A few considerations on breakdown phenomena

- Difference between breakdown initiation and sustained arc
- Mechanism for breakdown initiation
  - The role of field-emission
  - Time constants and power densities
  - (Taylor cones: dynamic formation of tips)
  - (Non-square-root heating)
- Breakdown rate
  - Fatigue
  - Gas ionisation

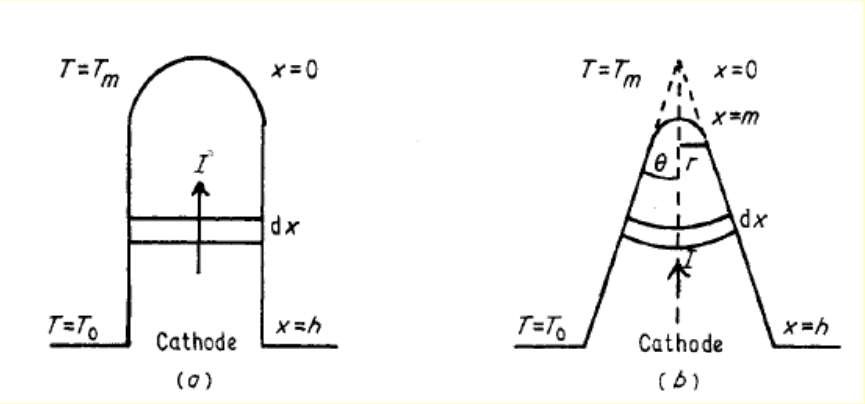
Triggering an arc

- An arc is an ionisation cascade, fuelled by the e.m. power available in a RF cavity (or by the energy stored in a capacitor in DC testing)
- This cascade must be triggered by “something”.
- There are strong indications that it is initiated by electron field emission:
  - Evidence for cathode-initiation in DC sparks
  - Surface conditioning and associated changes in β (field enhancement factor) both in DC and RF
  - Dark currents
- I will suggest that some conditions must also be met for initiation to be possible. In particular:
  - Duration of RF pulse
  - Local power density

Heating of tips by field emission

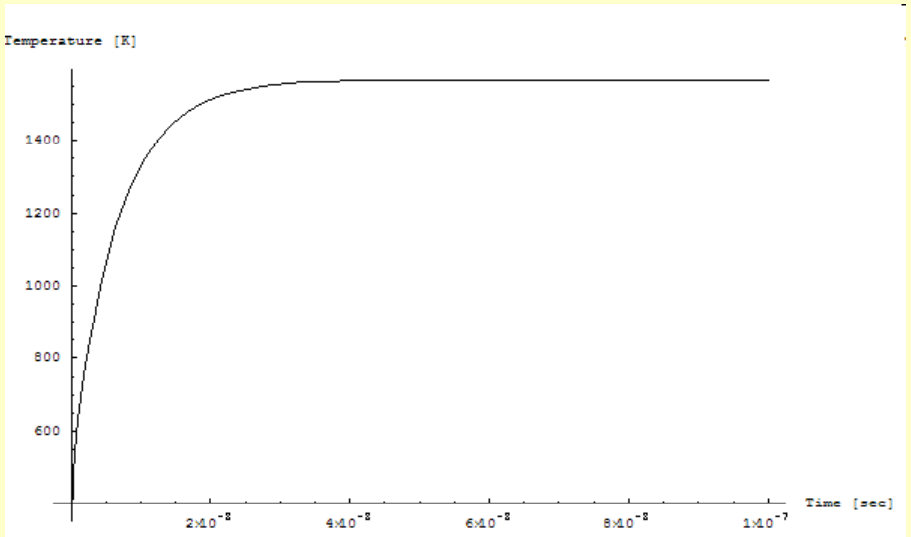
- Field emission currents flowing along a cylindrical or conical tip can heat it by Joule effect. The tip is assumed to have a fixed temperature at its base and have a temperature gradient along its height.
- If the resistivity is considered temperature-independent, a stable temperature is achieved (Chatterton Proc. Roy. Soc. 88 (1966) 231
- If the resistivity (other material parameters play a lesser role) is temperature dependent, then when it increases there is a larger power dissipation, resulting in a further increase in temperature and so on (Williams & Williams J. Appl. Phys. D 5 (1972) 280).
- Below a certain current threshold, a stable regime is reached
- Above the threshold, a runaway regime is demonstrated
- The T(t) can be calculated.

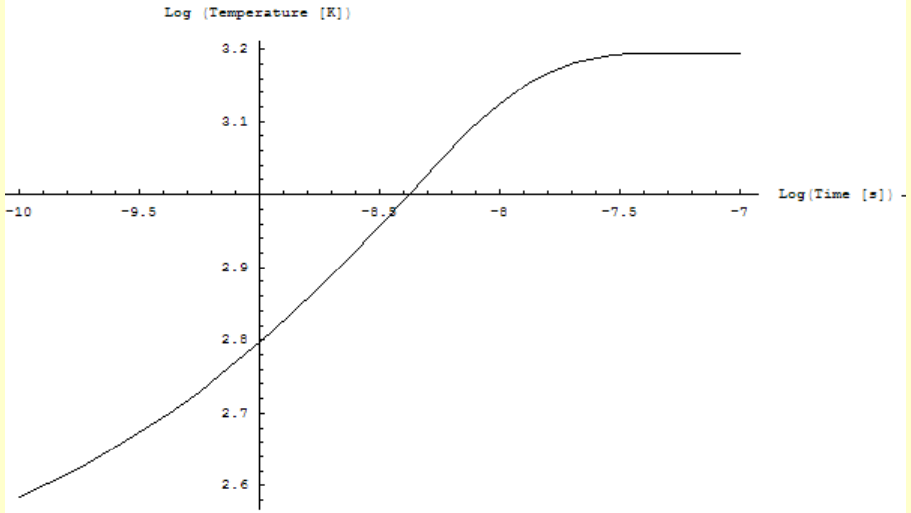
$$\frac{\partial T}{\partial t} = \frac{K}{\sigma S}\left(\frac{\partial^2 T}{\partial x^2} + \frac{2}{x}\frac{\partial T}{\partial x}\right) + \frac{\rho}{\sigma S}\left(\frac{I}{2\pi x^2(1-\cos\theta)}\right)^2.$$



