Breakdown Triggers and Breakdown Rate

Motivation of breakdown studies

- Breakdown rate is currently seen as the main obstacle in achieving the maximum possible gradient in CLIC accelerating structures
- Understanding the origin of breakdowns, experimentally and theoretically, may help in improving operating gradient
- Current strategy:
  - RF tests: breakdown rate experiments with new diagnostic tools for identifying the ion species produced from the emitted light, and searching for triggering mechanism
  - DC test: rapid turnover of samples, study of the properties of old/new candidate materials, measurements of breakdown rate and comparison with RF, diagnostics for studying breakdown physics
  - Modelling of breakdown initiation phenomena, both approximate and by atomistic simulations, and provide input parameters and ideas for RF design which could help suppressing or at least reducing breakdowns
  - … and over again.

Workshop Timetable

09:00	Welcome (05')	Jean-Pierre Delahaye (*CERN*)
09:05	Introduction (10')	Sergio Calatroni (*CERN*)

09:15->*10:35* **Review of Current Experimental Work I** (Convener: Sergio Calatroni (*CERN*))

09:15	RF Breakdowns: Experiments and Goals (30') (Slides)	Steffen Doebert (*CERN*)
09:45	Breakdown in RF Structures: Material Studies (30')	Gonzalo Arnau Izquierdo (*CERN*)
10:15	Ion Current from Breakdowns in RF Structures (20')	Magnus Johnson (*Department of Nuclear and Particle Physics, Uppsala university*)
10:35	Coffee break	

10:50->*12:00* **Review of Current Experimental Work II** (Convener: Volker Ziemann)

10:50	Spectroscopic Analysis of DC and RF Breakdowns (30') (Slides)	Jan Kovermann (*III. Physikalisches Institut (B) - Rheinisch-Westfaelische Tech.*)
11:20	DC Breakdown: Comparison of Different Materials (20') (Slides)	Antoine Descoeudres (*CERN*)
11:40	Outgassing Measurements in DC Breakdowns (20')	Yngve Inntjore Levinsen (*Norges Teknisk-Naturvitens. Univ. (NTNU)*)
12:00	Lunch Break	

13:30->*14:30* **Modelling I** (Convener: Kai Nordlund (*University of Helsinki*))

13:30	Atomistic Simulations of Breakdown Triggers: Progress Report (20')	Flyura Djurabekova (*University of Helsinki*)
13:50	Delay Times in Breakdown Triggering (20') (Slides)	Antoine Descoeudres (*CERN*)
14:10	Breakdown Triggers and Breakdown Rate (20')	Sergio Calatroni (*CERN*)

14:30->*16:00* **Modelling II** (Convener: Walter WUENSCH (*CERN*))

14:30	Scaling Laws in RF Accelerating Structures (30') (Slides)	Alexej Grudiev (*CERN*)
15:00	Some Observations During High Gradient Linac Testing at 17GHz using a Power Amplifying Dual Resonant Ring (15')	Jake Haimson
15:15	Power Circulation in a CLIC Accelerating Structure (15') (Slides)	Igor Syratchev (*CERN*)
15:30	RF Design Options for Quenching Breakdowns (30')	Riccardo Zennaro (*CERN*)
16:00	Coffee break	
16:15	Discussion and Perspectives (45')	
17:00	End of the meeting (20')	

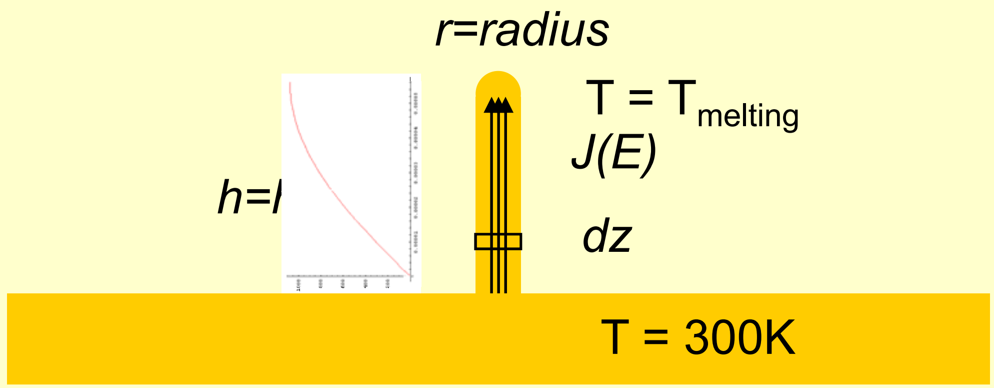
Triggering a breakdown

- A breakdown is an ionisation cascade, fuelled by some e.m. power (RF fields in a cavity, or 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
  - Existence of dark currents

- The following simple model suggests that some conditions must be fulfilled for initiating a breakdown. In particular:
  - Duration of RF pulse
  - Local power density

- The basic idea is that field emission currents, emitted by “tips”, heat the emitting sites by Joule effect

Heating of tips by field emission - I



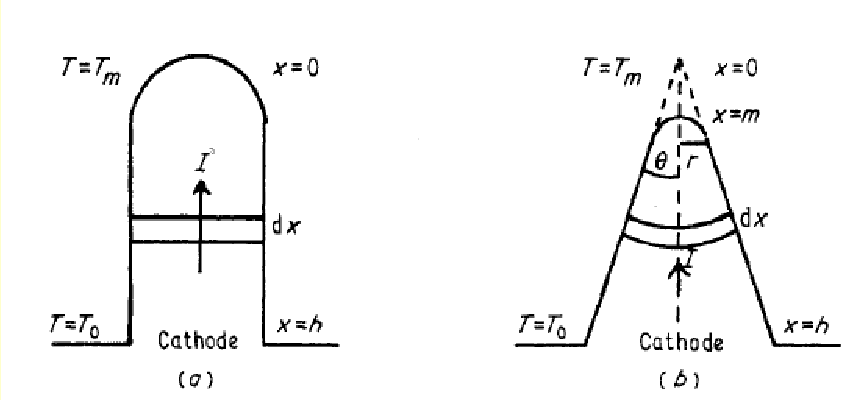
- The tip has a $\beta \approx$ *height/radius* (field enhancement factor)
- For a given value of applied E the Fowler-Nordheim law gives a current density $J(E)=A*(\beta E)^2*exp(-B/\beta E)$
- This current produces a power dissipation by Joule effect in each element *dz* of the tip, equal to $dP = (J \pi r^2)^2 \rho(z)\, dz / \pi r^2$
- The total dissipated power results in a temperature increase of the tip (the base is assumed fixed at 300 K). The resistivity itself if temperature dependent
- Using the equations we can, for example, find out for a given β what is the field that brings the “tip of the tip” up to the melting point, and in what time.

