TCT studies with scCVD diamonds at cryogenic temperatures

- 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

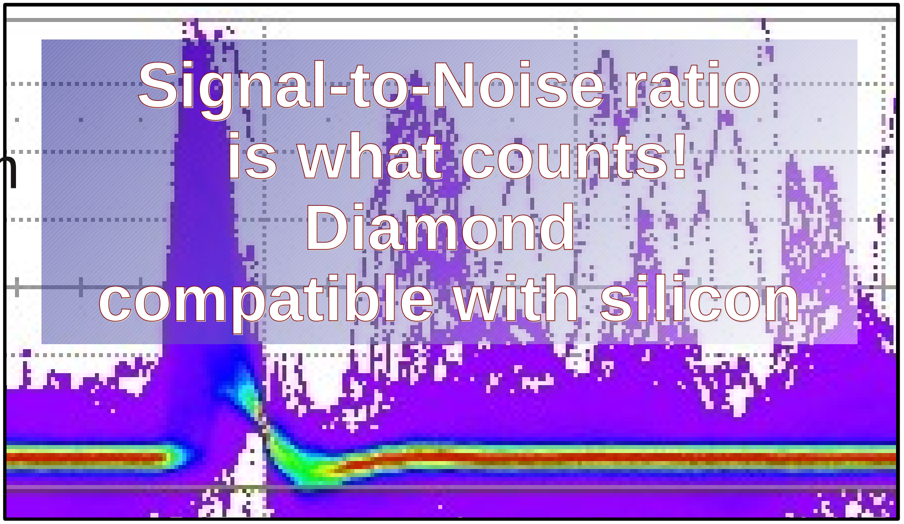
- Diamonds not tested yet at ultra-cold temperatures
  → Interesting!

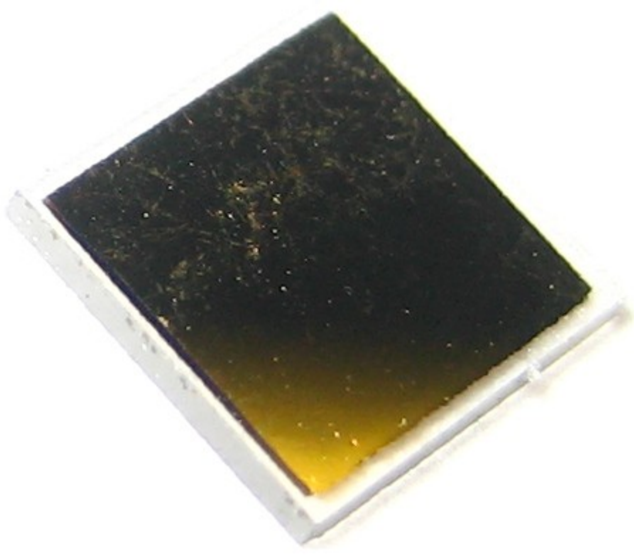
- Characterize scCVD diamonds at cryogenic temperatures
  with gaseous He cooling
  → Start at RT, decrease step-wise down to 67 K
  with liquid He cooling
  → Measure down to 4.5 K

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





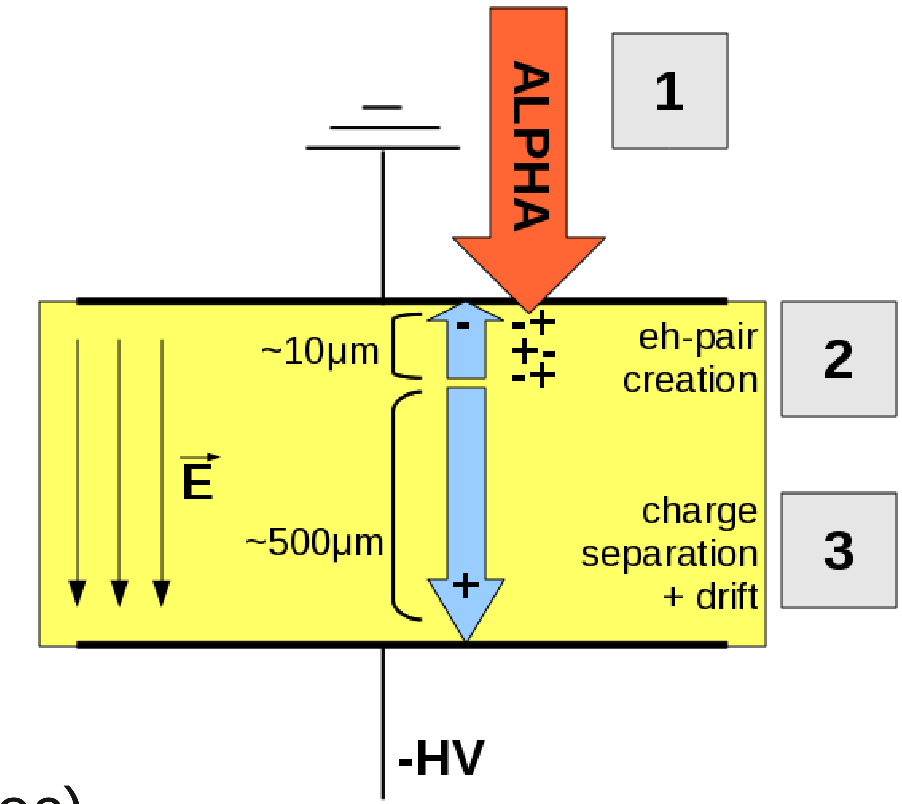
Cons:

- 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



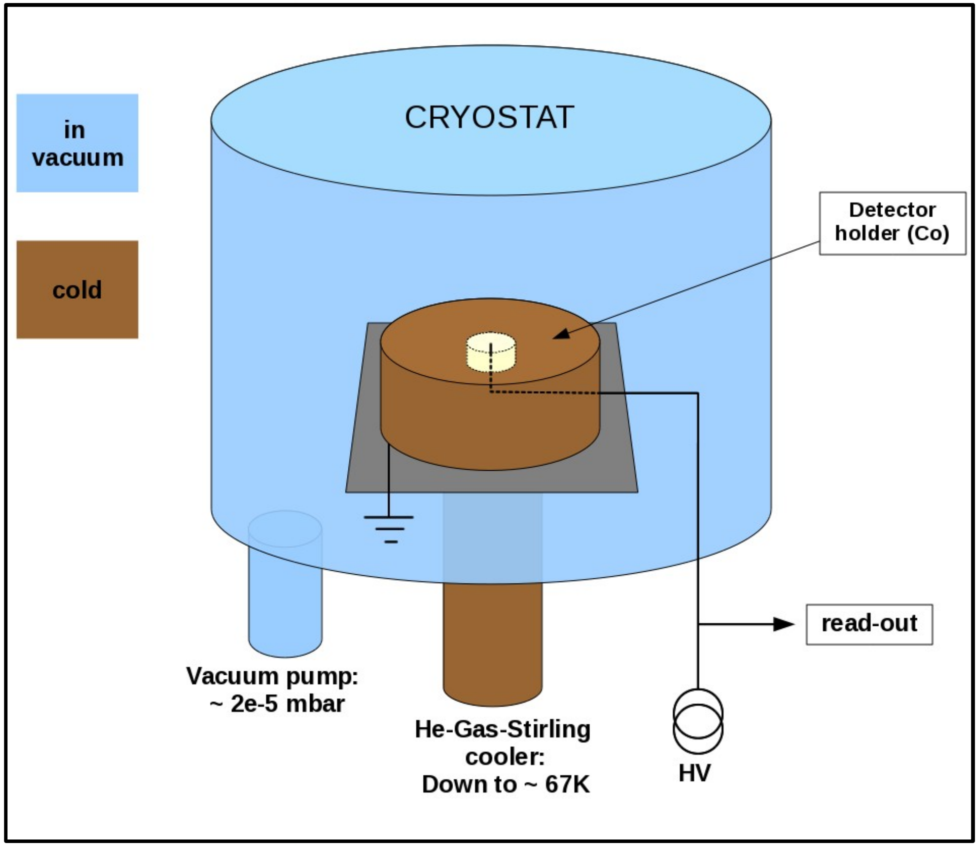
→ Pos. (neg.) bias → Measure e^- (h^+)

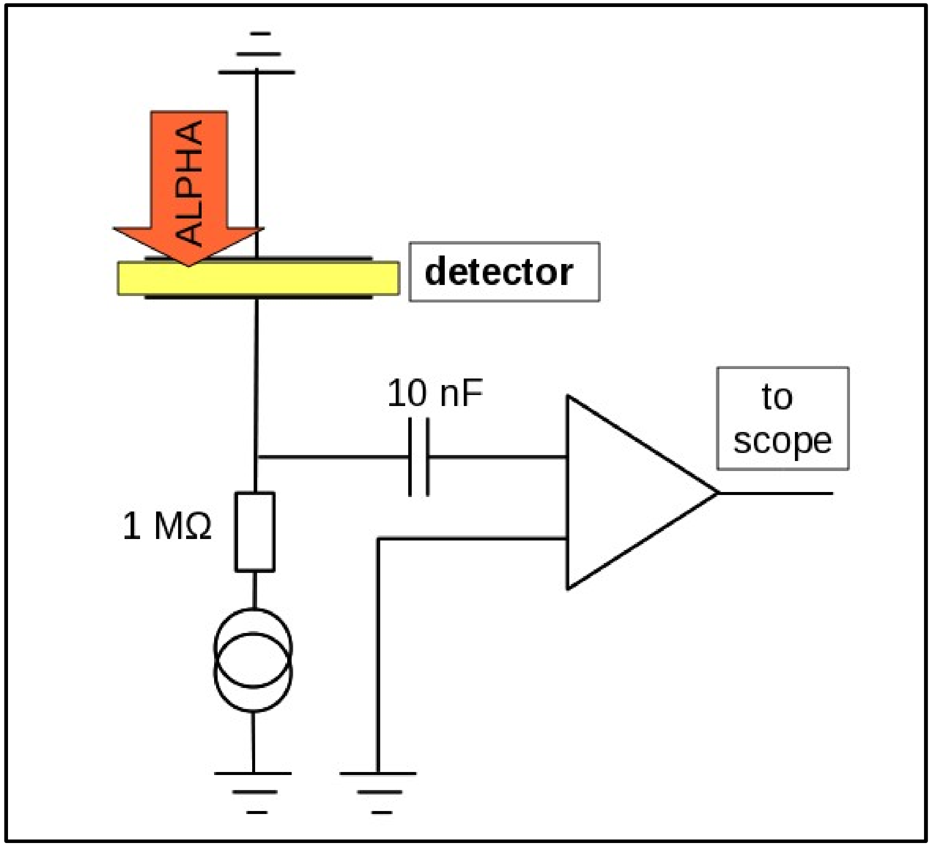
→ Use ultra-fast 2 GHz, 40 dB,
200 ps rise time current amplifier (cividec)

→ Use broad-band 3 GHz scope (LeCroy)