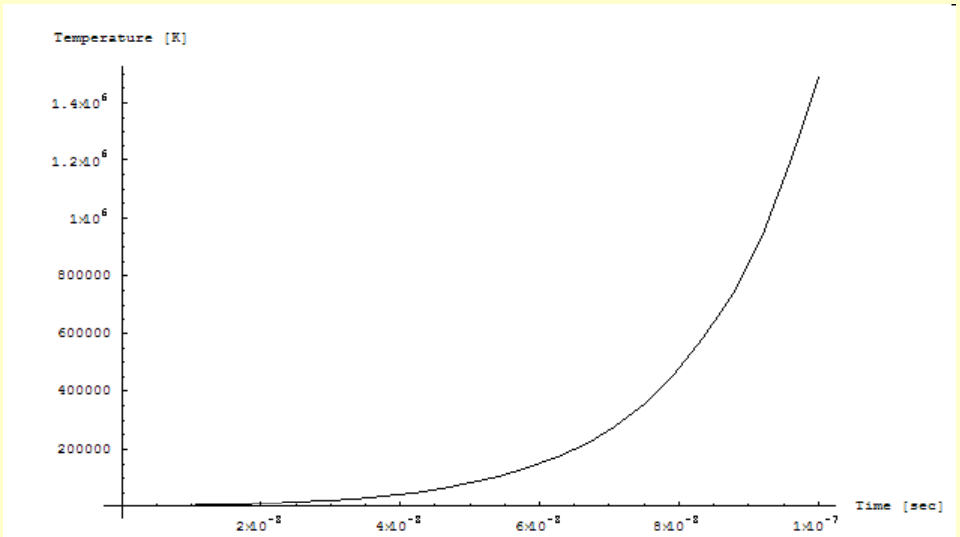
Simulation for Mo cone: diameter 20 nm, beta = 30

