Dependence of the breakdown rate on the pulse shape

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Motivation

- Majority of the data are measured with rectangular pulse shape

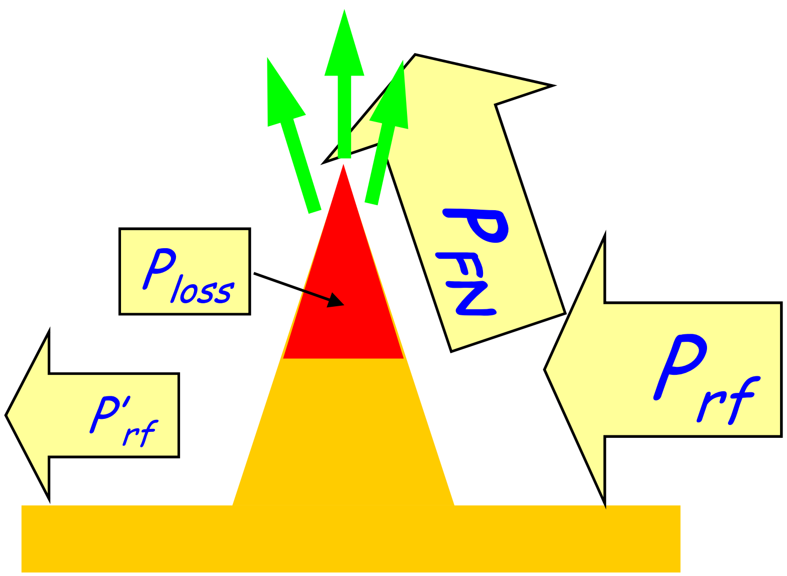
BUT

1. In standing wave structures, it is not rectangular
2. In traveling wave structures, the pulse must have a ramp in order to compensate the energy spread due to the beam loading transient effect

Field emission and rf power flow

Qualitative picture of breakdown initiation

- Field emission currents J_{FN} heat a (potential) breakdown site up to a temperature rise ΔT on each pulse.
- After a number of pulses the site got modified so that J_{FN} increases so that ΔT increases above a certain threshold.
- Breakdown takes place.



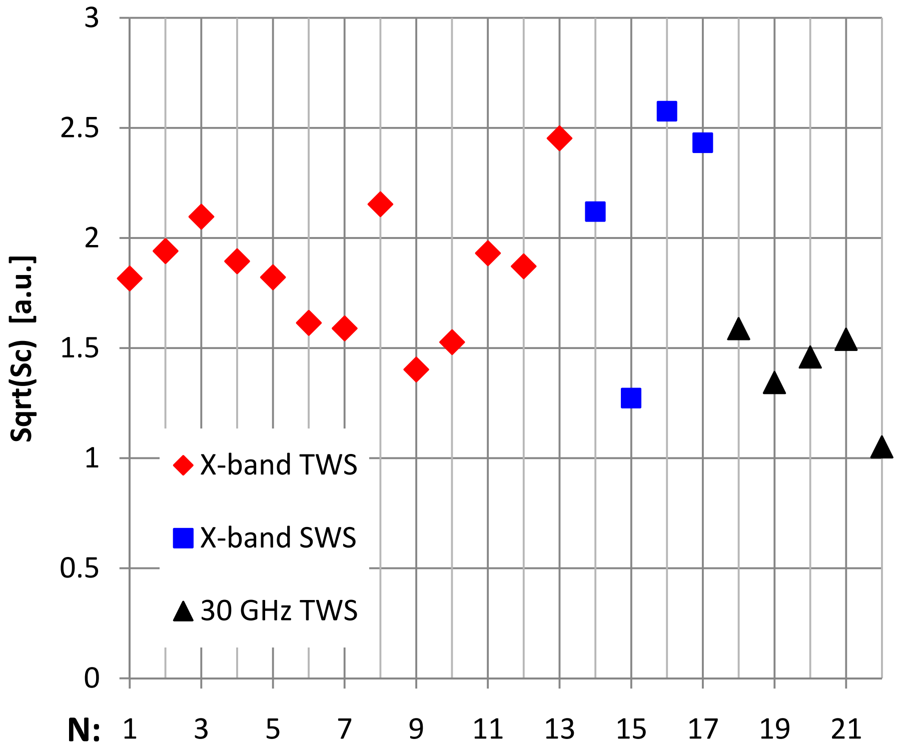
$$\Delta T \sim P_{loss} \ll P_{FN} \leq P_{rf}$$

