R&D of scCVD Diamond Beam Loss Monitors for the LHC

- H. Jansen [1], D. Dobos [1], H. Pernegger [1], N. Wermes [2], V. Eremin [3]

[1] CERN
[2] University of Bonn
[3] Ioffe Physical-Technical Institute

Outline

- Idea and motivation
  for cryogenic diamond Beam Loss Monitors (BLMs) for the LHC

- Details of measuring set-up
  for diamond characterization via TCT

- The Plasma Effect
  for heavy ionizing particles in scCVD diamonds

- Raw measurements and derived charge-carrier properties
  for scCVD diamonds

- Conclusion

Idea and Motivation

- Place BLMs as close to the beam as possible
  → Detector operation at 1.9 K, within the cold mass

- Choose detector material
  → Candidates are: CVD diamond,
  silicon, liquid He

- Diamonds not tested yet at
  ultra-cold temperatures
  → Interesting!

- Characterize scCVD diamonds at cryogenic temperatures
  with gaseous He cooling
  → Start at RT, decrease stepwise down to 67 K
  with liquid He cooling
  → Start at 1.9 K, increase slowly to 60 K

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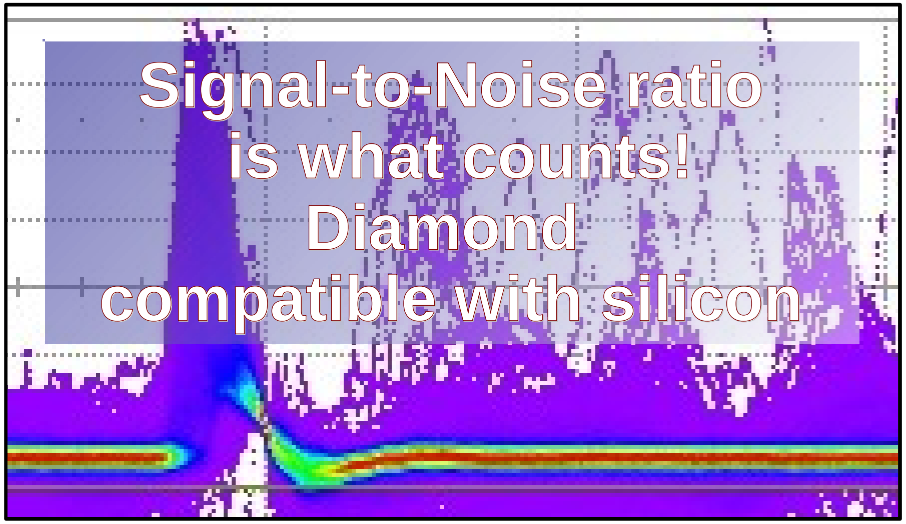
DONE!

First test
this week!

Why Diamond

Pros:

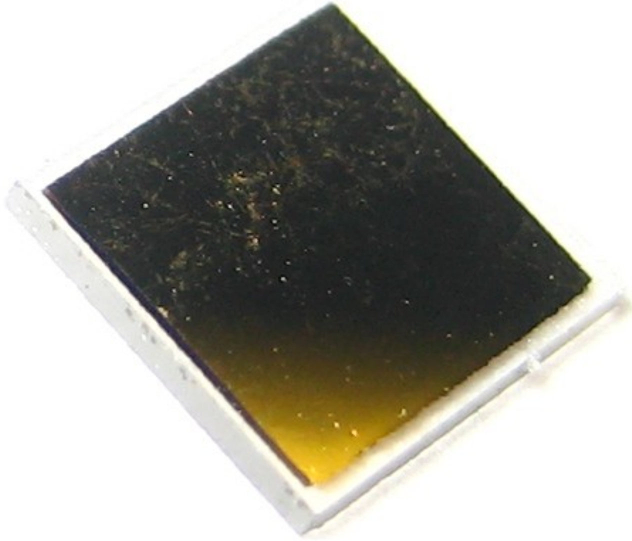
- High band gap (5.5 eV)
  - → Very high breakdown field > 1e7 V/cm
  - → Very high resistivity > 1e11 Ωcm
  - → Very low leakage current ≲ 1 pA
- Low dielectric constant (5.7)
  - → Low capacitance
    - → Low noise
- High displacement energy (43 eV/atom)
  - → Radiation hard



Signal-to-Noise ratio is what counts!
Diamond compatible with silicon

Cons:

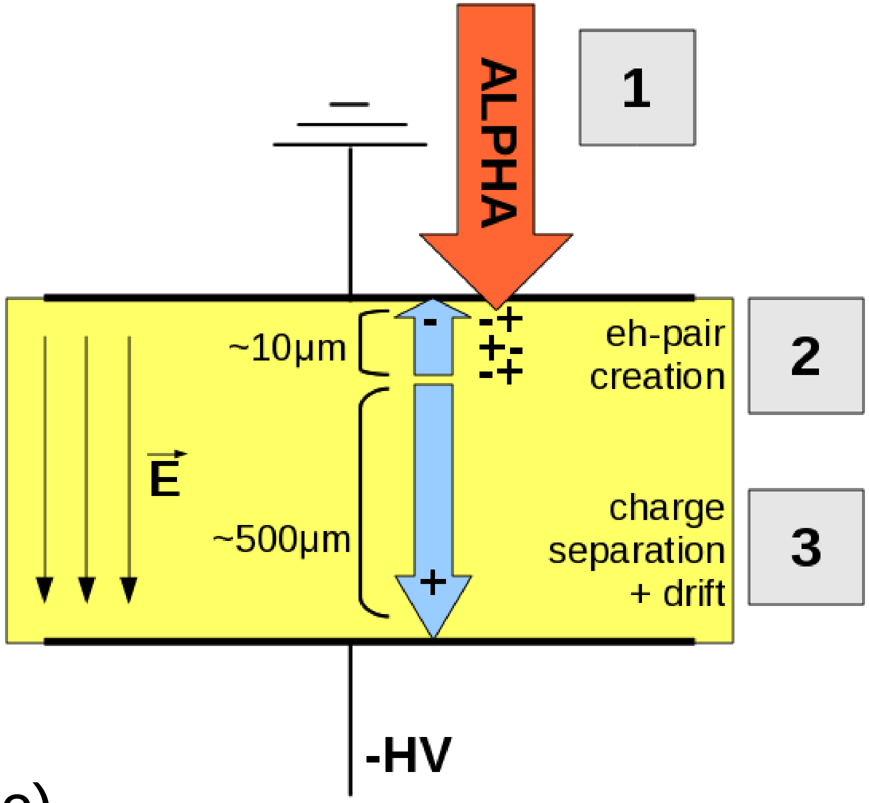
- High pair creation energy (13.5 eV)
  - → Less signal (but less noise!)



Details of Measuring Set-up

- The Transient-Current Technique (TCT) measurement:

→ measure the transient current
1) α particles impinge on top side
2) Create eh-pairs close to electrode
3) Electric field separates charges
4) Drifting charges induce current



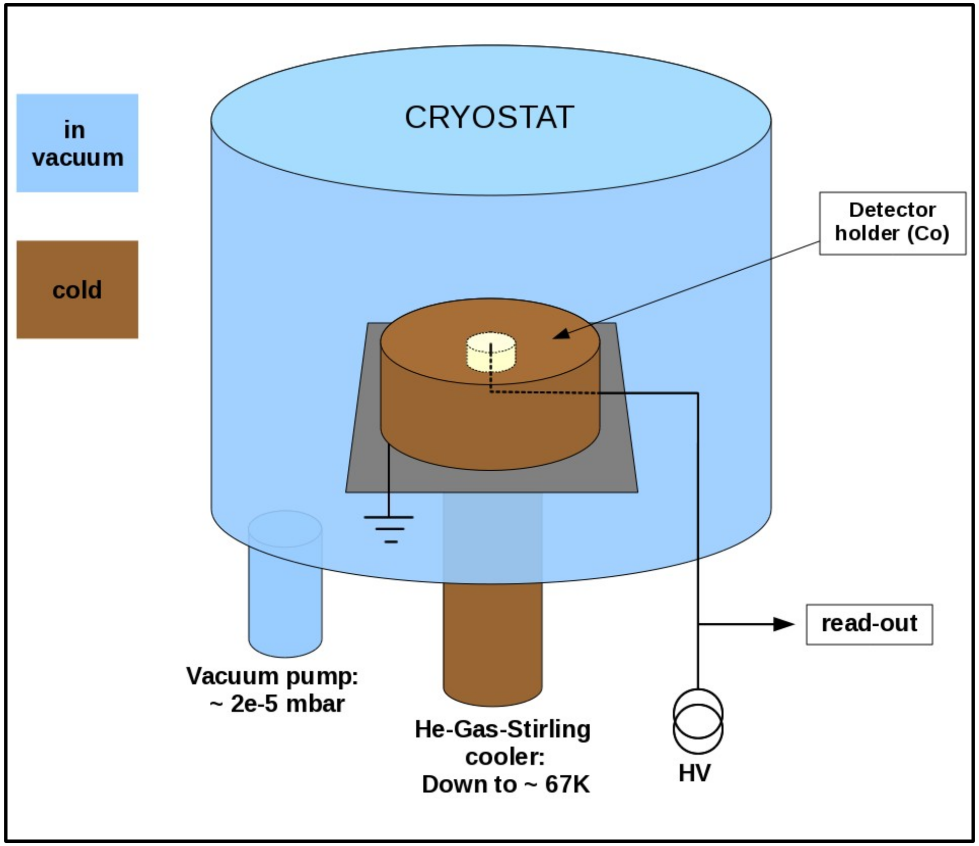
→ Pos. (neg.) bias → Measure e^{-} (h^{+})

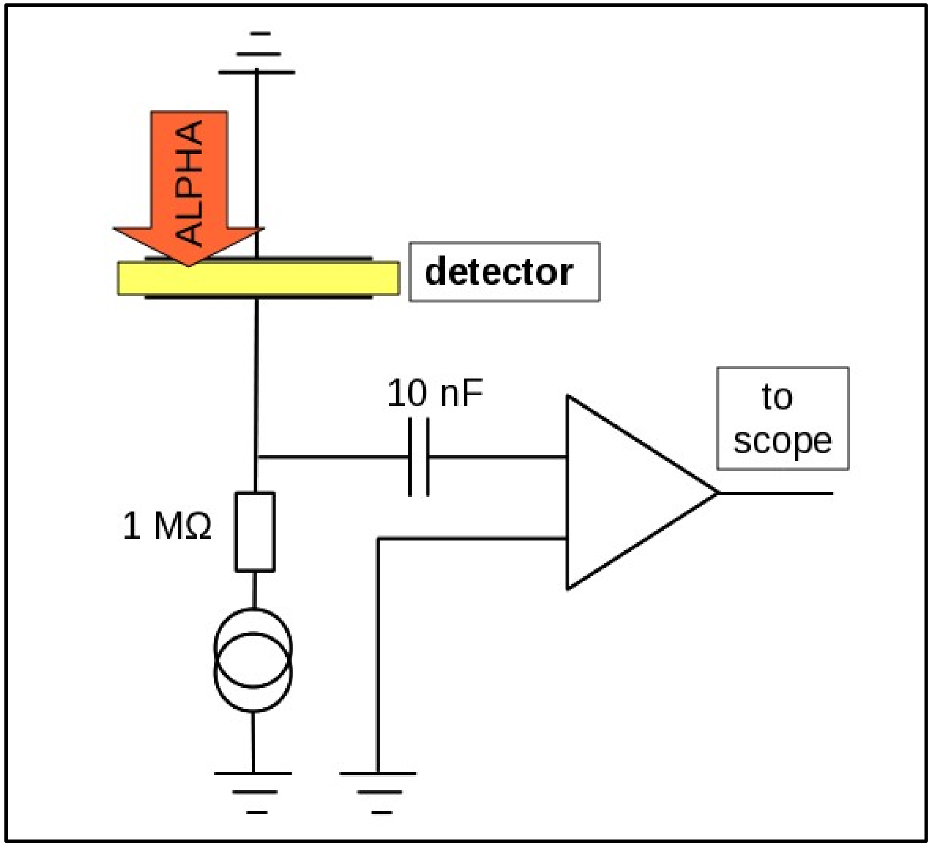
→ Use ultra-fast 2 GHz, 40 dB,
200 ps rise time current amplifier (cividec)