Heating of tips by field emission - II

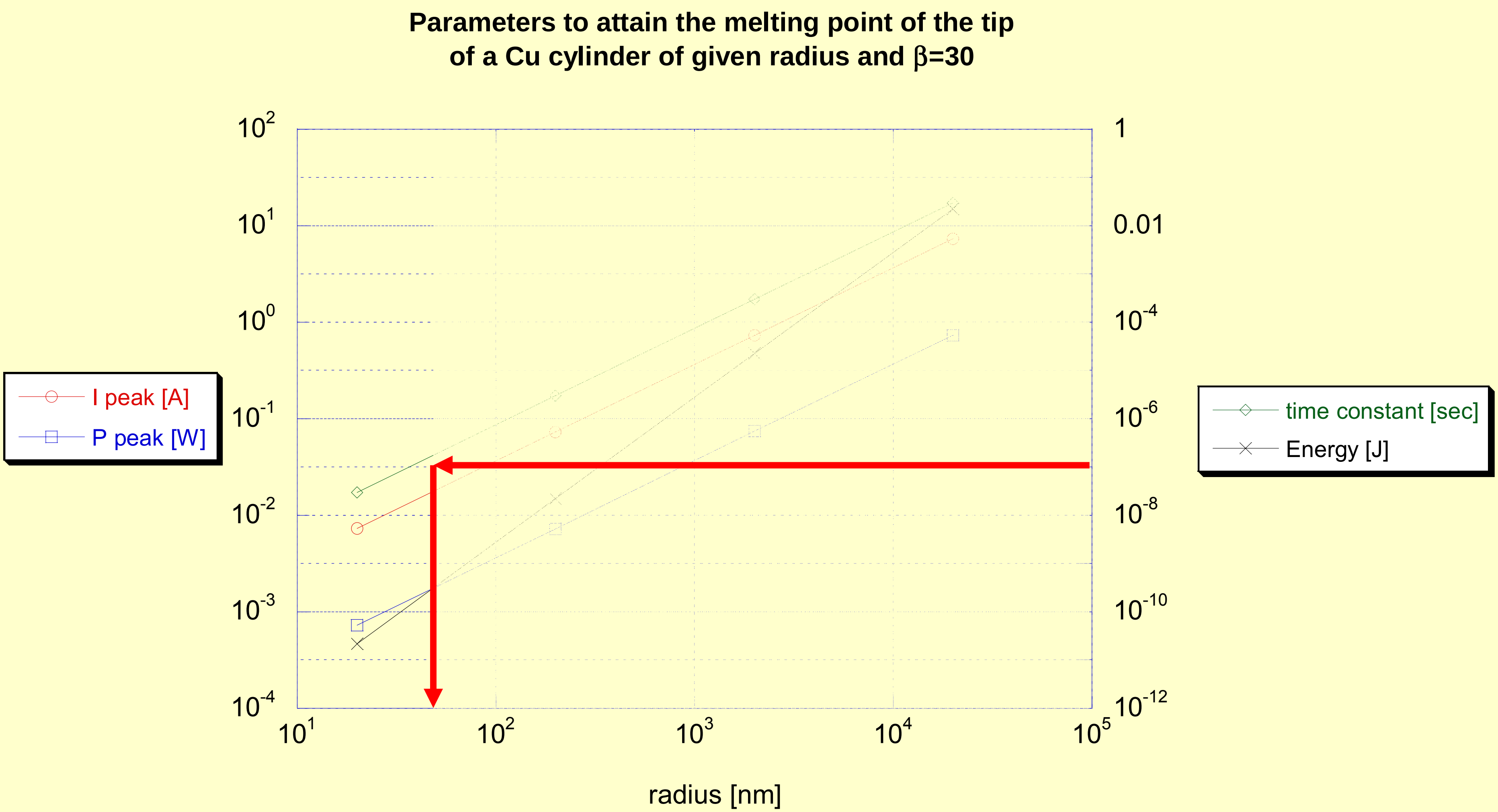
- If the resistivity is considered temperature-independent, a stable temperature is always achieved [Chatterton Proc. Roy. Soc. 88 (1966) 231]
- If the resistivity (other material parameters play a lesser role) is temperature dependent, then its increase produces a larger power dissipation, resulting in a further temperature increase 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 time dependence of the temperature can be calculated.

$$\frac{\partial T}{\partial t}=\frac{K}{\sigma S}\frac{\partial^2 T}{\partial x^2}+\frac{I^2\rho_0}{\pi r^2\sigma S}\{1+\alpha(T-T_0)\},$$

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

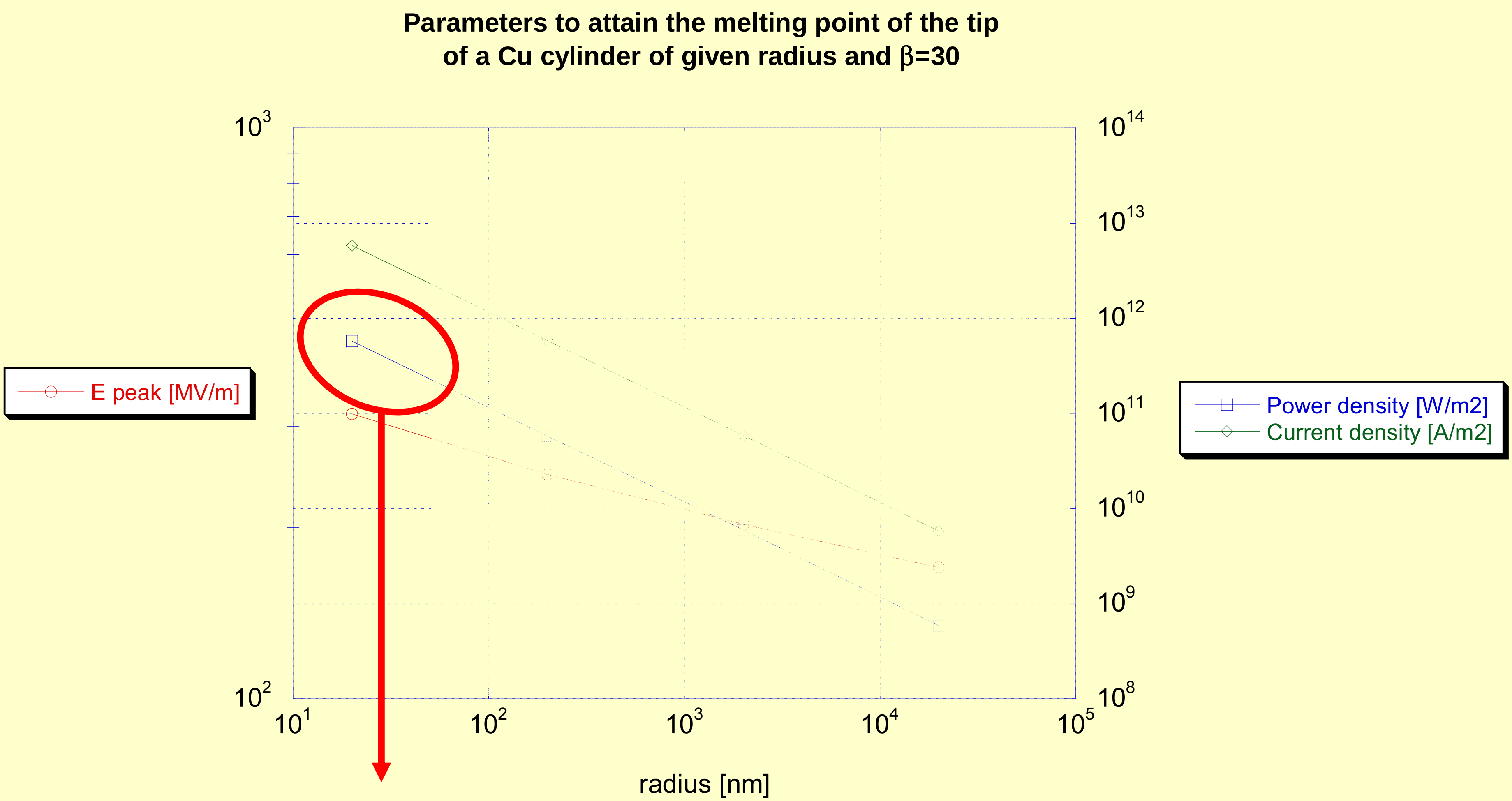


Time constant to reach the copper melting point (cylinders, β=30)



