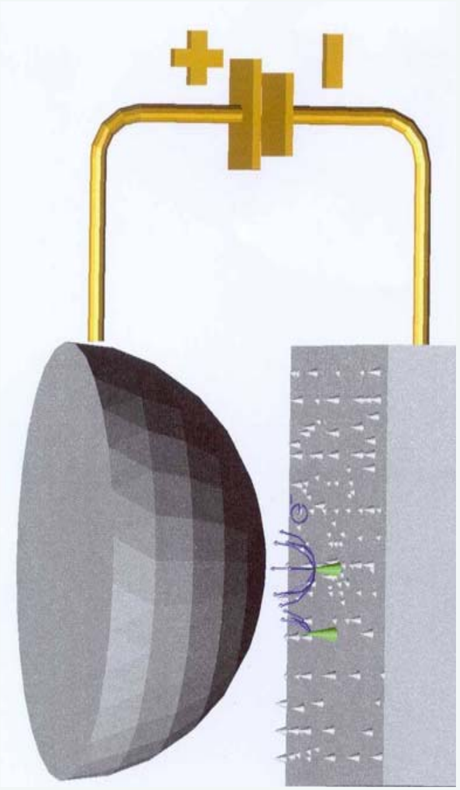
DC Spark Test System for CLIC



Trond Ramsvik

TS / MME

10 June 05

Outline

- *Introduction*
  - *Motivation, Origin of Breakdown, Materials*
- *Experimental Setup*
- *Field Emission*
- *Breakdown Field*
- *Local Field*
- *Automatic Spark Conditioning*
- *Effect of Residual Gas*
- *Further work*
- *Conclusions*

Introduction: Why DC spark experiments?

With a DC spark-test system, materials can be subjected to high electric fields, and their properties and responds to different treatments can be examined relatively easy and quickly.

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

Need to understand the details of the breakdown phenomena

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
      - ohmic heating from high field emission current density
      - fracture of the surface due to the tensile stress produced by the electric field
  - *Exchange*
    - Avalanche of mutual secondary emission of ions, electrons between the electrodes

*High Voltage Vacuum Insulation, edited by R. V. Latham (Academic, New York, 1995).

Introduction: Choice of materials

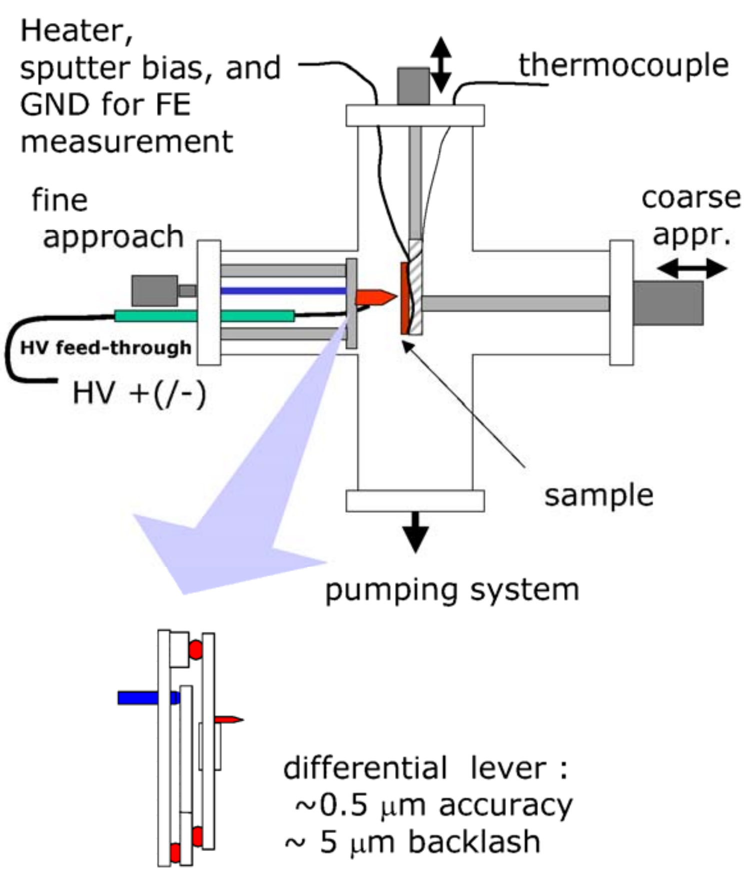
Criteria:

- *low vapor pressure*
- *high tensile strength*
- *high melting point*
- *high thermal conductivity*
- *high electrical conductivity*