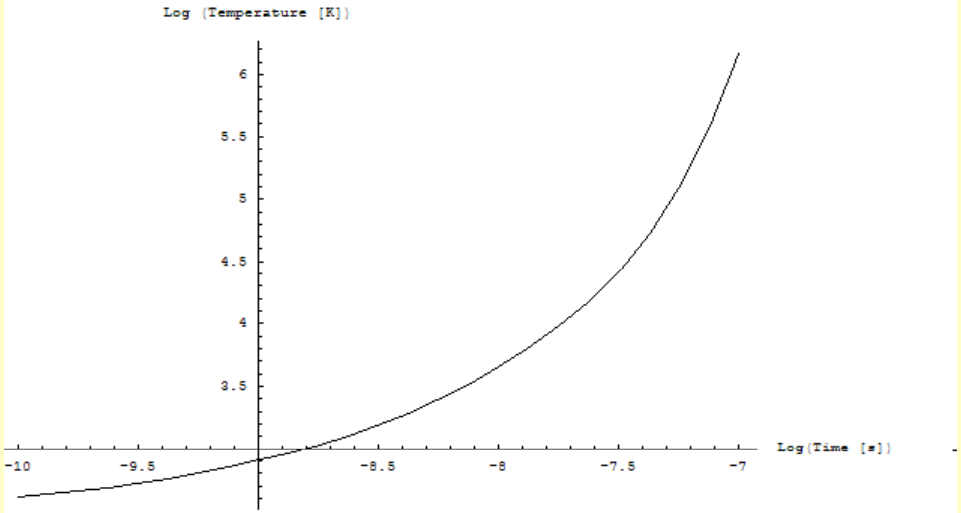
E=374 MV/m



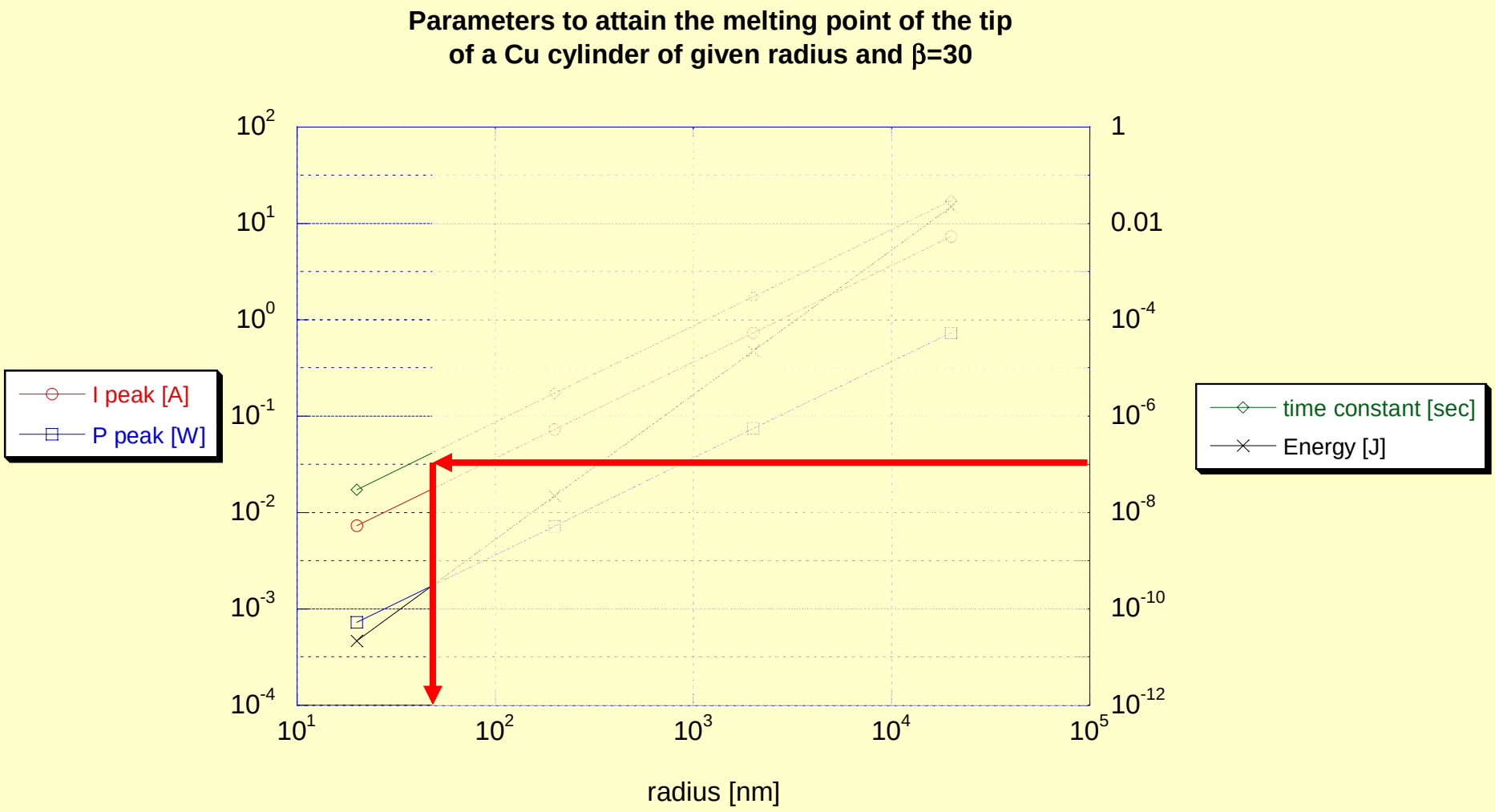


E=378 MV/m

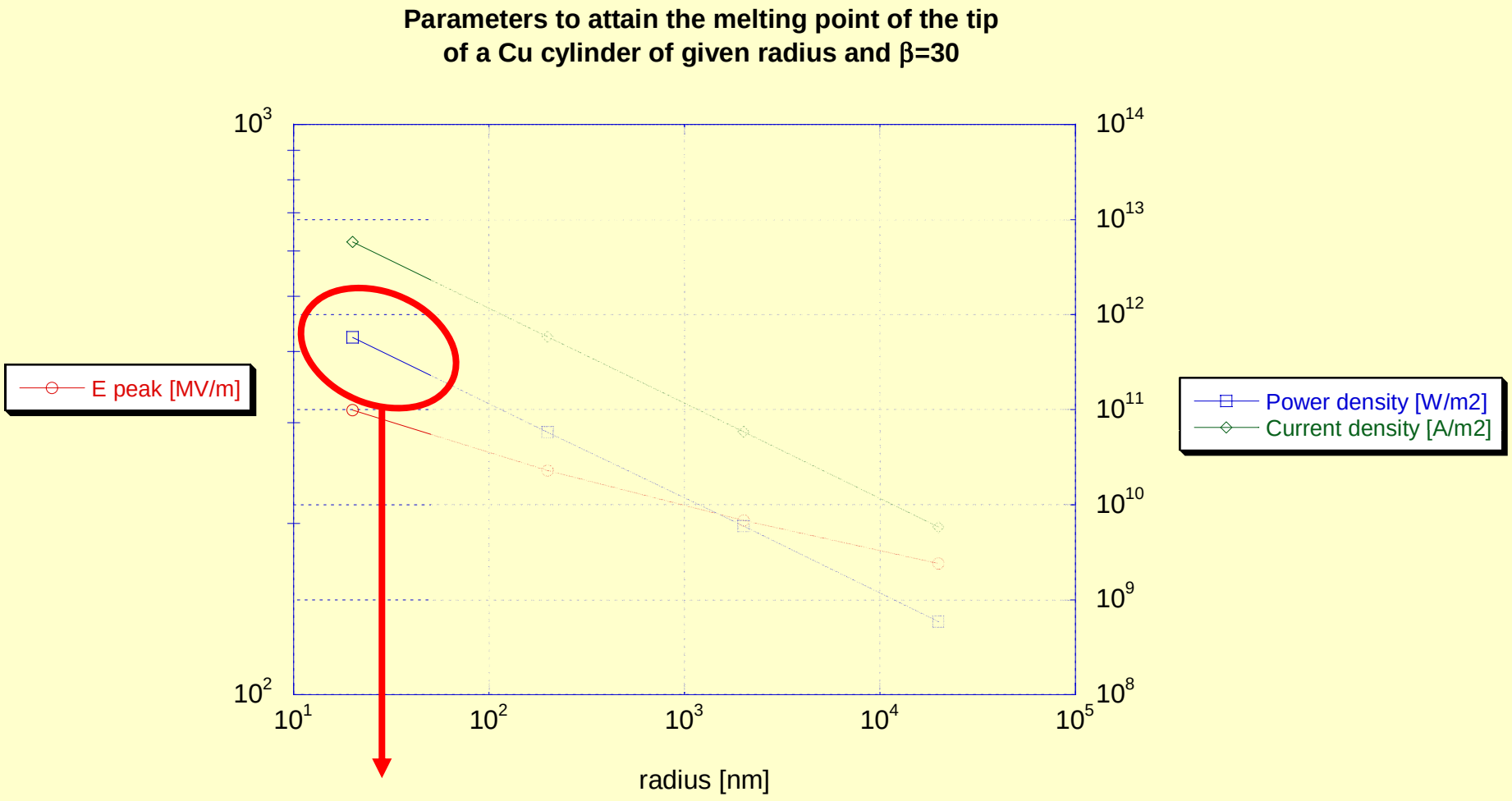




Time constant to reach the copper melting point (cylinders, β=30)

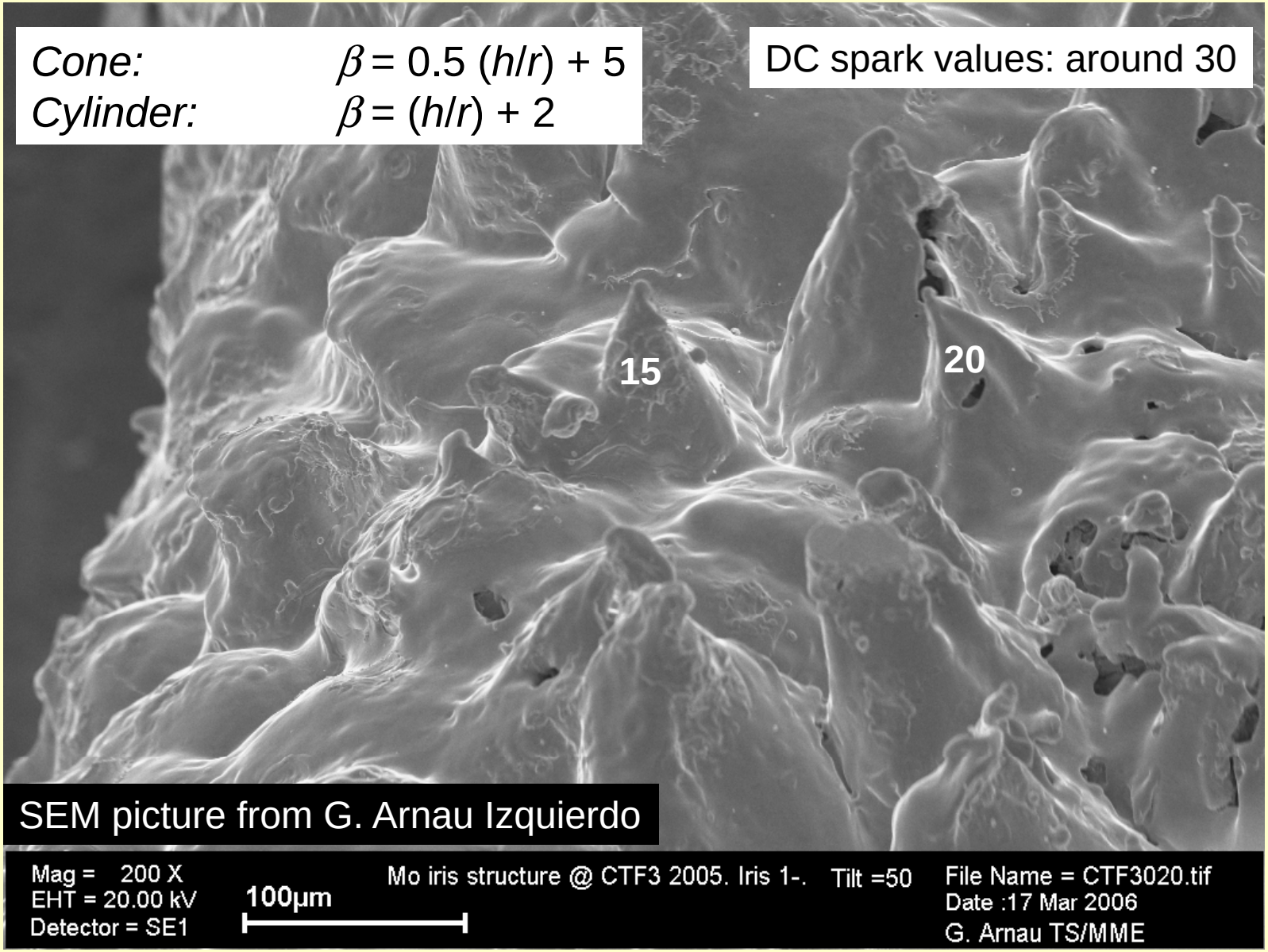


Power density at the copper melting point (cylinders, β=30)