The tips which are of interest for us are extremely tiny, <100 nm (i.e. almost invisible even with an electron microscope)

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



Power density (power flow) during the pulse is a key issue.
See talk by A. Grudiev for RF structures scaling based on Poyinting vector

Breakdown: ionisation probability

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

- 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.
- The probability of igniting a cascade depends linearly on the amount of gas available and on the primary electron current

$$P_{breakdown} \propto I_{electrons} \, pressure_{gas}$$

- Where do the electrons and the gas come from?

Electron current and gas sources

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

$$I_{electrons} = Const * (\beta E)^2 \exp(-B/\beta E)$$

- The constant includes the emitter area, the work function. $I_{electrons}$ is "exponential" with E (steep slope like in measured breakdown probabilities)
- β can be material dependent, and the tips might as well be "dynamical" tips, thus depending on field, number of pulses etc.

- The gas molecules can be either metallic vapours or other gas released by thermal outgassing (or both!), due to Joule heating
- T depend on pulse duration (simulations suggest that T is proportional to [current density J]^2 and grows with exp[time τ].

Metal vapour pressure
(H_0 is the heat of vaporisation)

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

Outgassing
(sign depends on endo/exothermic)

$$p = p_0 c_H^2 \exp(\frac{\pm E}{RT})$$

Pressures and number of molecules

- Order-of-magnitude estimate (1):
  - Vapour pressure of Cu at $T_{melting}$ ~ 10^{-3} mbar.
  - Tip radius = 25 nm, ~ 10^6 copper atoms emitted / second (0.1 atoms / 100 nsec: impossible to start a breakdown) √
  - At $T_{sublimation}$ (vapour pressure 1 bar) we have 6 orders of magnitude more atoms emitted √

- Order-of-magnitude estimate (2):
  - At $T_{melting}$, the equilibrium pressure for 10 ppm of H in Cu is ~ 1 bar √
  - Electron stimulated desorption. If we have currents in the mA range before breakdown, this may results in ESD ~ $5*10^{13}$ H_2 / sec (yield 10^{-2}) √

- Order-of-magnitude estimate (3):
  - Tip β=30 radius=25 nm ⇒ ~10^8 copper atoms √
  - 10 ppm of hydrogen in such a tip ⇒ ~10^3 hydrogen atoms (seems small) √

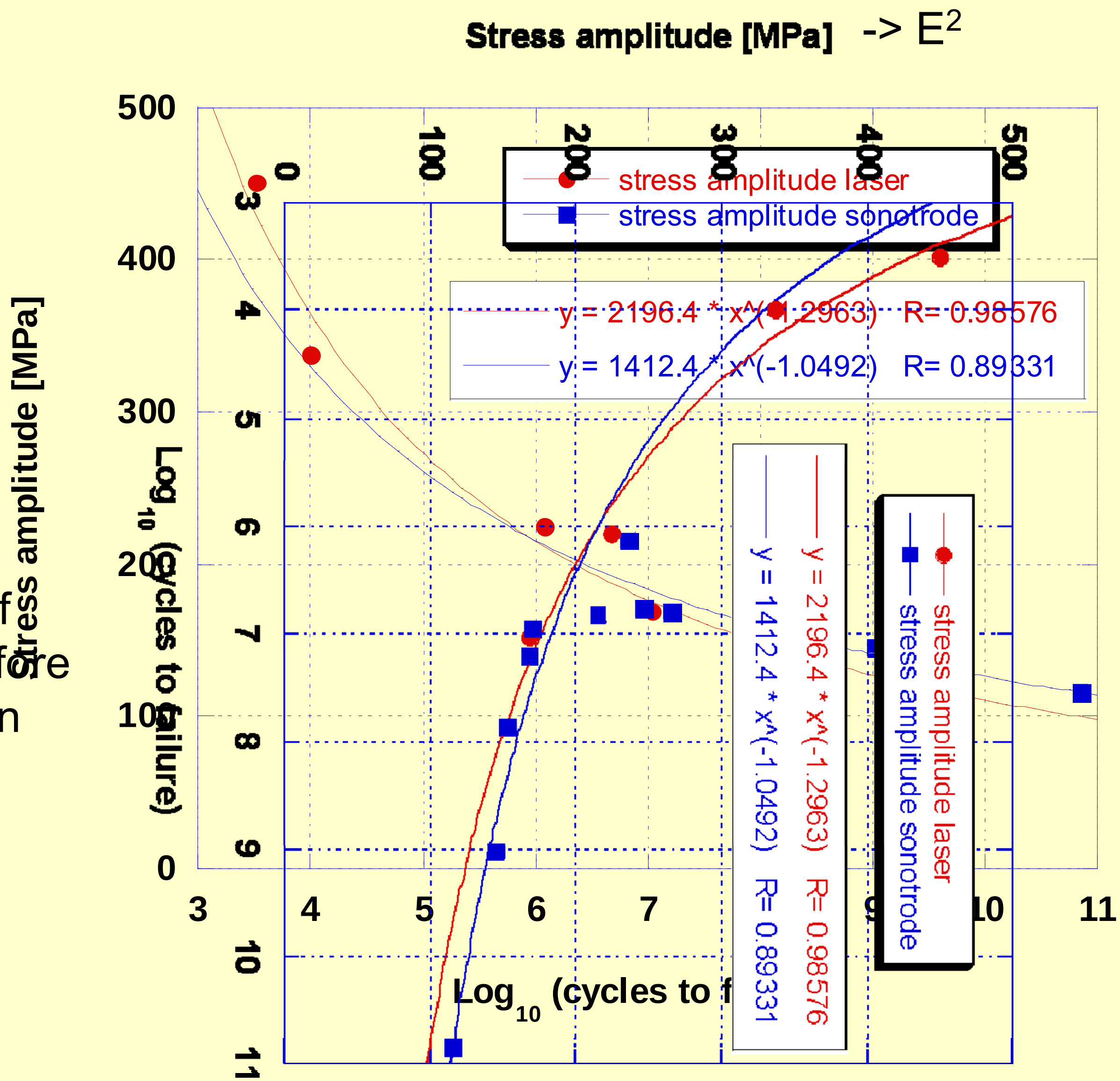
Breakdown probability as result of fatigue

- Two possible schemes for breakdown by fatigue:
  - Sites can get (very) hot because of Joule heating
  - Field emission → heating → mechanical stress → fatigue → material break-up
- Or:
  - Tips are simply pulled by electric field
  - Tip with field enhancement → pulling with force ~E^2 → mechanical stress → fatigue → material break-up

- In the first case, the stress should go with temperature, which is proportional to J^2 (in turn related "exponentially" to E field) and exponentially with pulse duration. However the stress profile is unclear to me (there are no constrained surfaces)

- In the second case, the stress goes with E^2 and should not depend on the pulse duration, unless there is some change of mechanical properties due to temperature (and in this case we fall back partially in the FN-dominated mode).