→ Use RF components

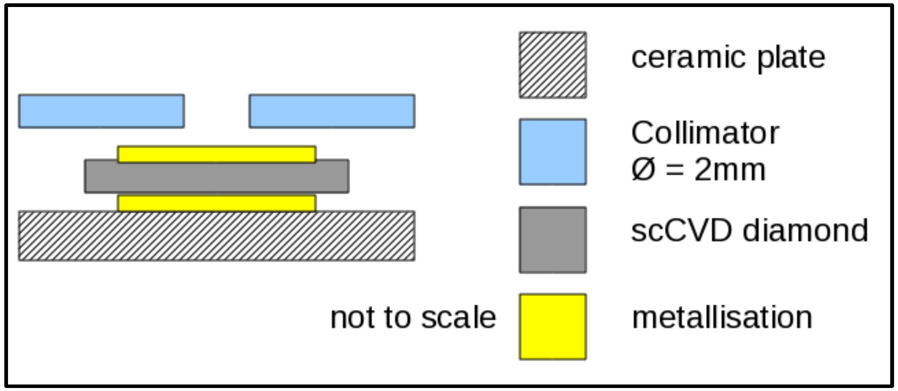
Details of Measuring Set-up

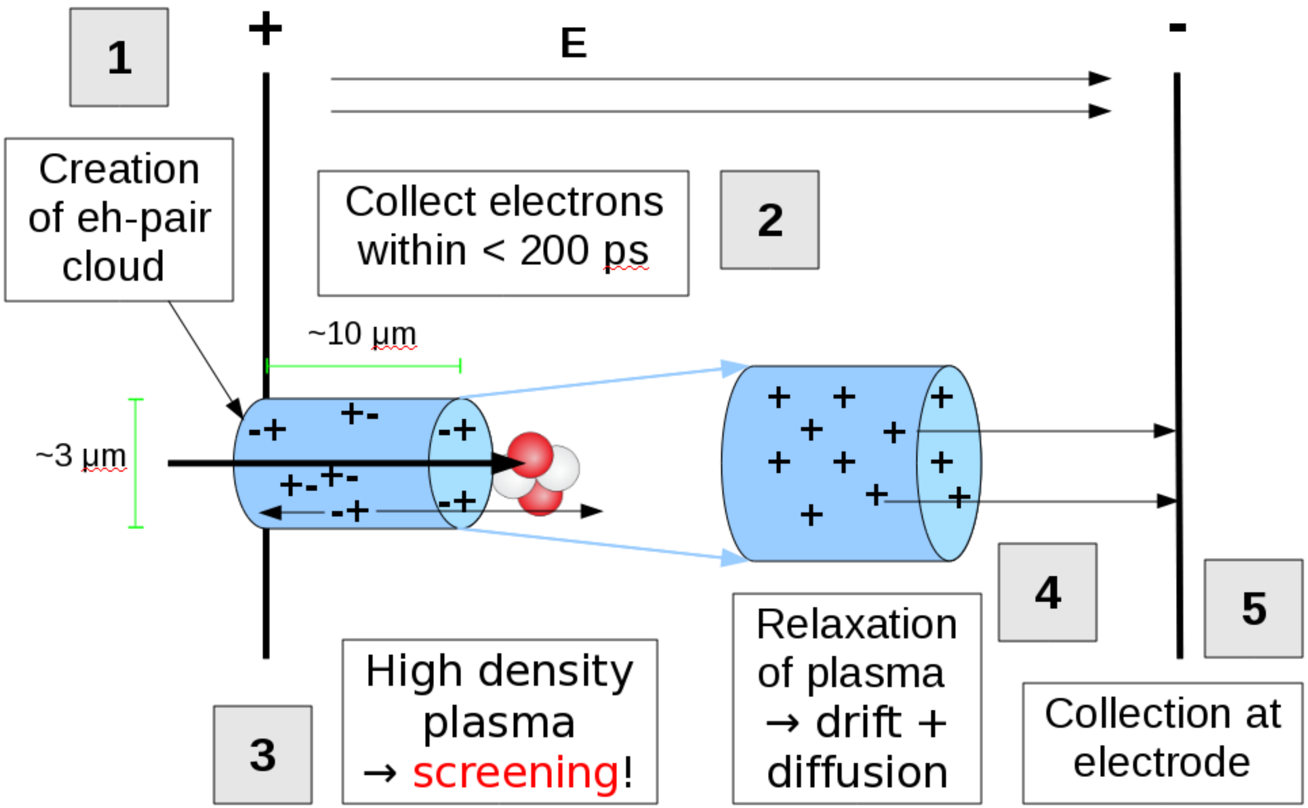




- **SETTINGS:**

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





From Ramo-Theorem:

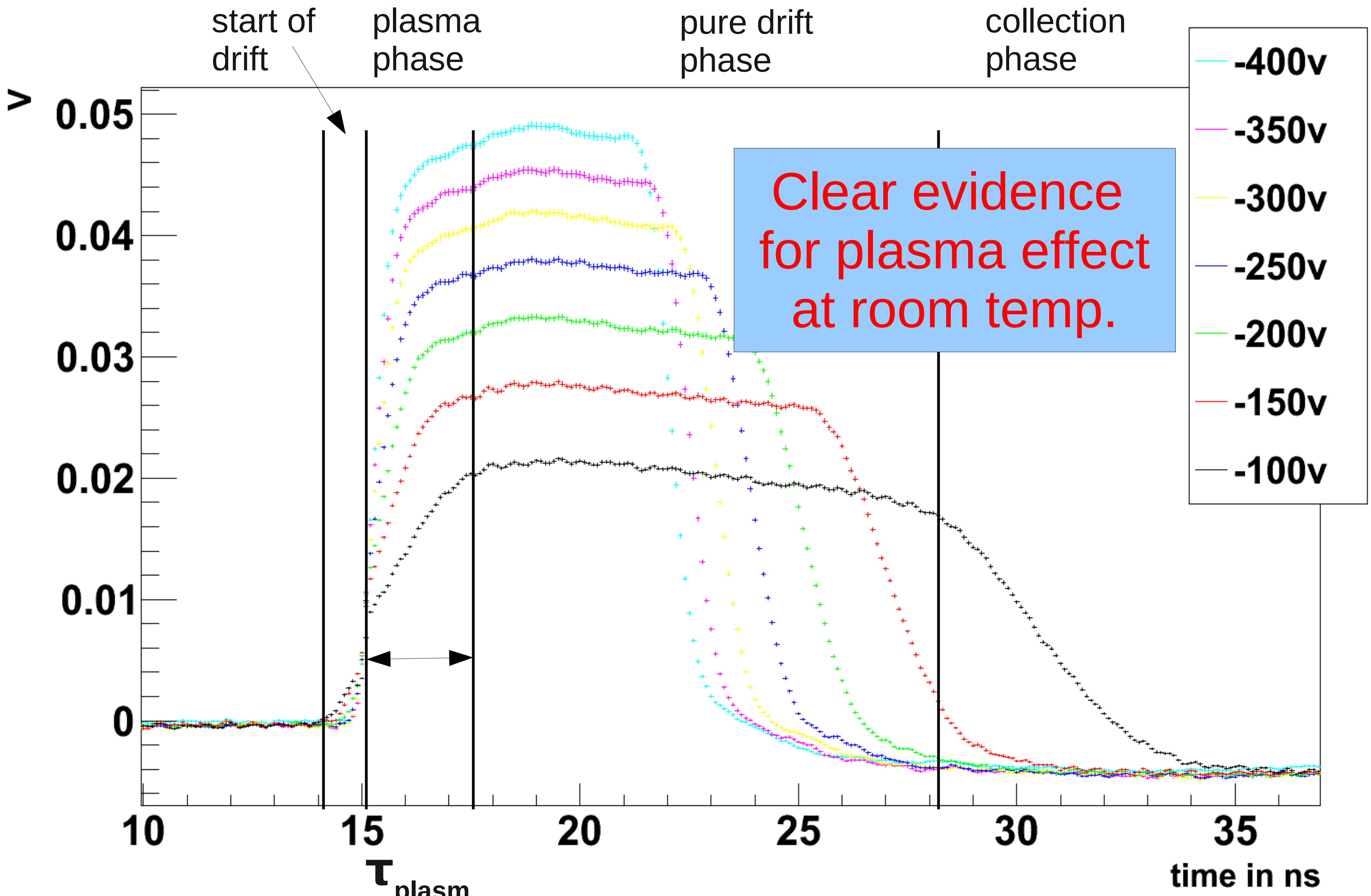
$$i(t) = \sum_k i_k(t) = \sum_k e\, E_w\, v_k(t) = \frac{e}{d} \sum_k v_k(t - t_k^{start});$$

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

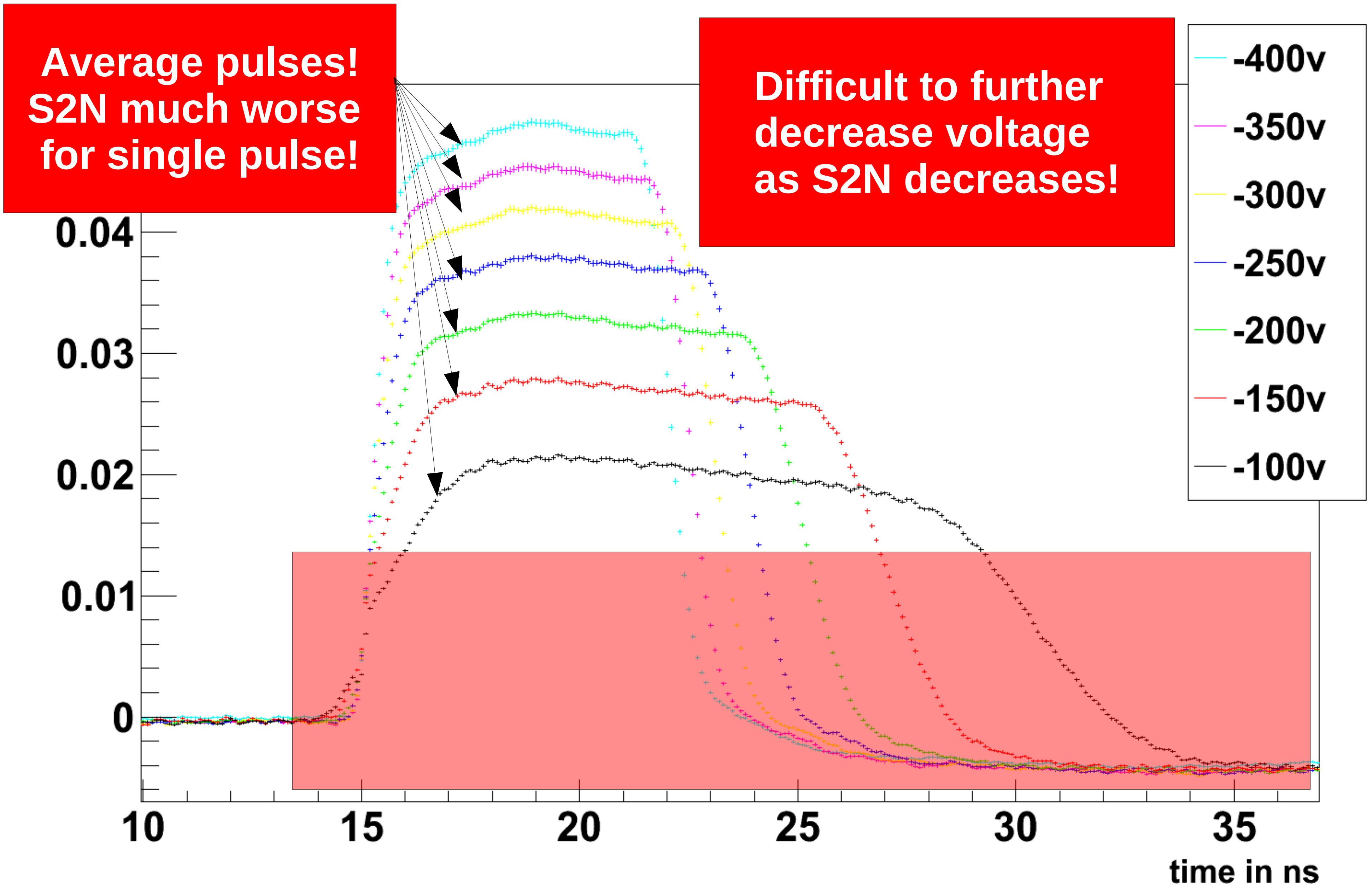
- **FACTS:**
  - → αs produce high density charge cloud
  - → Outer charges screen inner ones
    - → E-Field decreases inside the plasma
  - → Increased E-Field decreases lifetime of plasma