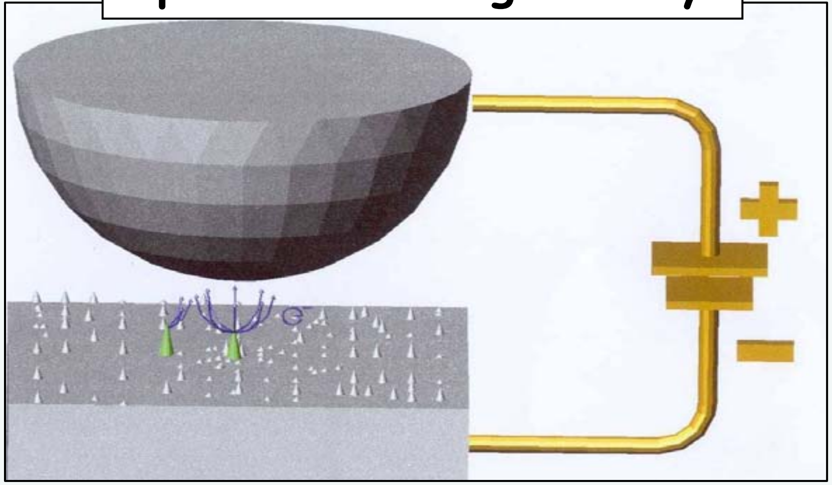
⇨ *Molybdenum & Tungsten*

Experimental Setup

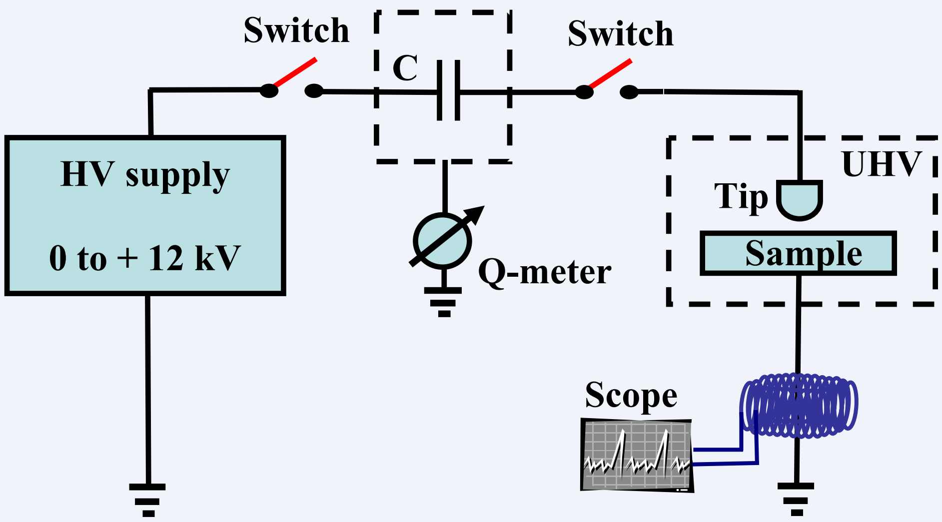
Spark test UHV chamber



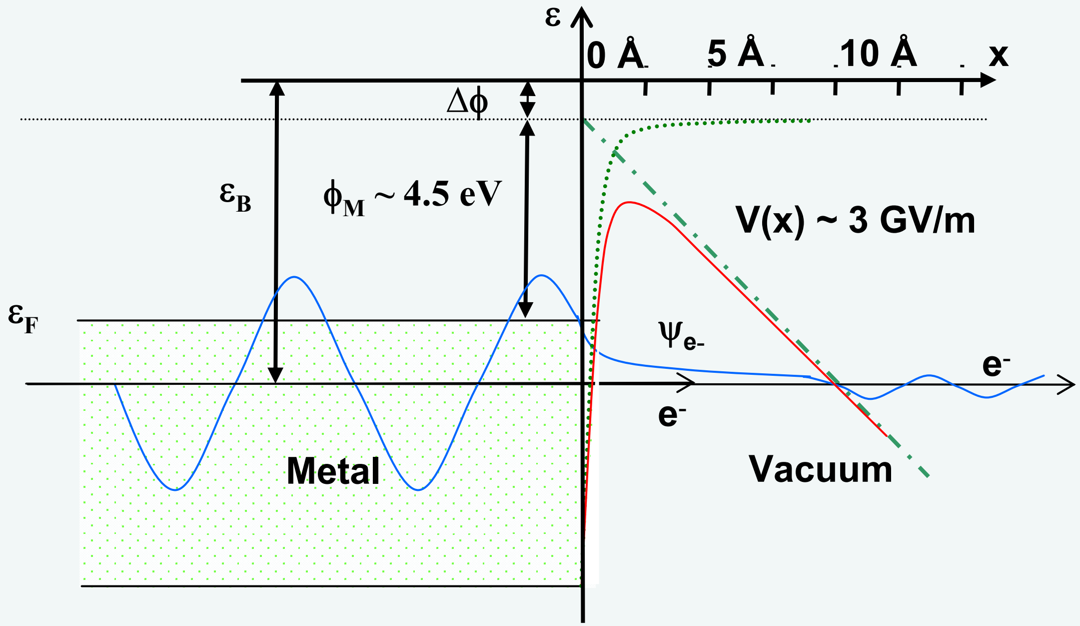
Sphere / Plane geometry

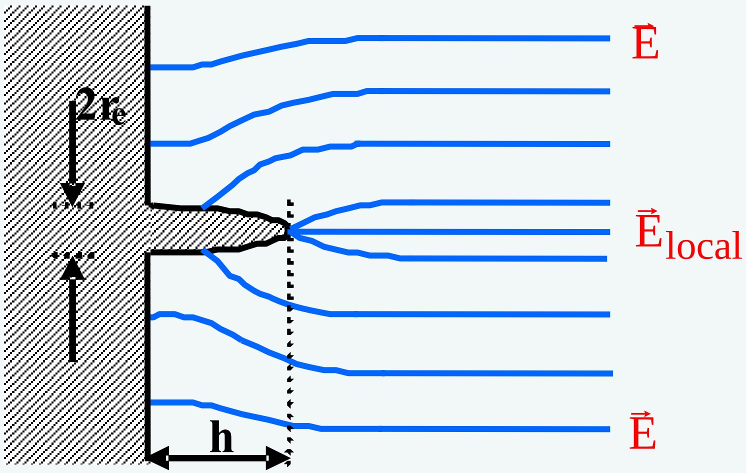


Breakdown Measurements



Field Emission





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

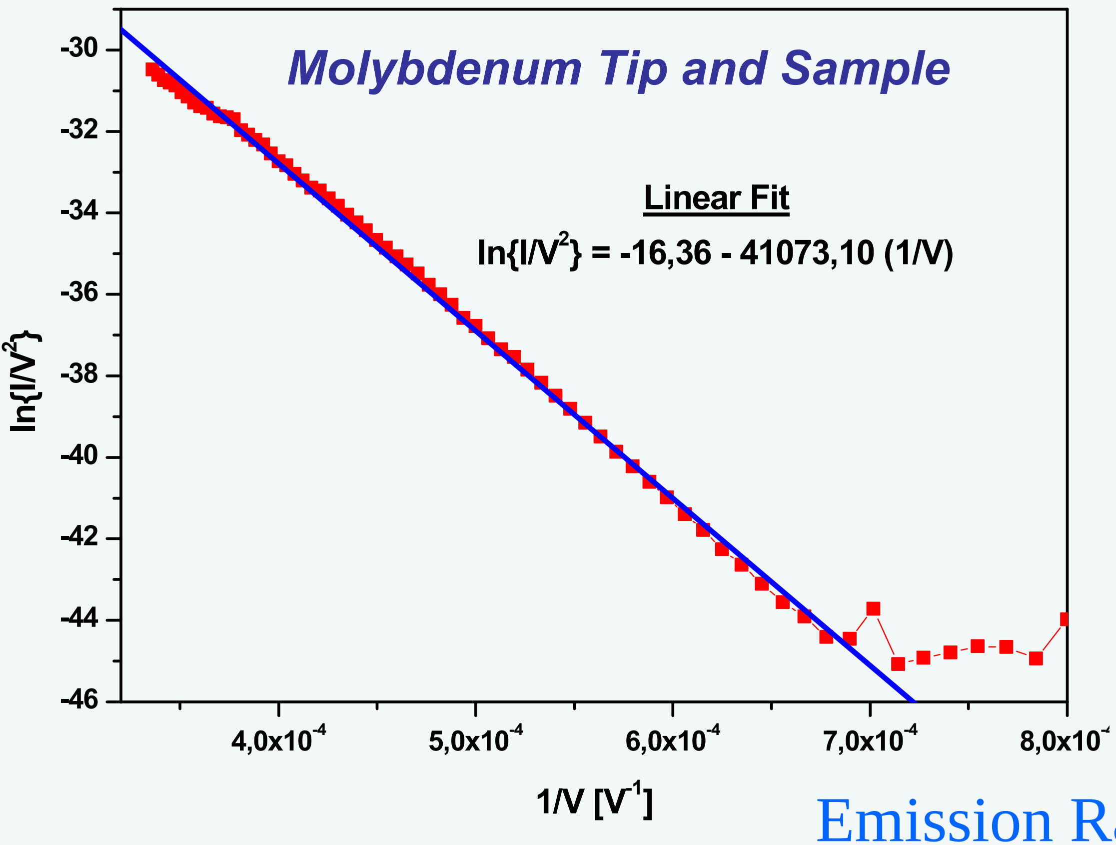
$$V \approx E\,d$$

Fowler – Nordheim plot:

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

- 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:

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

$$\Downarrow$$

$$\beta \approx 23$$

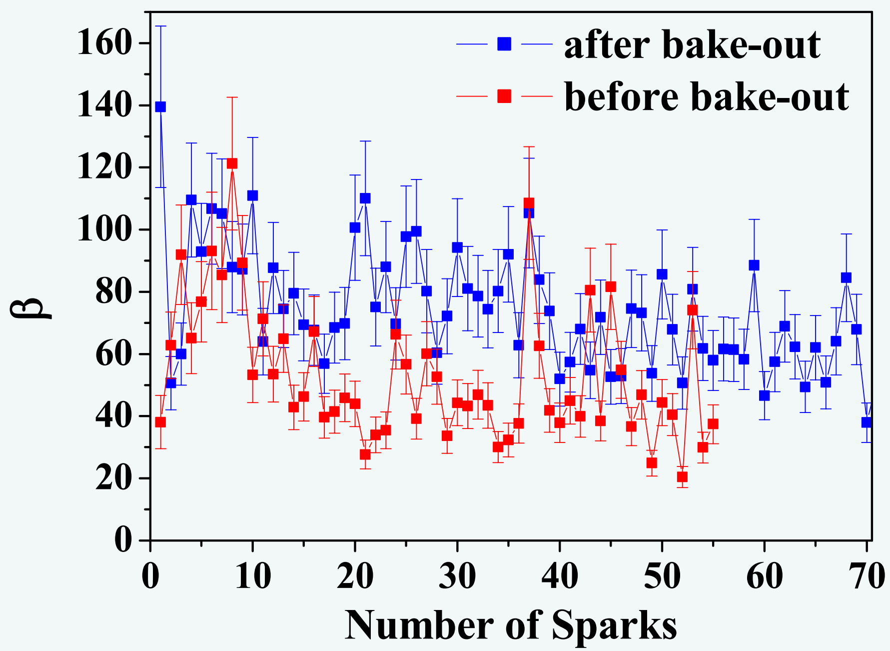
Emission Radius:

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

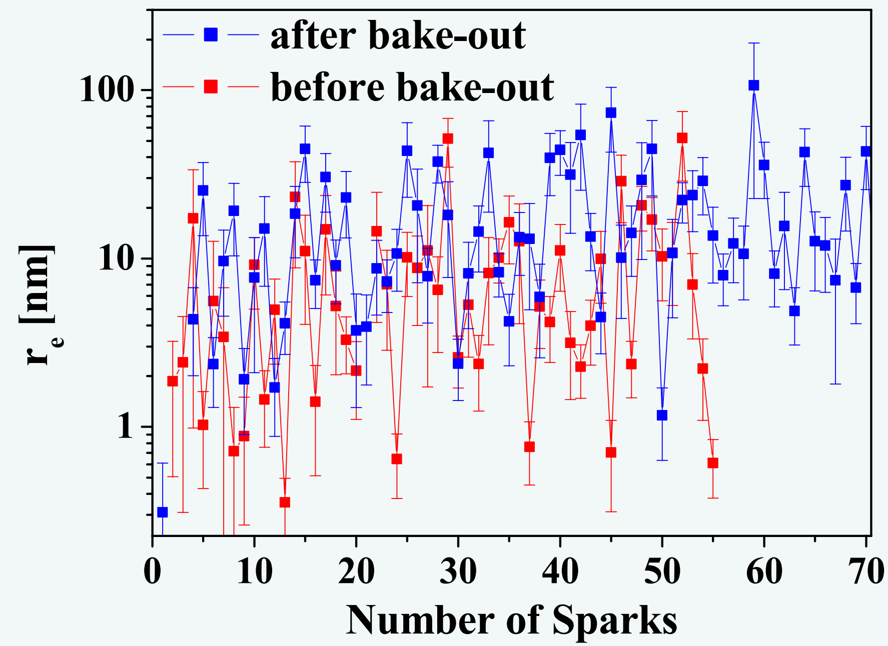
Results from Fowler - Nordheim plots

Molybdenum Tip and Sample

Enhancement Factor (β)



Emission Radius (r_e) [nm]



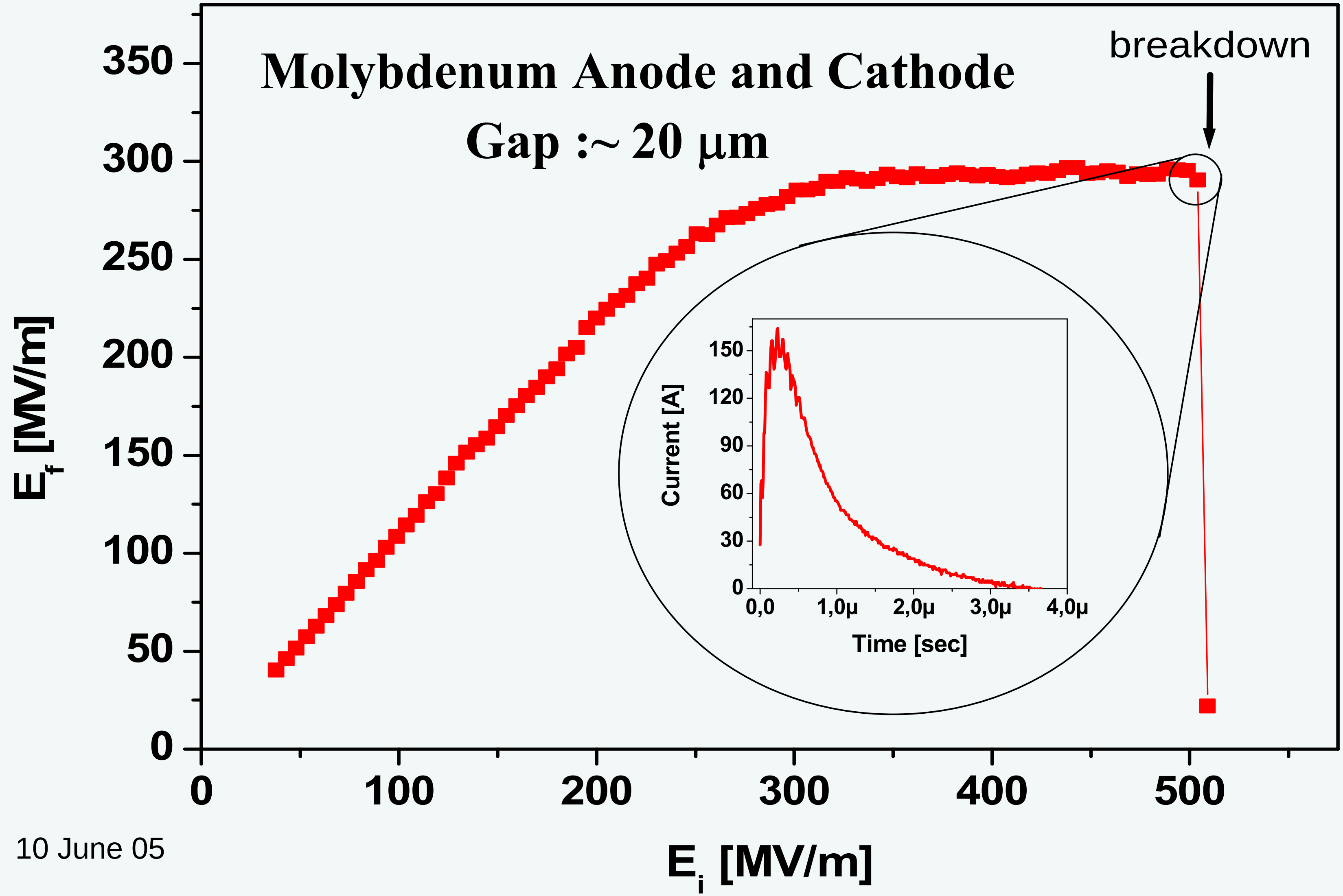
Before bake-out: $\beta \sim (40 \pm 10)$ $r_e \sim (2 \rightarrow 11)$ nm