Fatigue by pulling



Number of pulses before breakdown

7 orders of magnitude in # of cycles, with ¼ stress (½ gradient?)

Breakdown by fatigue

- In case breakdown is due simply to pulling, some numbers are very easy

- The electrostatic pulling stress is: σ [Pa] = $0.5\varepsilon_0 E^2$
- E = 200 MV/m $\Rightarrow$ σ = $1.8*10^5$ Pa (should be divided by 2 to have RMS field values).
- However: for β = 50 the stress increases by a factor 2500 $\Rightarrow$ σ=$2.5*10^{\wedge 8}$ Pa. This is 250 MPa, 125 MPa amplitude.
- For info, pulsed heating target for Cu at 10^{11} cycles is 80 MPa stress amplitude for copper. 125 MPa correspond to 10^6 cycles lifetime.

- But still no pulse length dependance…

Conclusions

- Modelling of breakdown precursors as tips heated by Joule effect due to FN currents seems globally reasonable.
- This naturally may lead to breakdowns (by simple ionisation or by explosive process in extreme conditions)

- However understanding of why there should be a breakdown rate needs still efforts. Simple pictures as illustrated before do not satisfy all known dependences on field or pulse length
- Other possible paths (atomistic simulations):
  - Development of tips under E-field
  - Coupled with vaporization
  - And outgassing
  - And change of mechanical properties with temperature
  - And with fatigue.

Acknowledgements

- Mauro Taborelli
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- Alexej Grudiev
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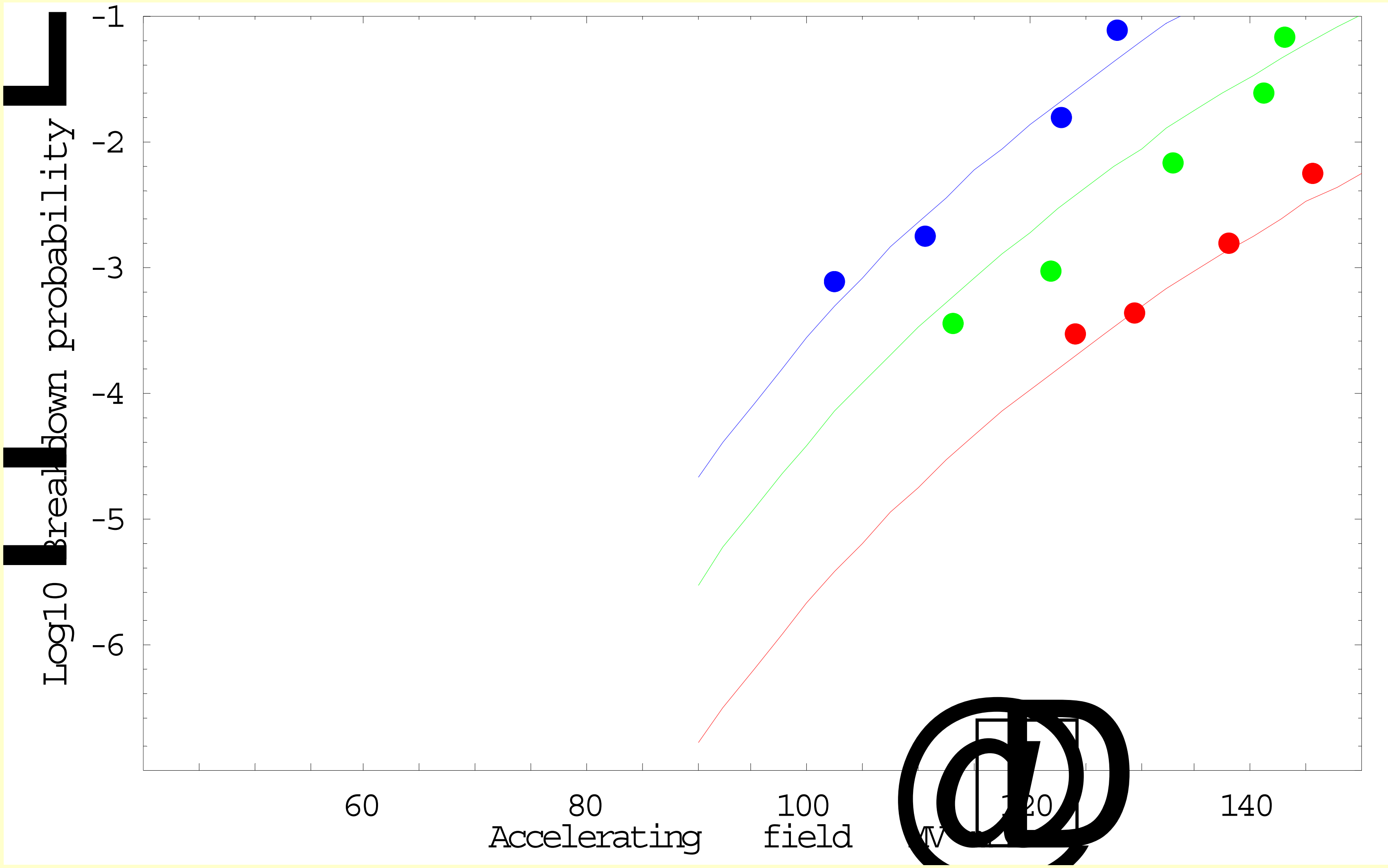
- Yngve Lenvinsen
- Trond Ramsvik
- Igor Syratchev
- Riccardo Zennaro