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

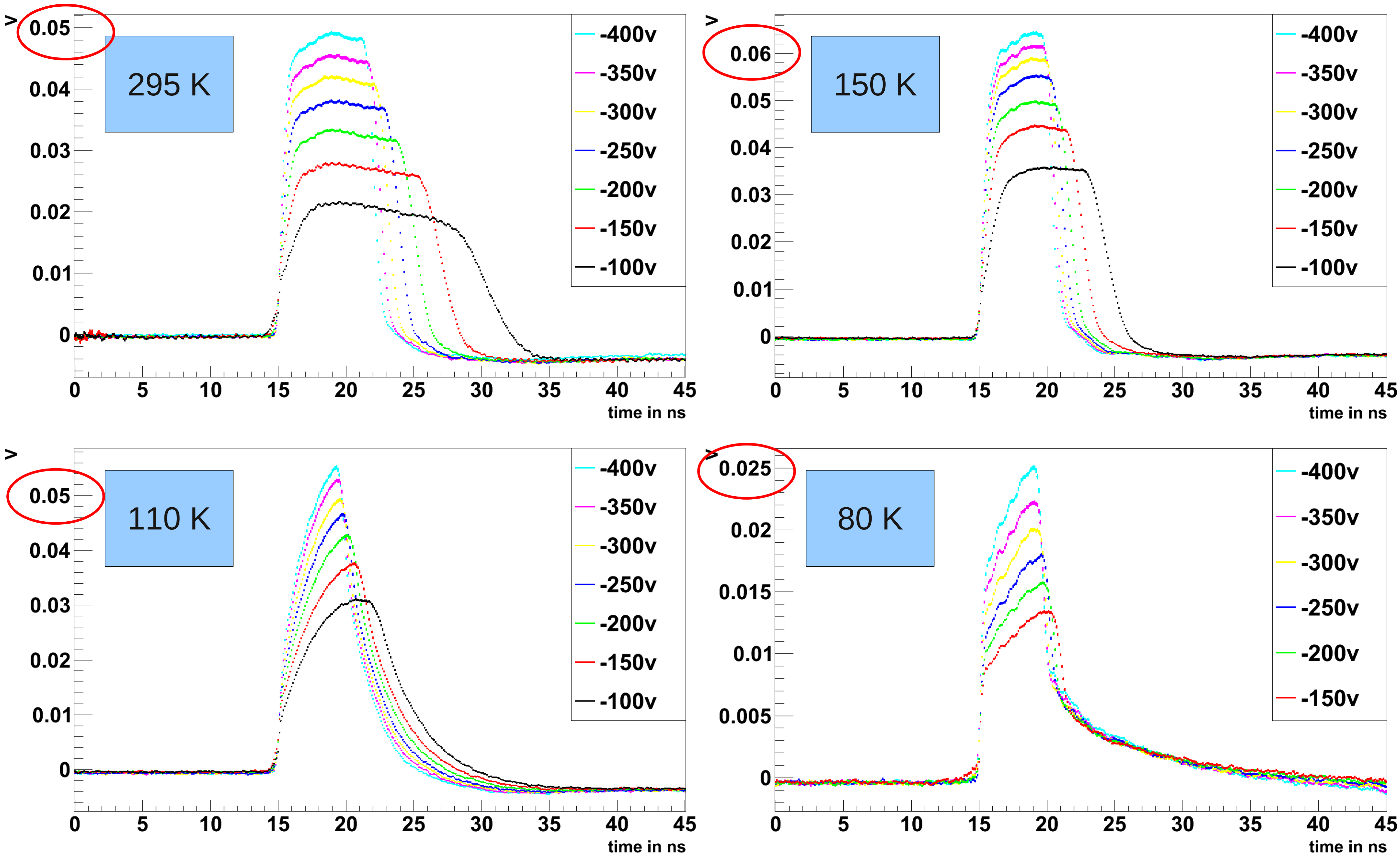
Plasma Effect at 295 K



Difficulties



TCT Hole Pulses



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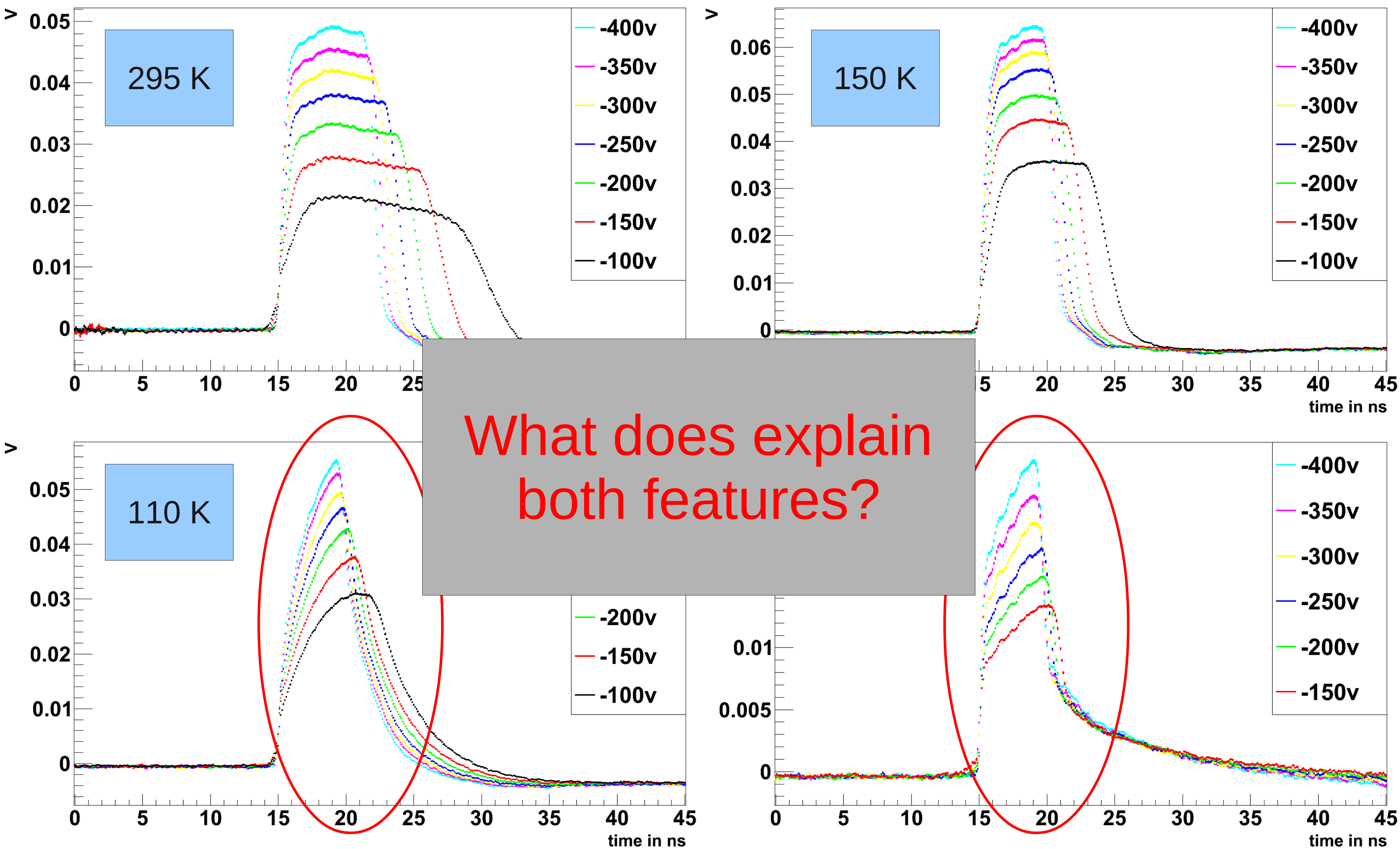
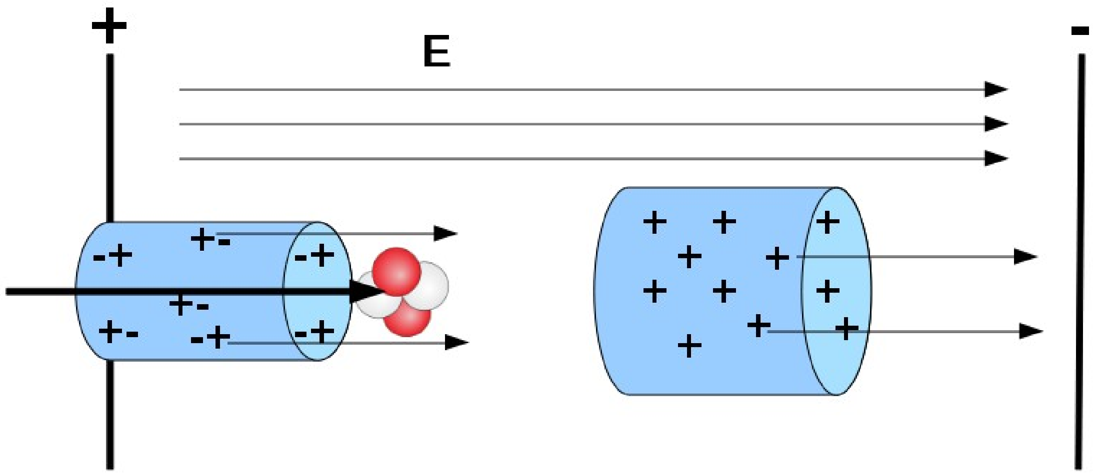
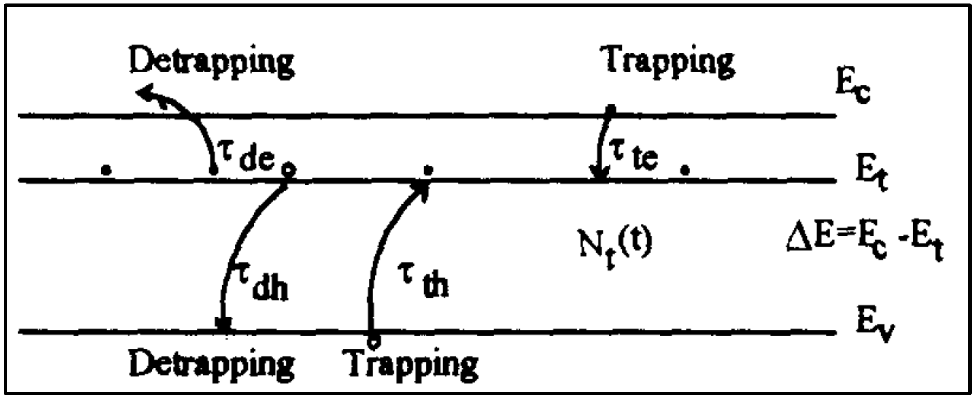


Trapping in Plasma





Below ~150 K:

