can withstand before a vacuum breakdown occurs. The effect of introducing various gases in the pressure range 10^{-7}–10^{-2} Torr on the breakdown potential of point-plane gaps is investigated. Maxima are observed in the breakdown voltage and pressure curves in the range 10^{-4}–10^{-3} Torr. Helium and nitrogen give the highest breakdown voltage of about 90 kV for a gap length of 0.2 mm at about 10^{-4} Torr. The observed improvements in the breakdown potential that the gap can withstand with certain gases are attributed to the increase in the work function of the combined metal-gas system.

Field Emission





$$\vec{E}_{local} = \beta\, \vec{E}_{applied} = \beta\, \vec{E}$$

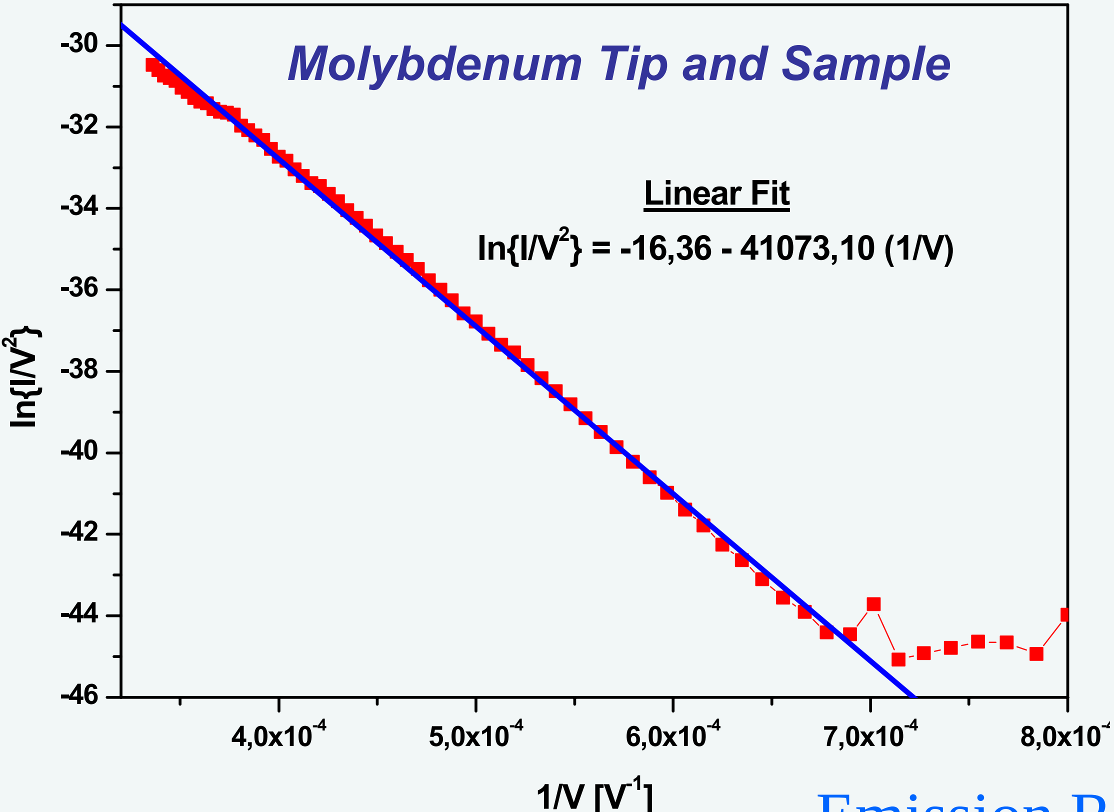
$$V \approx E\, d$$

Fowler – Nordheim plot:

$$\ln\left[\frac{I_{FN}}{V^2}\right] = \ln\left[\frac{1.54\times10^{-6} A_e \beta^2}{\phi d^2}\times 10^{4.52\phi^{-\frac{1}{2}}}\right] - \frac{2.84\times10^{9}\, d\, \phi^{1.5}}{\beta}\frac{1}{V}$$

- R. A. Millikan and C. C. Lauritsen, Proc. Nat. Acad. Sci. (US), 14, 45-49 (1928)
- R. H. Fowler and L. Nordheim, Proc. Roy. Soc. A 119 (1928) 173.

Fowler - Nordheim plot



Enhancement factor:

$$\frac{d\left(\ln\left(\frac{I_{FN}}{V^2}\right)\right)}{d\left(\frac{1}{V}\right)} \propto \frac{d\,\varphi^{1.5}}{\beta}$$

$$\Downarrow$$

$$\beta \approx 23$$

Emission Radius:

$$\left[\ln\left(\frac{I_{FN}}{V^2}\right)\right]_{V=\infty} \propto \ln\left\{\frac{A_e\,\beta^2\,10^{4.52\,\varphi^{-\frac{1}{2}}}}{\varphi\, d^2}\right\} \Rightarrow r_e \approx 62\,nm$$

Spark Cycle

The voltage over the gap is increased until breakdown occurs