→ Use broad-band 3 GHz scope (LeCroy)

→ Use RF components

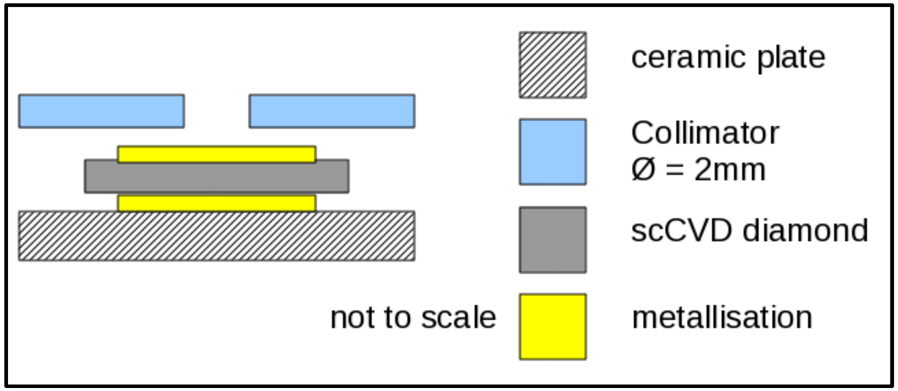
Details of Measuring Set-up



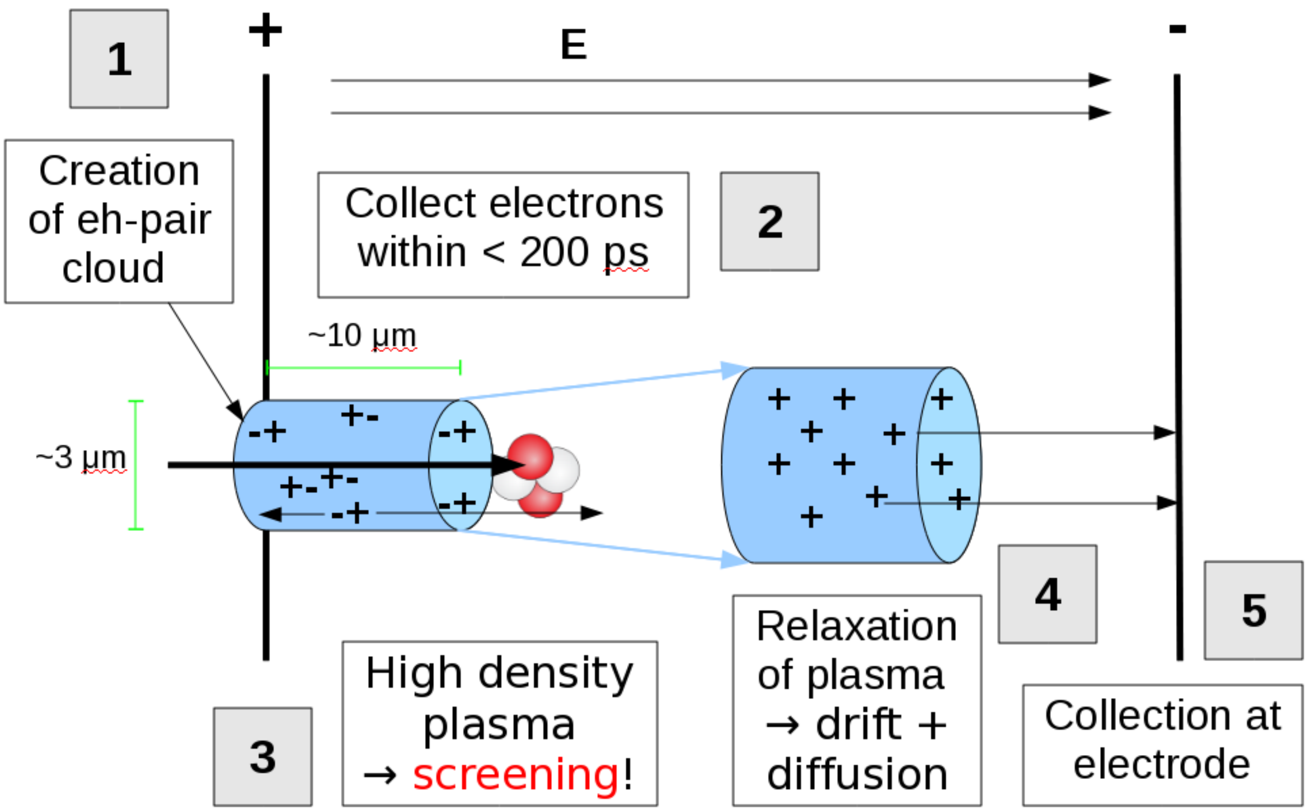


- **SETTINGS:**

→ TCT in vacuum
→ Temp: 67 K - 300 K, bias ≤ 600 V
→ Read-out from HV-side
→ Use collimator (avoid edge-effects)



TCT and the Plasma Effect



Creation of eh-pair cloud

Collect electrons within < 200 ps

High density plasma → screening!

Relaxation of plasma → drift + diffusion

Collection at electrode

From Ramo-Theorem:

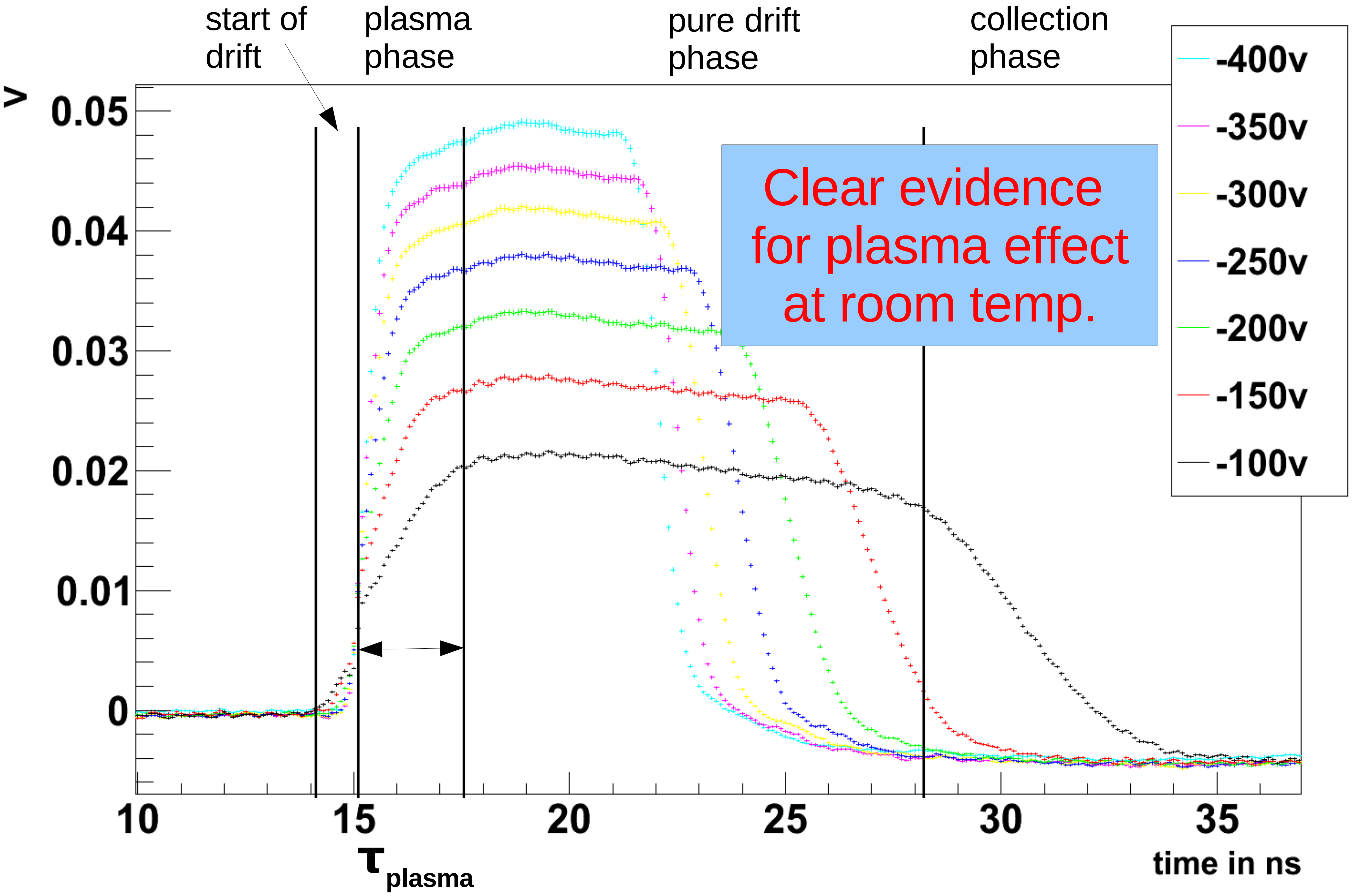
$$i(t) = \sum_k i_k(t) = \sum_k e\, E_w\, v_k(t) = \frac{e}{d} \sum_k v_k(t - t_k^{start});$$

$$v_k(t) = 0 \quad for \quad t < 0$$

- **FACTS:**
  - → αs produce high density charge cloud
  - → Outer charges screen inner ones
    - → E-Field decreases inside the plasma
  - → Increased E-Field decreases lifetime of plasma

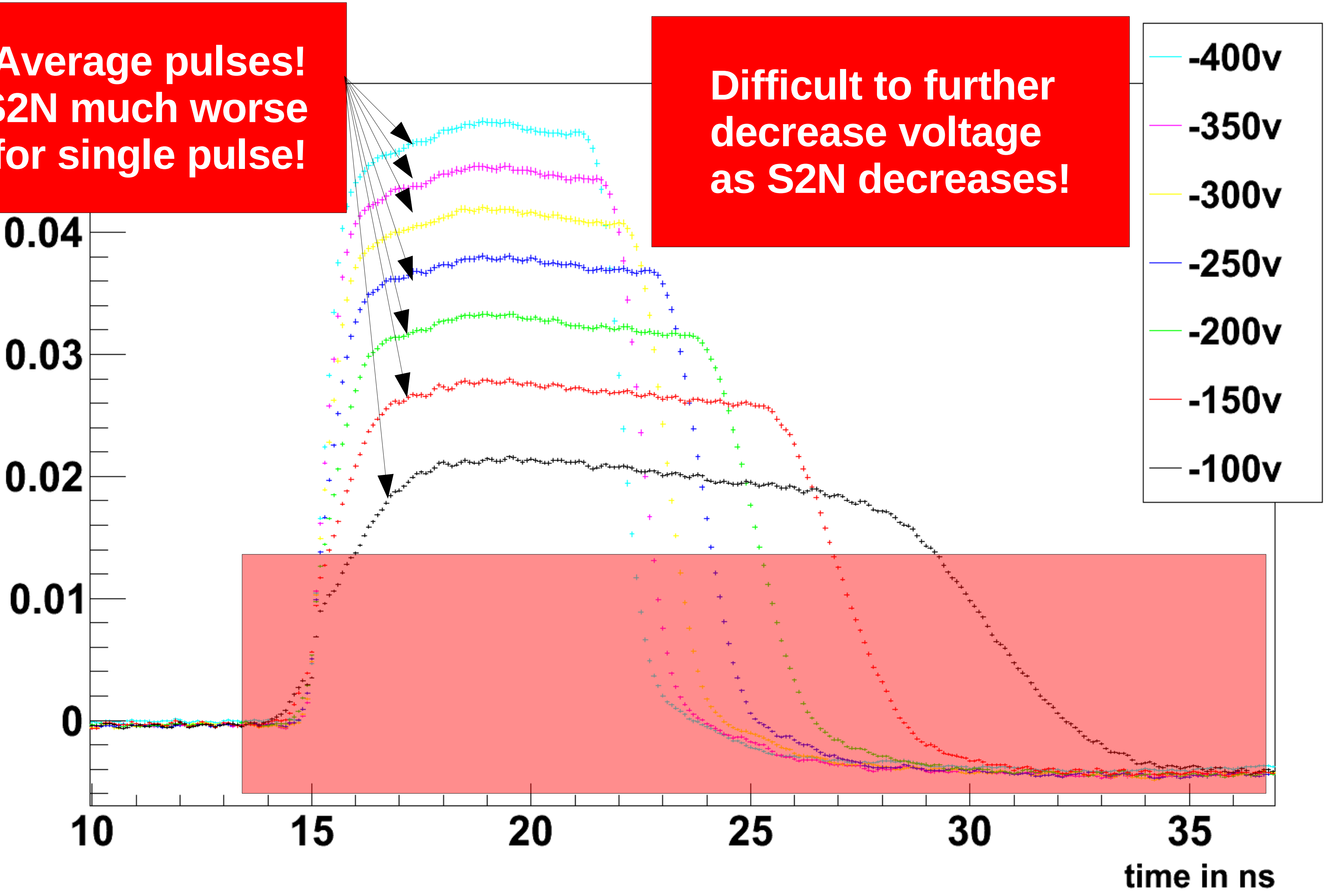
$$\rho_{cloud} \approx \frac{3 \cdot 10^5\, pairs}{(3\,\mu m)^2 \pi\, 10\,\mu m} \approx 10^{15}\, cm^{-3}$$

Plasma Effect at 295 K



Clear evidence for plasma effect at room temp.