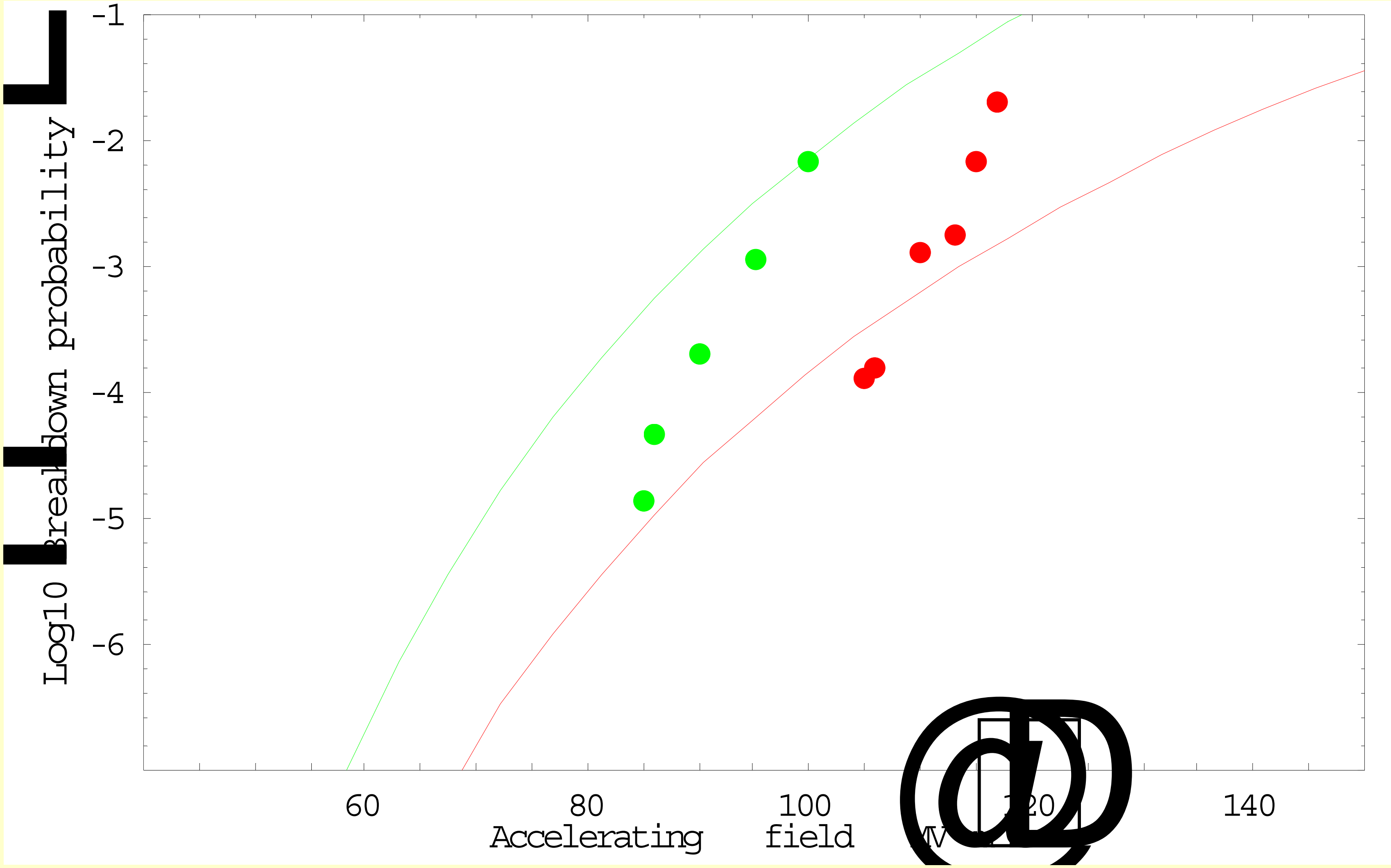
Fit to Mo data, 30 GHz circular iris

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



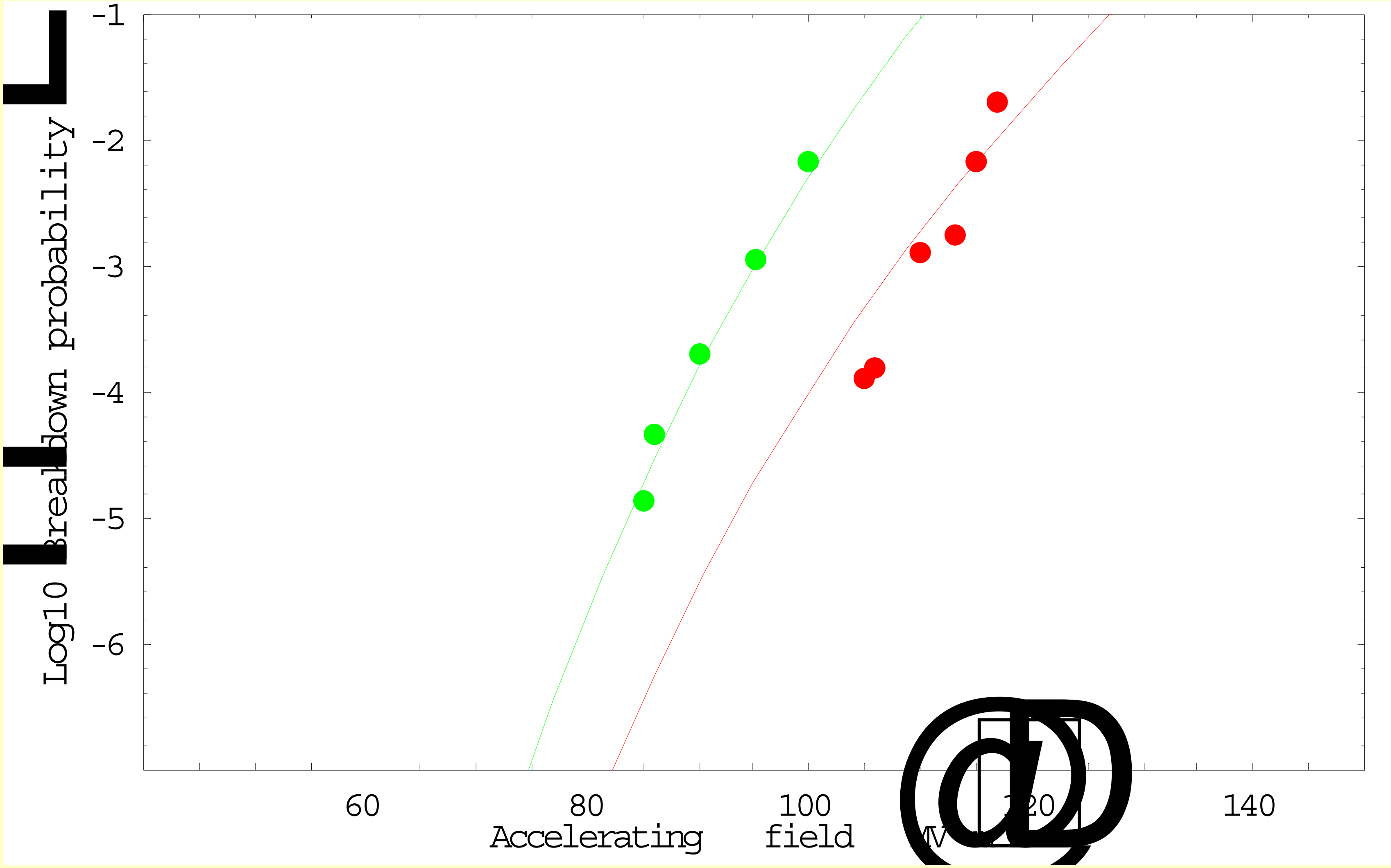
Keeping the same fit parameters and comparing to Cu data, 30 GHz

- $\beta = 45$, $k = 400\ Wm^{-1}K^{-1}$, $p_0 = 10^{12}$ 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



Temperature rise calculations

- Here starts the main part of the talk

- 1D, 2D, 3D time dependent heating
  - Relevant for the discussion on breakdown limit