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

High uncertainty

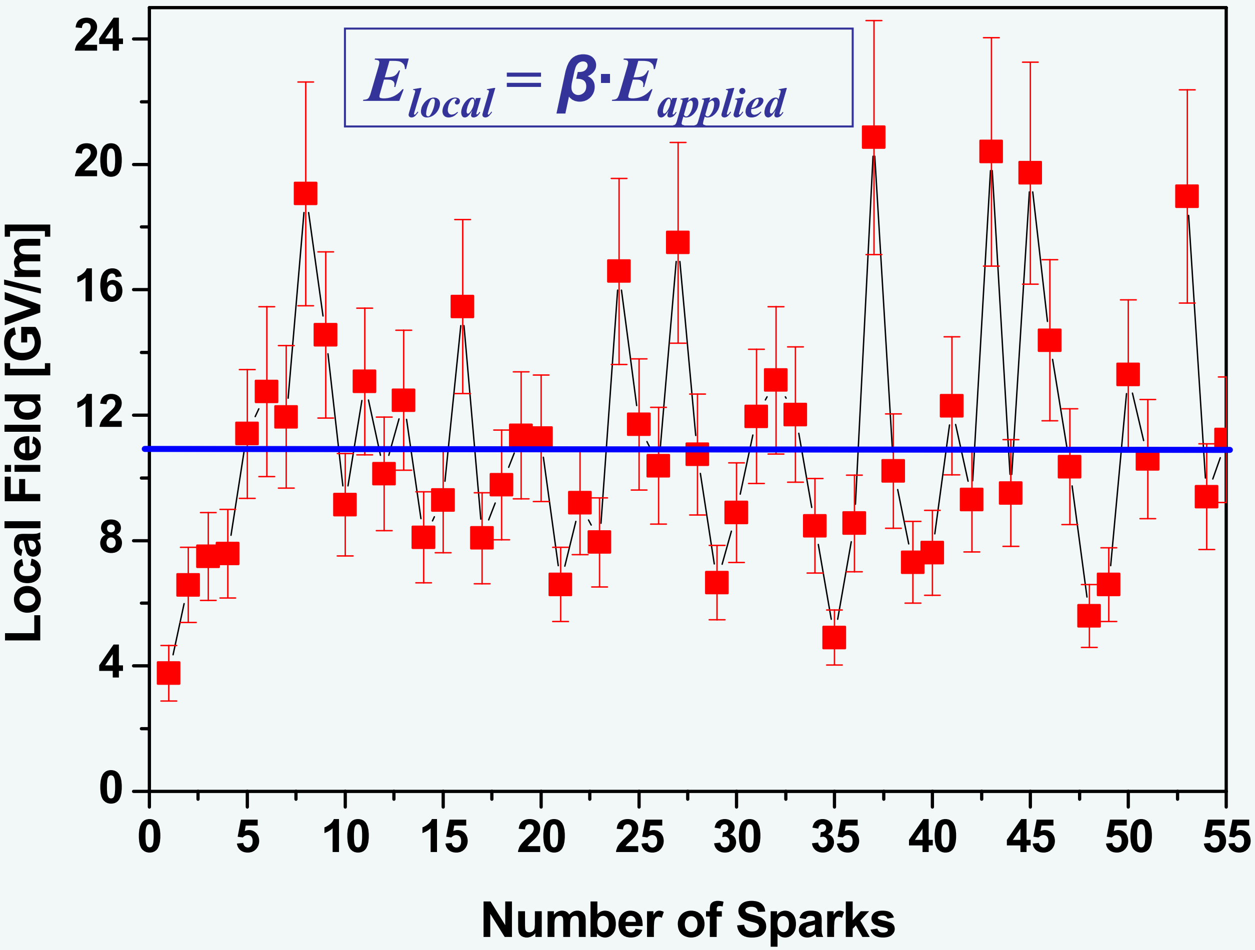
Spark Cycle

The voltage over the gap is increased until breakdown occurs



Local Field

Field evaporation ↔ Tensile Strength



Measured tensile strength of Mo:*

750 MPa

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

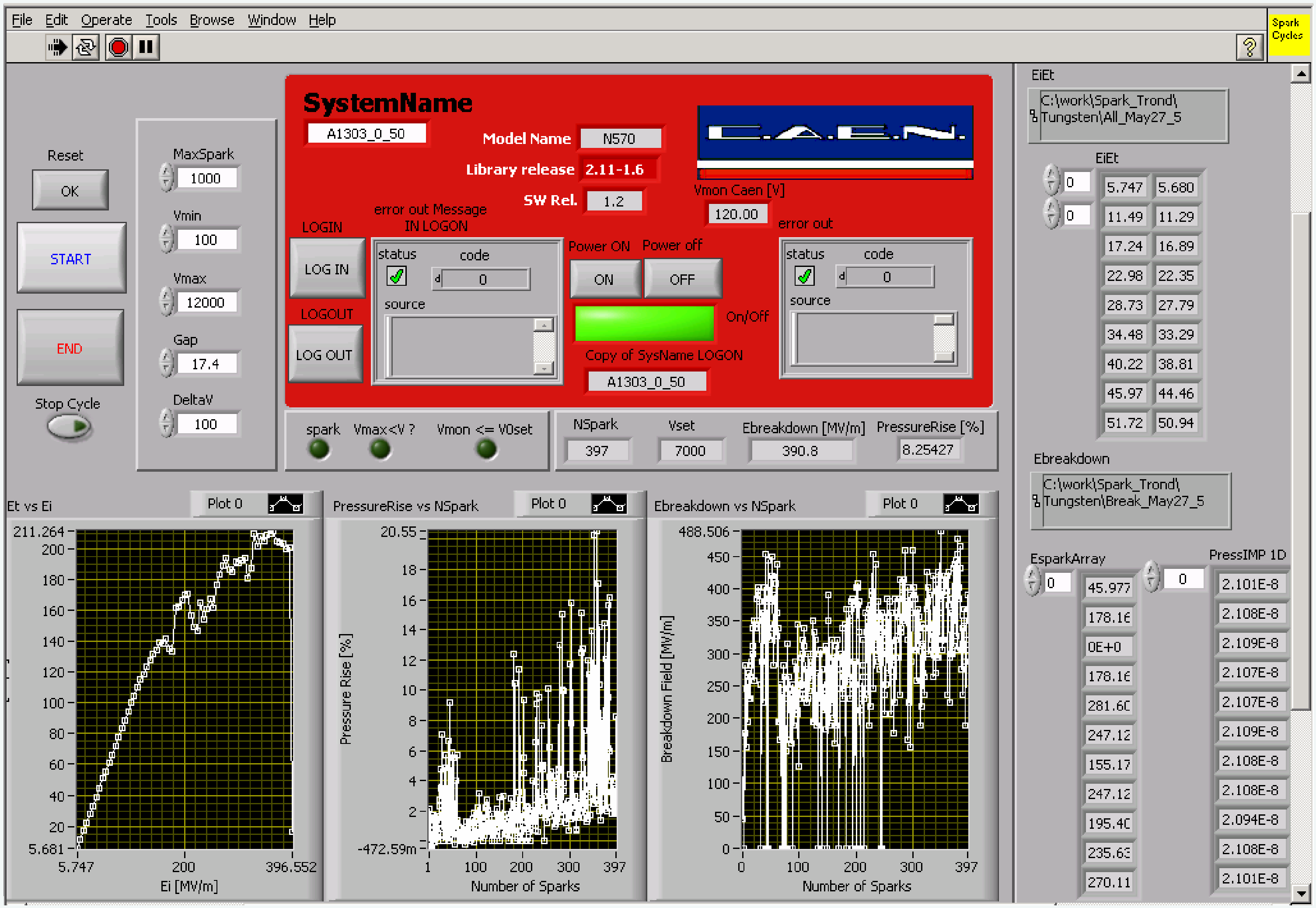
$E_{local} \approx 11$ *GV/m*
(max 21 GV/m)