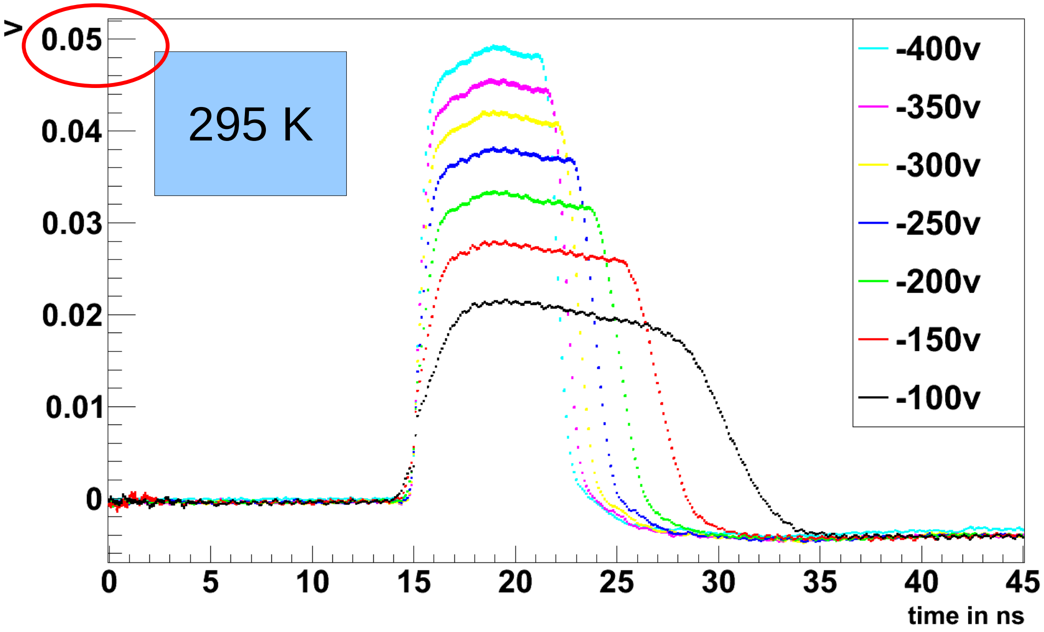
Difficulties

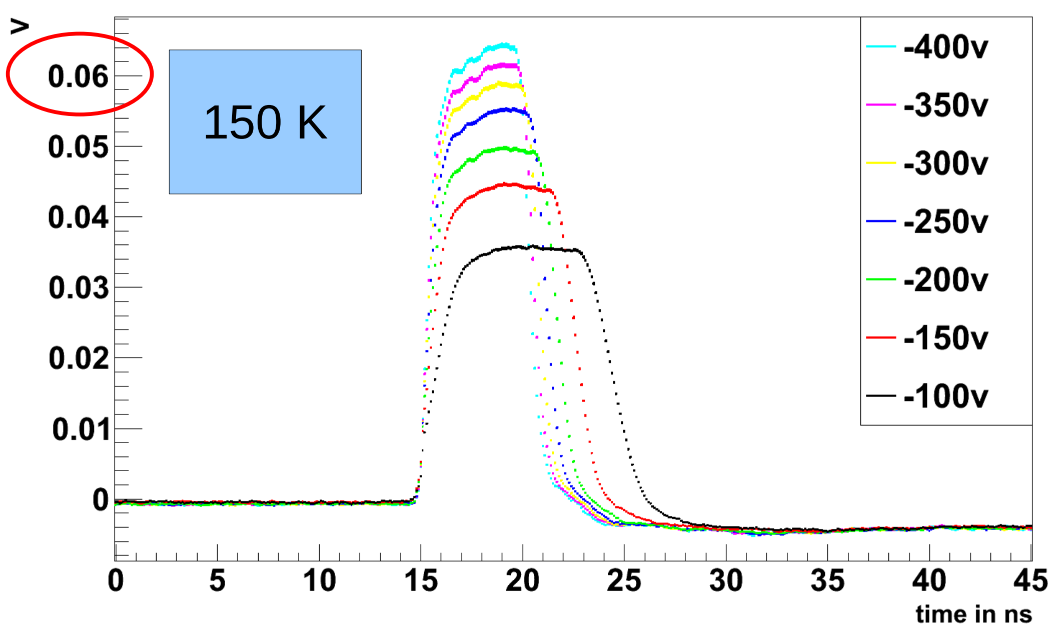


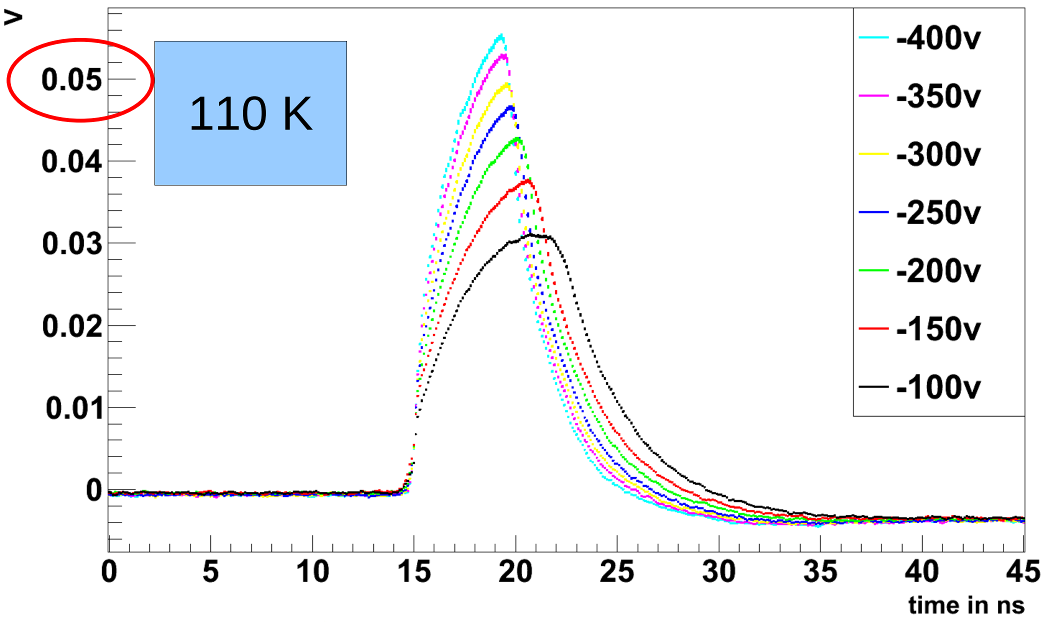
Average pulses!
S2N much worse for single pulse!

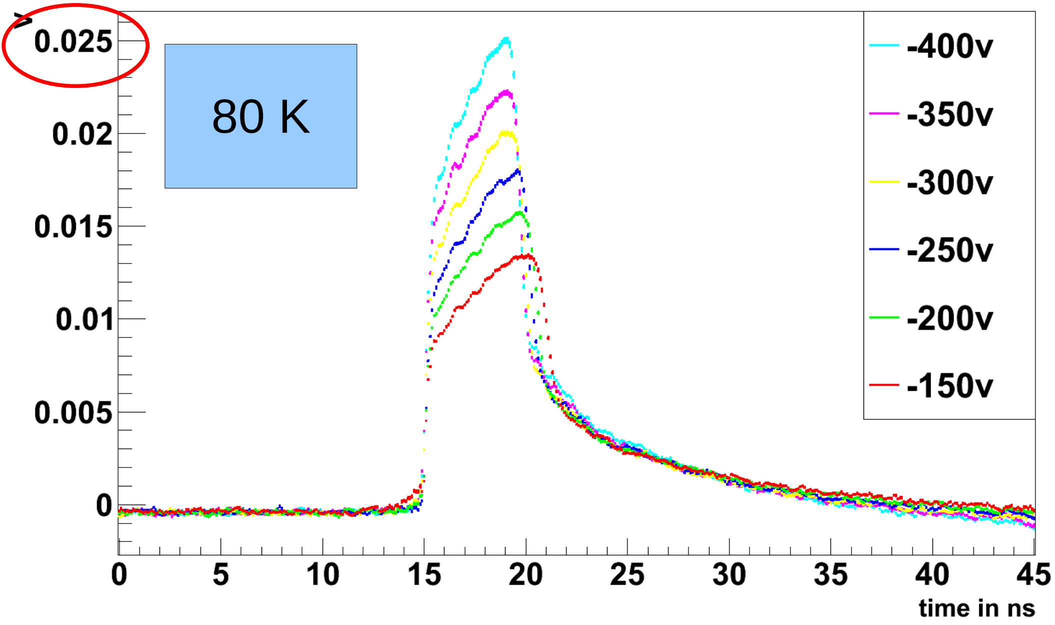
Difficult to further decrease voltage as S2N decreases!

