C-TCT measurements on scCVD diamond and its use at CNGS

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Outline

- Motivation and Concept

  Why and how to investigate charge transport/collection at cold temperatures?

- The Set-up

  Why diamond?
  The experimental technique

- Results and Model

  Current pulses and what we can learn from them

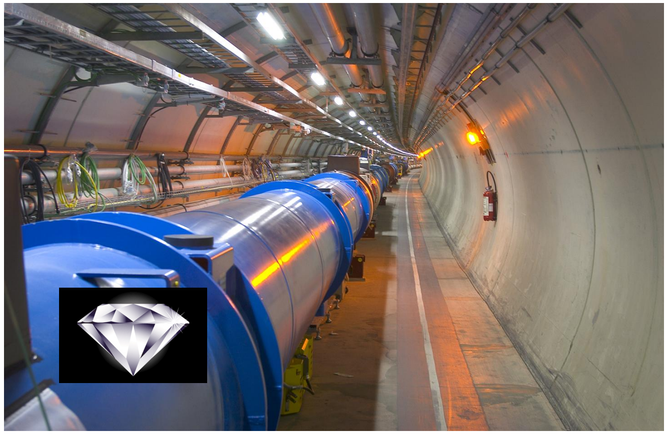
- Diamonds at CNGS

Motivation and Concept

- Understand charge transport over a wide temp. range:

  - Beam Loss Monitors within the LHC magnets
    → Operate detector at 1.9 K

  - Electrical Devices in space crafts
    → Huge temperature range



- Perform transient current technique (TCT)
  at various controlled temperatures and field strengths:
  → Provides a powerful technique
  for study of transport characteristics

- Analyse current pulses in terms of transit time, area, ...
  → compare data to model

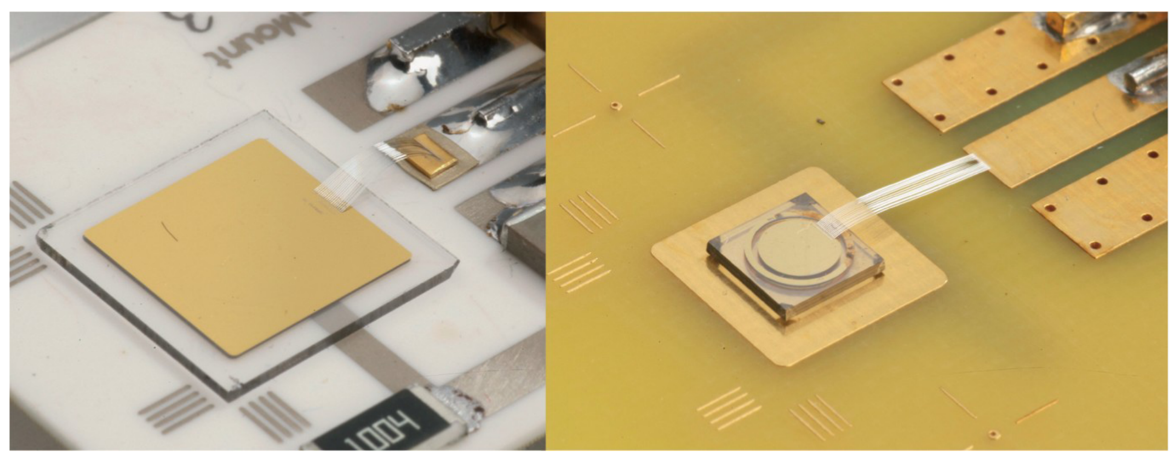
Why Diamond

Pros:

- High band gap (5.5 eV)
  → Very high breakdown field > 1e7 V/cm
  → Very high resistivity > 1e11 Ωcm
    → Large area
  → Very low leakage current ~ few pA
- Low dielectric constant (5.7)
  → Low capacitance → Low noise
- High displacement energy (43 eV/atom)
  → Radiation hard → No replacement
- High mobility (~2000 cm^2/Vs)
  → Fast signals
    → High collision rate
- Very wide sensitivity range
  → Single MIP to few THz tested
- Wide operational temperature range