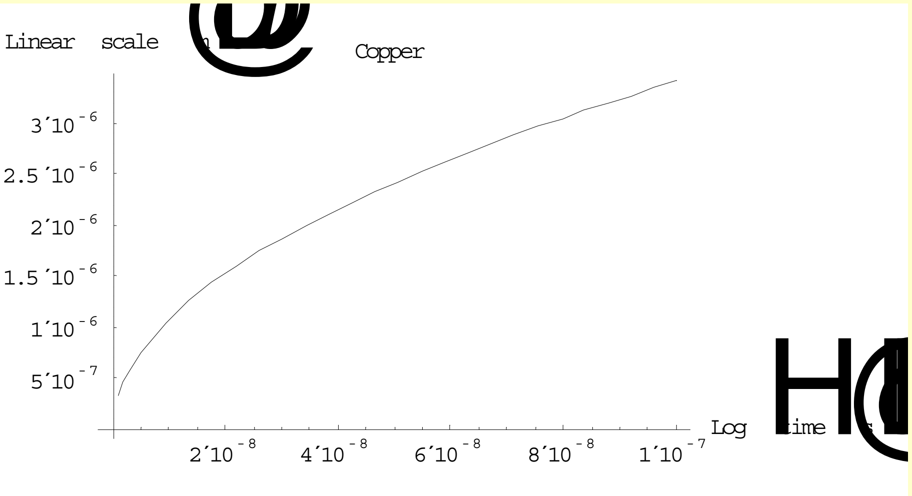
- Heating of tips by field emission currents
  - Relevant for the discussion on breakdown probability

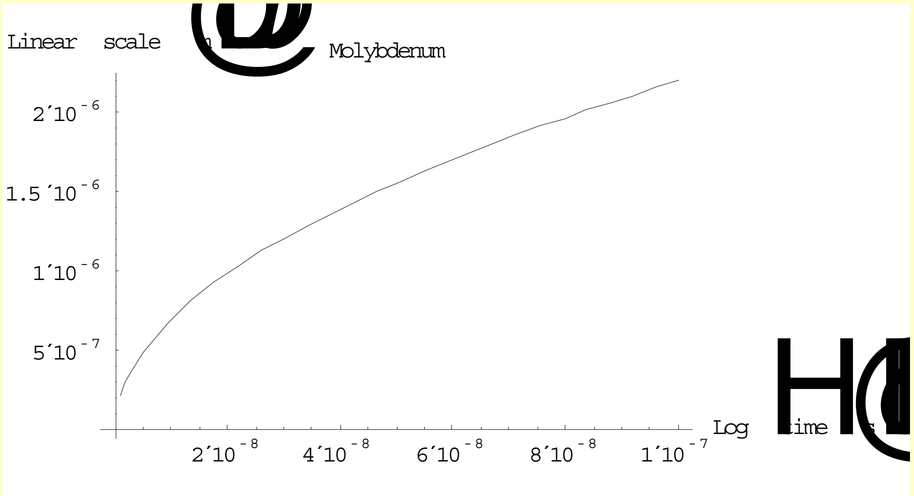
Time-dependent heating

- 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
- In-time dependent calculations the distinction between a “fast” and “slow” regime is based on the diffusivity time $\tau_D = R^2/\alpha$. R is the linear scale of the phenomena that are under consideration