⇩

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

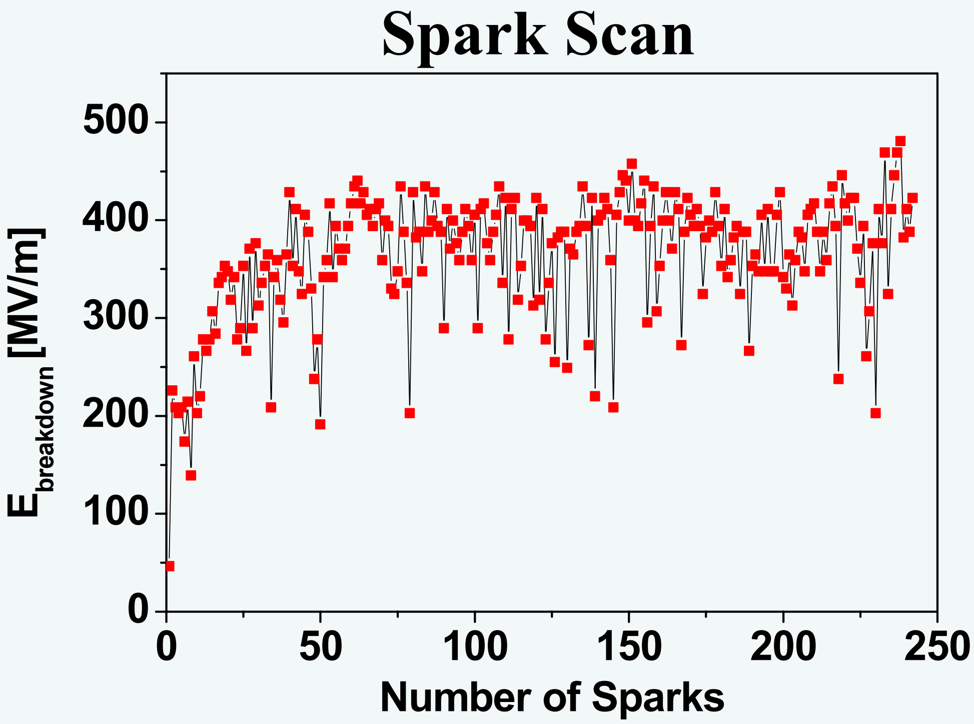
Automatic Spark Conditioning

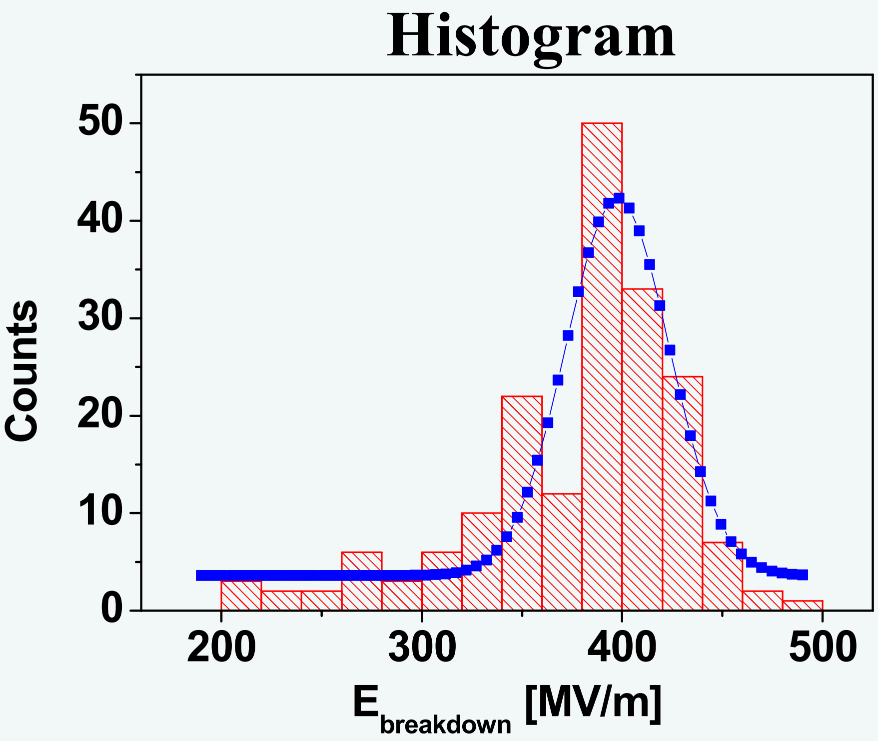
Results of Spark Conditioning



Automatic Spark Conditioning

Molybdenum (Mo) – Tip and Sample





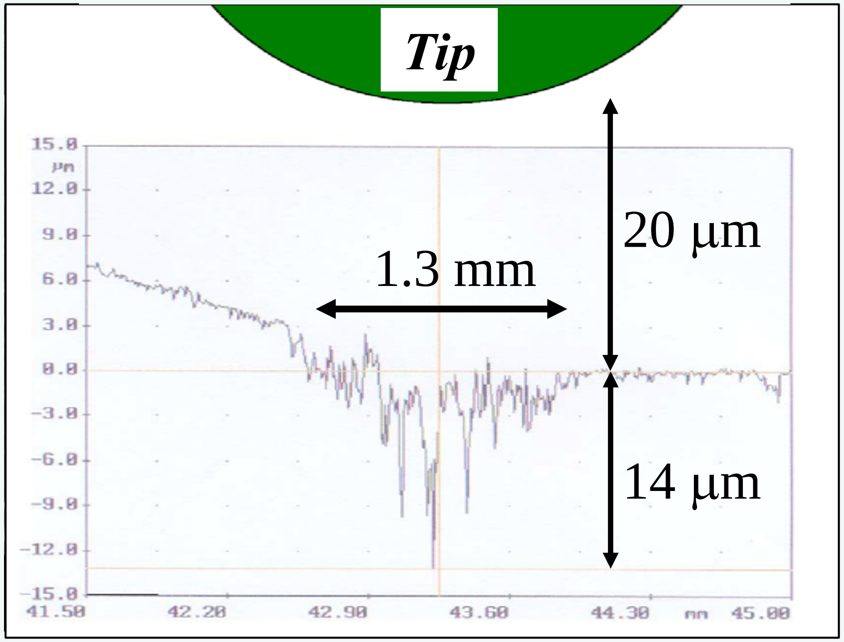
$$E_{breakdown}^{sat} \cong (398 \pm 4)\ MV/m\ at \sim 4 \times 10^{-8}\ mbar$$

Scanning Electron Microscopy

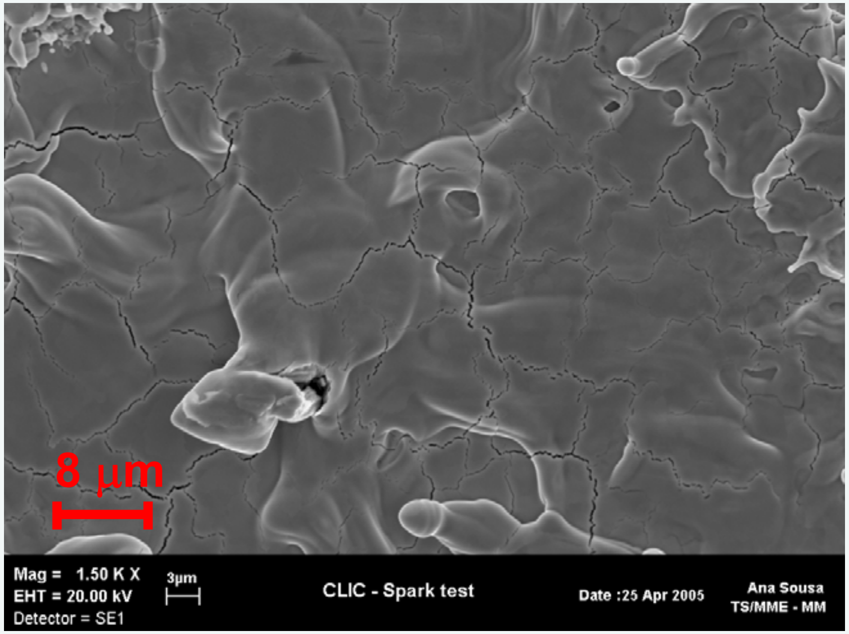
Molybdenum surface after ~ 1600 sparks

Average energy per spark: 0.8 J

Depth Profile / Inside Spot



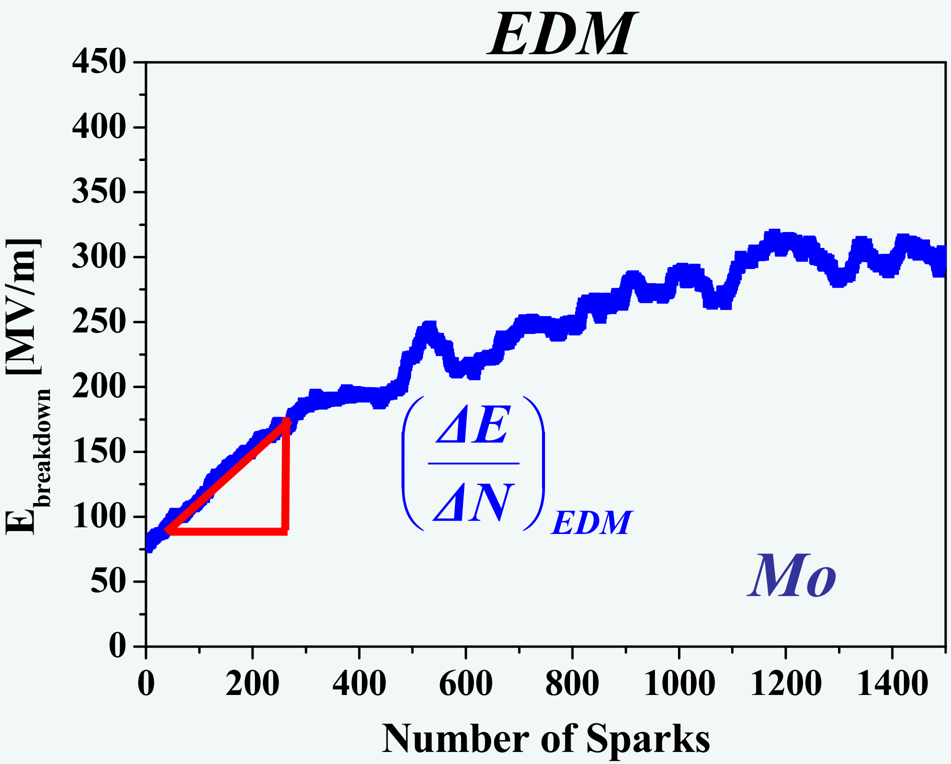
Inside spot

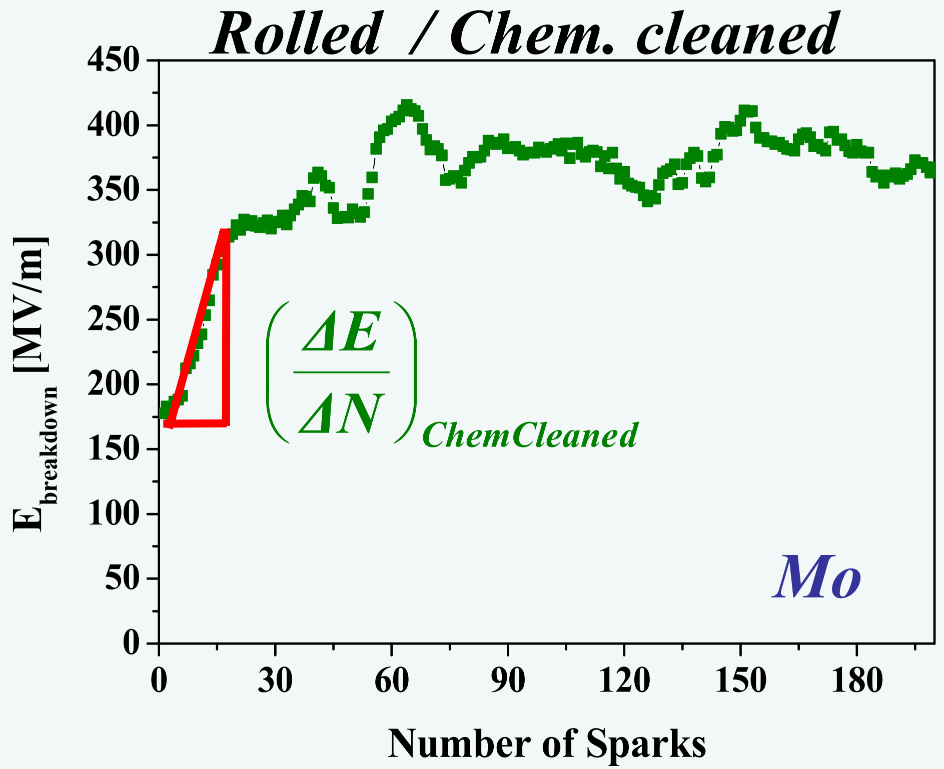


Local Melting smoothes out the surface

➡ ***Number of micro-protrusions strongly reduced***

Electro Discharge Machined (EDM)