TCT Hole Pulses

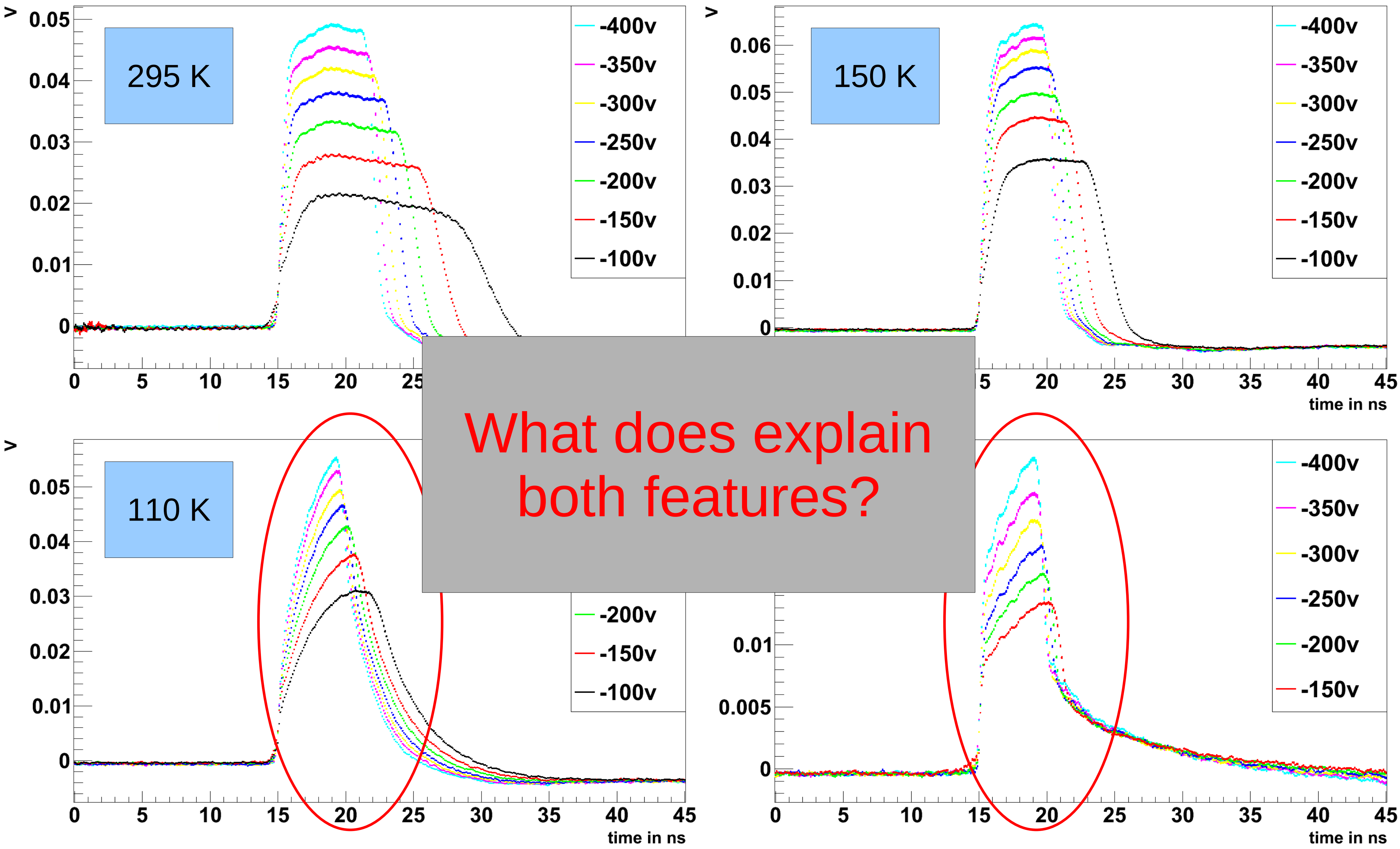






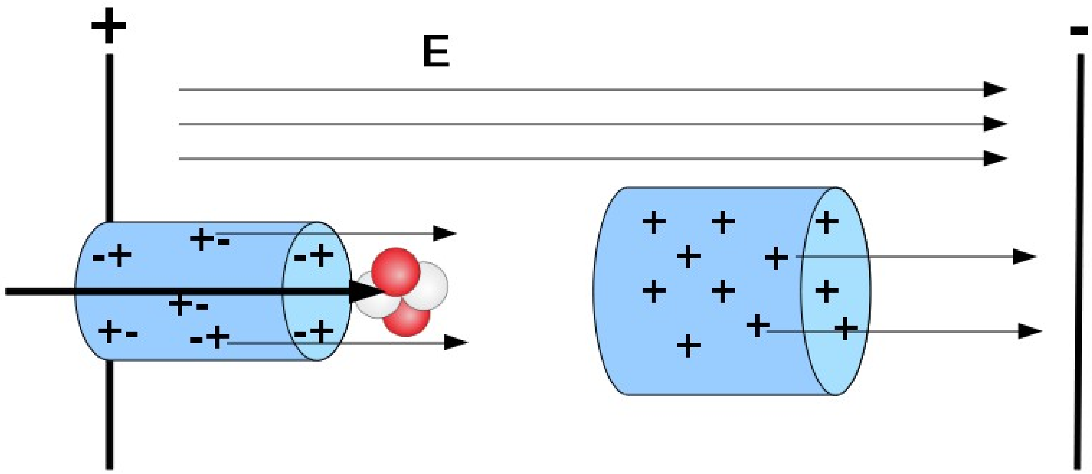


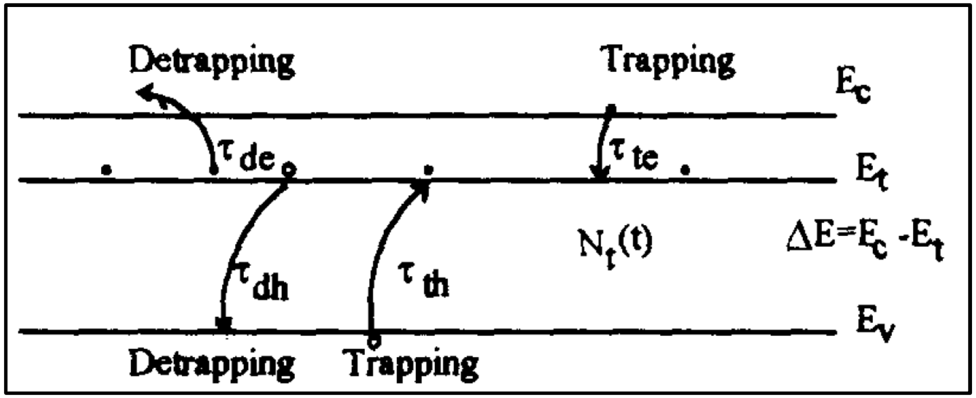
TCT Hole Pulses



What does explain both features?

Trapping in Plasma





Below ~150 K:

- Field-free region within plasma cloud → immediate trapping and increased recombination
- Detrapping if E_{trap} / kT large enough
- Distinguish 2 types of trapping!

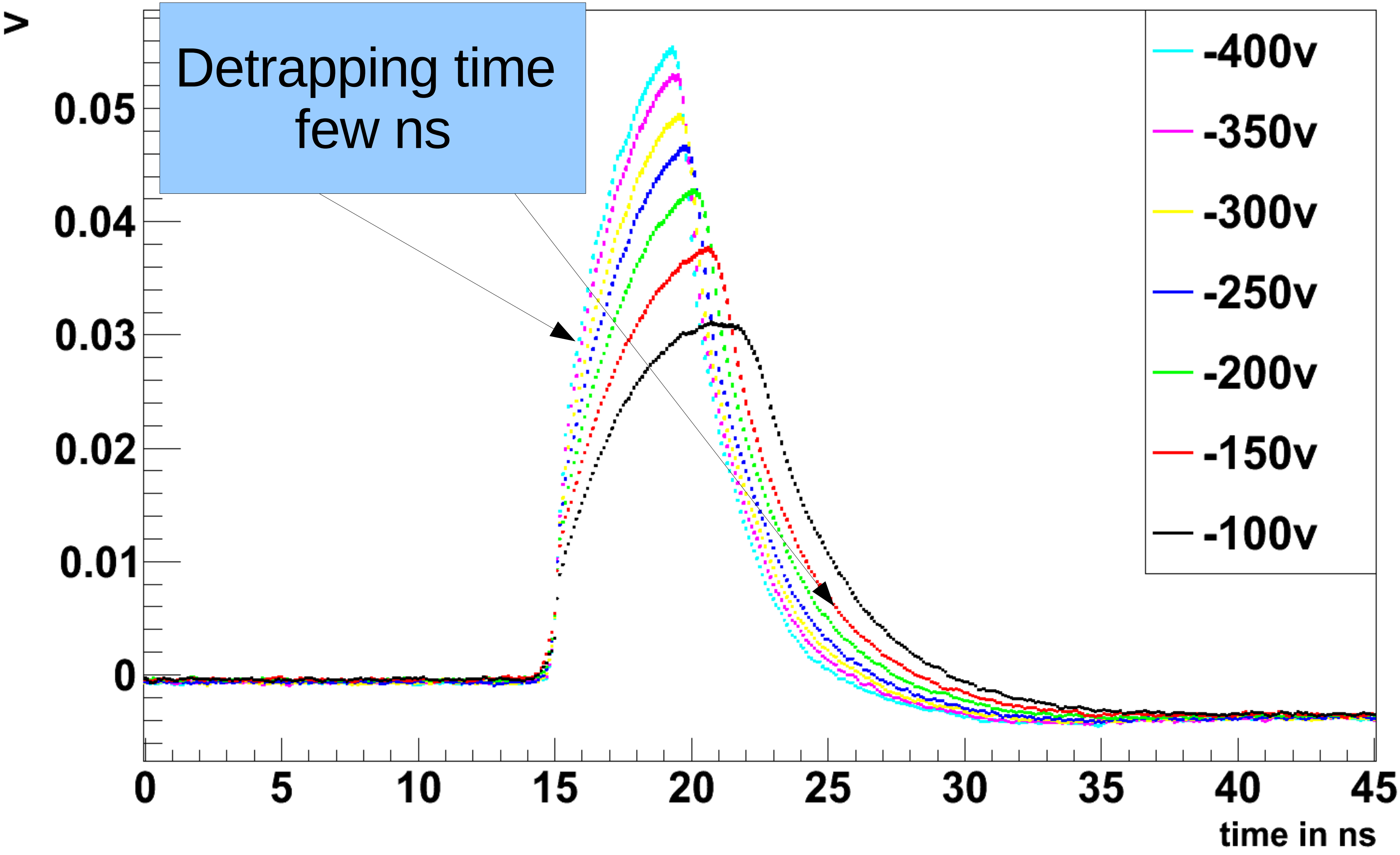
$$\tau_{trap}^{plasma} \ll \tau_{trap}^{drift}$$

From Ramo-Theorem:

$$i_{(t)} = i_{not-trapped}(t) + i_{released}(t)$$
$$= \frac{e}{d} \sum_{i,\,not-trapped} v_i(t - t_i^{start})$$
$$+ \frac{e}{d} \sum_{i,\,released} v_i(t - t_i^{detrap});$$

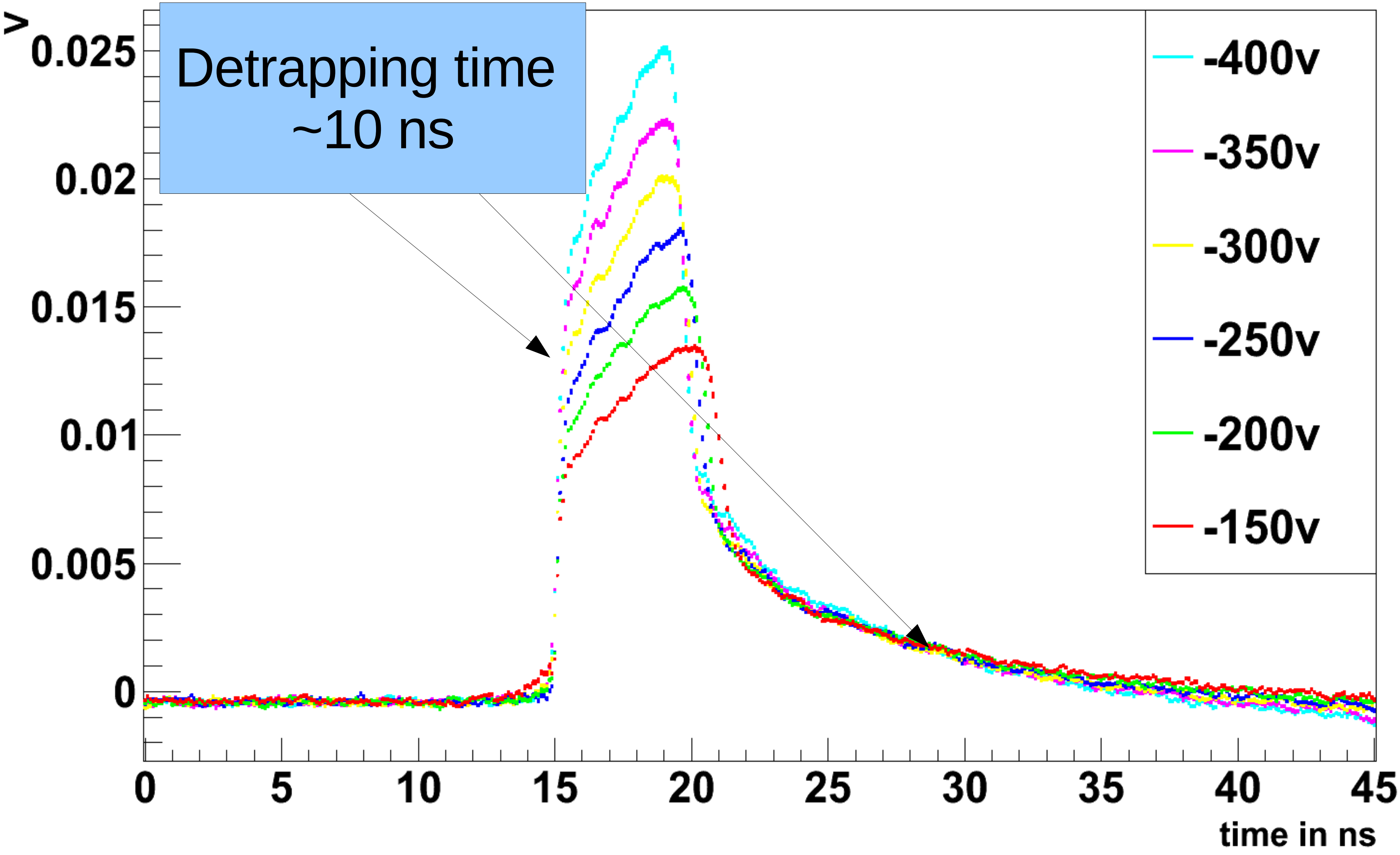
$$Q_{released}(t) = Q_{trapped}(1 - \exp(-t/\tau_{detrap}));$$