Power density during the pulse is a key issue. See tomorrow's talk by A. Grudiev

Beta calculations from SEM observation - Mo

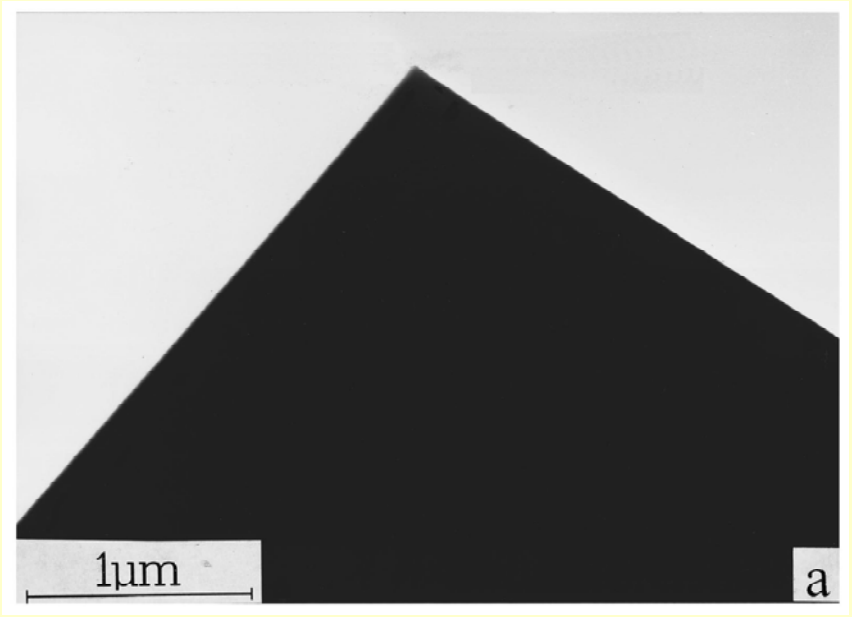


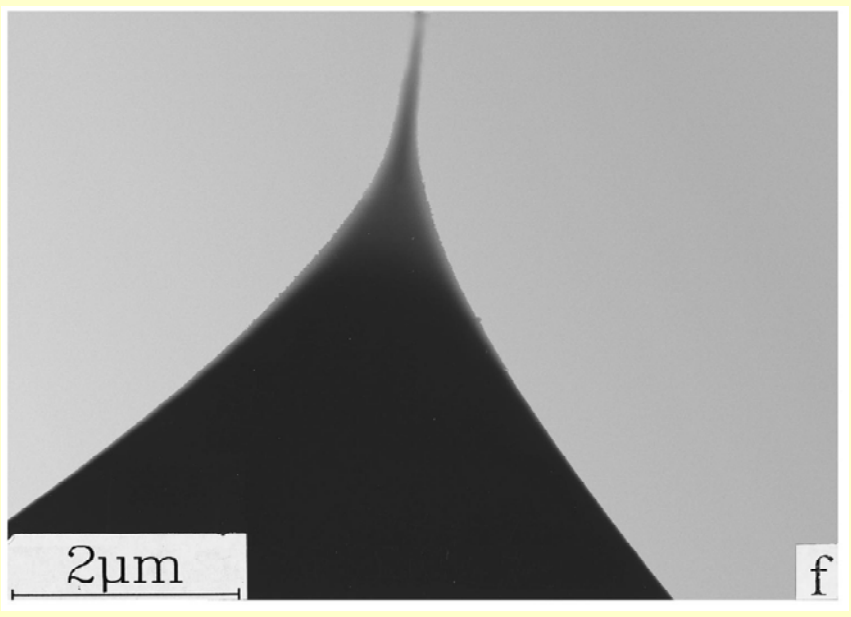
Pulling of liquid? Taylor cones

- The “tips” and the “cones” might be the result of the E-field pulling over the molten metal. Models of this process exist in the literature.

- When a molten metal is pulled with an electric field, the metal surface is deformed. The resulting shape is due to the balance between the electrostatic force and the surface tension.
- At the highest field the limiting shape is conical, with an half-opening angle of 49.3 degrees (Taylor cone, Proc. Roy Soc. A 280 (1964) 383).
- This shape is independent of the material. When further increasing the field, ion emission starts with a jet. Locally, the atoms binding energy is overcome by electrostatic forces.
- The shape and dynamics of the jet depend on viscous forces
- This process is used in so-called Liquid Metal Ion Sources (for example Cs)

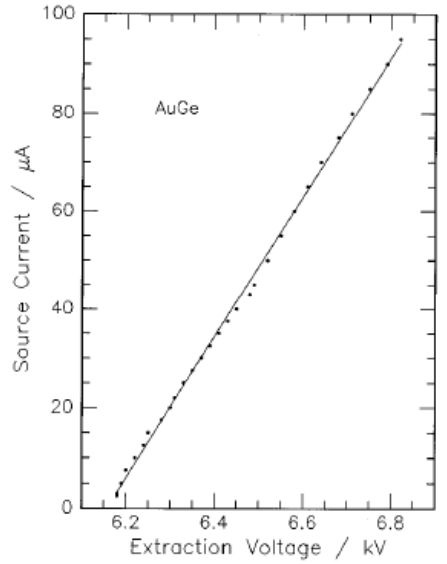
Taylor cones - images





(From Driesel et al.J. Vac. Sci. Technol. B 14 (1996) 3367) - AuGe alloy

- Shape with minimal ion emission (angle close to theoretical value) – left
- Shape with strong ion jet emission - right. Ion current 95 µA, Field 6.8 kV / 1.5 mm, estimated jet diameter 175 nm.
- $\Rightarrow$ flux = 6 * 10^{14} ions/sec
- $\Rightarrow$ equivalent pressure = 2.5 bar



Taylor cones: time for formatio

- Growth time of cones (Suvarov et al. J. Appl. Phys. D 33 (2000) 1245) – Mercury at 240 MV/m applied field

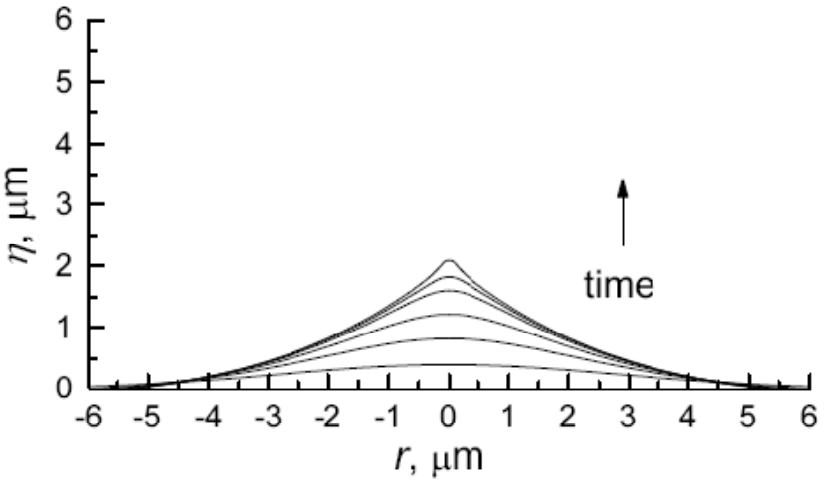


Figure 2. The surface time evolution; initial form is Gaussian with $\lambda = 4\ \mu$m, $h = \lambda/10$. The surfaces are consecutively represented at time: 0, 0.56, 0.73, 0.81, 0.83 and 0.85 μs.