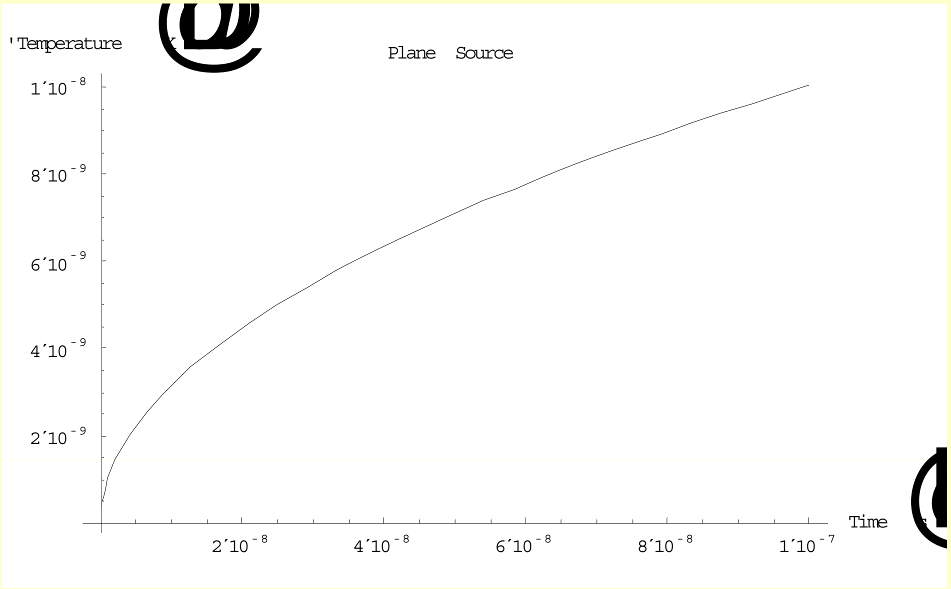


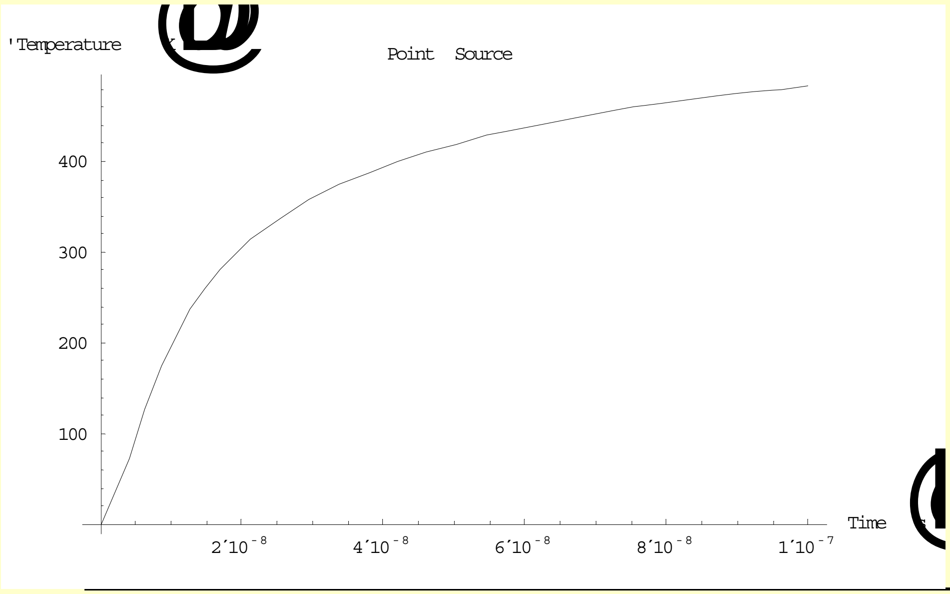


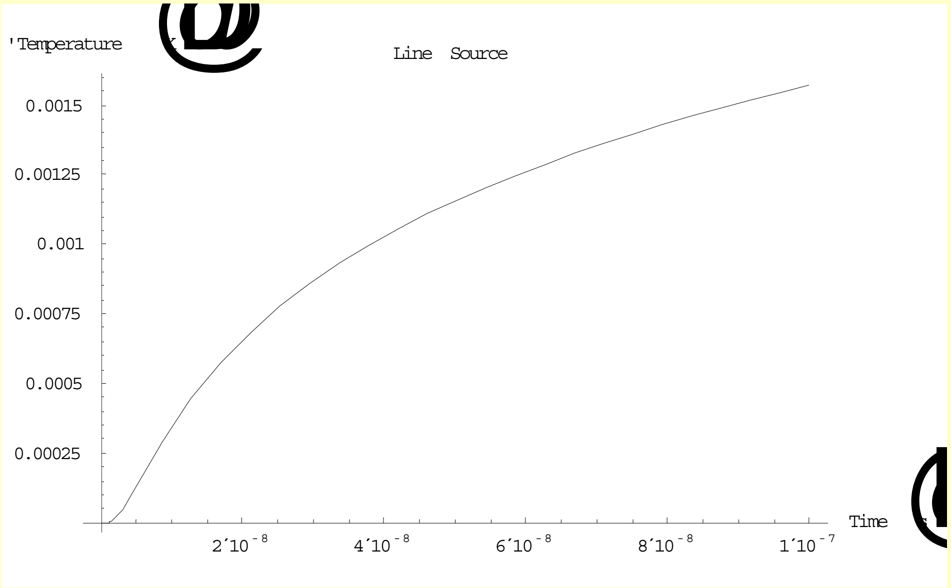
1D, 2D, 3D heating profiles inside a solid, or over a semi-infinite solid

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

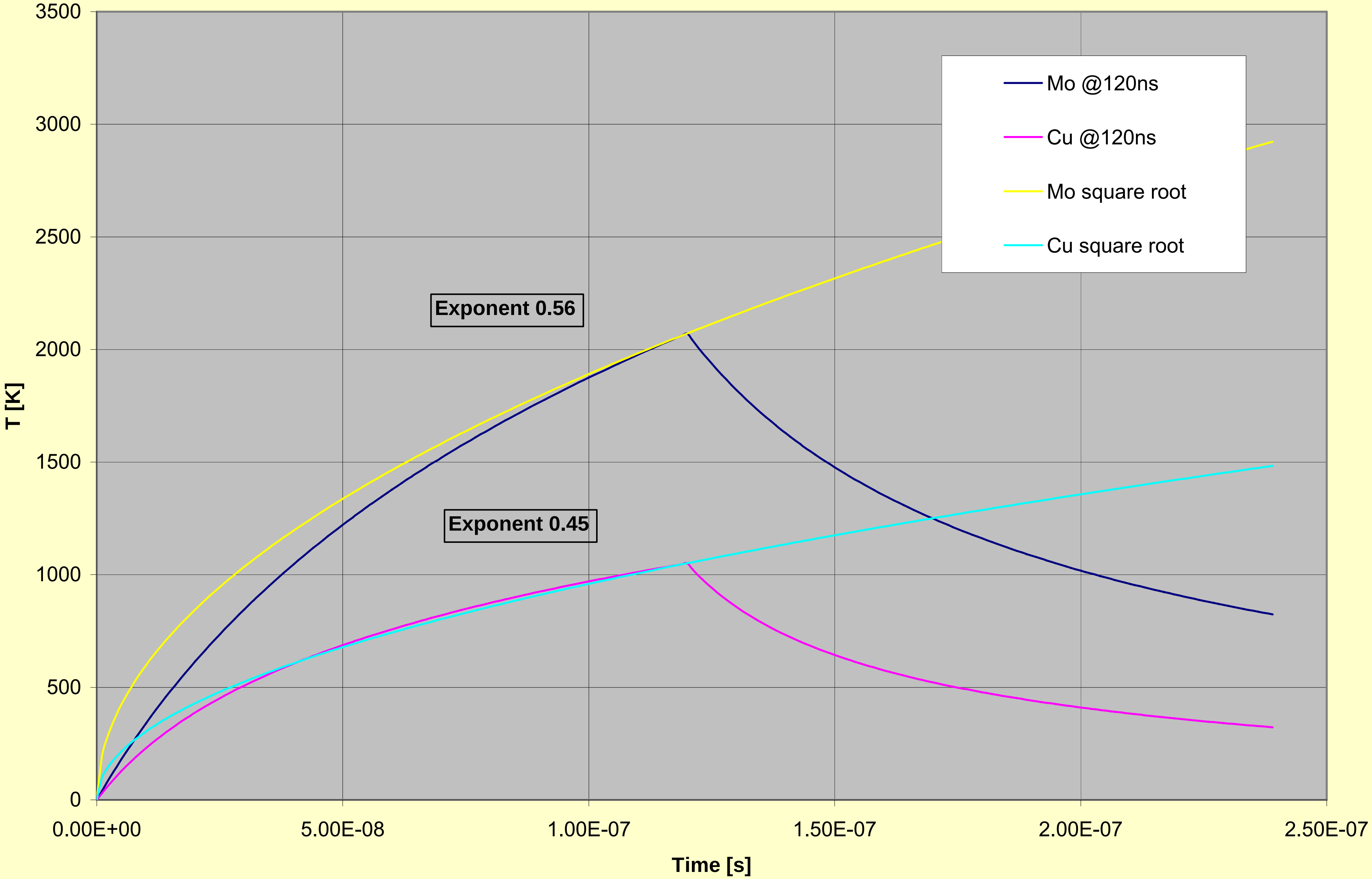
- 2D heat flow → line source
- 3D heat flow → point source





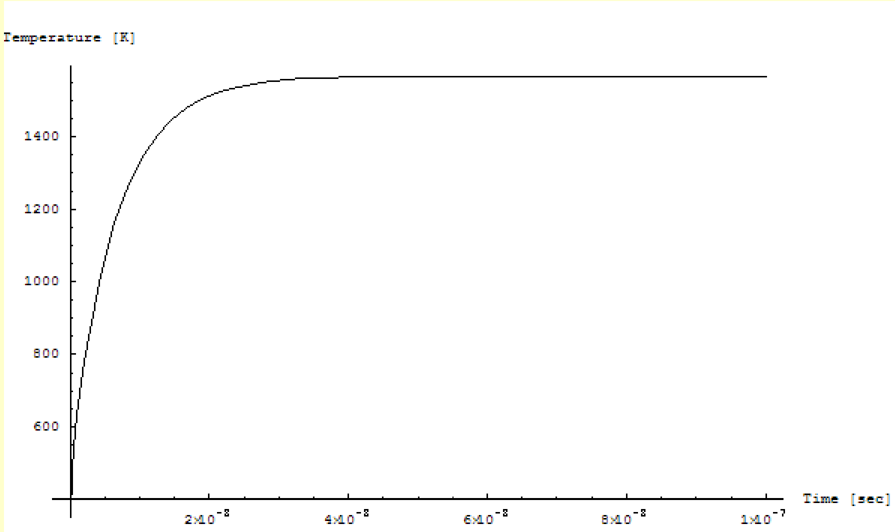


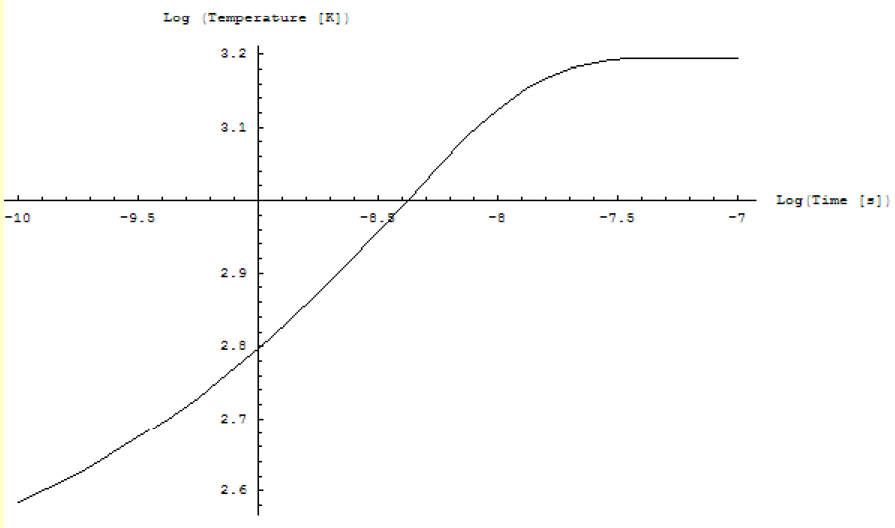
From Alessandro Bertarelli: 2μm x 2μm heat source