$$P_{loss} = \int_V J_{FN}^2 \rho \, dv$$

$$P_{FN} = \oint_S E \times H_{FN} \, ds \sim E \cdot I_{FN}$$

$$P_{rf} = \oint_S E \times H \, ds$$

New rf breakdown constraint S_c



$$S_c = \mathrm{Re}\{\mathbf{S}\} + \mathrm{Im}\{\mathbf{S}\}/6$$

$S_c = 4 \div 5\ [MW/mm^2]$

at 200ns, BDR=1e-6

$S_c^{15} t_p^{5} / BDR = const$

Summary on gradient scaling

For a fixed pulse length

$$BDR \sim E_a^{30}$$

For a fixed BDR

$$E_a \cdot t_p^{1/6} = const$$

$$\frac{E_a^{30} \cdot t_p^5}{BDR} = const$$

- In **a** Cu structure, ultimate gradient E_a can be scaled to certain BDR and rectangular pulse length using above power law.

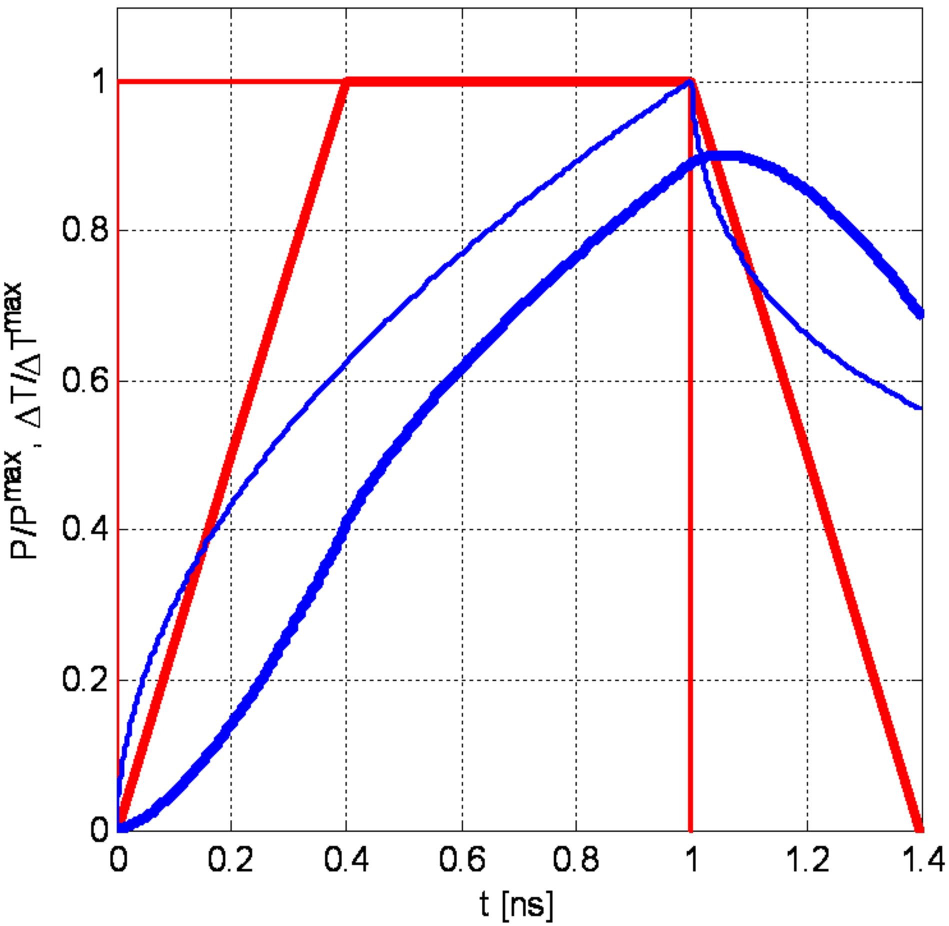
What is t_p for non-rectangular pulse ?

Conventional pulsed surface heating

$$\Delta T(t) \sim \int_0^t \frac{P(t')}{\sqrt{t-t'}}\,dt'$$

For rect pulse:

$$\Delta T(t_p) \sim P_0 \cdot \sqrt{t_p}$$



Pulsed heating by Field Emission

BDR=const means ΔT=const

$$\Delta T(t_p) \sim P_0 \cdot \sqrt[3]{t_p}$$

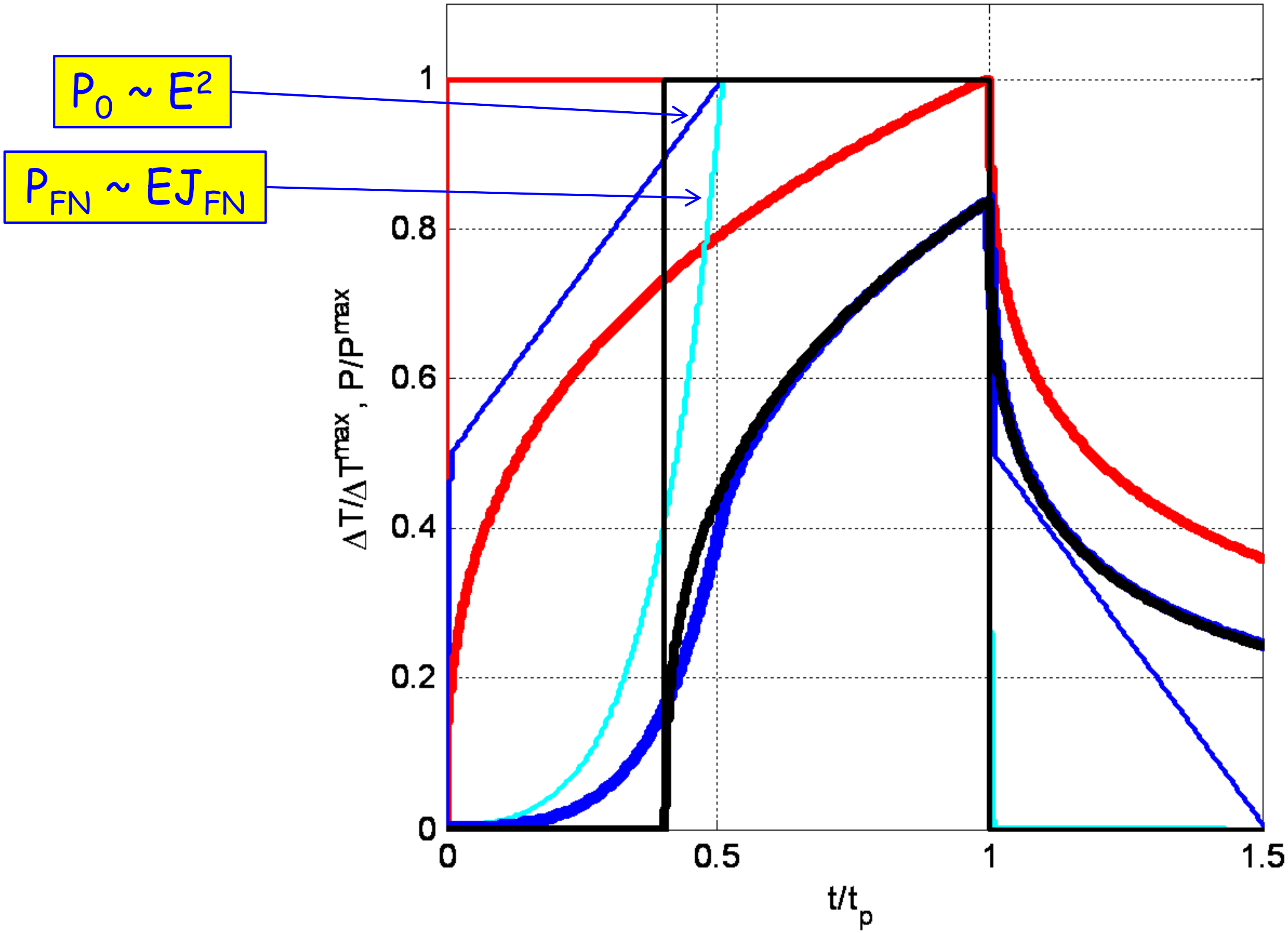
Using power loss expressed as