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

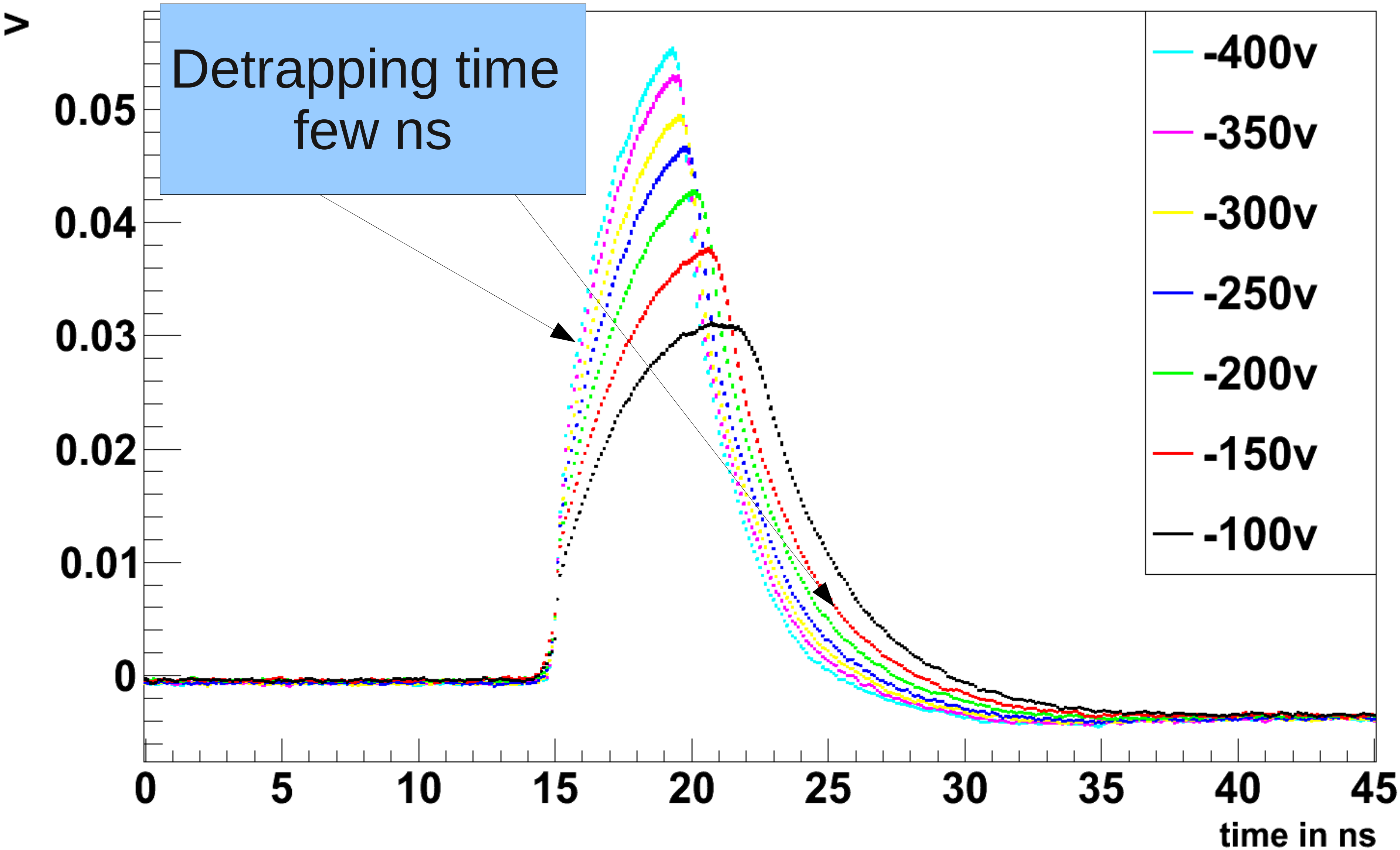
$$\tau_{trap}^{plasma} \ll \tau_{trap}^{drift}$$

From Ramo-Theorem:

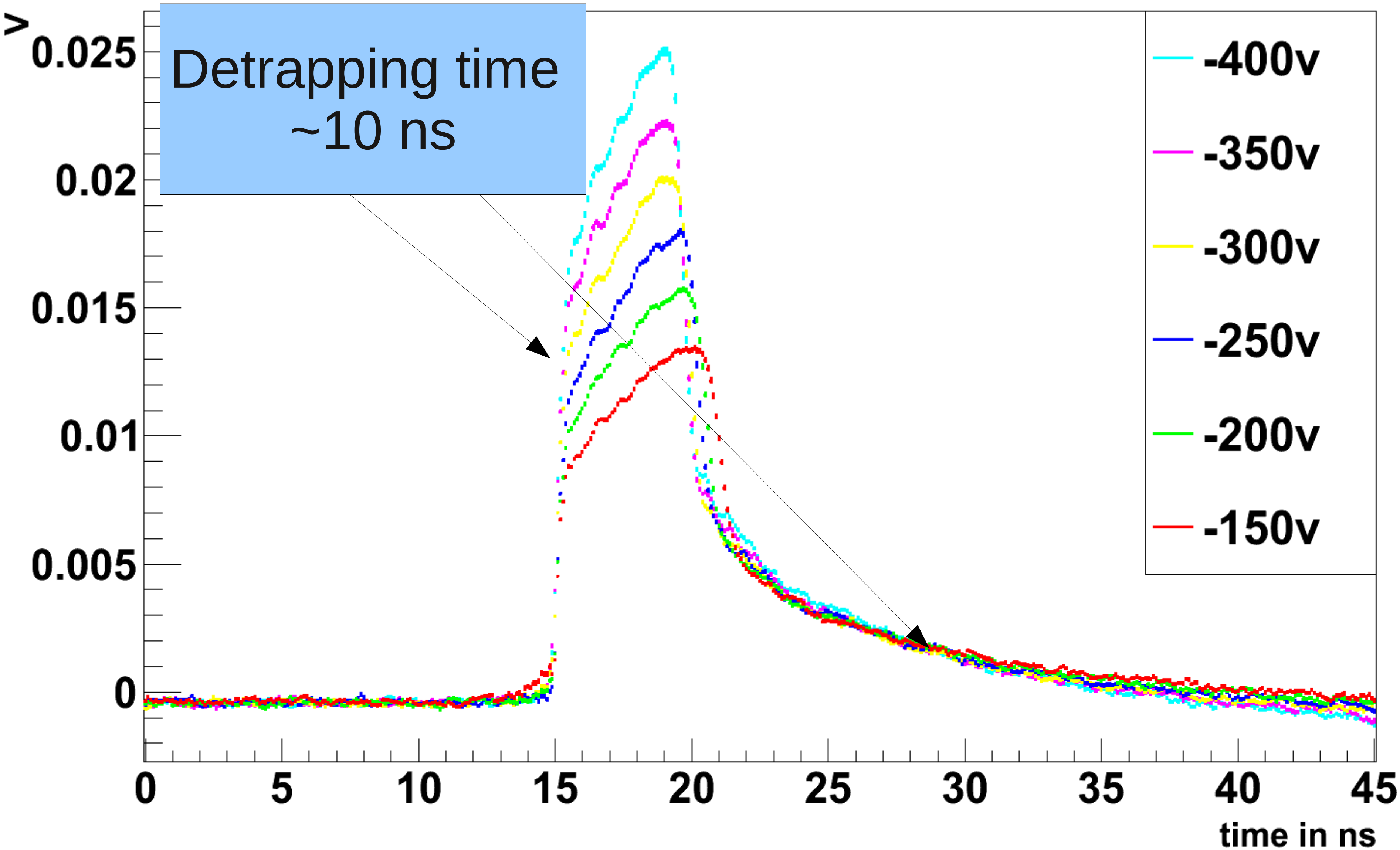
$$i_{(t)} = i_{not-trapped}(t) + i_{released}(t)$$
$$= \frac{e}{d} \sum_{i,\,not-trapped} v_i (t - t_i^{start})$$
$$+ \frac{e}{d} \sum_{i,\,released} v_i (t - t_i^{detrap});$$

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

Trapping/Detrapping at 110 K



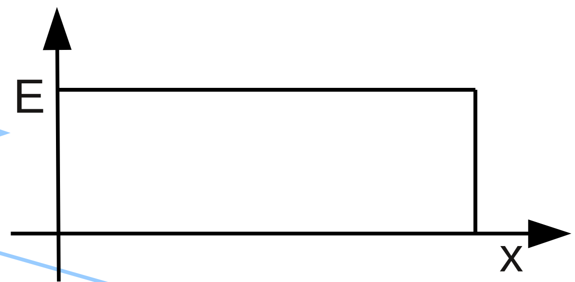
Trapping/Detrapping at 80 K

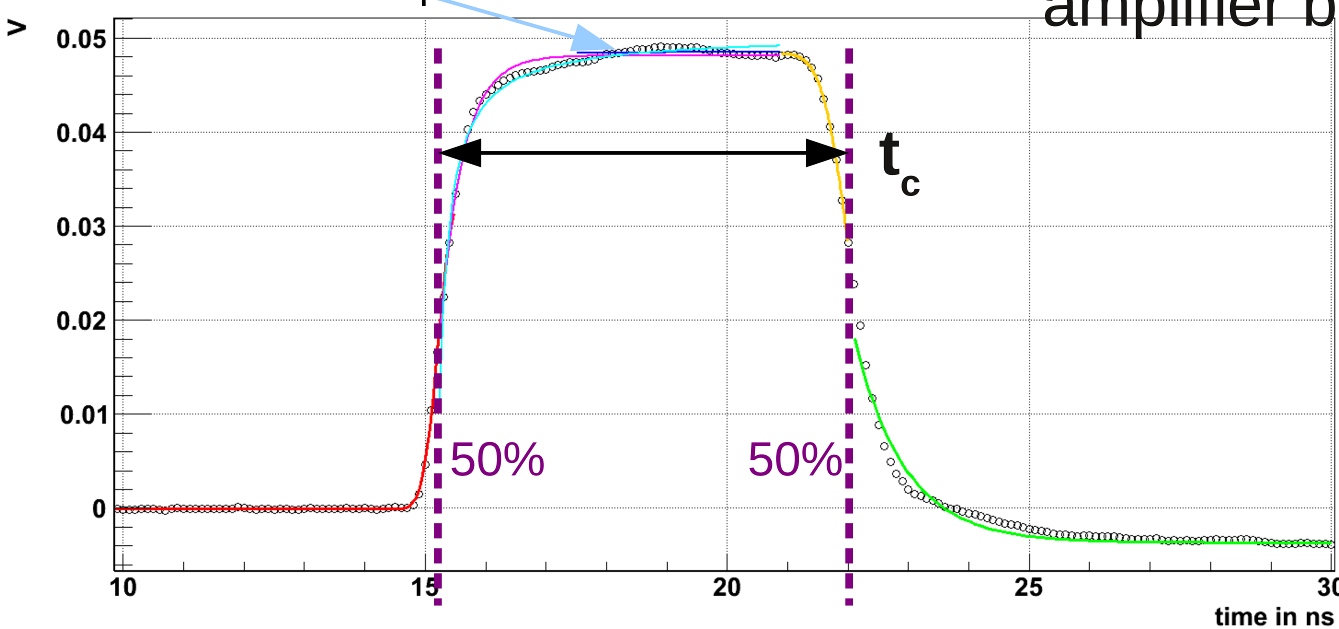


Analysis of TCT Pulses

- Four phases:
  1) Start of drift
  2) Current saturation
  3) Collection at electrode
  4) Tail