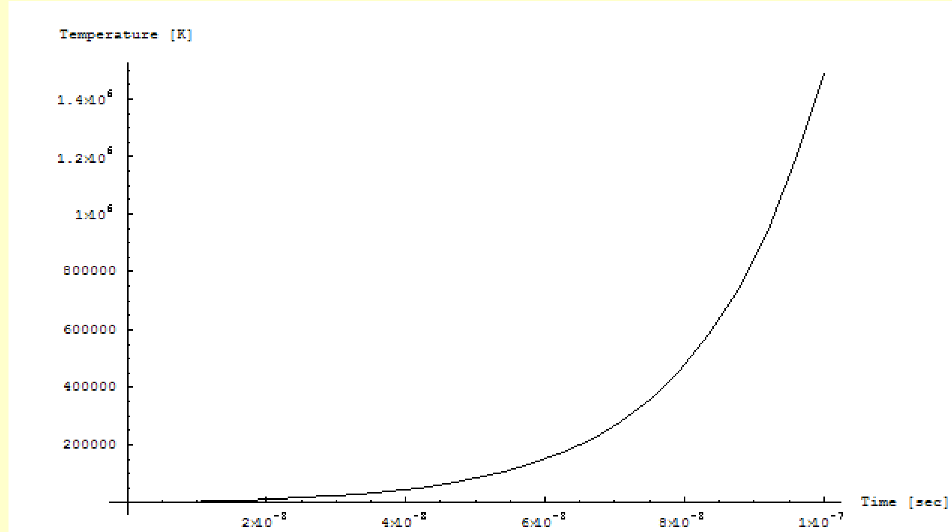
Simulation for Mo cone: diameter 20 nm, beta = 30

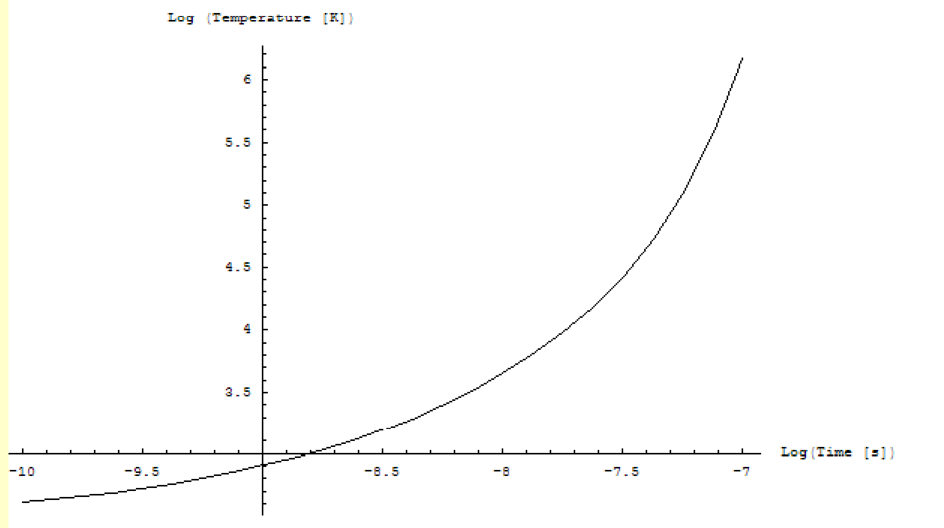
E=374 MV/m





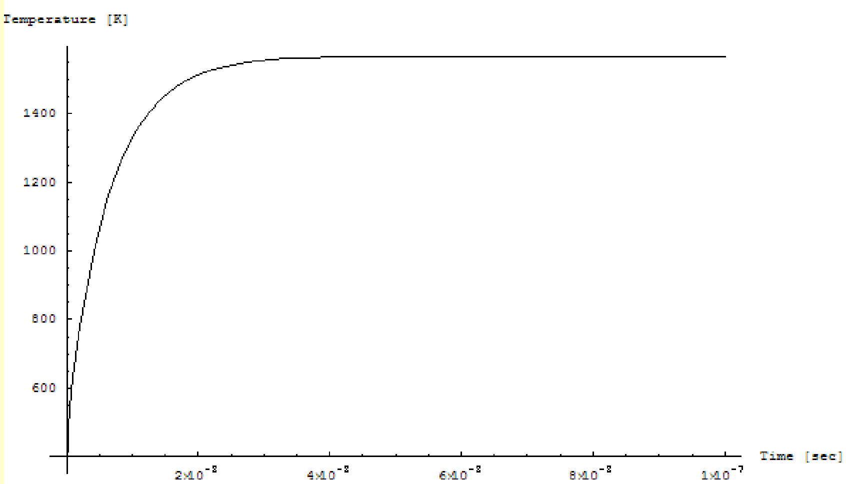
E=378 MV/m

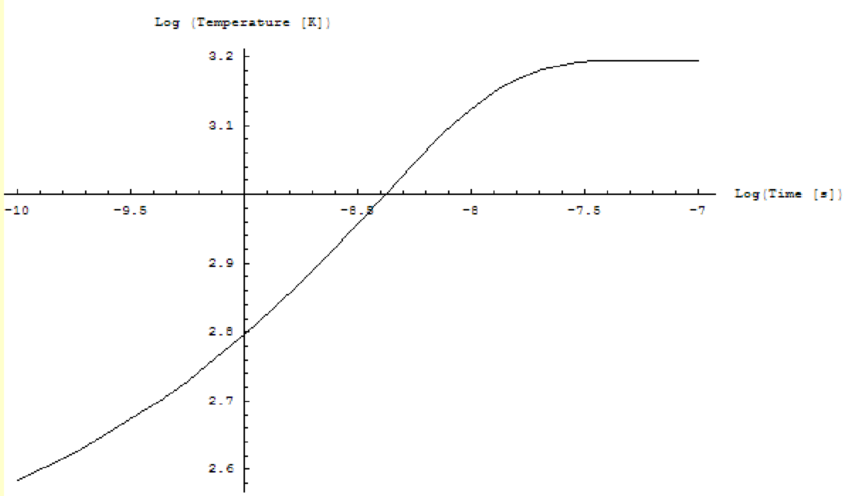




Simulation for Mo cone: beta = 30

Diameter 20 nm, E=374 MV/m, current = 0.028 A





Diameter 2000 nm, E=226 MV/m, current = 2.8 A