$$P_{FN}(t) \sim E \cdot I_{FN}$$

$$\sim E(\beta E)^2 e^{-\frac{62GV/m}{\beta E}}$$

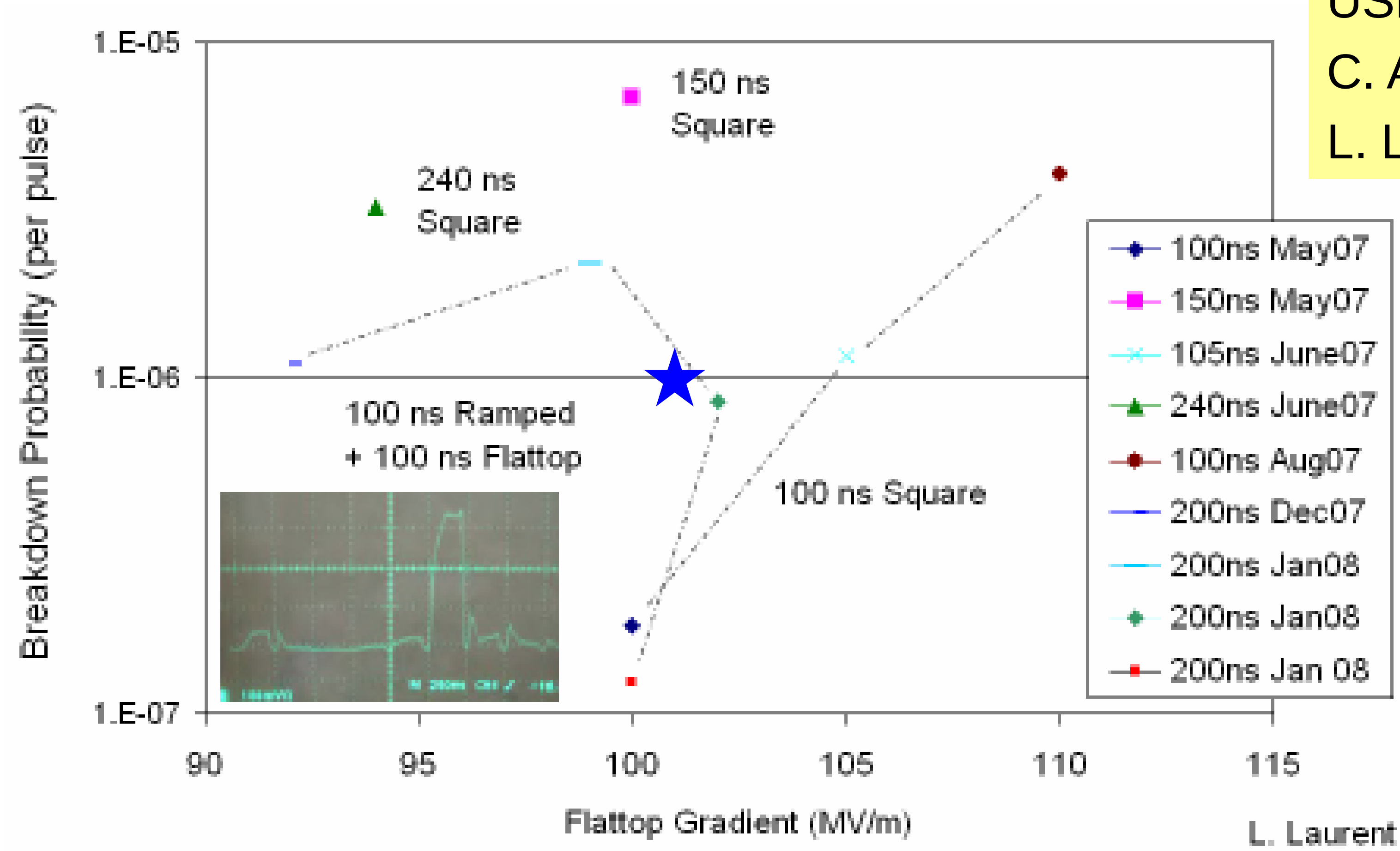
$$\Delta T_{FN}(t) \sim \int_0^t \frac{P_{FN}(t')}{(t-t')^{2/3}} dt'$$