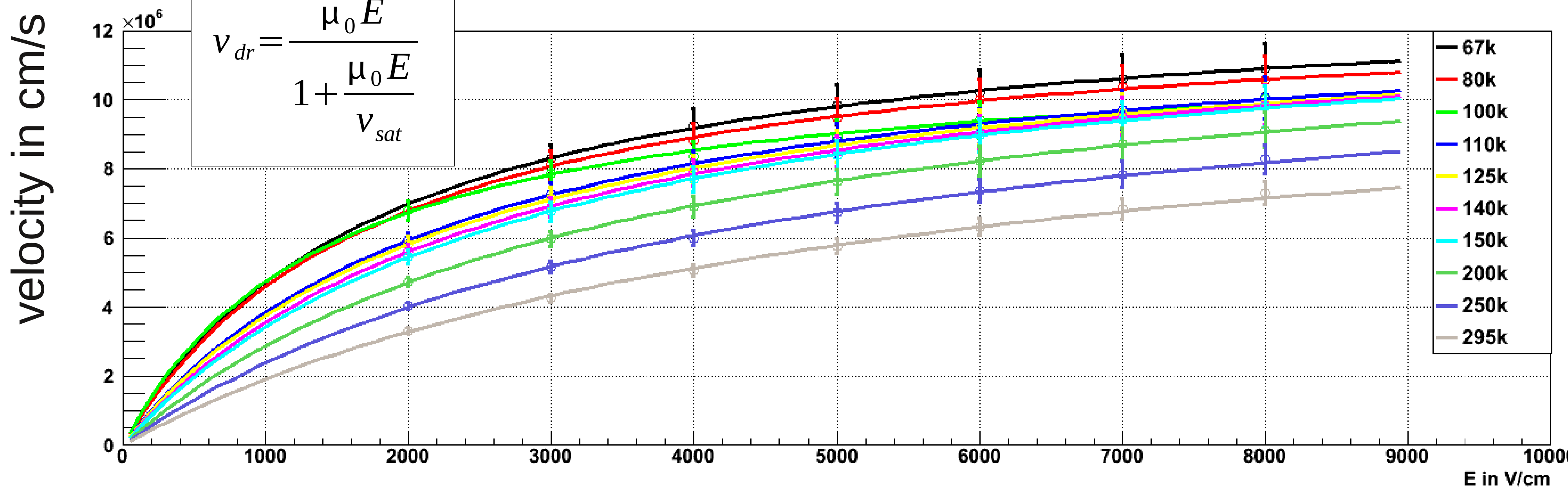
FLAT TOP
→ const. E!





- 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



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

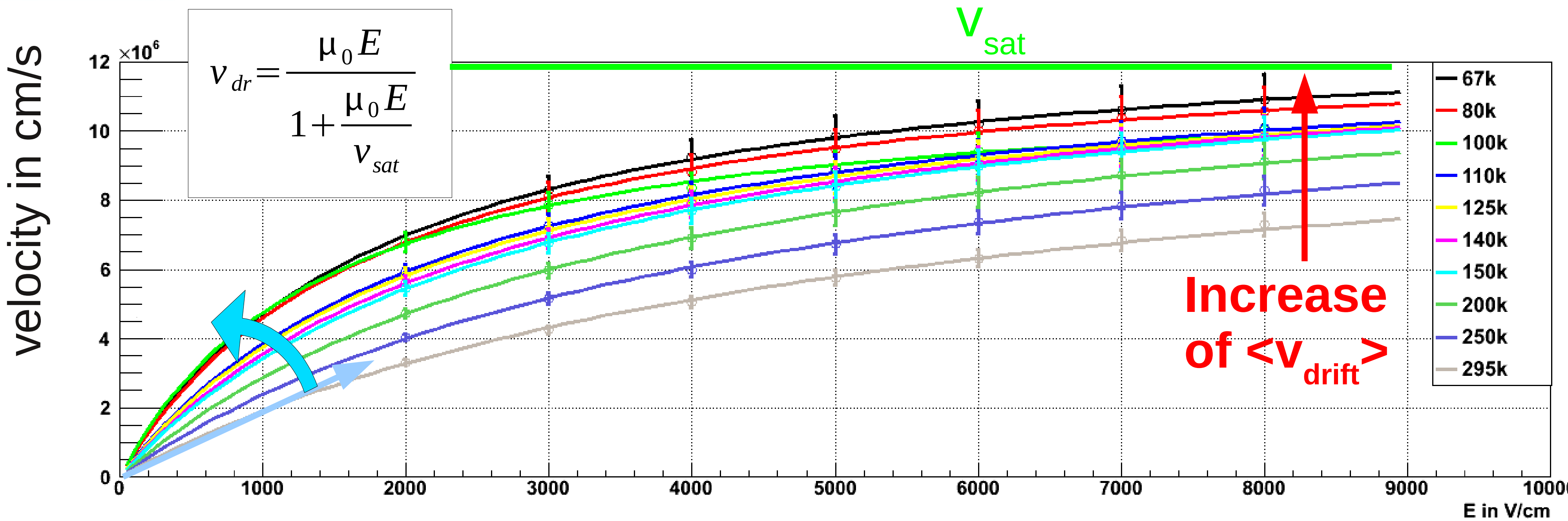
Fits yield:

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

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

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

Hole Mobility and Velocity



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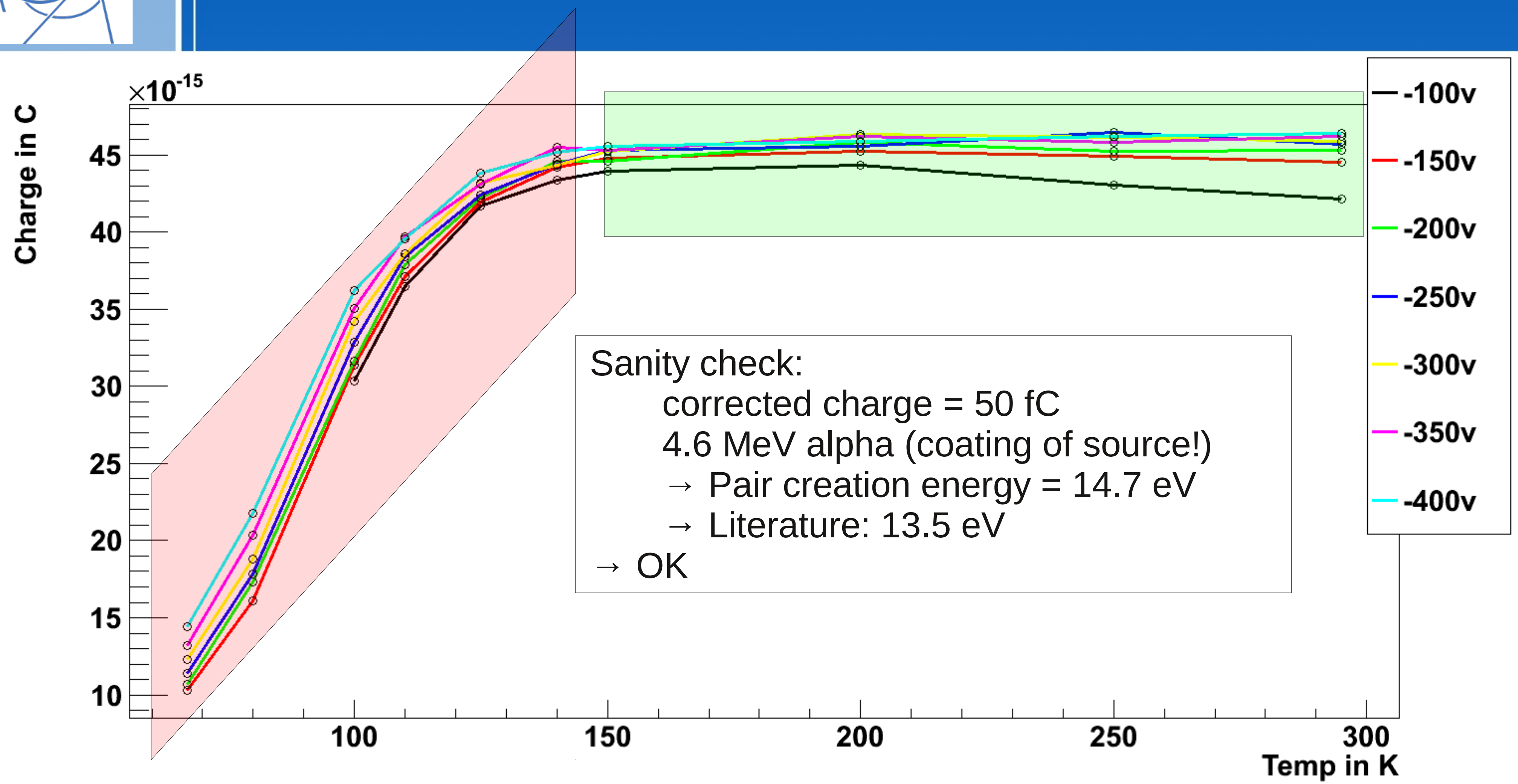
Integrated Charge



Sanity check:

corrected charge = 50 fC

4.6 MeV alpha (coating of source!)

→ Pair creation energy = 14.7 eV

→ Literature: 13.5 eV

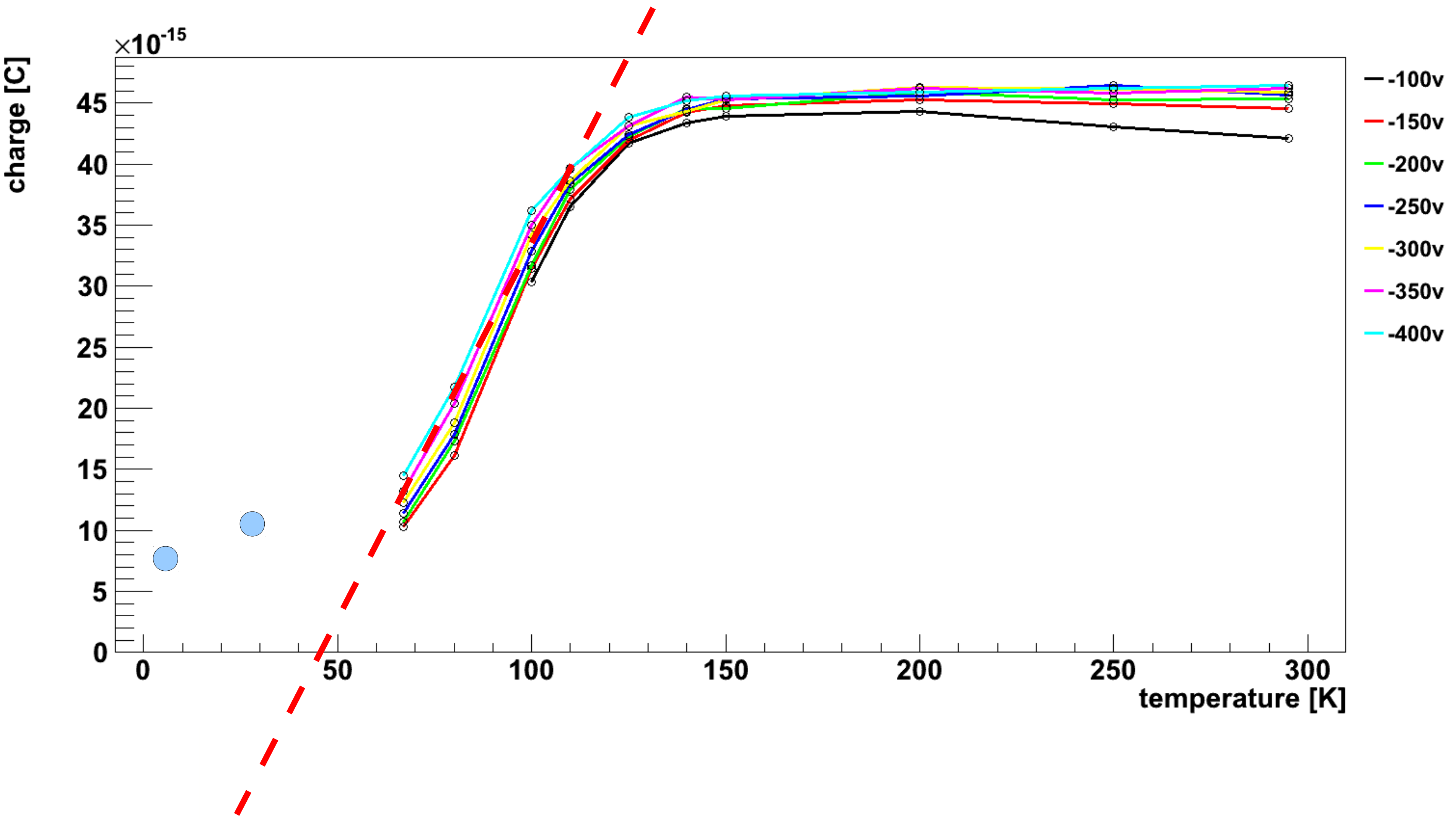
→ OK

- Charge constant in range 140 K to 300 K
- Steep drop from 140K down to 67 K

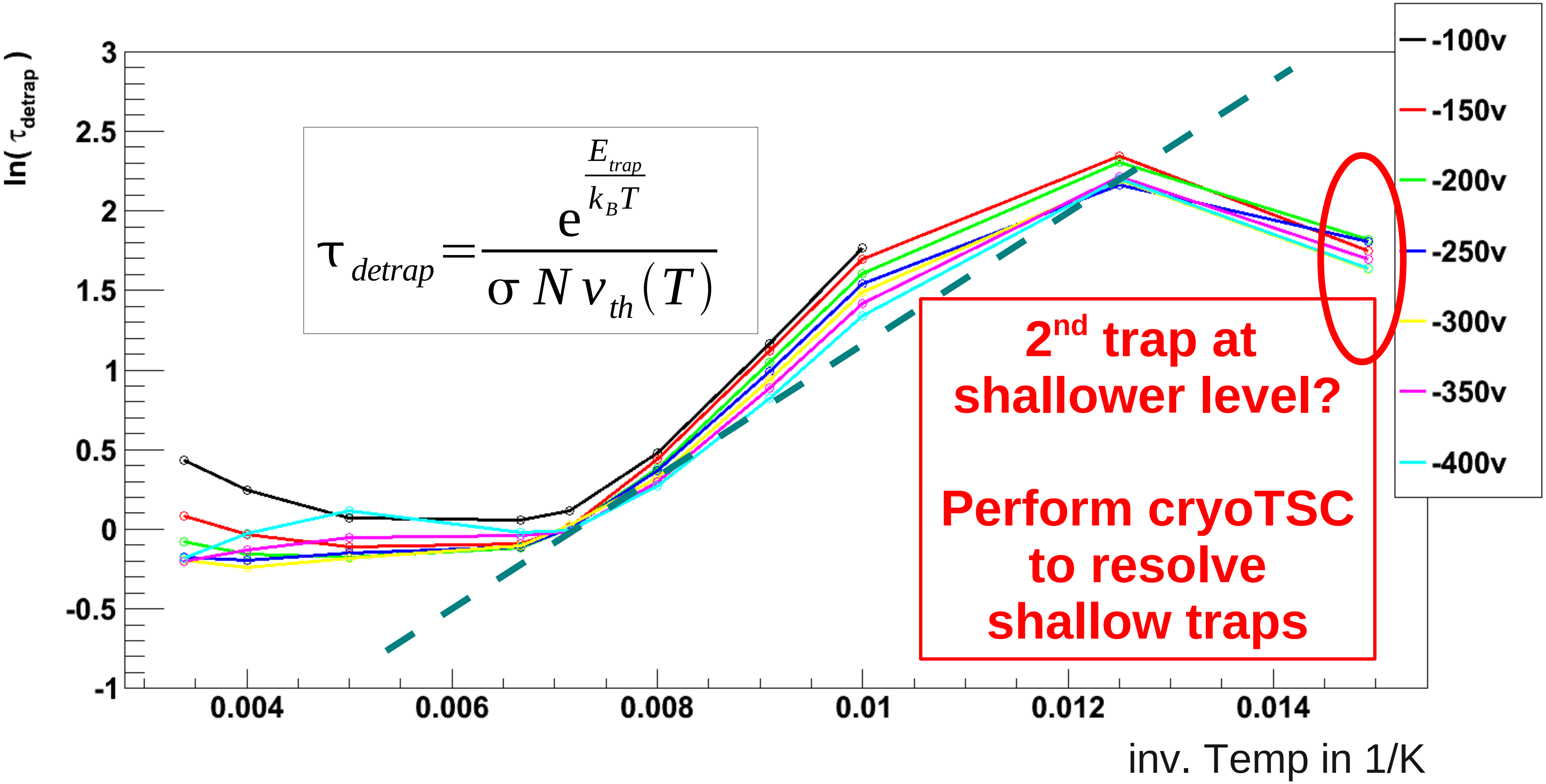
  → plasma associated trapping and recombination

Integrated charge

- New data taken with LiHe cooling!



Detrapping Time Constant



- Plot $\ln(\tau_{dt})$ 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

Conclusion

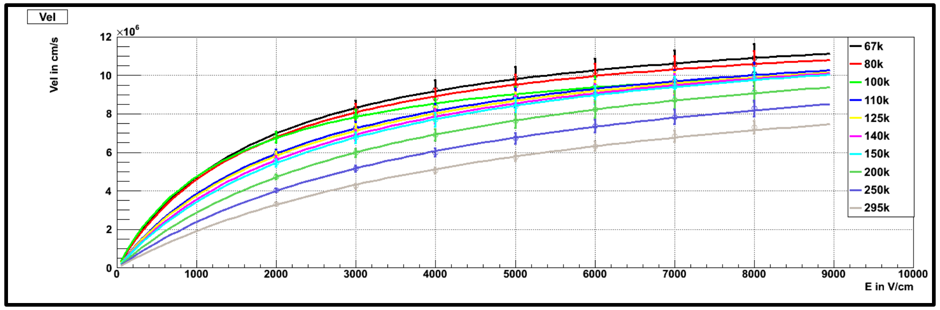
- TCT offers eminent possibility
  to characterize detectors

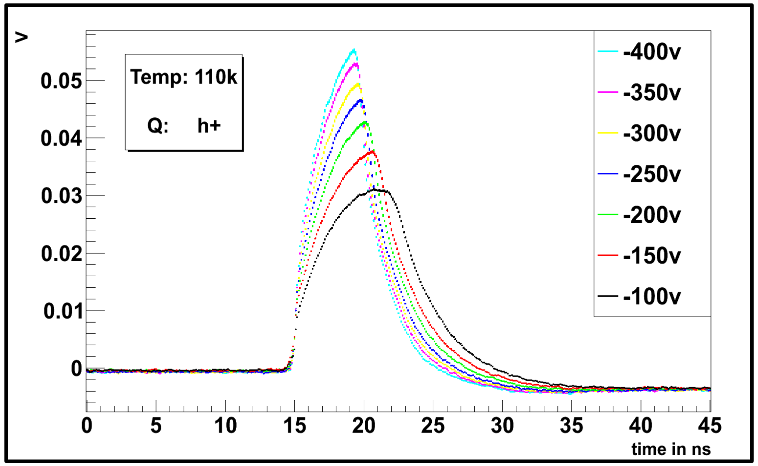
- Temperature dependence of
  - drift mobility and velocity
  - total charge
  - trapping-detrapping mechanism
  - pulse shape

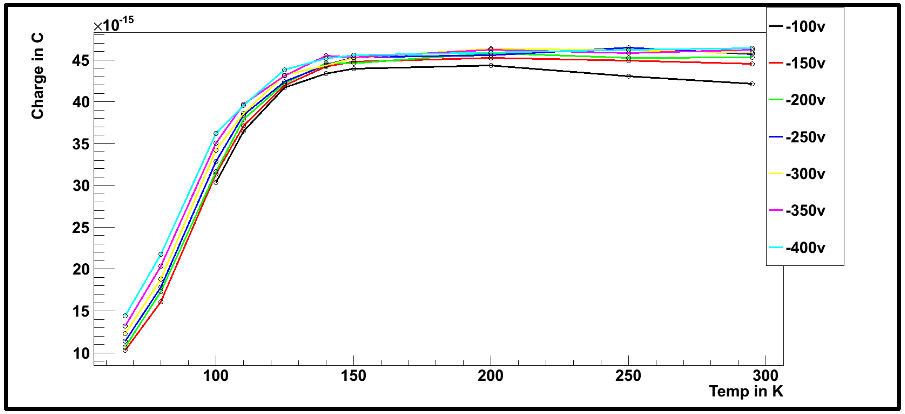
  in scCVD diamonds

- Total charge drops for T < 150 K,
  need to understand this

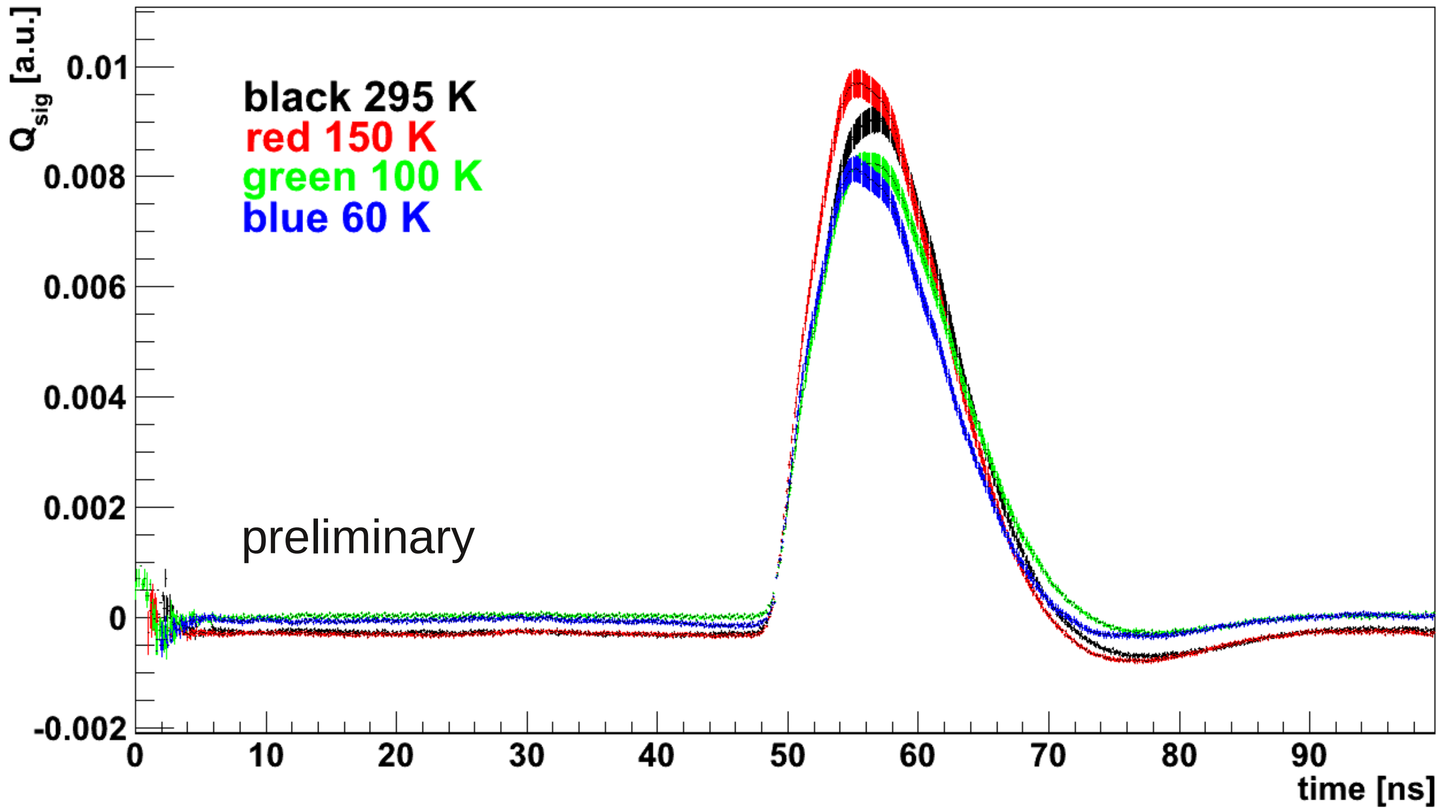
  trapping? recombination?
  formation of excitons?