Trapping/Detrapping at 110 K



Detrapping time few ns

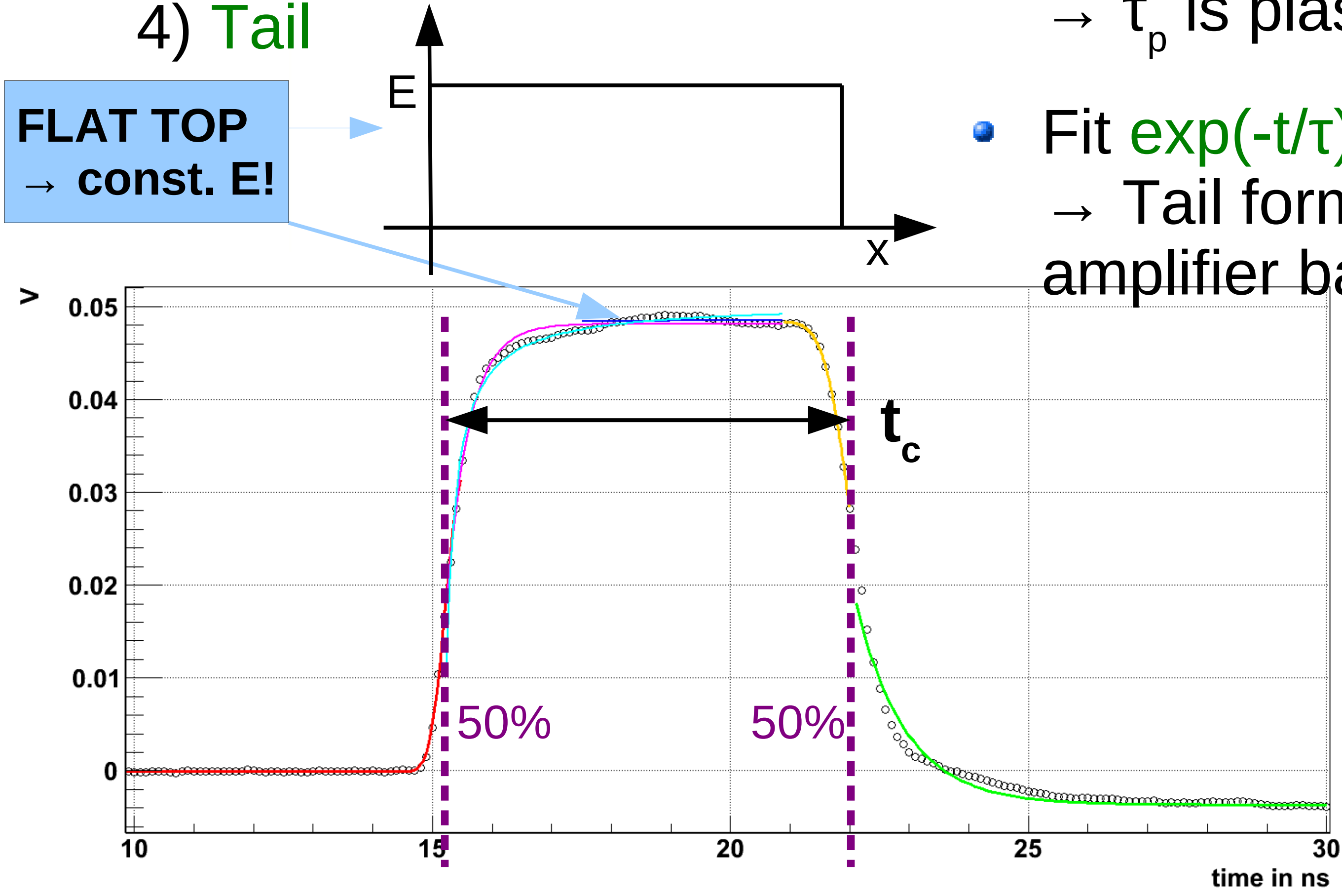
Trapping/Detrapping at 80 K


Detrapping time ~10 ns

Analysis of TCT Pulses

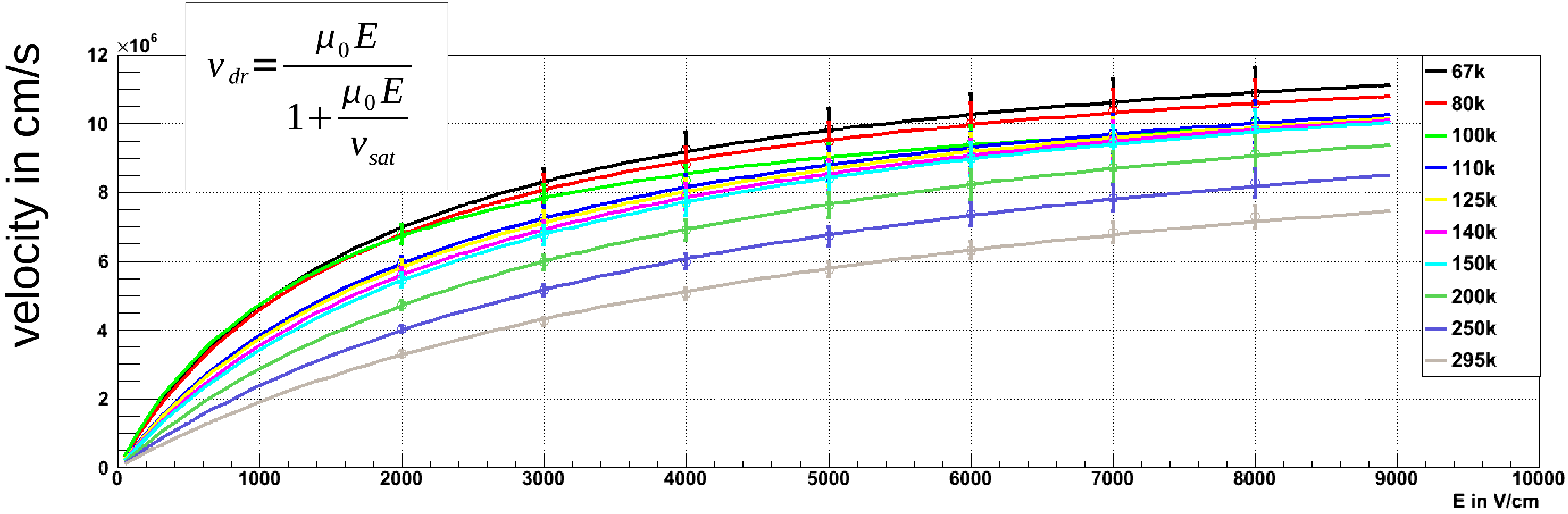
- Four phases:

  1) Start of drift
  2) Current saturation
  3) Collection at electrode
  4) Tail


FLAT TOP
→ const. E!

- Fit Erfc(t) to rising/falling edge:
  → 50% levels mark start/end time
  → Derive drift mobility and velocity
- Fit $1-\exp(-t/\tau_p)$ to saturation:
  → τ_p is plasma lifetime
- Fit $\exp(-t/\tau)$ to tail:
  → Tail formed by cable effects, amplifier bandwidth limits, diffusion

Hole Mobility and Velocity



$$v_{dr}=\frac{\mu_0 E}{1+\frac{\mu_0 E}{v_{sat}}}$$

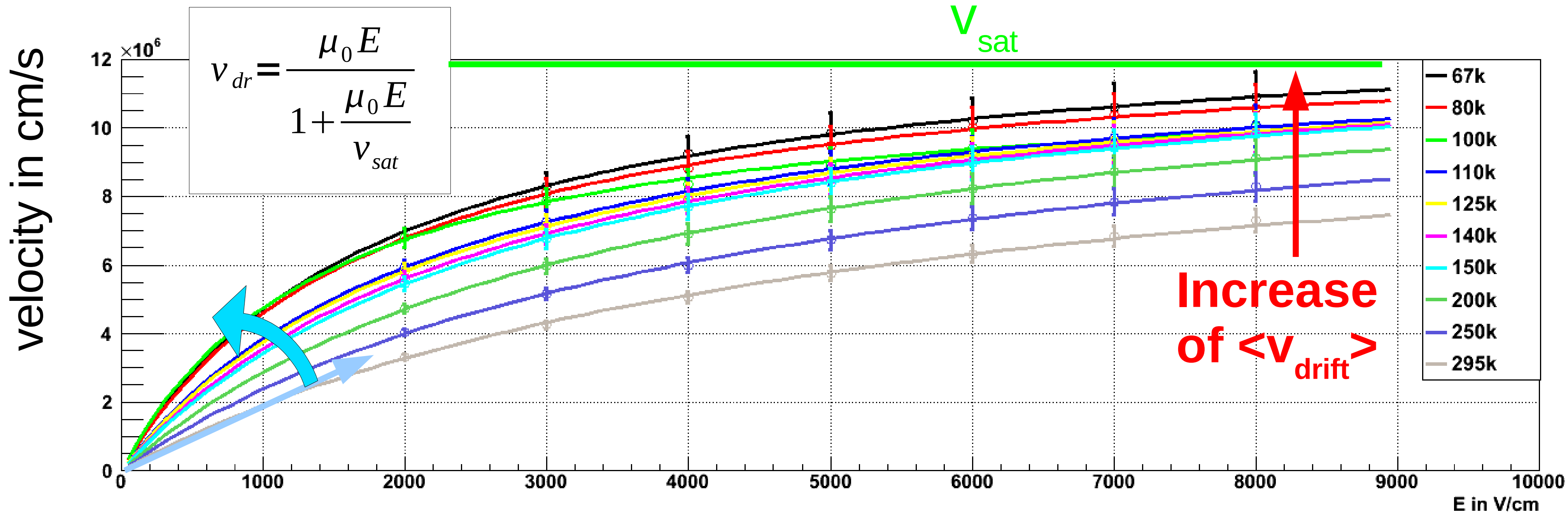
Fits yield:

$$\mu_{0,h}^{295\,K}=2278\pm110\,cm^2/Vs \qquad \mu_{0,h}^{67\,K}=7300\pm1850\,cm^2/Vs$$

$$v_{sat}^{295\,K}=11.8\cdot10^6\pm0.8\cdot10^6\,cm/s \qquad v_{sat}^{67\,K}=13.4\cdot10^6\pm1.4\cdot10^6\,cm/s$$

- Mobility μ_h and avg. drift velocity $<v_{drift}>$ at RT as expected
- μ_h increases down to 67 K (→ $<v_{drift}>$ increases as well)
  → no onset of impurity scattering
- v_{sat} ~ constant with temperature

Hole Mobility and Velocity



$$v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_{sat}}}$$

Fits yield:

$$\mu_{0,h}^{295\,K} = 2278 \pm 110\, cm^2/Vs \qquad \mu_{0,h}^{67\,K} = 7300 \pm 1850\, cm^2/Vs$$

$$v_{sat}^{295\,K} = 11.8 \cdot 10^6 \pm 0.8 \cdot 10^6\, cm/s \qquad v_{sat}^{67\,K} = 13.4 \cdot 10^6 \pm 1.4 \cdot 10^6\, cm/s$$