Simulation of T53vg3MC experiment



Short Pulse Operation of T53VG3MC

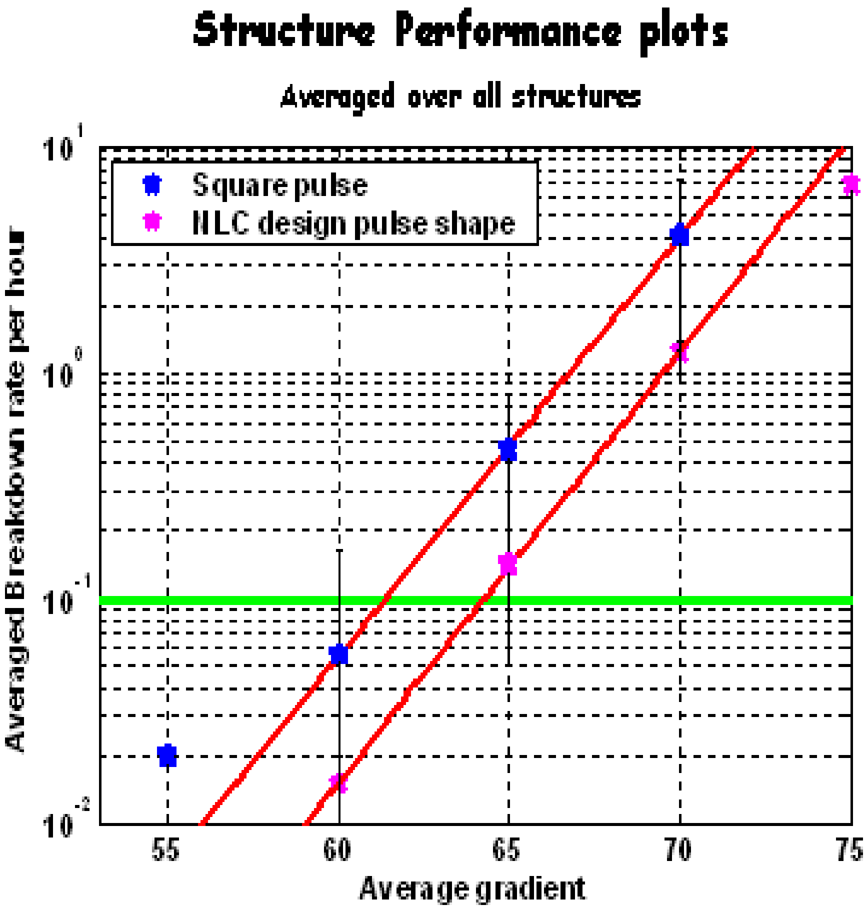
USHG-2008:
C. Adolphsen
L. Laurent

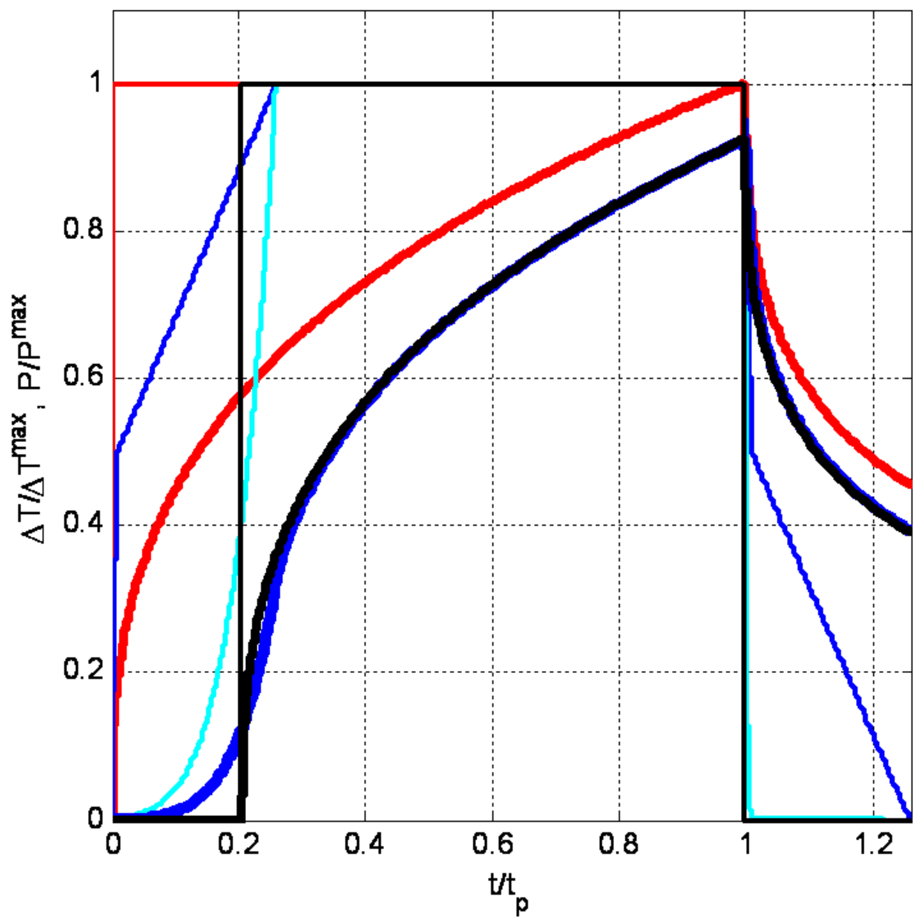


NLC structure

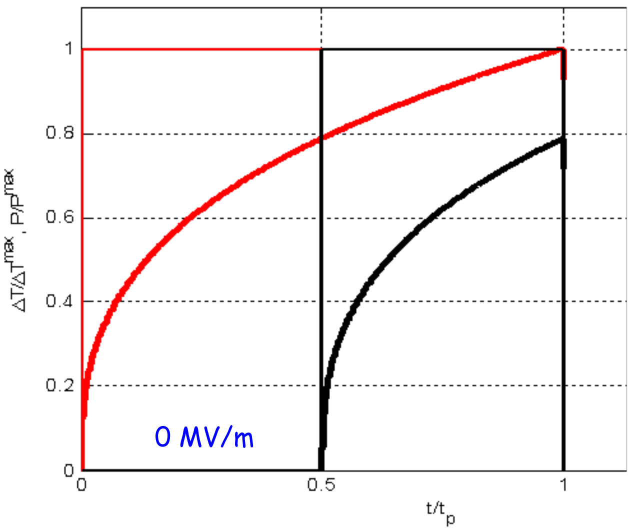
Rect-pulse => NLC-pulse
65 MV/m => 67.5 MV/m