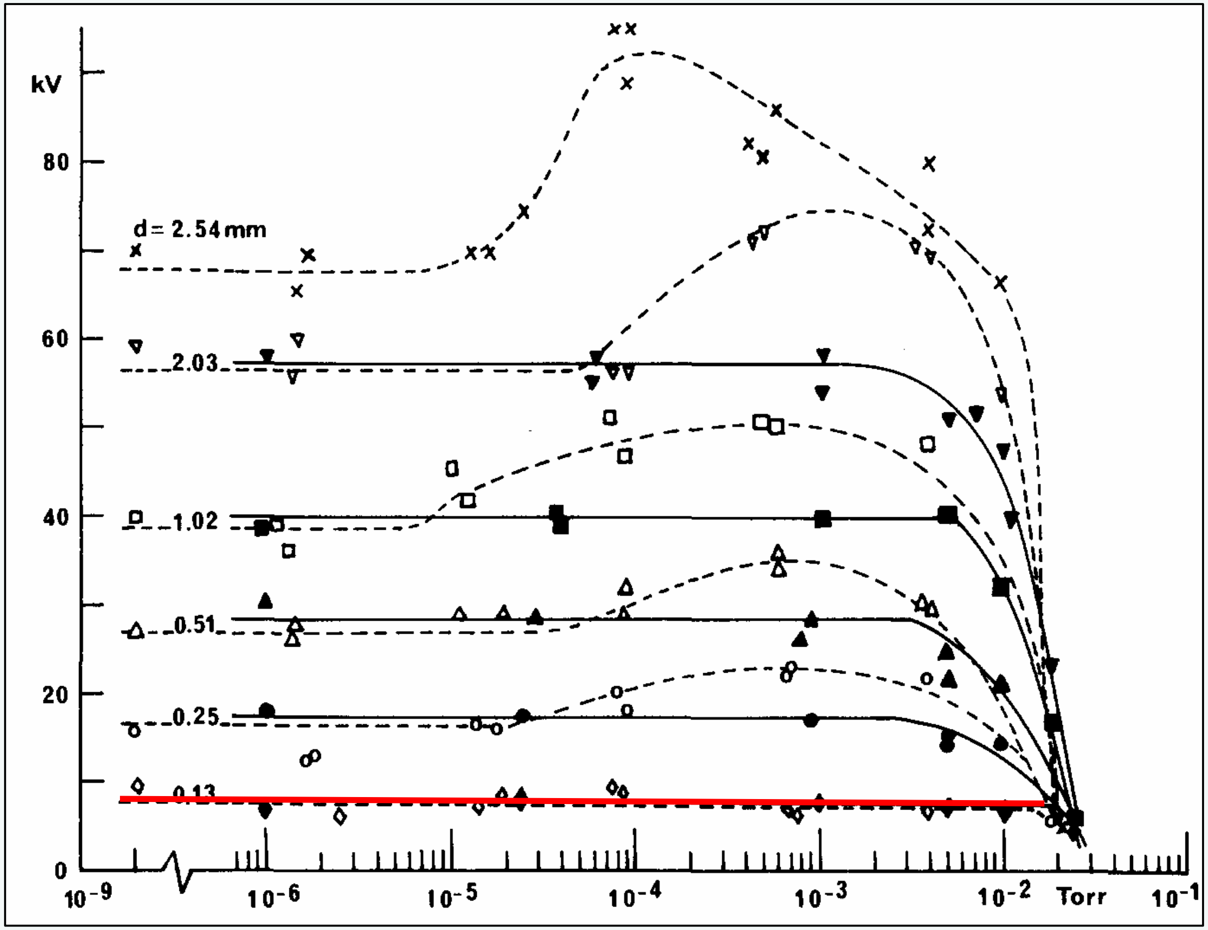


$$\left(\frac{\Delta E}{\Delta N}\right)_{EDM} \approx 0{,}4 \ \frac{MV/m}{spark}$$

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

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

Gas Experiments

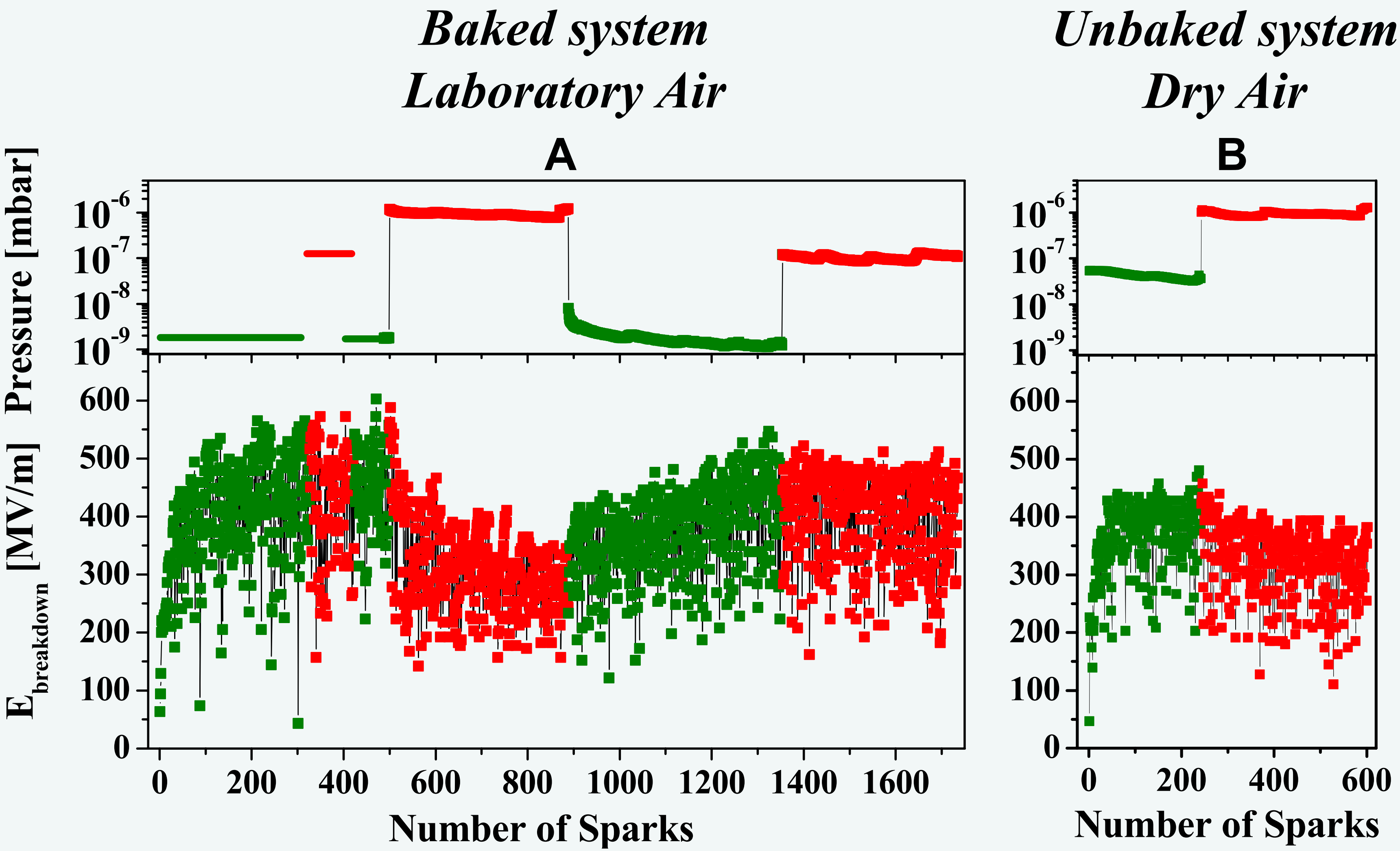


From literature:

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

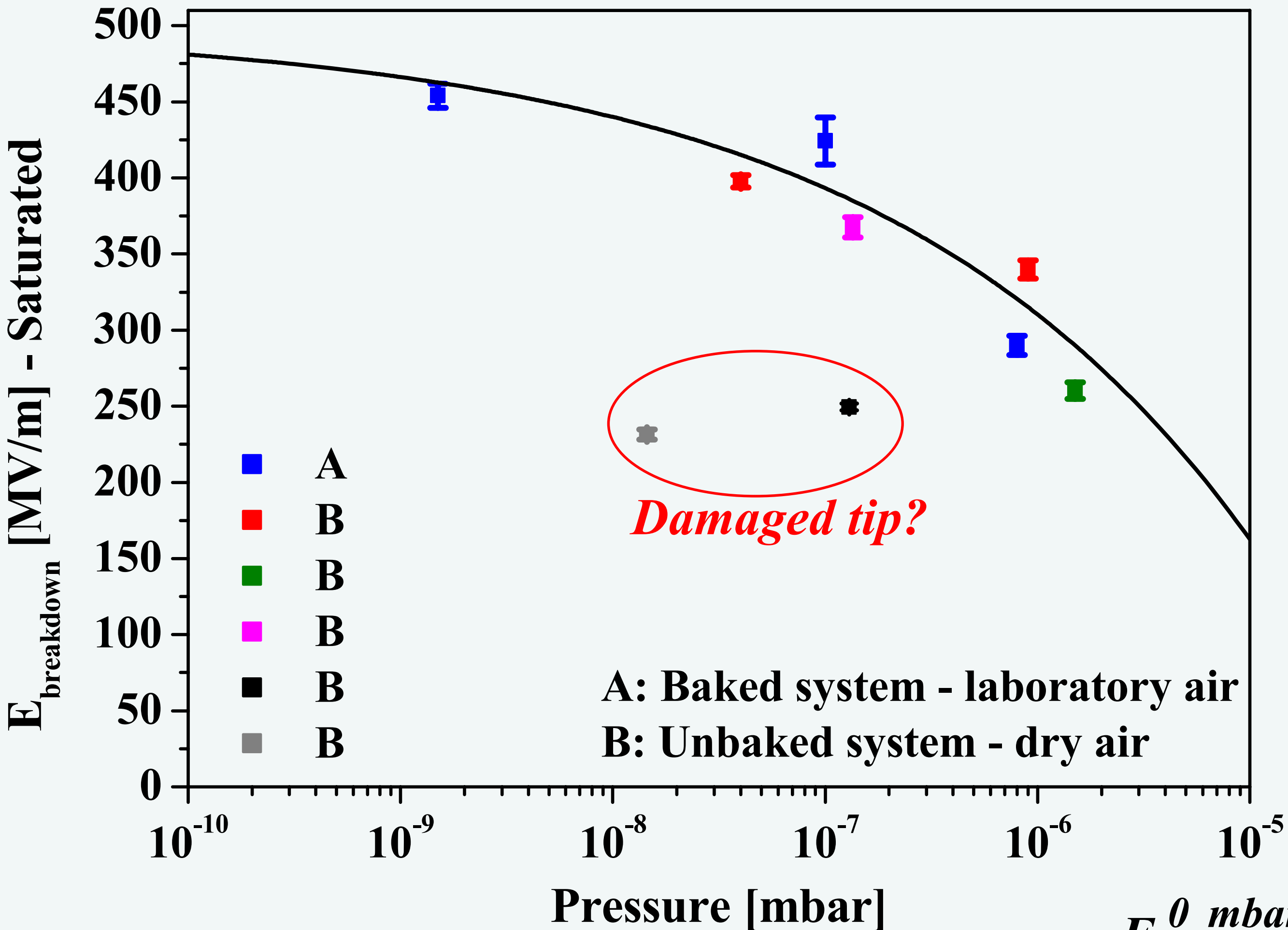
R. Hackham and L. Altcheh, J. Appl. Phys., 46, 627-36 (1975)

Gas Experiments



Clear effect on pressure also at high vacuum / small gap (!)