- Mobility μ_h and avg. drift velocity $\langle v_{drift} \rangle$ at RT as expected
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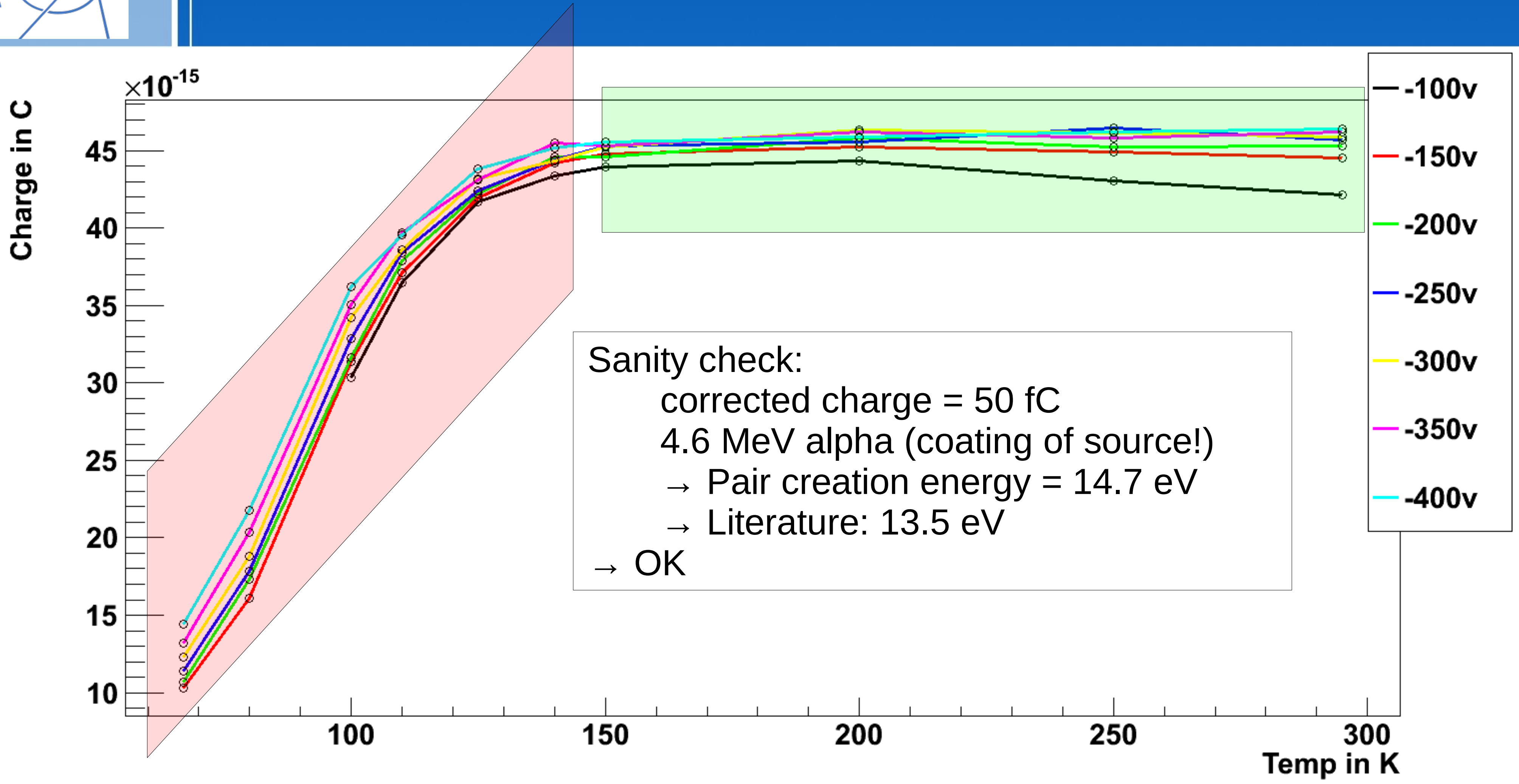
Integrated Charge



Sanity check:

corrected charge = 50 fC

4.6 MeV alpha (coating of source!)

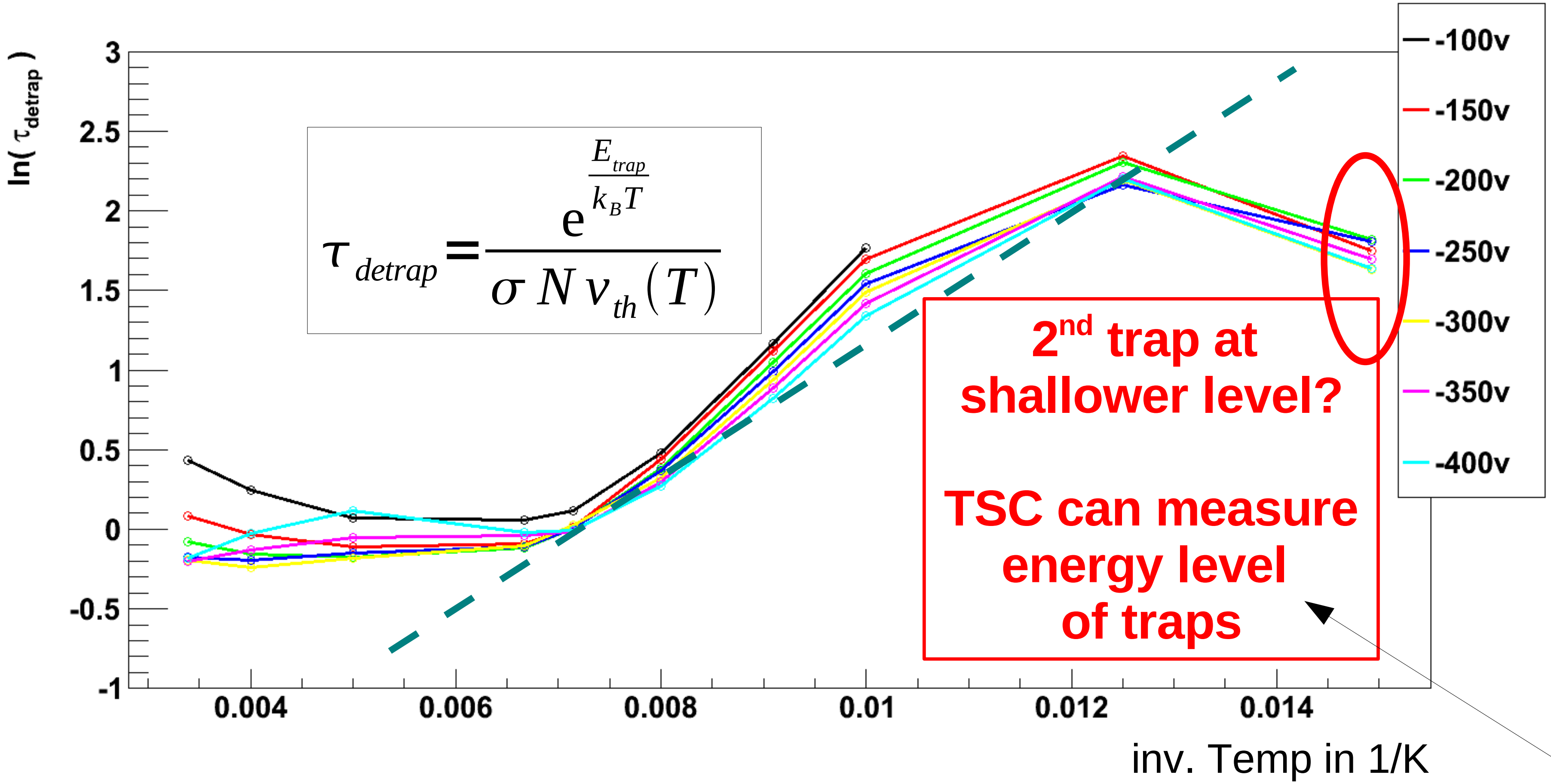
→ Pair creation energy = 14.7 eV

→ Literature: 13.5 eV

→ OK

- Charge constant in range 140 K to 300 K
- Steep drop from 140K down to 67 K
  → plasma associated trapping and recombination

Detrapping Time Constant



$$\tau_{detrap} = \frac{e^{\frac{E_{trap}}{k_B T}}}{\sigma N v_{th}(T)}$$

2nd trap at shallower level?

TSC can measure energy level of traps

- Plot ln(τ_{dt}) vs 1/T, do line fit:

$$E^{h}_{trap} \approx 40\,\mathrm{meV} \pm 10\,\mathrm{meV}$$

→ lowest shallow trap

→ investigate further energy levels of traps via Thermally Stimulated Current technique

In contact with Uni Hamburg

Conclusion

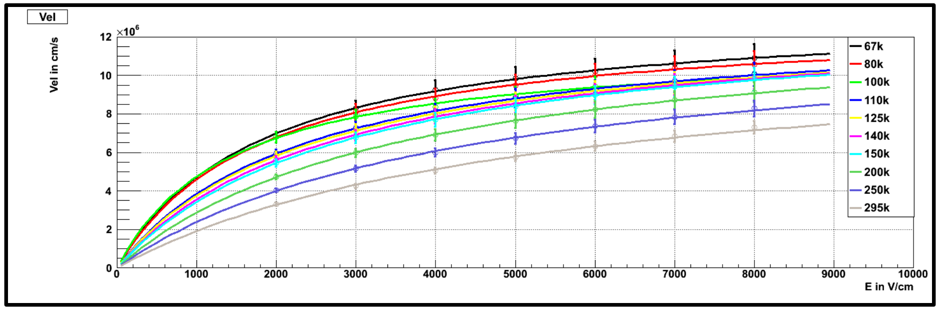
- TCT offers eminent possibility
  to characterize detectors

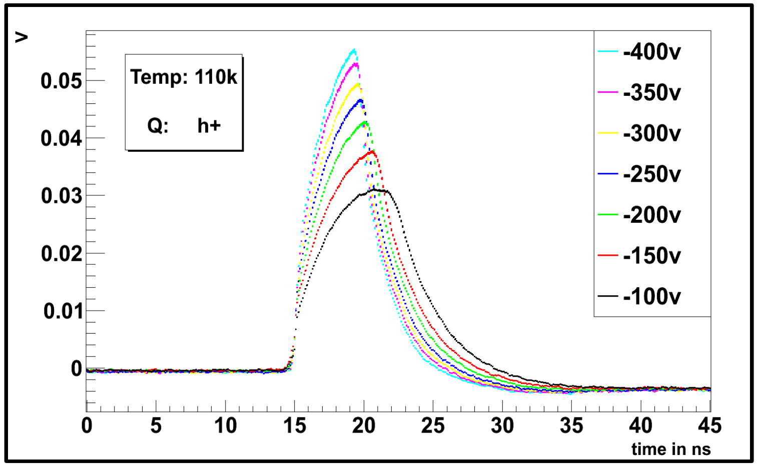
- Temperature dependence of
  - drift mobility and velocity
  - total charge
  - trapping-detrapping mechanism
  - pulse shape