Cosmic Muons in scCVD



- Use charge-sensitive amplifier here
- Charge degradation much less with MIPs
  - lower charge density!
- See next talk (C. Kurfuerst)

Outlook

- Paper in preparation

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

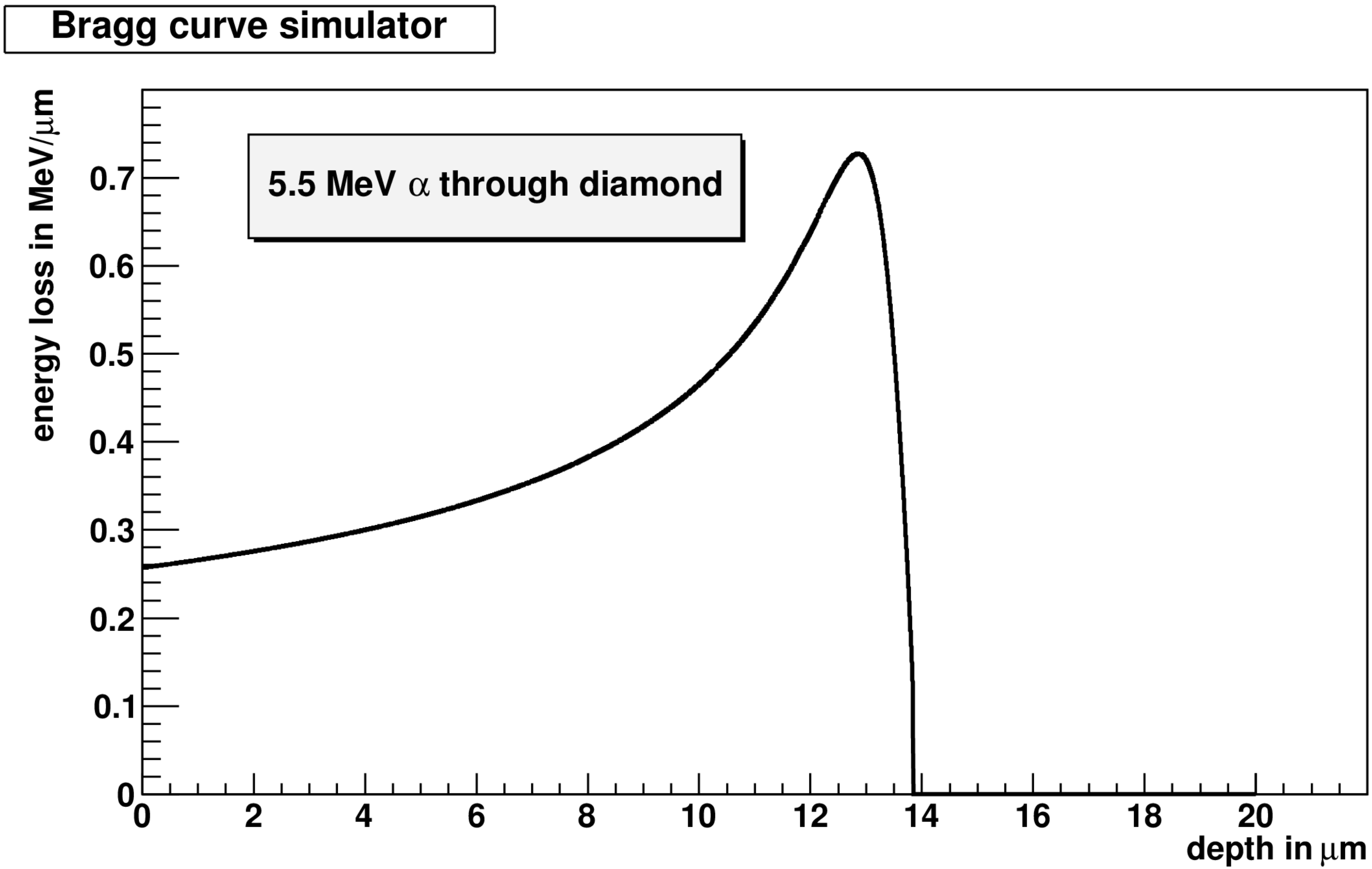
- TCT with β-source (this spring)
  → test MIP-like signal with diamond
  → density of charge cloud much smaller
  → cleaner measurement than with test-beam

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

- Cryogenic TSC set-up in preparation
  → resolve shallow traps

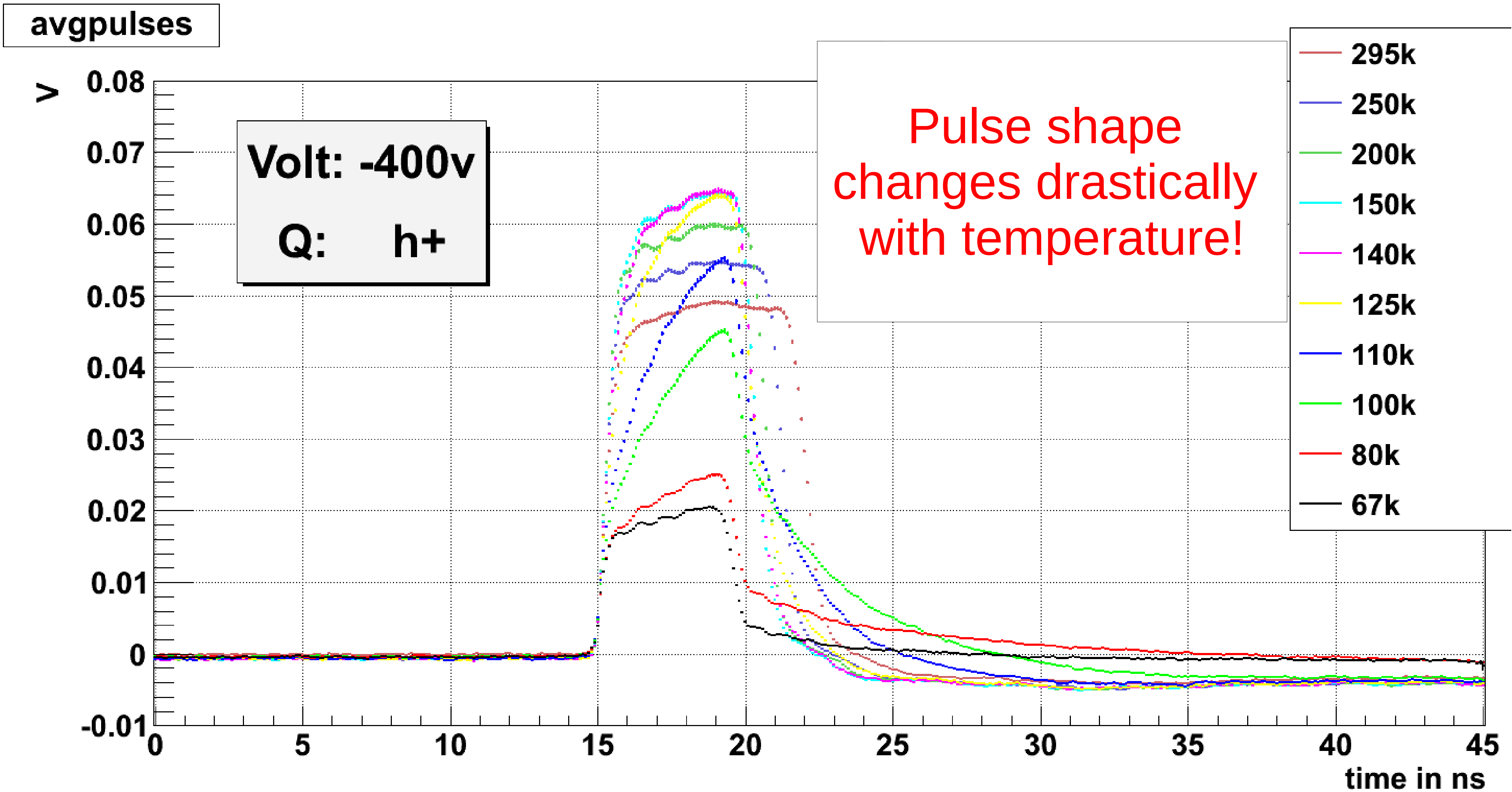
BACKUP SLIDES

Energy Loss in Diamond



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

Pulse Shape for Constant Voltage



Two Contributions to Signal

from Ramo-Theorem:

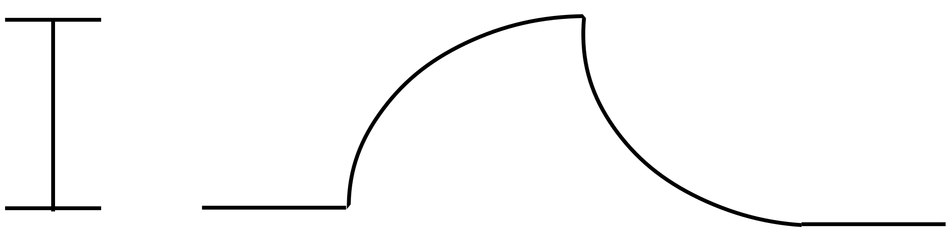
$$i_{(t)} = i_{non-trapped}(t) + i_{released}(t)$$
$$= \frac{e}{d} \sum_{i,\,not-trapped} v_i (t - t_i^{start})$$
$$+ \frac{e}{d} \sum_{i,\,released} v_i (t - t_i^{detrap});$$