Gas Experiments



From ~1×10^{-9} mbar to ~ 1×10^{-6} mbar

The saturated breakdown field is reduced by ~150 MV/m

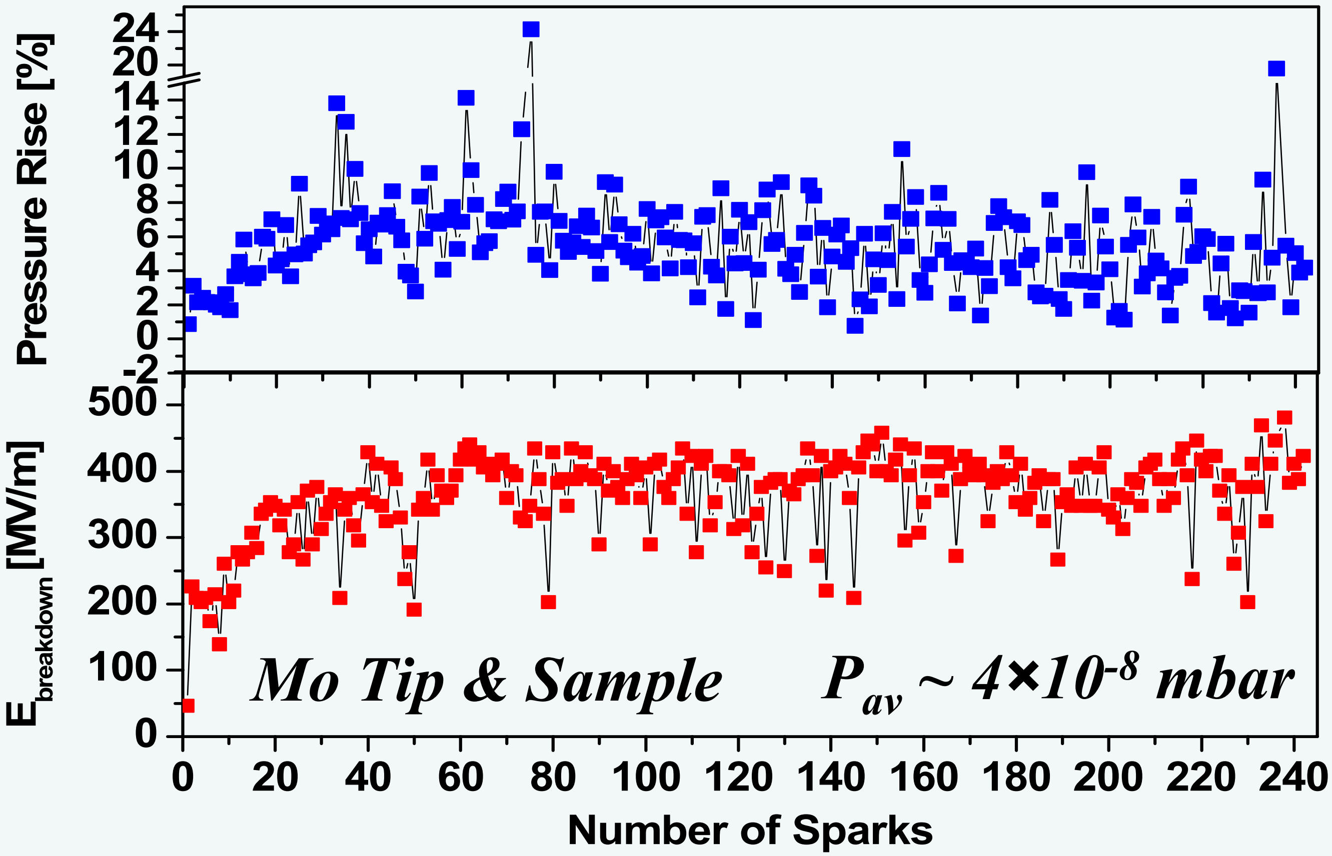
$$E_{breakdown} = E^{0\ mbar}_{breakdown} - k \cdot \{P\}^n$$

$$E^{0\ mbar}_{breakdown} \approx 500\ MV/m$$

$$k \approx 6000\ MV/m\ (mbar)^{-1}$$

$$n \approx 1/4$$

Spark Conditioning vs. Pressure Rise

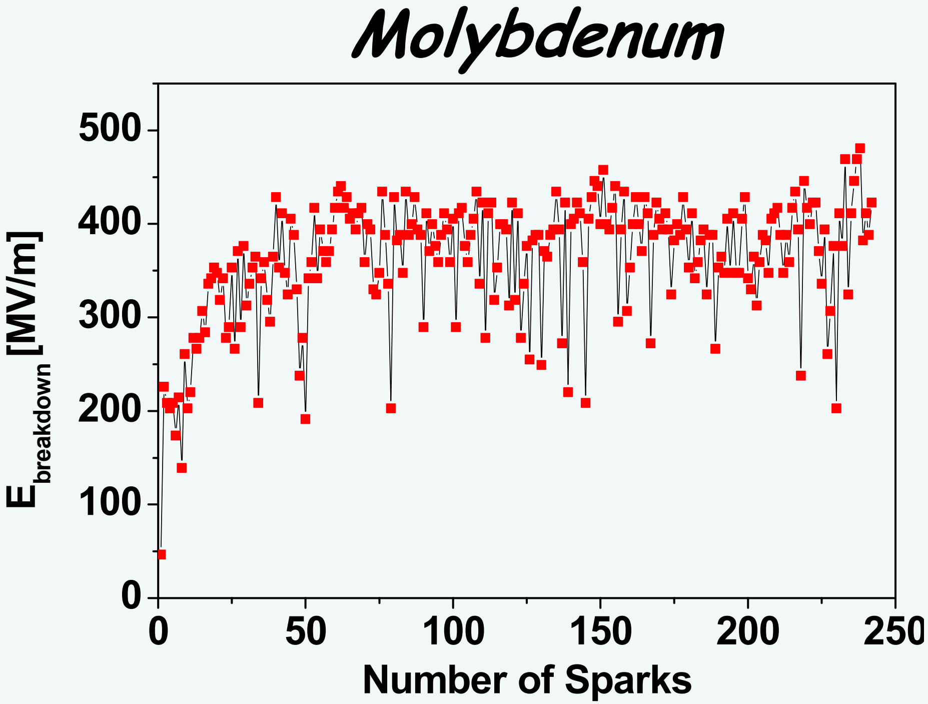


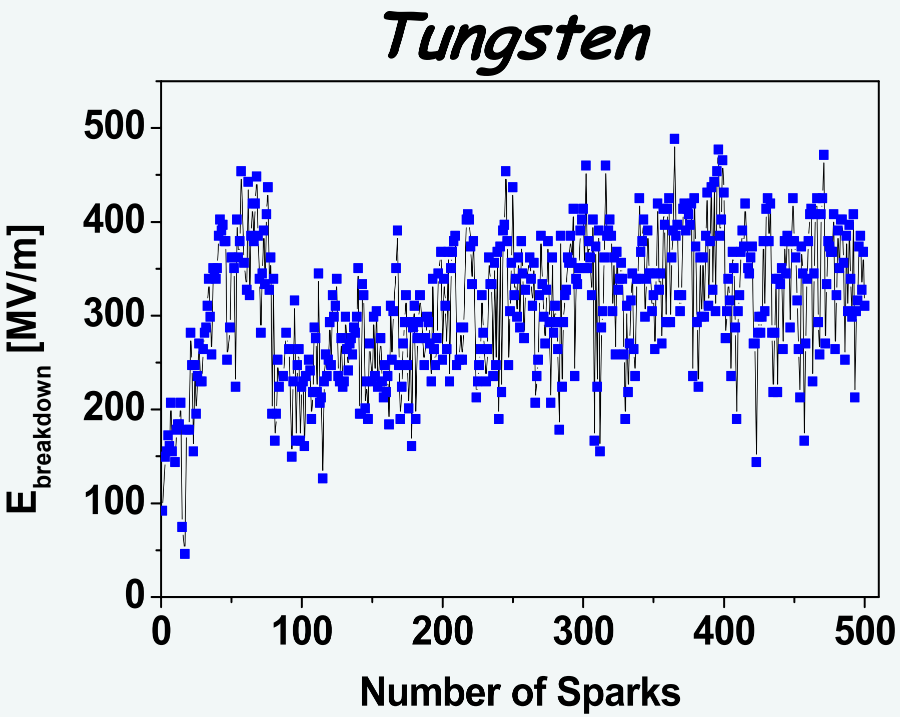
At start: Follows the amount of energy deposited over the gap

Slight decrease in pressure rise during spark

Pressure rise typically in the order of a few percentage per spark

Comparison Molybdenum - Tungsten

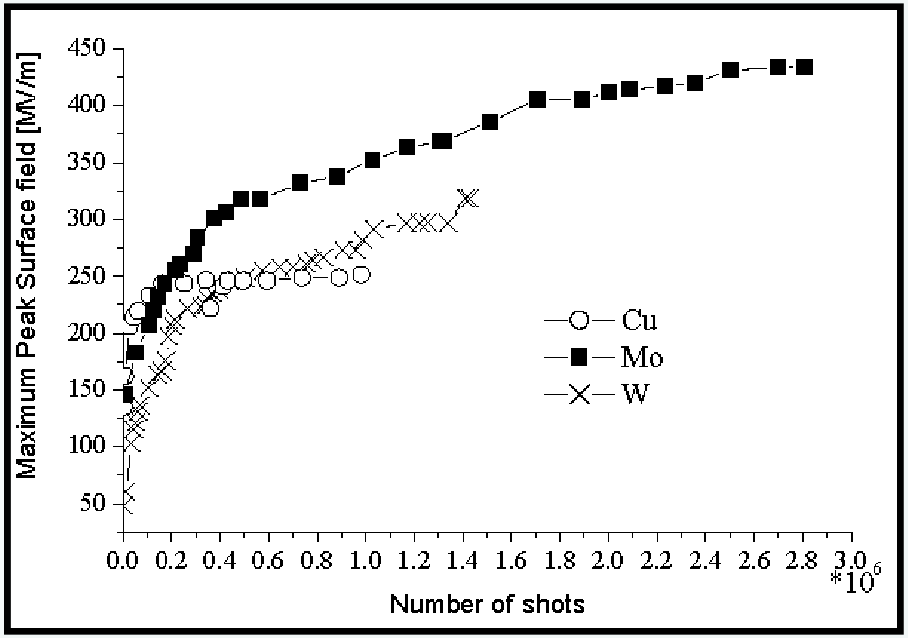




Mo: $E_{breakdown}^{sat} \cong (398 \pm 4)\ MV/m\ at \sim 4 \times 10^{-8}\ mbar$

W: $E_{breakdown}^{sat} \cong (349 \pm 6)\ MV/m\ at \sim 2 \times 10^{-8}\ mbar$

Comparisons - 30 GHz measurements



	E_{breakd}^{sat} (DC) [MV/m]	Max. surface field in RF [MV/m]
Cu	170†	260
W	350‡	340
Mo	400‡	420

DC and RF breakdown measurements give similar breakdown fields

Superior behavior of both Mo and W with respect to Cu.