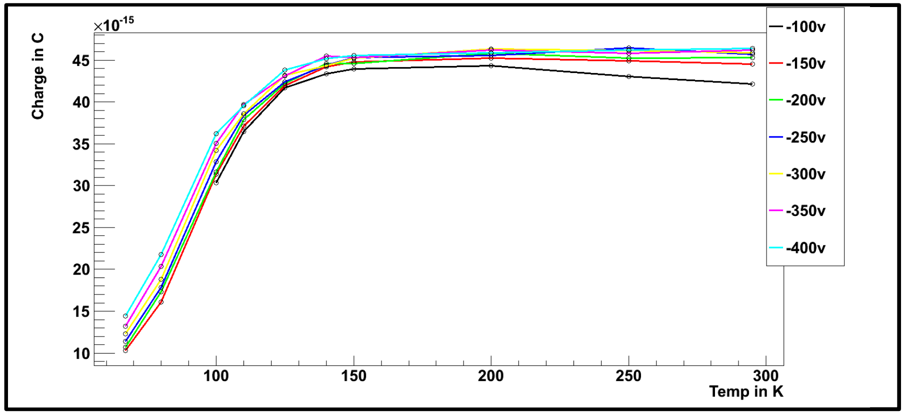
  in scCVD diamonds

- Plasma associated trapping reduces
  total charge yield at T < 150 K

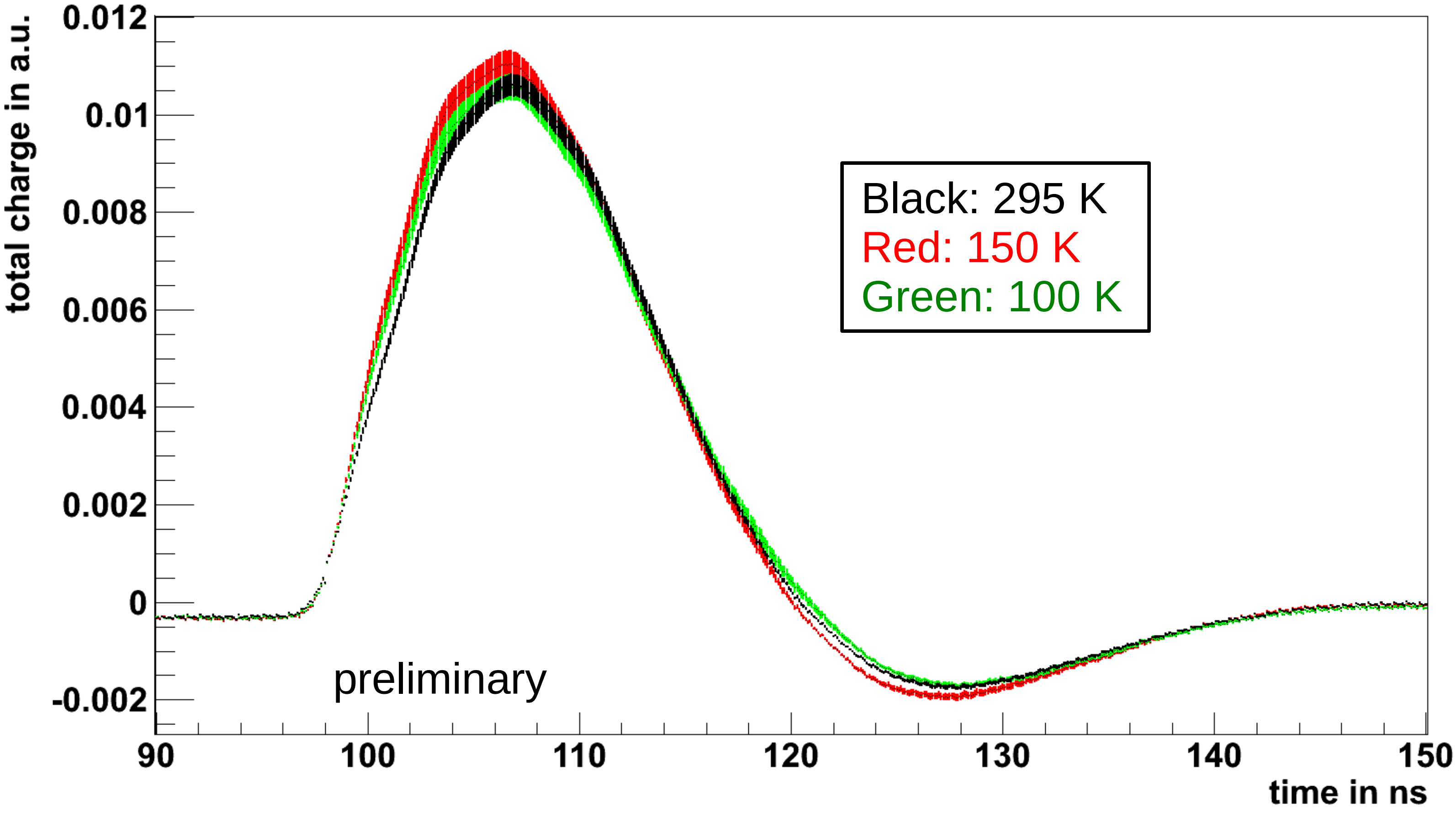
→ Q_{signal} -> 0 for T -> 1.9 K ??







Cosmic Muons in scCVD



- Use charge-sensitive amplifier here
- No sign of charge degradation (20% with αs at 100K)
- Work in progress!

Outlook

- Paper in preparation

- Simulate pulse shapes
  including plasma effect and trapping-detrapping mechanism

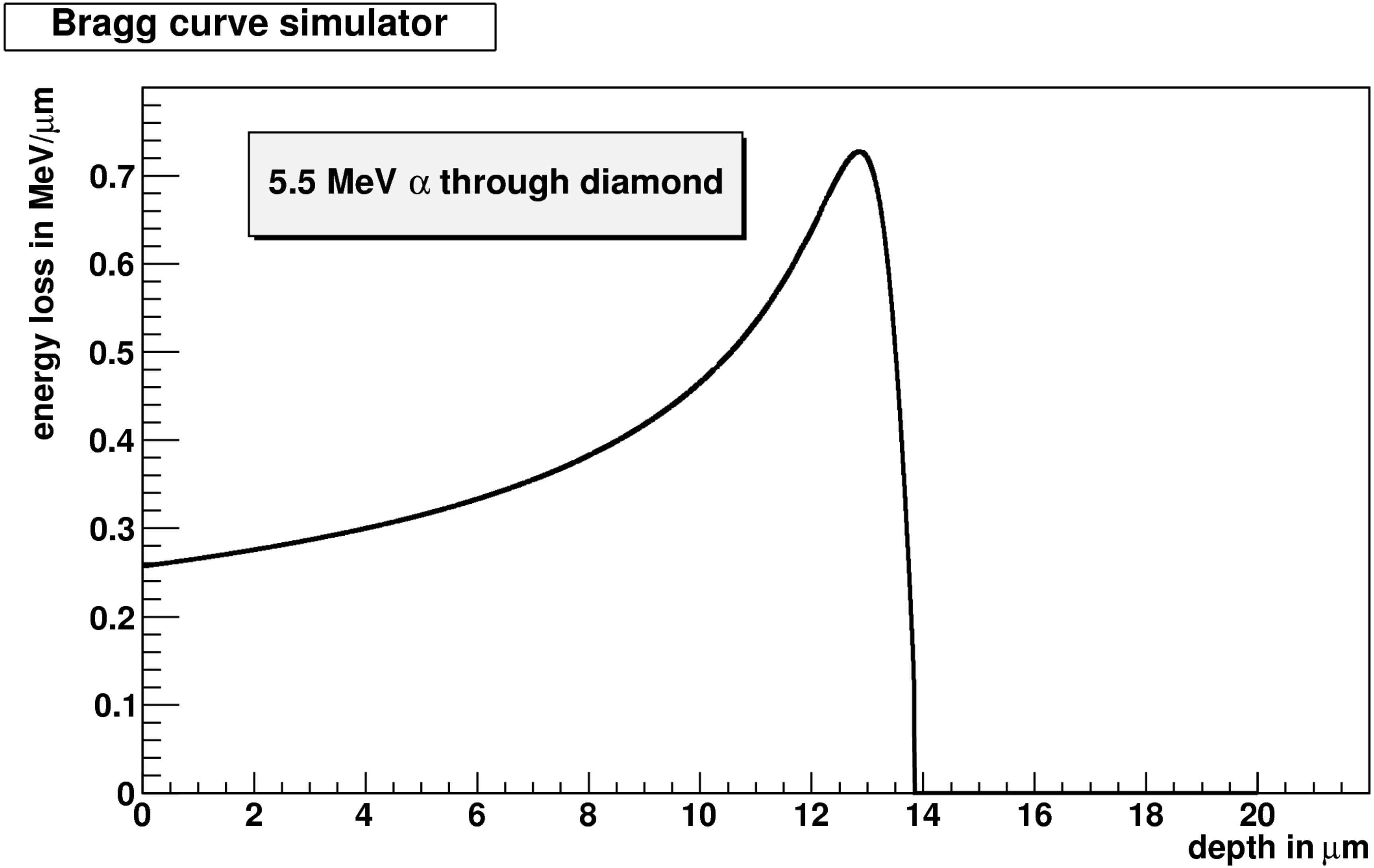
- TCT with β-source (this summer)
  → test MIP-like signal with diamond
  → density of charge cloud much smaller
    → no (little) plasma effect expected

- Beam tests at 1.9 K

- TCT with irradiated samples
  → compare scCVD diamond with Si detectors
  → expect better performance for scCVDs!

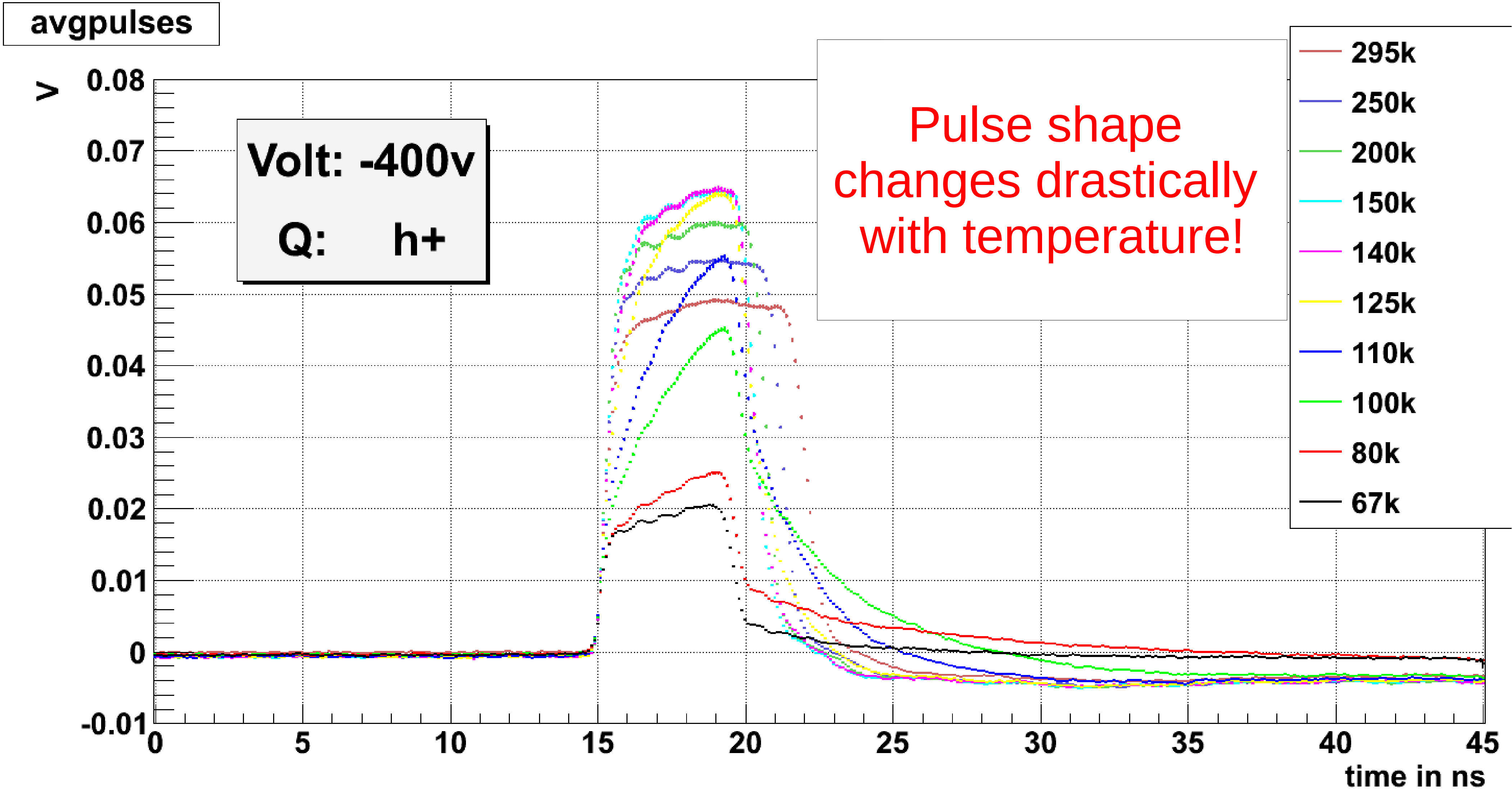
BACKUP SLIDES

Energy Loss in Diamond



http://www.nist.gov/pml/data/star/index.cfm

Pulse Shape for Constant Voltage



Pulse shape changes drastically with temperature!