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

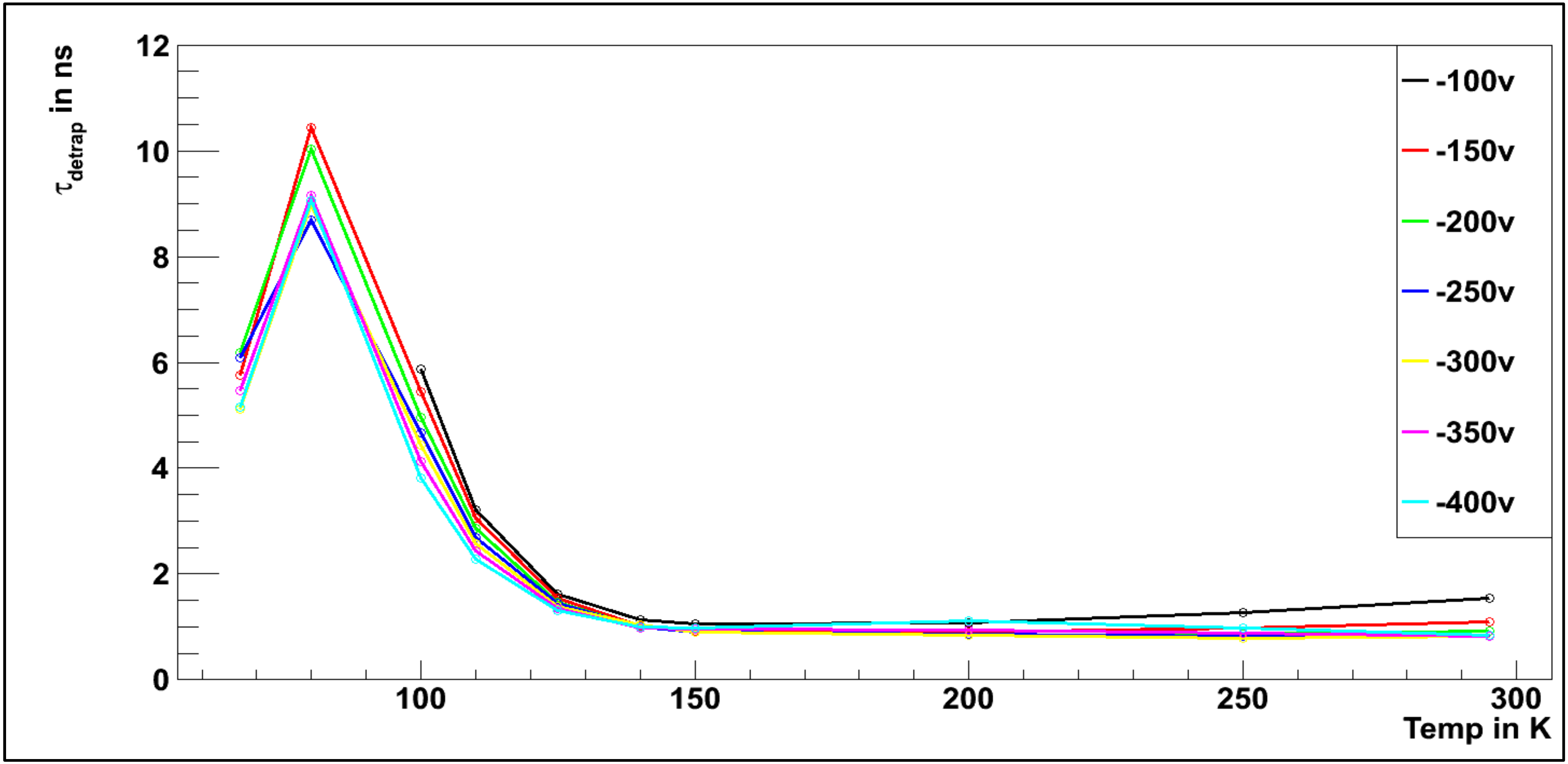
non-trappped

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

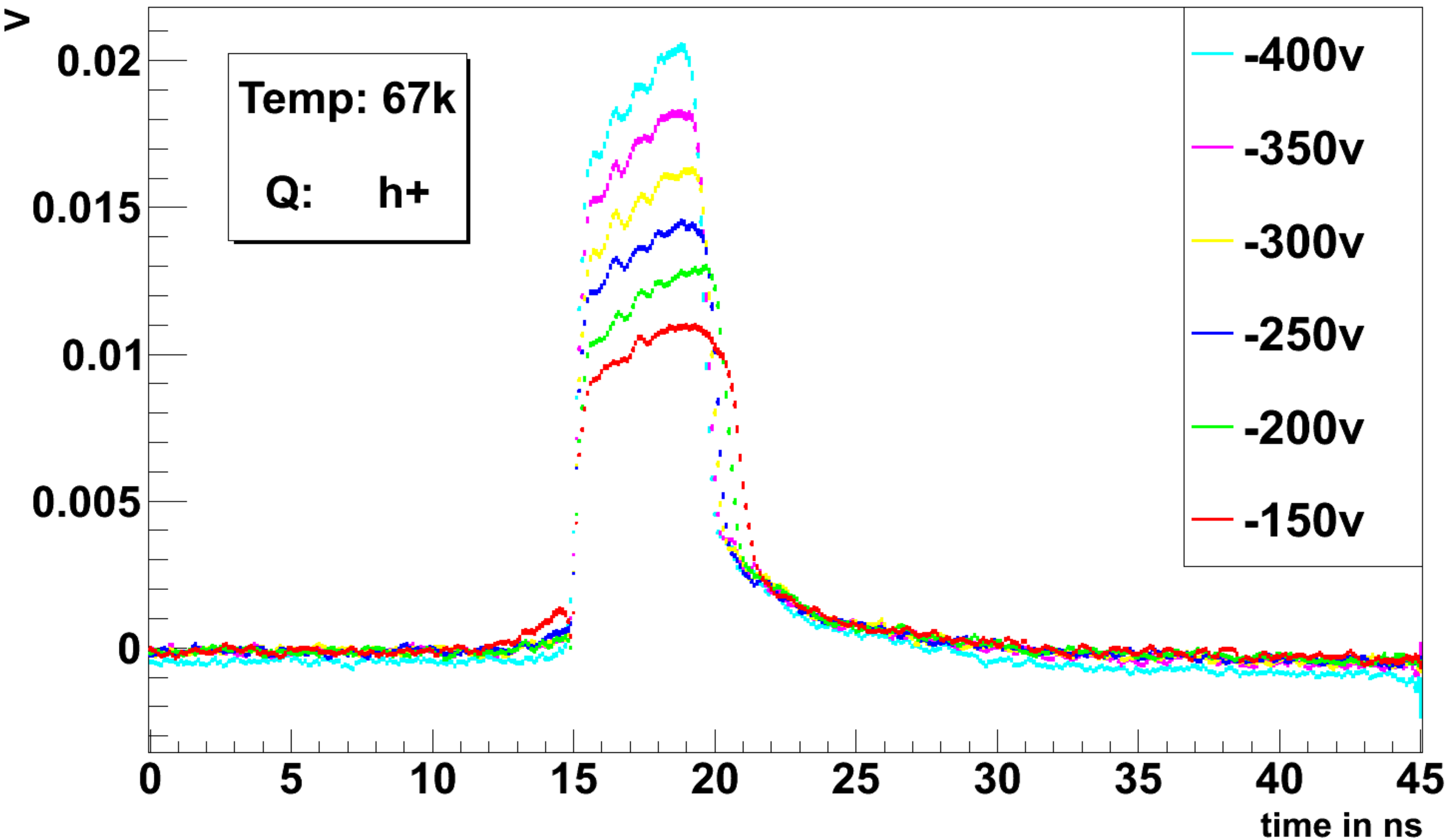
released



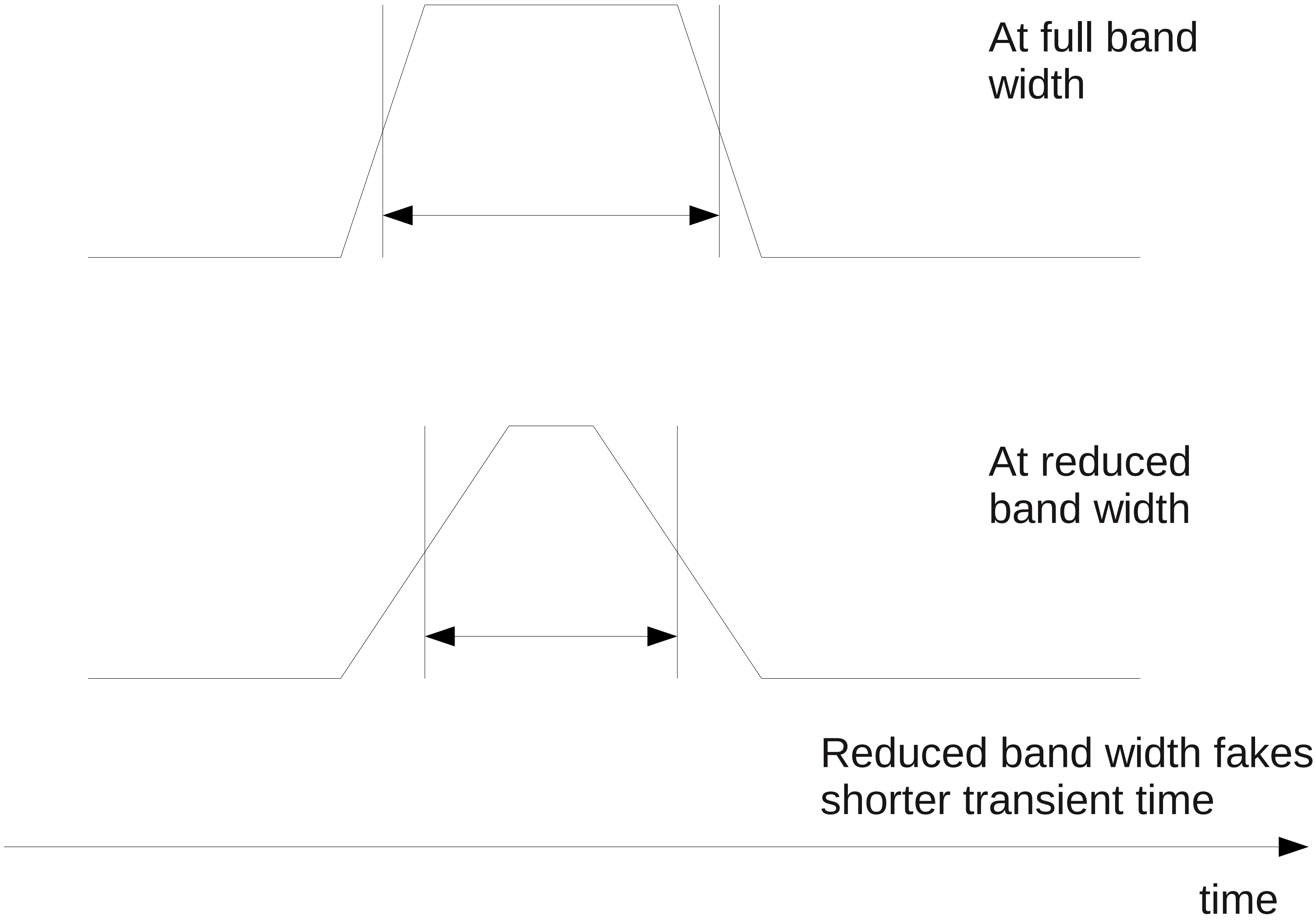
Detrapping vs. T



Pulse shape at 67 K



Band width



At full band width
At reduced band width
Reduced band width fakes shorter transient time
time