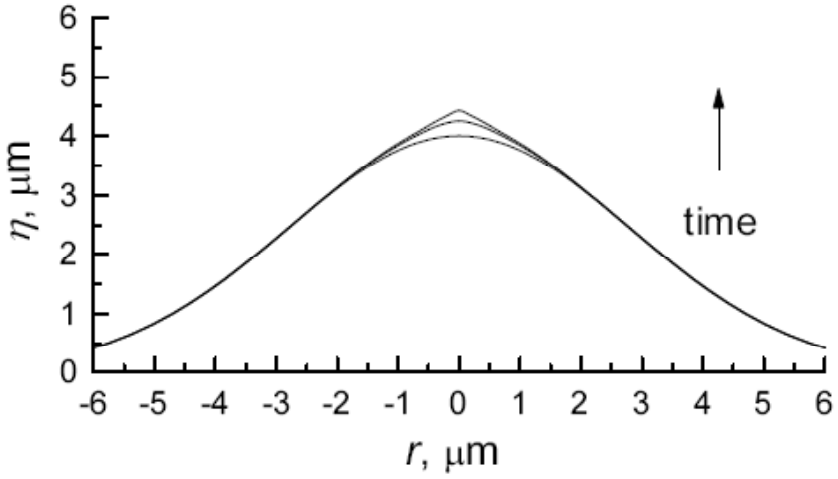


Figure 3. The surface time evolution; initial form is Gaussian with $\lambda = 4\ \mu$m, $h = \lambda$. The surfaces are consecutively represented at time: 0, 0.048 and 0.057 μs.

- Growth time can be very fast depending on starting conditions
- See talk by F. Djurabekova on molecular simulations of dynamic phenomena

Time-dependent heating

- In the model of emitting tips it is assumed that the base of the field-emitting sites remains at the fixed temperature of the substrate
- This is highly idealised, the heat diffusion into the substrate should be taken into account.

- The breakdown limit of materials in RF tests is observed to follow the dependence: $P\tau^a$ with a=1/3 for copper and a=2/3 for molybdenum

- Is there any intrinsic material dependence? Heat flow equation:

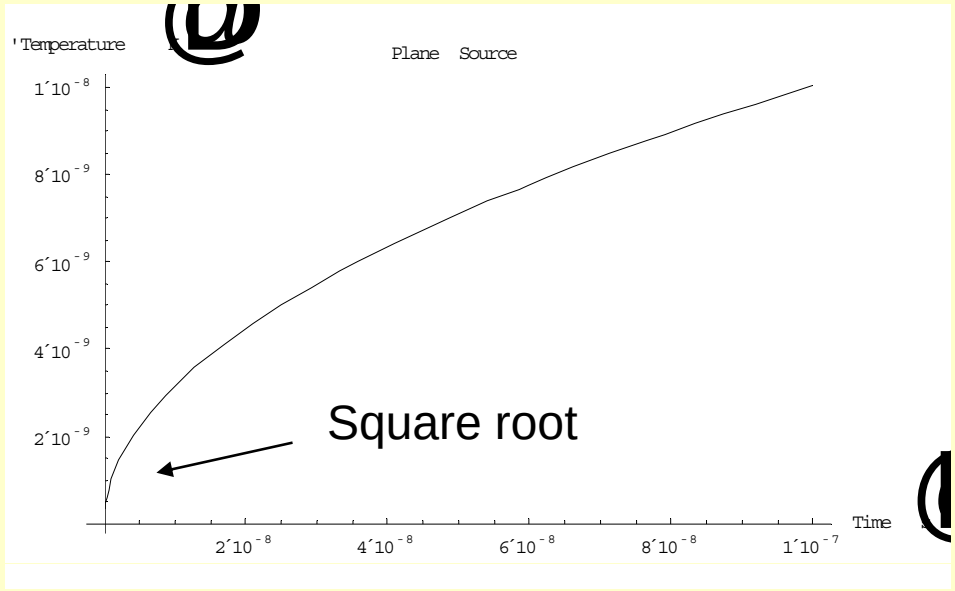
$$\nabla^2 T + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

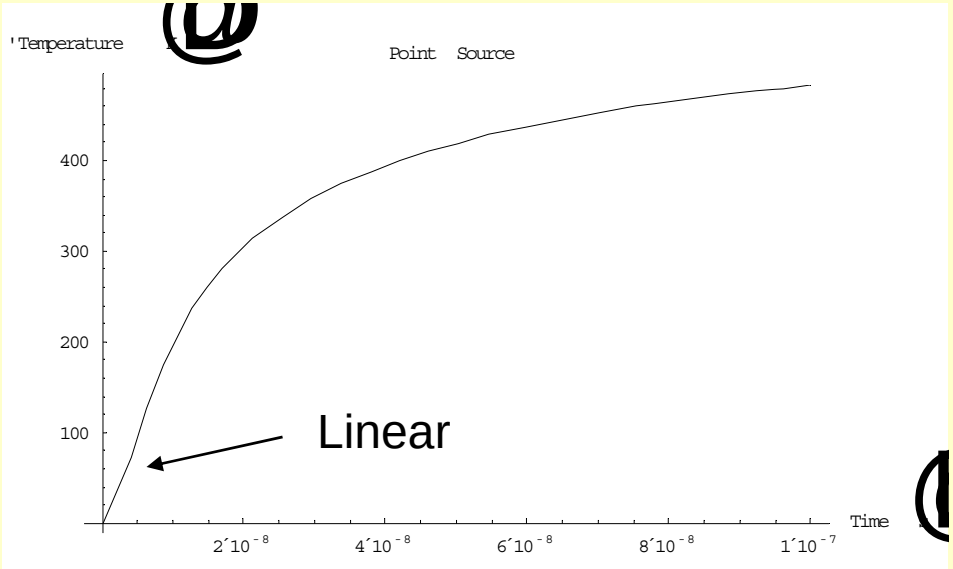
- With: k = thermal conductivity, $\alpha = k/(c^*\rho)$, c = specific heat, ρ = density