Assuming: $E_a * t_p^{1/6}$ = const
400ns => 320ns

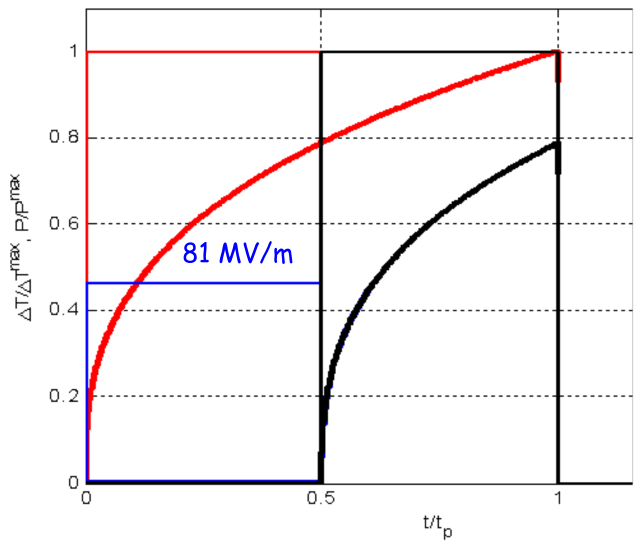




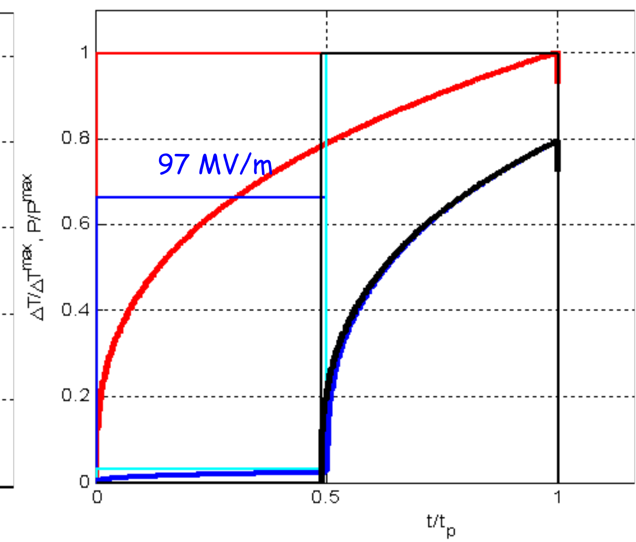
Staircase pulse shape



0 %

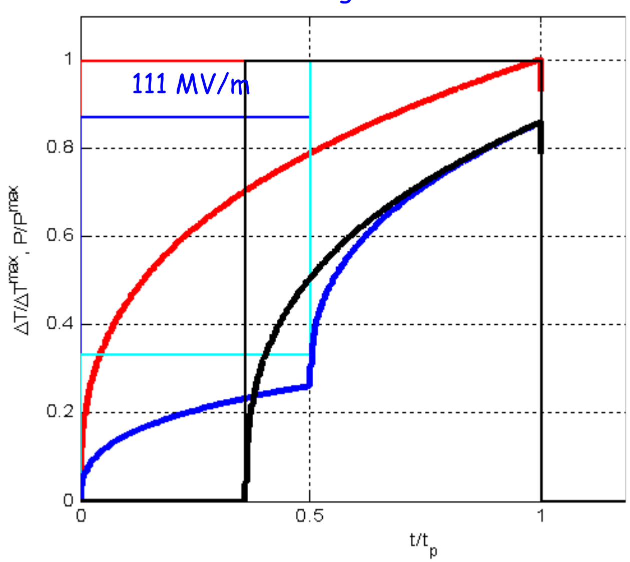


68 % in gradient

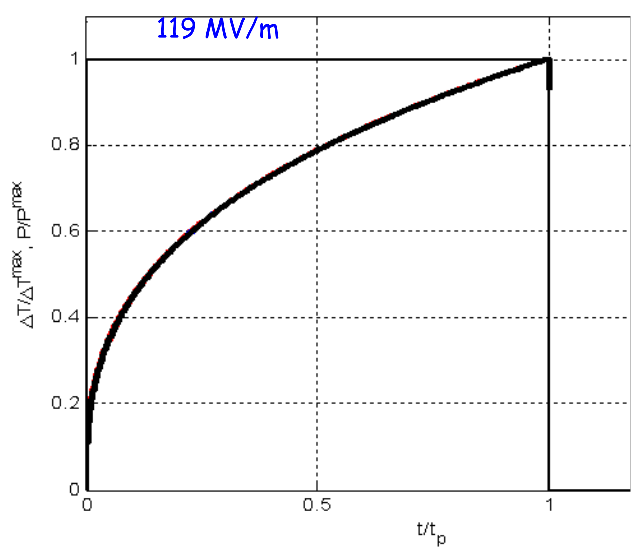


82 % in gradient

- *No influence on BDR for gradients below 80%*
- *Strong influence on the BDR for gradients above 90%*
- *Very good agreement with SLAC data*