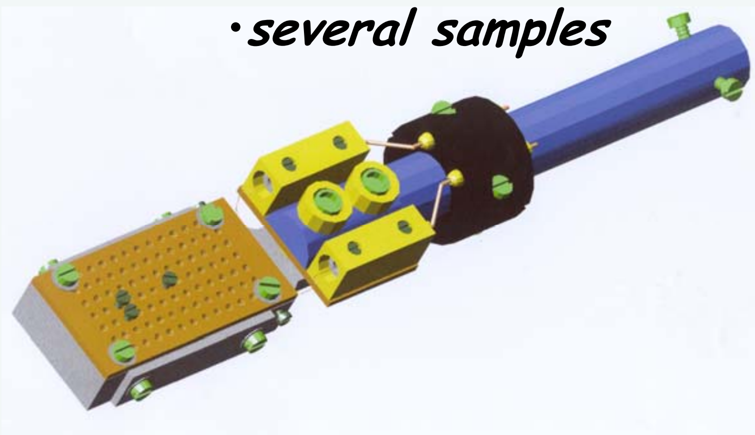
OBS! Not saturated!

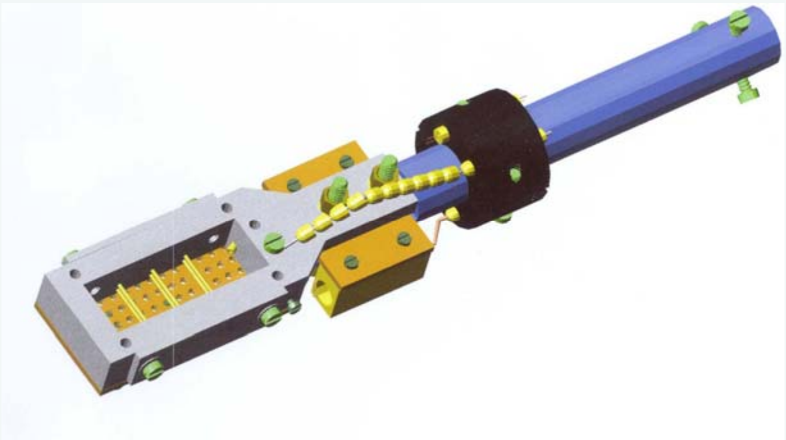
†*M. Kildemo, S. Calatroni and M. Taborelli, PRST-AB, 7, 092003 (2004)*

‡*Saturation breakdown field measured at (2-4)×10^{-8} mbar*

Future Work

- ***Installing new sampleholder and manipulator***
  - ***XYZ movements***
  - ***E-beam heating → ~ 1000°C***
    - → ***"In-situ" annealing***
  - ***several samples***





- ***more experiments to study the effect of residual gas on the Mo breakdown field***
- ***pressure rise studies at UHV (~1×10^{-9} mbar)***
- ***other materials: CuZr, Ti, Mo-Re alloys, W-films,…***

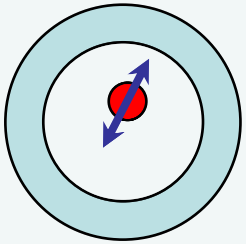
Conclusions

- ***Surface preparation techniques influence the conditioning speed***
- ***There is a residual gas effect on the breakdown field also for high vacuum and small gaps***
  - *From 1×10^{-9} mbar to 1×10^{-6} mbar a reduction in the saturated breakdown field of ~150 MV/m is seen*
- ***Molybdenum shows higher DC saturation breakdown field than Tungsten after extensive spark conditioning***
  - *Similar to the results found for RF*