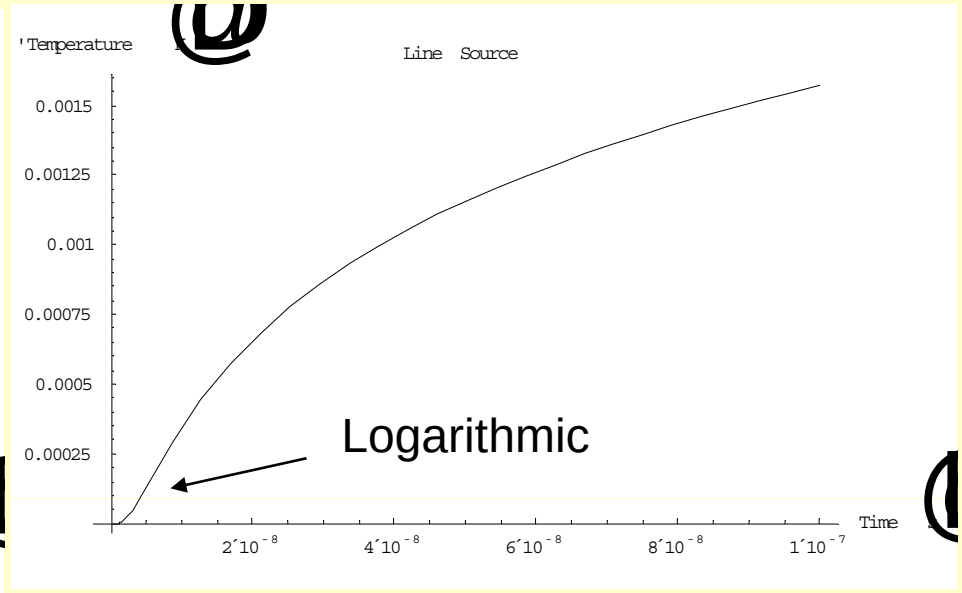
1D, 2D, 3D heating profiles inside a solid, or over a semi-infinite solid

- Clockwise:
- 1D heat flow → plane source gives square-root time dependence

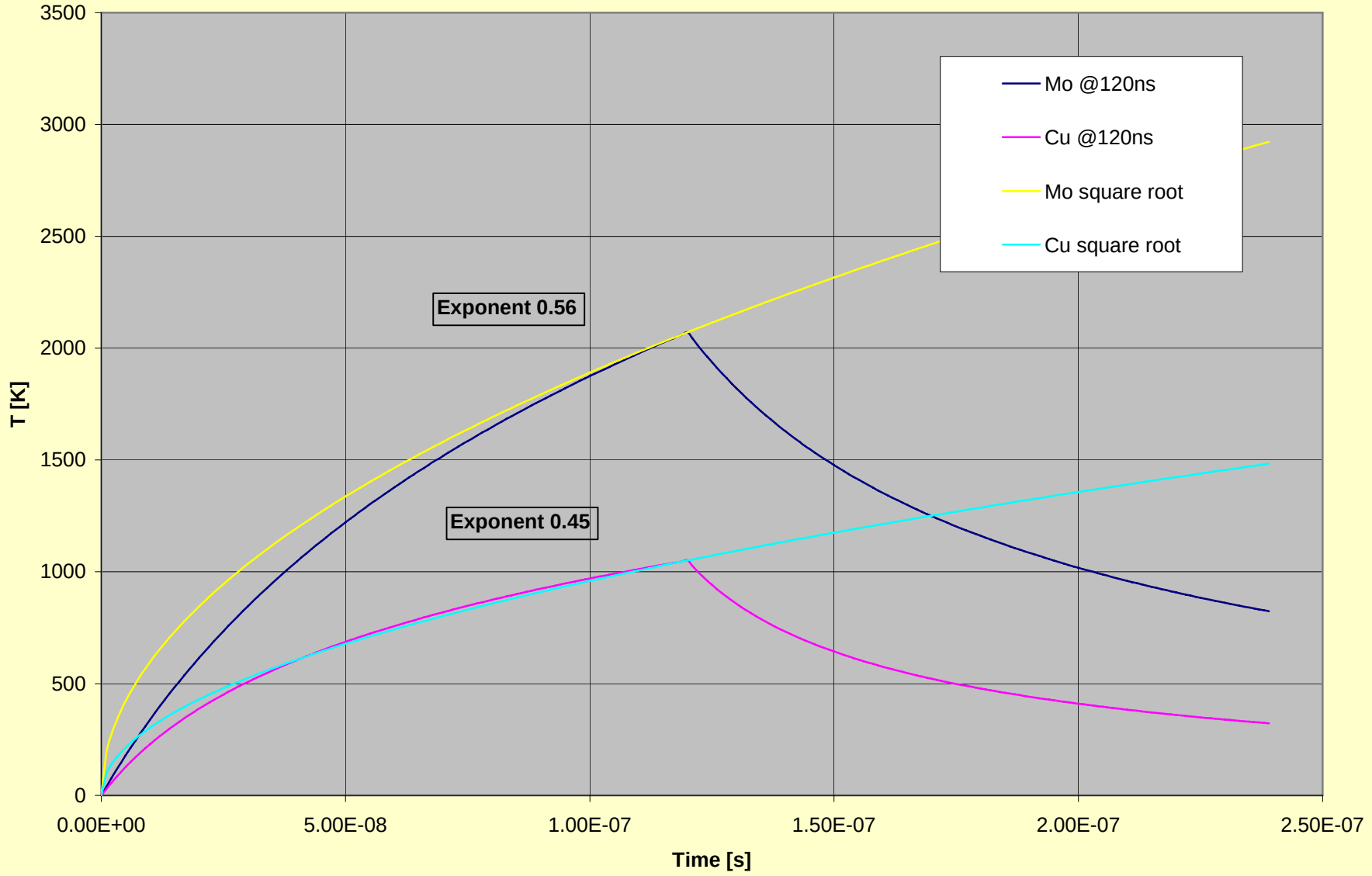
- 2D heat flow → line source
- 3D heat flow → point source







From A. Bertarelli: 2µm x 2µm heat source



Thoughts on breakdown rate

- Breakdown rate is (IMHO) the most important problem that we need to understand and master in order to make CLIC-grade accelerating structures.

- Still unclear why, without apparent changes in the experimental conditions, suddenly breakdowns appear after some breakdown-free operation

  (True also in DC. See tomorrow's talk by A. Descoeudres)

- …but there are ideas:
  - Breakdown probability depends on fatigue
  - Breakdown probability depends on ionisation probability

Breakdown probability as result of fatigue

- Seen in previous slides that emitting sites can get (very) hot because of Joule heating
- Field emission → heating → mechanical stress → fatigue → material break-up

- Pros of the model:
  - Fatigue is a statistical phenomenon. For a given stress value the number of cycles leading to break-up are Gauss-distributed with large variance
  - “Exponential” field dependence intrinsic
  - Very simple physics

- Cons of the model:
  - Pulse length dependence should probably saturate at some point (DC could say a word on this)
  - Detailed stress pattern difficult do identify
  - The material breaks-up, but how this precisely starts an arc is not understood