93 % in gradient

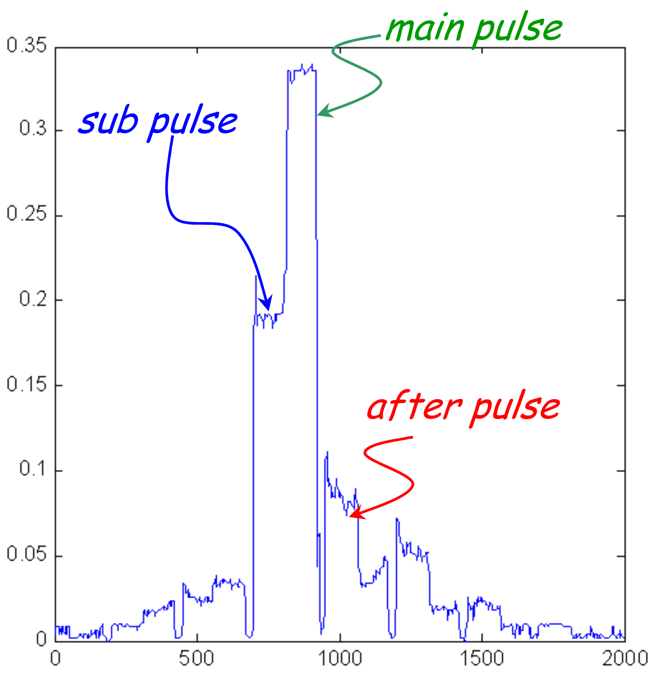


100 %

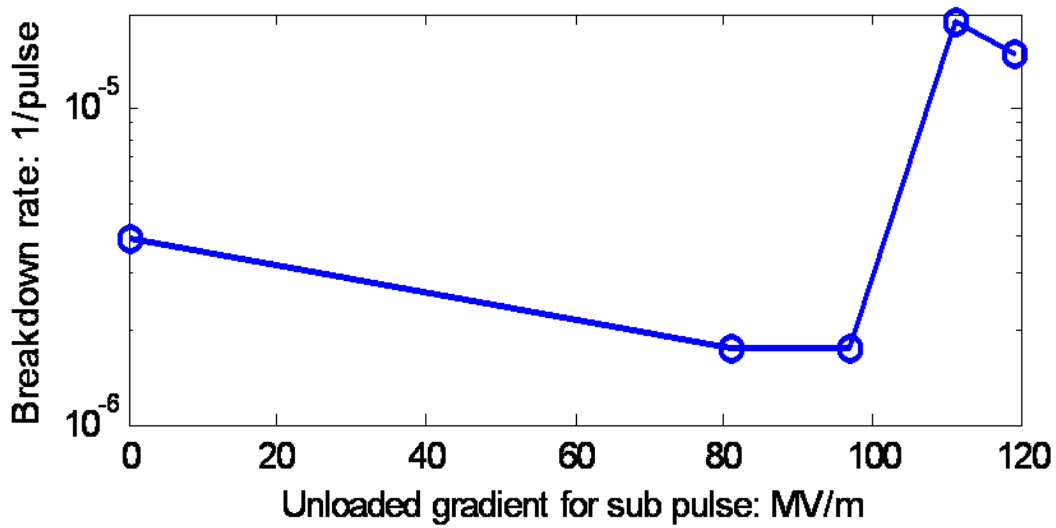
Staircase pulse shape experiment

Sub pulse width and average unloaded gradient	Main pulse width and average unloaded gradient	Time: hr	BKD Events	BKD Rate (1/pulse)
No sub pulse	100ns@119MV/m (*150MV/m)	19	16	3.9e-6
100ns@81MV/m	100ns@119MV/m (*150MV/m)	16	6	1.74e-6
100ns@97MV/m	100ns@119MV/m (*150MV/m)	21	8	1.76e-6
100ns@111MV/m	100ns@119MV/m (*150MV/m)	20	81	1.88e-5
100ns@119MV/m	100ns@119MV/m (*150MV/m)	21	68	1.5e-5