Contributors

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

Movement of electrons in RF



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

Phase of RF field

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

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

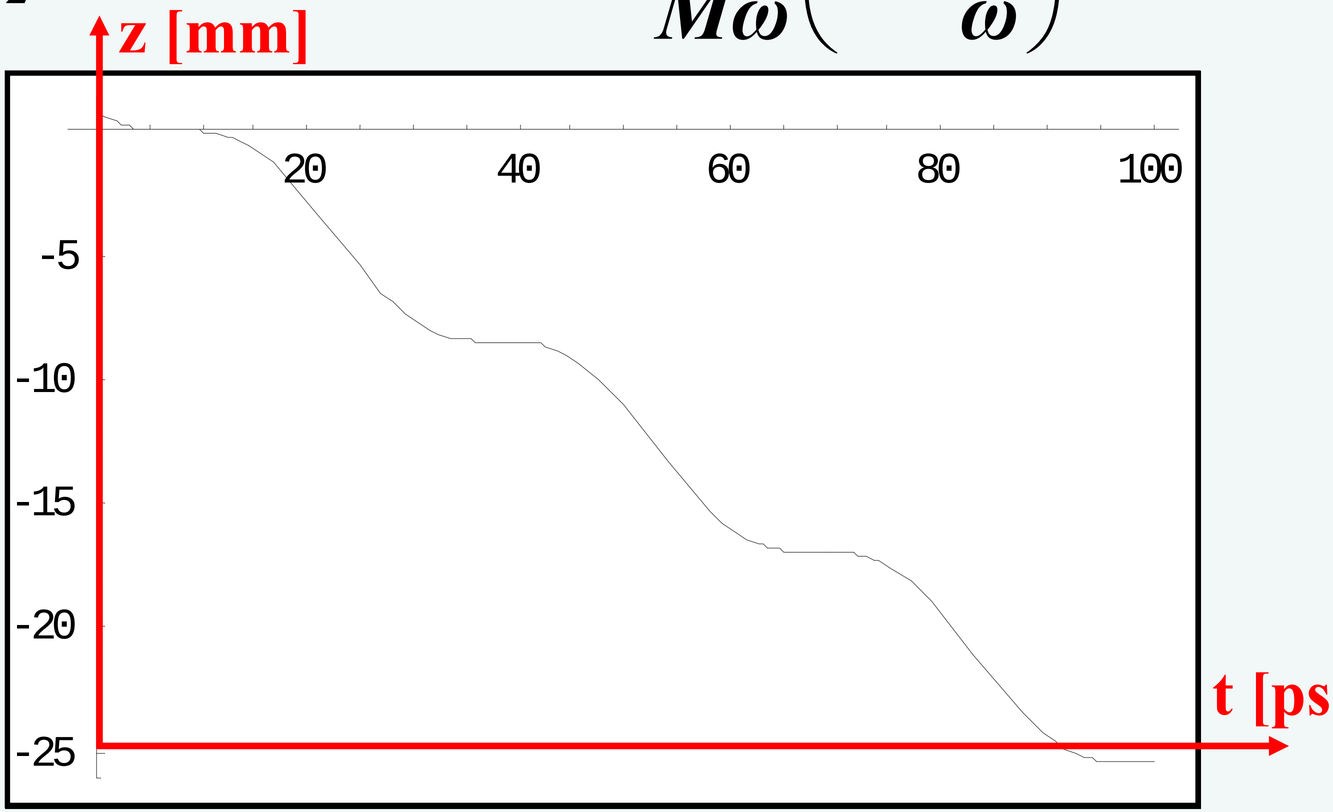
$q = 1.6\times10^{-19}$ C

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

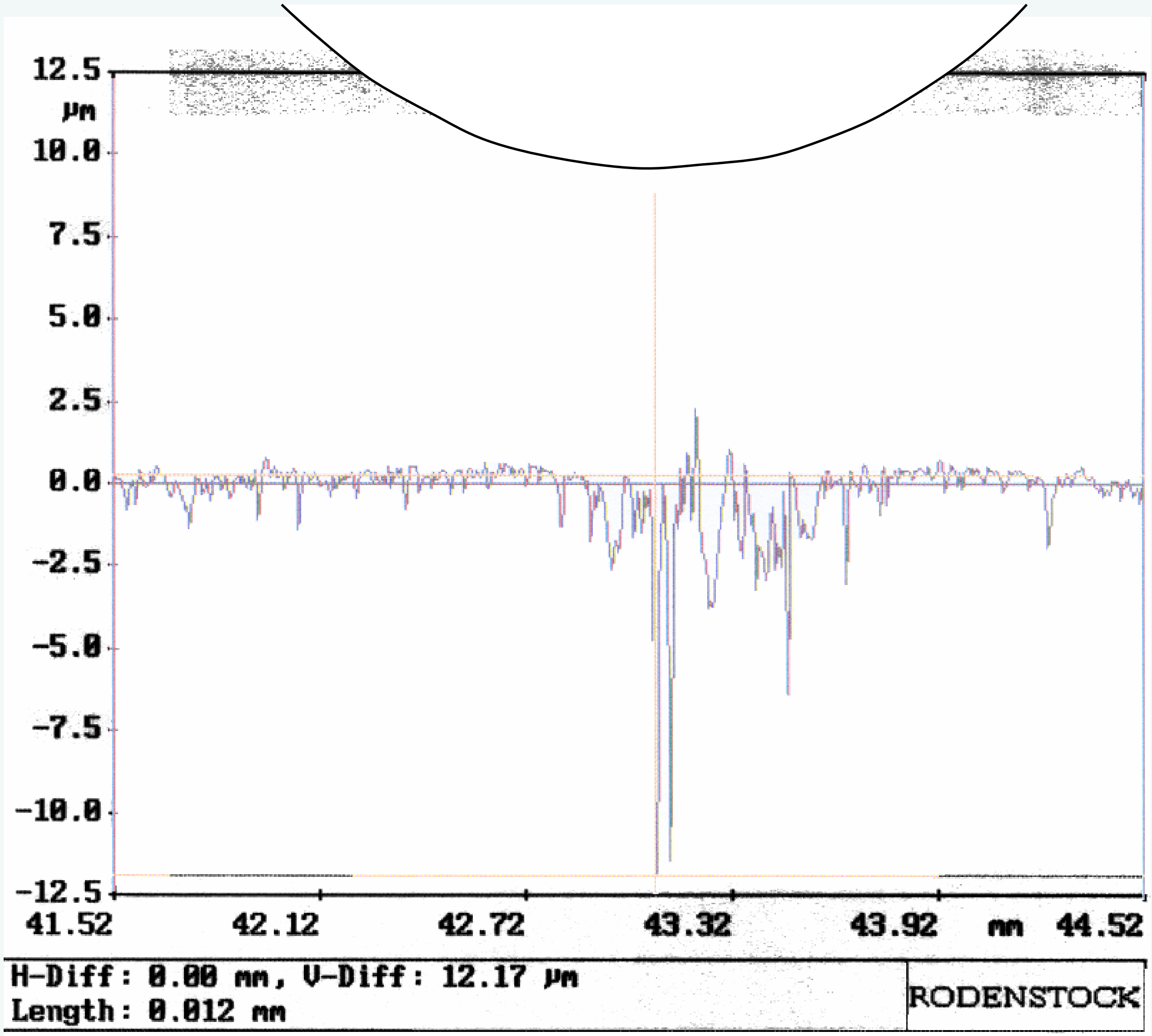
$M_e = 9.1\times10^{-31}$ kg

$\varphi = \pi/2$

$z_0 = 0$

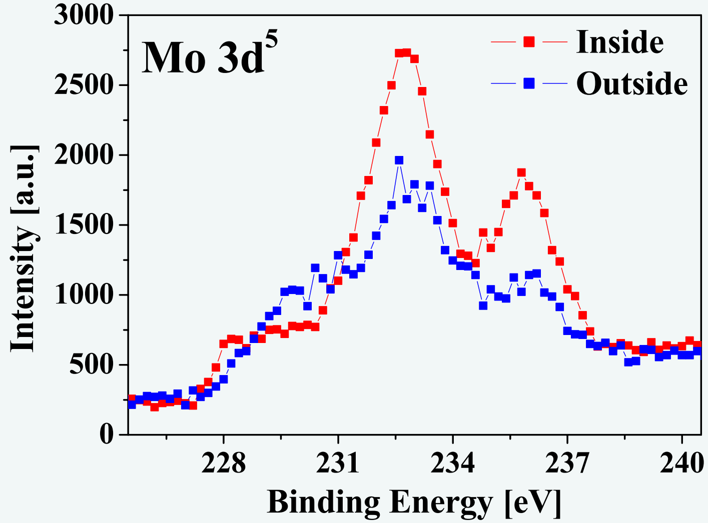


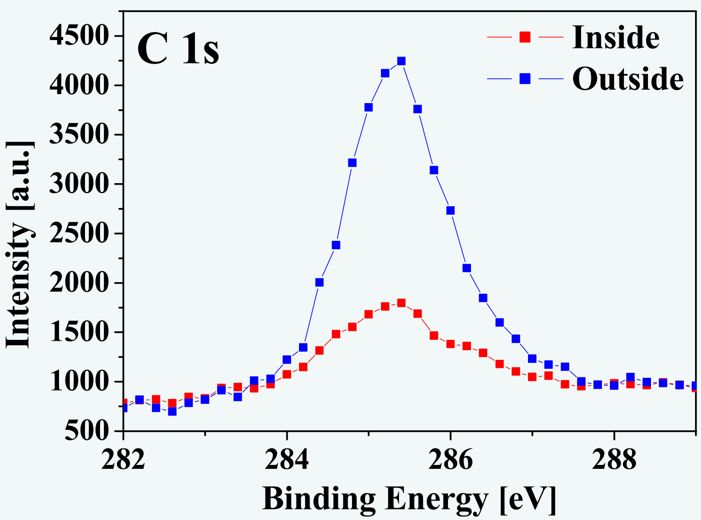
Depth profile / ca. 100 sparks

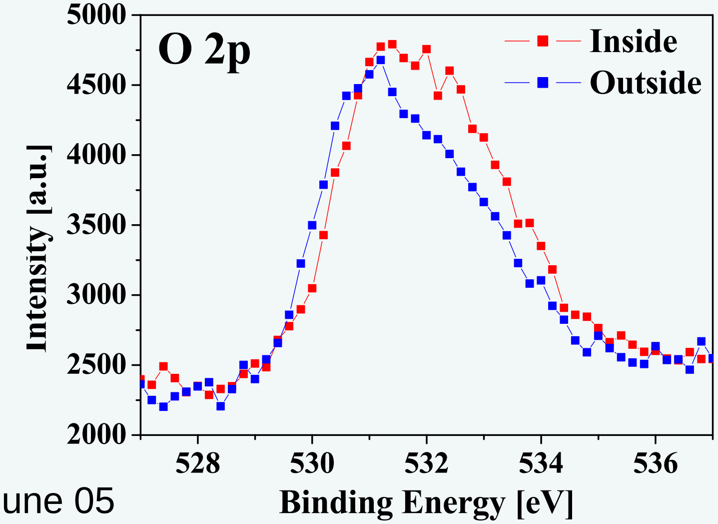


XPS

After ~1600 sparks and exposed to air



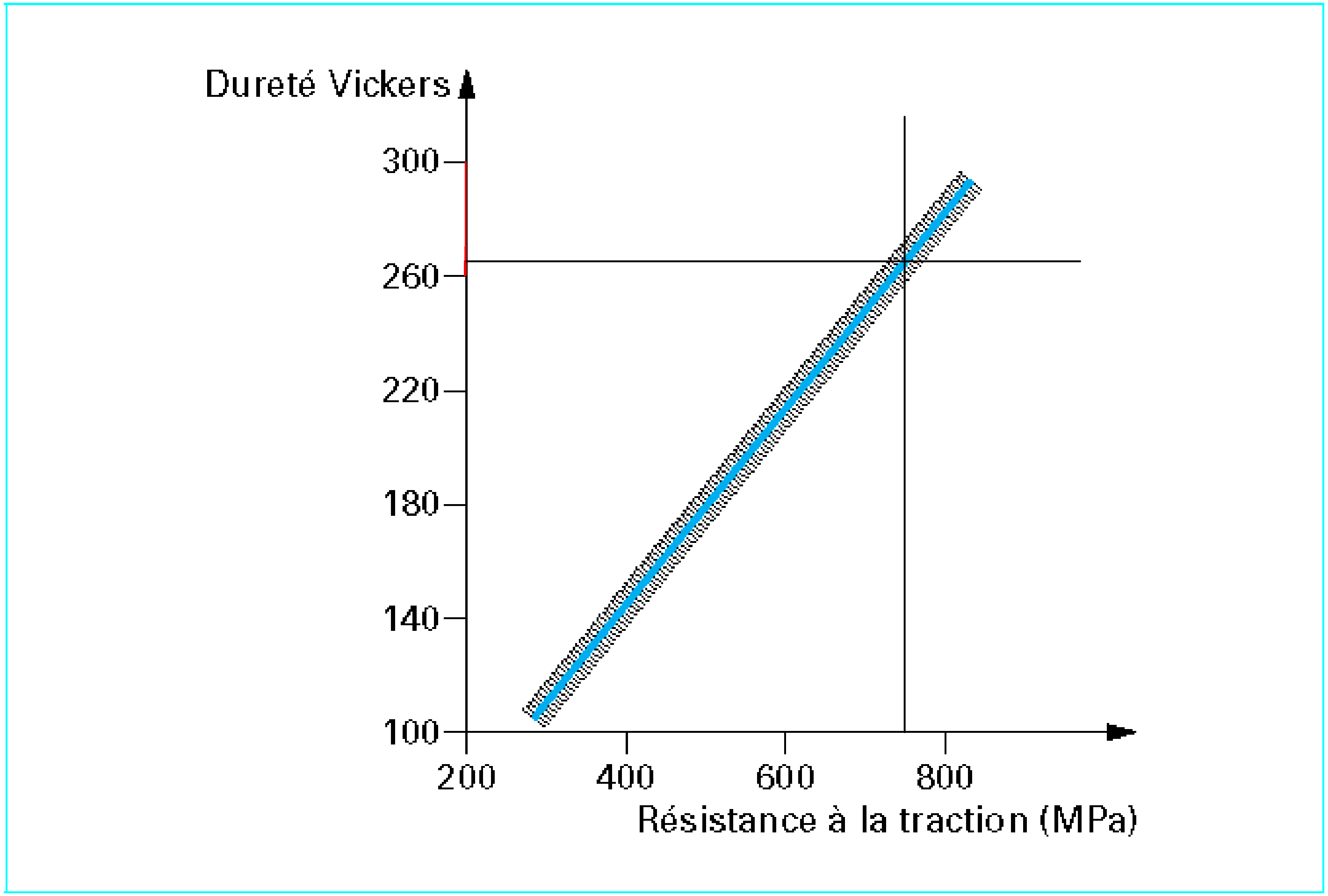




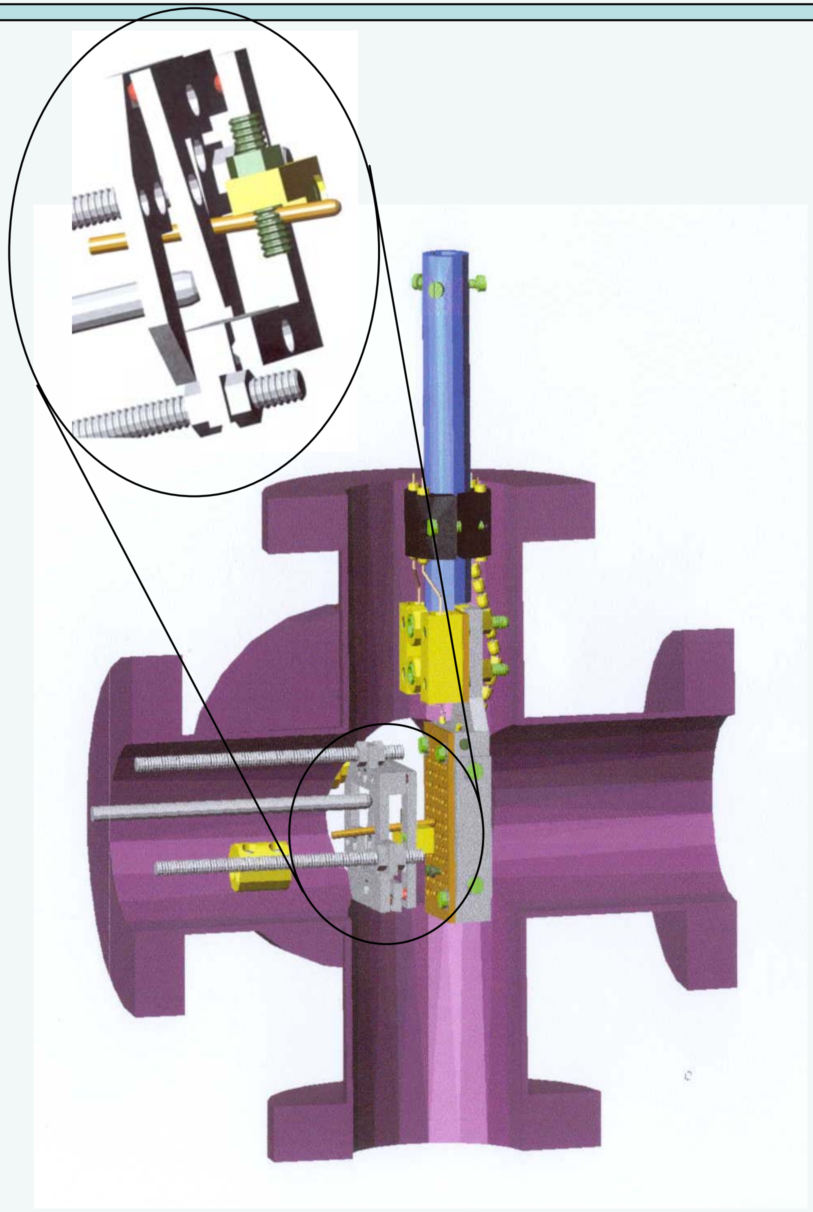
- ***Carbon reduced***
- ***Oxygen unchanged***
- ***Molybdenum peaks stronger***

Alessandra Reginelli TS/MME

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