Breakdown probability as result of gas ionisation

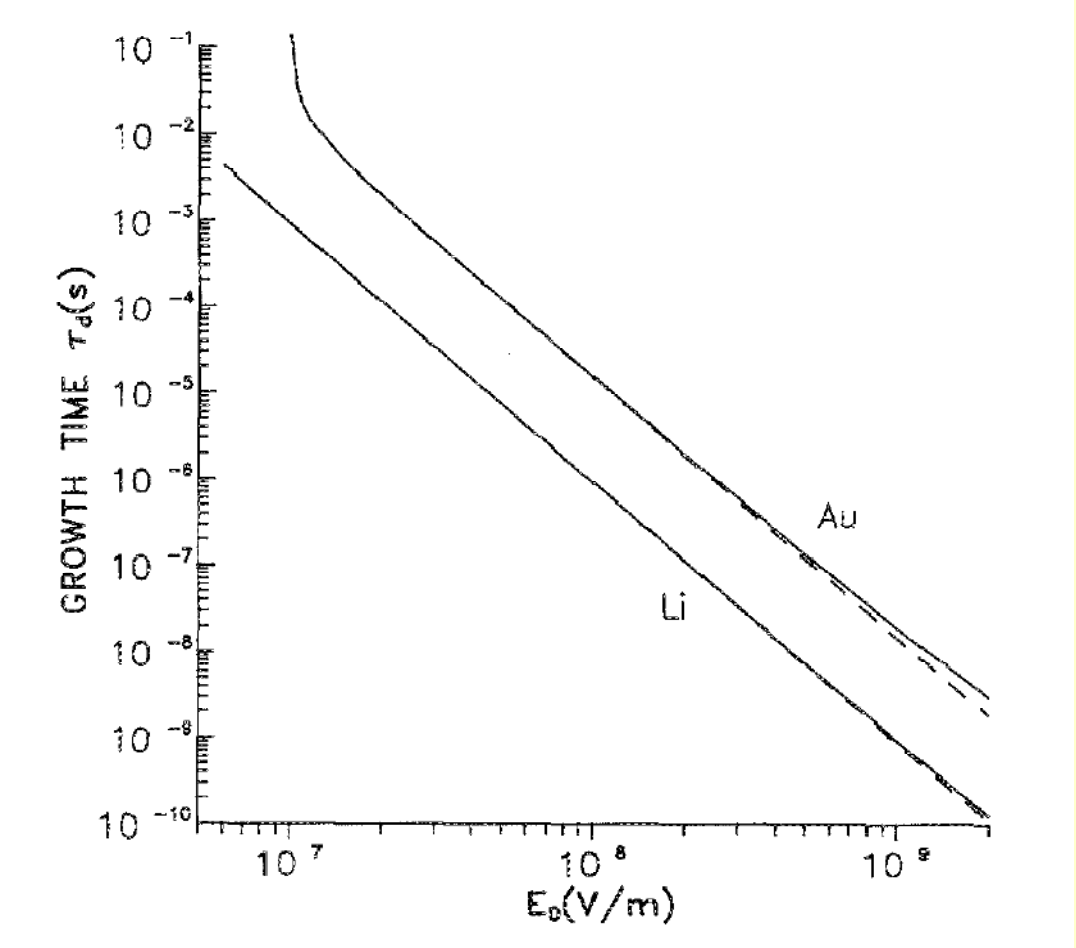
- Emitting sites can get (very) hot because of Joule heating, and emit metallic vapours which get ionised by field-emission current
- Field emission → heating → metallic vapours → ionised by electrons → ionisation cascade

- Pros of the model:
  - Both vapour pressure and electron current are “exponential” with field
  - Ionisation probability and cascade ignition are known to depend linearly on electron current and vapour pressure
  - ….I made some calculations on it

- Cons of the model:
  - Although most relevant material parameters are known, numerical predictions are distinctly not trivial
  - Pulse dependence not clear (saturation?)

Taylor cones: time for formation I

- Formation of instability waves on a flat molten surface (He et al. J. Appl. Phys. 68 (1990) 1475



- Seems slow compared to CLIC situation

Comparison with breakdown rate measurements?

- The breakdown probability: $P(x_1, x_2, ..., x_n) = f(x_1) f(x_2) ... f(x_n)$
- Where x_i might be E, τ or a even a combination of these or other physical quantities.
- I make the assumption that the ignition of a breakdown is due only to gas ionisation by electrons. A breakdown is of course an ionisation cascade
- I assume that the probability of igniting a cascade depends linearly on the amount of gas available and on the primary electron current
- In this case: $P_{breakdown} \propto I_{electrons}\, pressure_{gas}$

- Normalisation should of course be applied
- Where do the electrons and the gas come from?

Comparison with breakdown rate measurements?

- The electron current is given by the standard Fowler-Nordheim equation:

$$I_{electrons} = FN(\beta E)$$

$$FN(\beta E) = Const * (\beta E)^2 \exp(-B/\beta E)$$

- The constant includes the emitter area

- The gas molecules that get ionised (and allow me this far-fetched assumption!) are indeed the metal vapours created at the tip of the emitters, because of Joule heating by the F-N current.
- It is very difficult to use the full heating model seen before. I made the very crude assumption that the temperature grows with (time)$^{0.5}$ and scales inversely with the (thermal conductivity)$^{0.5}$.
- The vapour pressure is then given by:

$$p = p_0 \exp(\frac{-H_0}{RT})$$

- Where H_0 is the heat of vaporisation and R the gas constant. p_0 is a normalisation factor, there is a ratio of approximately 10^$^{2.5}$ between Mo and Cu

Comparison with breakdown rate measurements?

- All this gives (k is the thermal conductivity, τ the length of the RF pulse):

$$P_{breakdown} \propto I_{FN}(\beta E) * p_0 \exp\left(\frac{-H_0 k^{0.5}}{C\tau^{0.5} J_{FN}^2}\right)$$