*:Max gradient in the structure

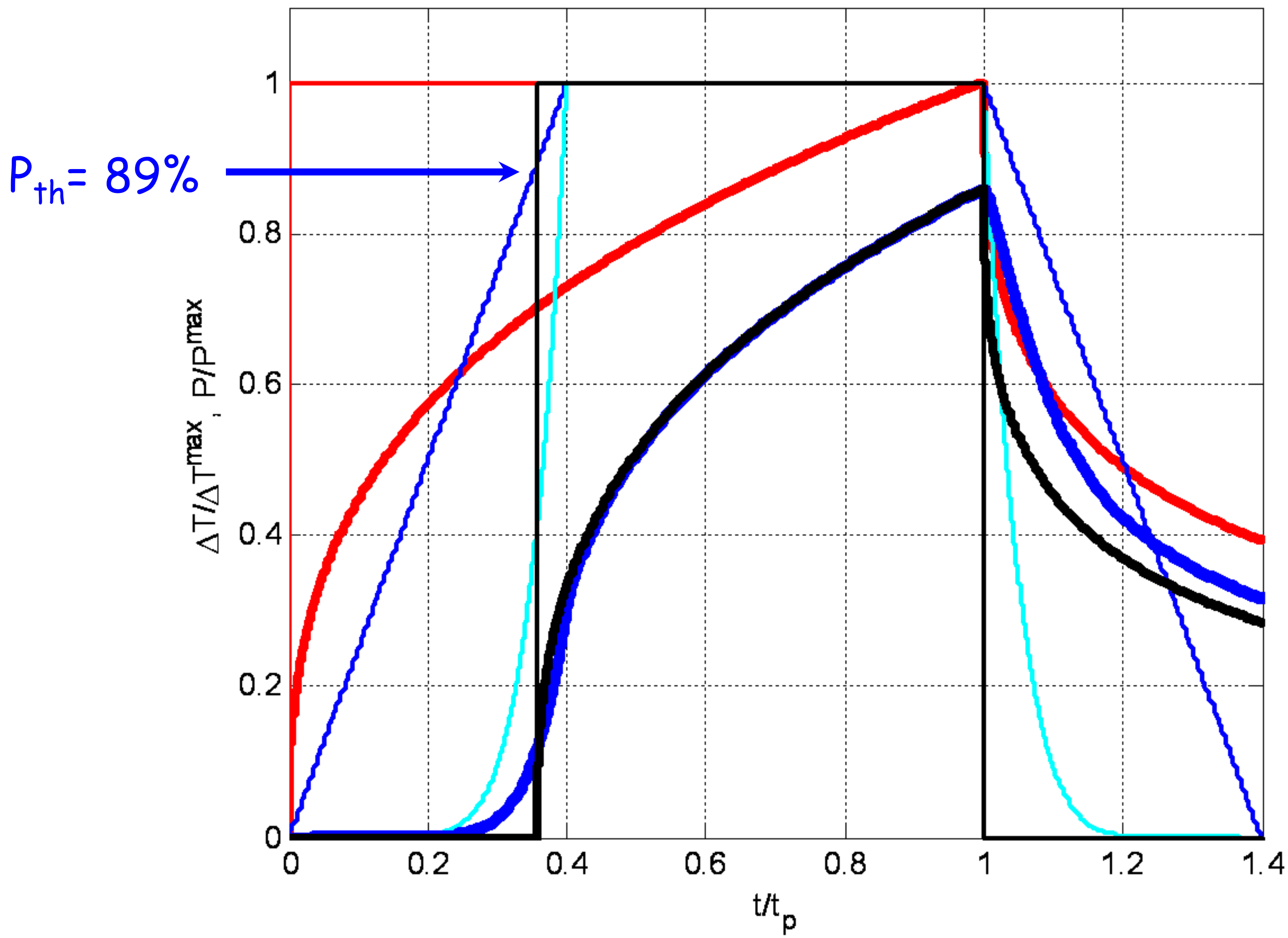


SLED output pulse



Chris, Faya

CLIC pulse shape



Conclusions

- A theoretical model based on the pulsed heating of field emission sites has been proposed to determine the threshold power level.
- It is found that
  - P_{th} varies from 83 to 89 % depending on the local electric field βE_0 , from 10 to 5 GV/m, respectively.
  - P_{th} is weakly dependent on the pulse shape (in the range of reasonable pulse shapes which can be used for acceleration)
  - It is also found that the time when power decreases from flat-top value down to threshold value does not contribute to the effective pulse length
- Modified model for effective pulse length definition is proposed. To take the flat-top time t_b plus the time when the power exceeds 85% of the flat-top level only during ramping up.
- The model predictions agree well with available experimental results on pulse shape dependence of the breakdown rate.