Two Contributions to Signal

from Ramo-Theorem:

$$i_{(t)} = i_{non-trapped}(t) + i_{released}(t)$$

$$= \frac{e}{d} \sum_{i,not-trapped} v_i (t - t_i^{start})$$

$$+ \frac{e}{d} \sum_{i,released} v_i (t - t_i^{detrap});$$

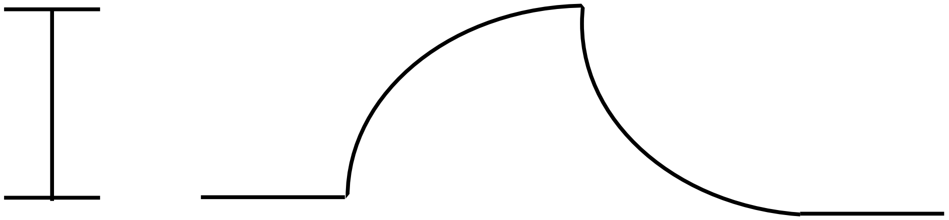
$$Q_{released}(t) =$$

$$Q_{trapped}(1 - \exp(-t/\tau_{detrap}));$$

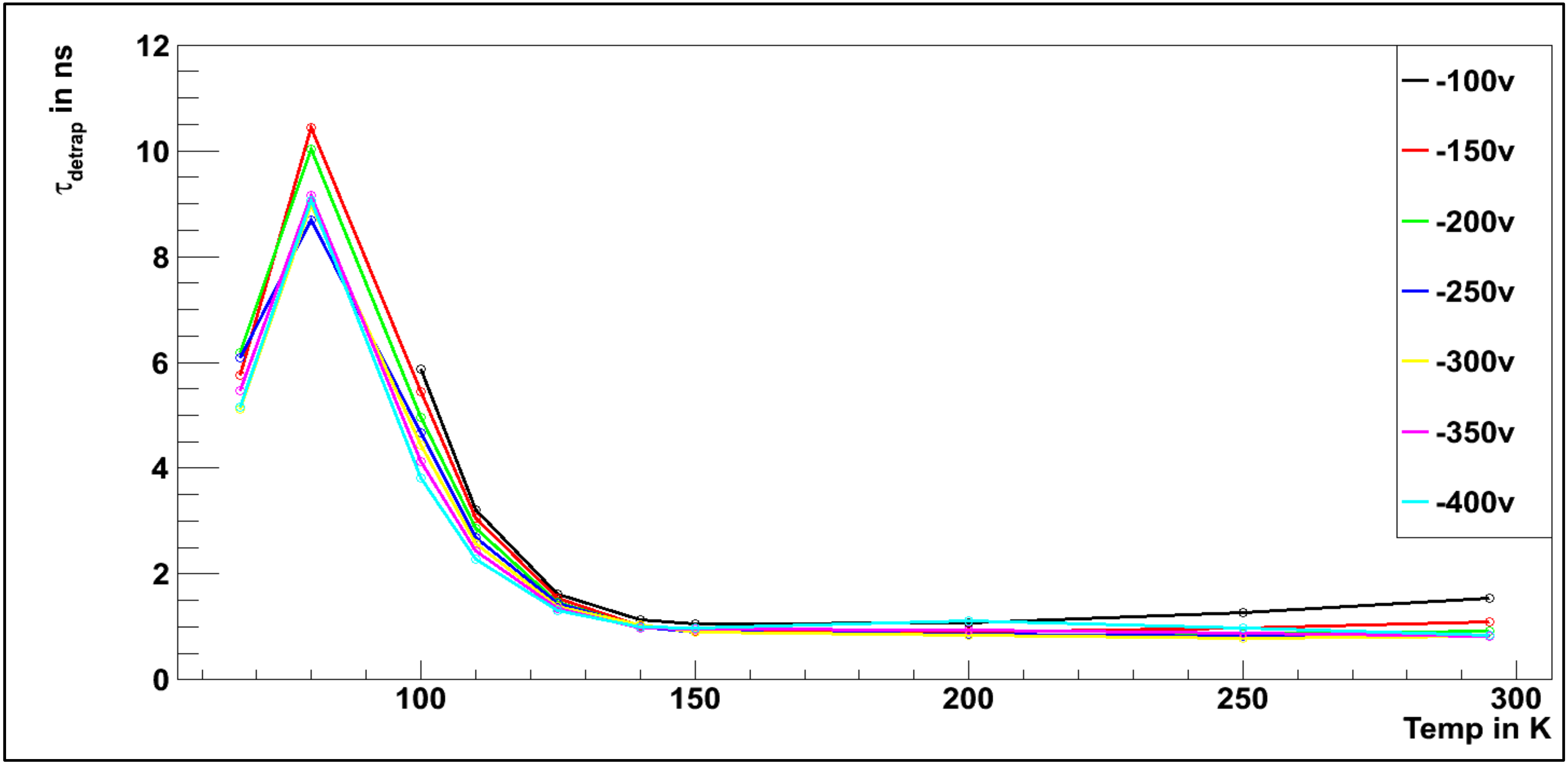
non-trappped

$$Q_{not-trapped} = Q_{\alpha-induced} - Q_{trapped}$$

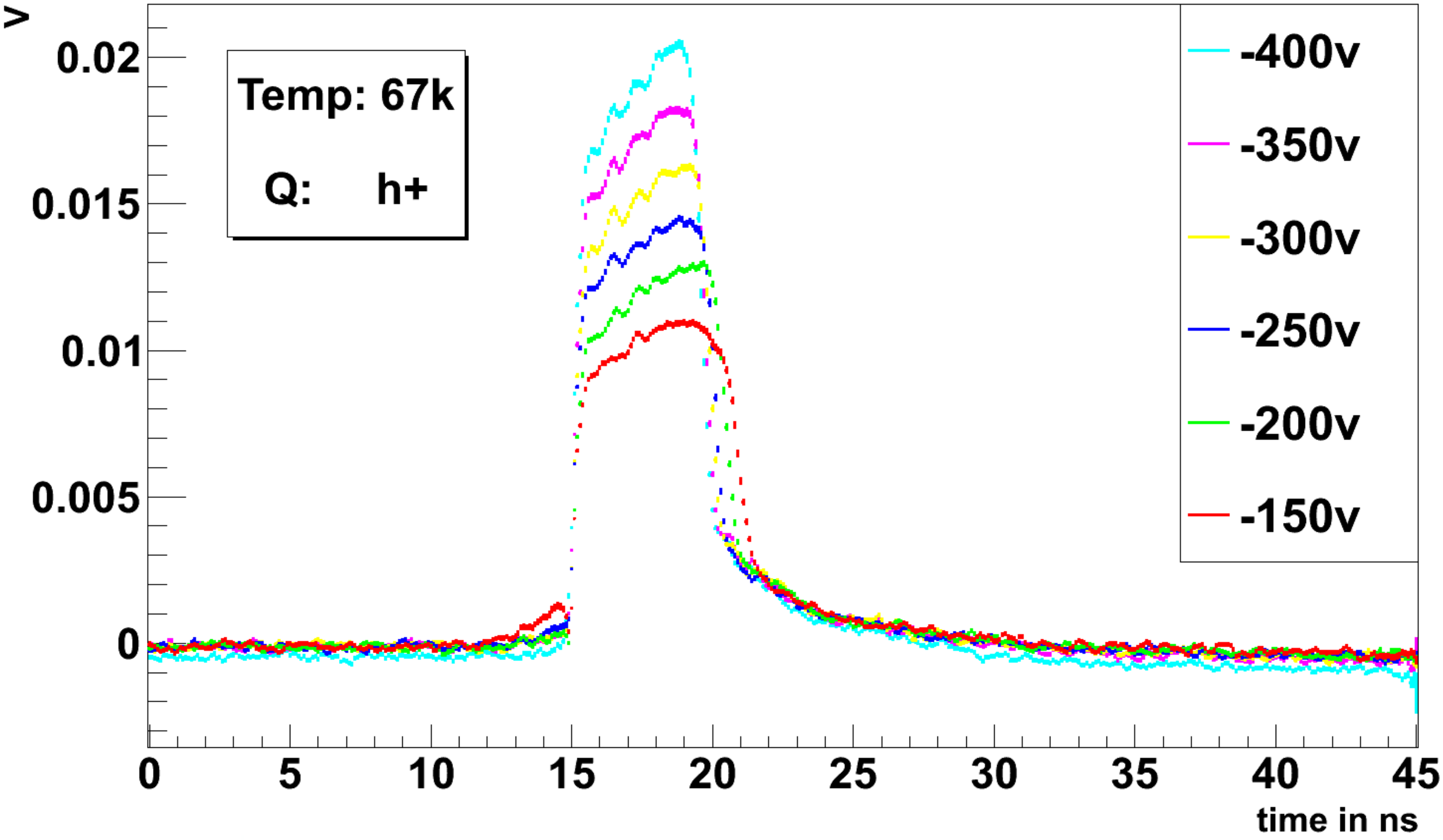
released



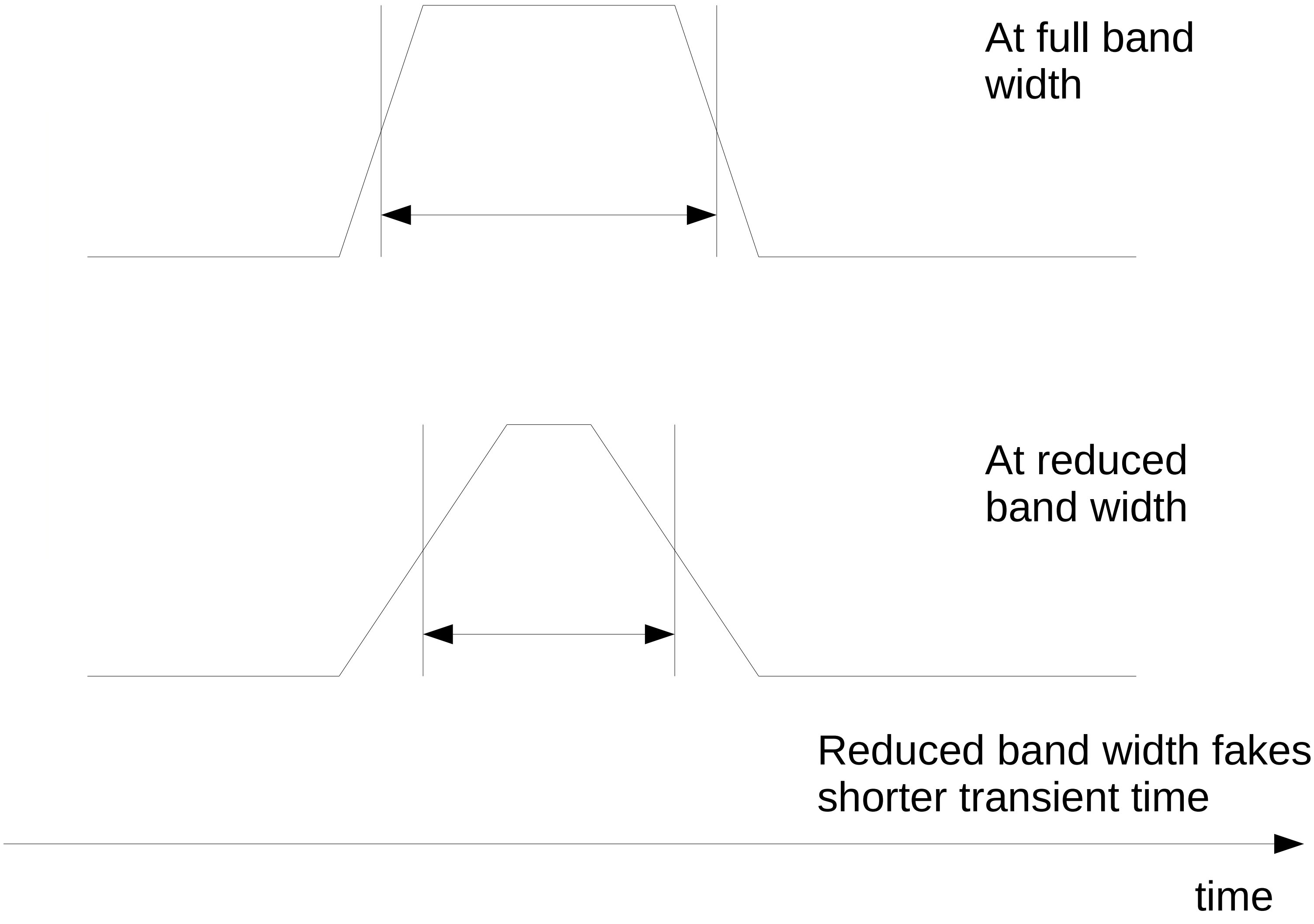
Detrapping vs. T



Pulse shape at 67 K



Band width



At full band width

At reduced band width

Reduced band width fakes shorter transient time

time