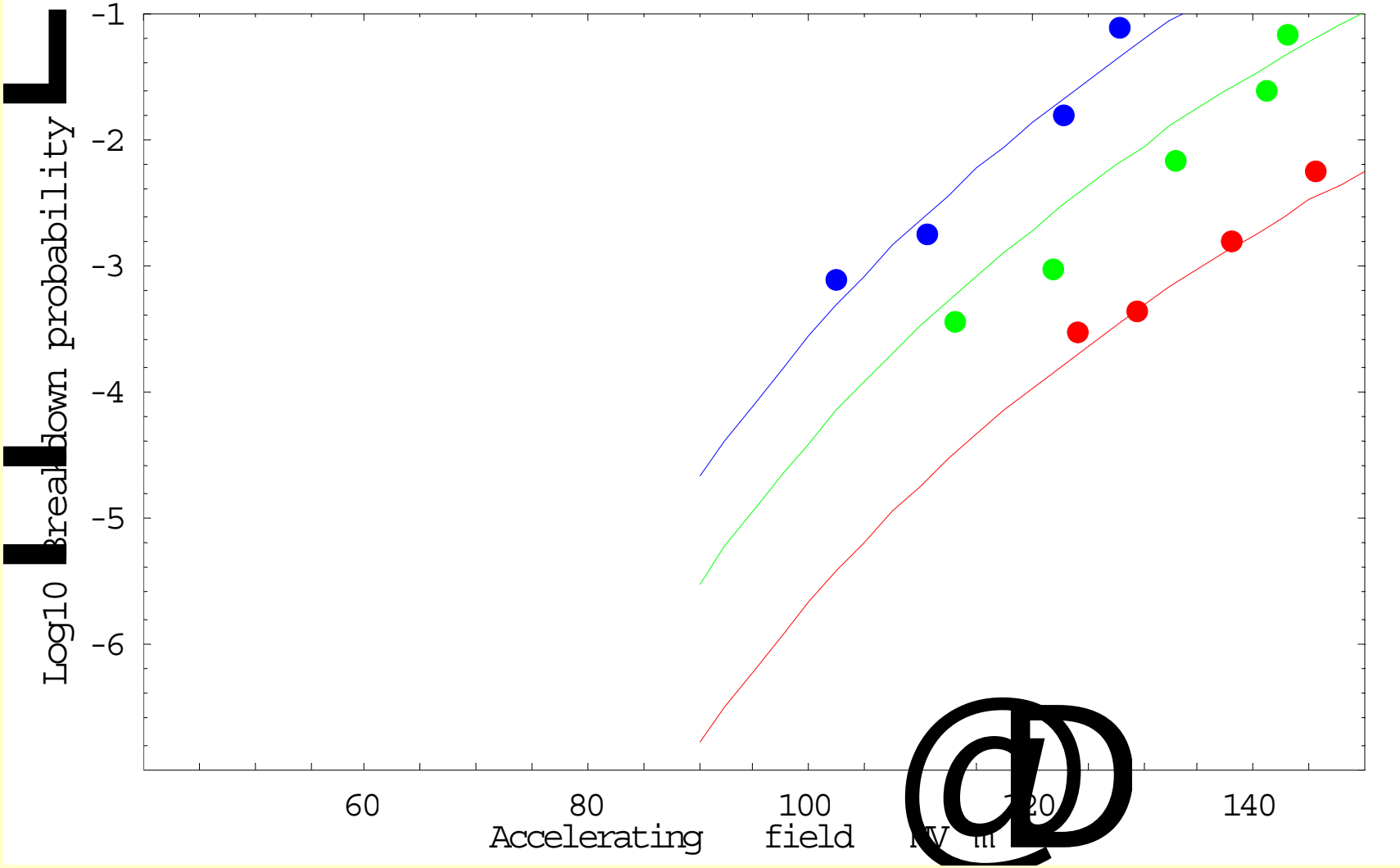
- Taking the Log_{10}, and applying a single proportionality constant for all the multiplicative factors (only the exponential part of the F-N equation is used):

$$Log(P_{breakdown}) = A + p_0 + 2Log(\beta E) - \frac{B}{\beta E} - \frac{H_0 k^{0.5}}{C\tau^{0.5} J_{FN}^2}$$

- Where *A, B, C* are fit to the experimental data (and include for example the ionisation cross section, the field emitter area, the probability normalization…)

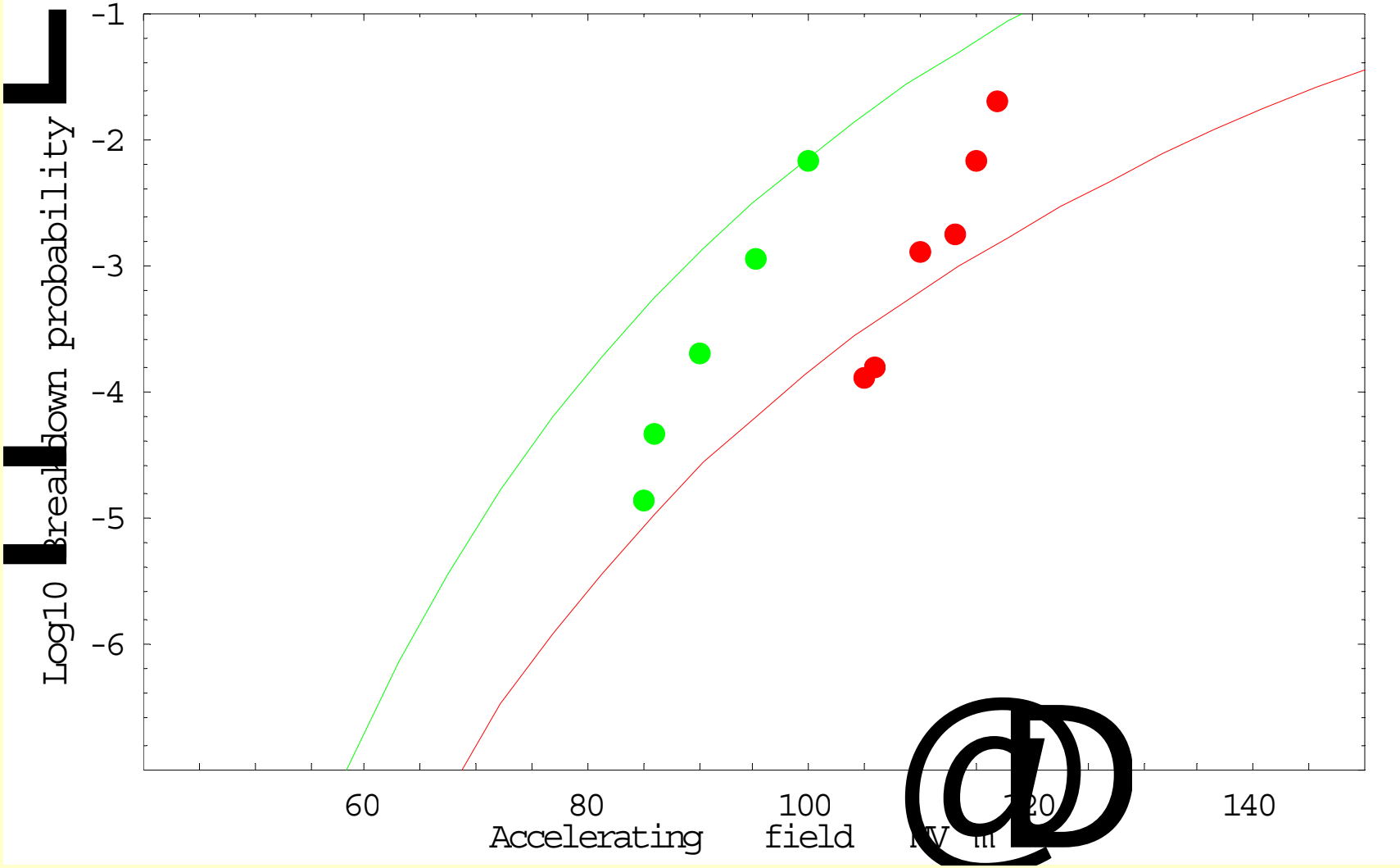
Fit to Mo data, 30 GHz circular iris

- $\beta = 30$, $k = 138$ $Wm^{-1}K^{-1}$, $p_0 = 10^{\wedge 14.5}$ mbar, $H_0 = 598$ kJ/mol



Keeping the same fit parameters and comparing to Cu data, 30 GHz

- $\beta = 45$, $k = 400$ $Wm^{-1}K^{-1}$, $p_0 = 10^{\wedge 12}$ mbar, $H_0 = 300$ kJ/mol.



Letting free the F-N fit parameters and comparing to Cu data, 30 GHz

- *B* doubles and *A* increases of 6 units