Cons:

- High $E_{pair-creation}$ (13.5 eV)
  → Less signal, but S2N-ratio comparable to Si
- Rather high costs
- Not as well understood as Si
  → More R&D efforts needed



The Experimental Technique

- The Transient-Current Technique (TCT) measurement:

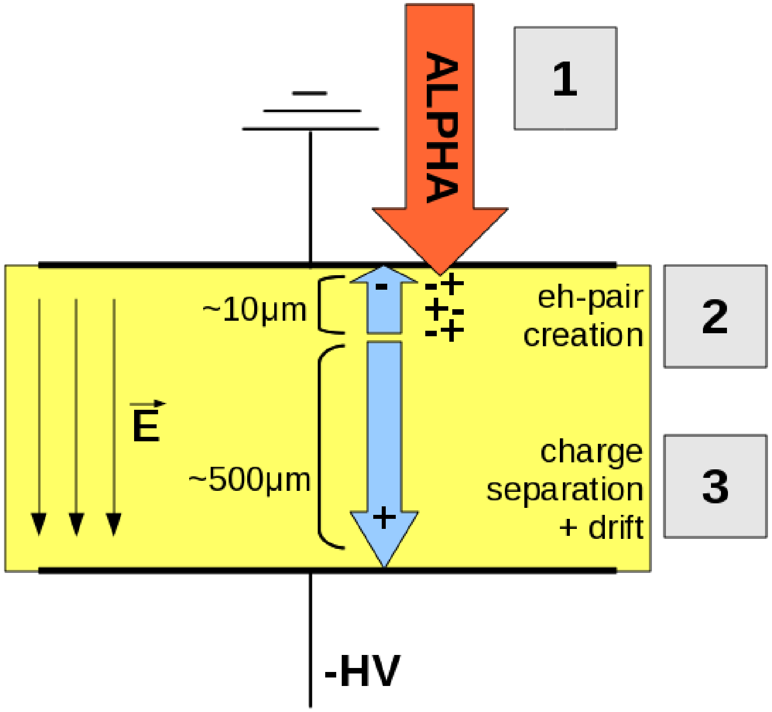
  1) α particles impinge on top side
  2) Create eh-pairs close to electrode
  3) Electric field separates charges
  4) Drifting charges induce current

  → measure the transient current

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

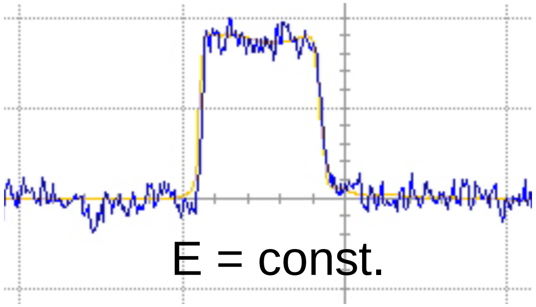
  → Use fast (2 GHz), low noise (3 mV) current amplifier, 40 dB

  → record signal with oscilloscope

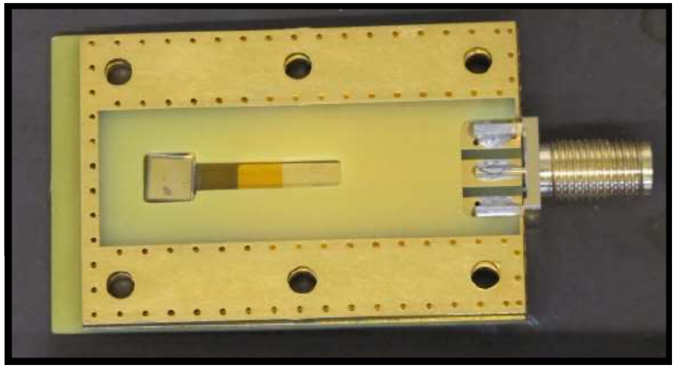


4

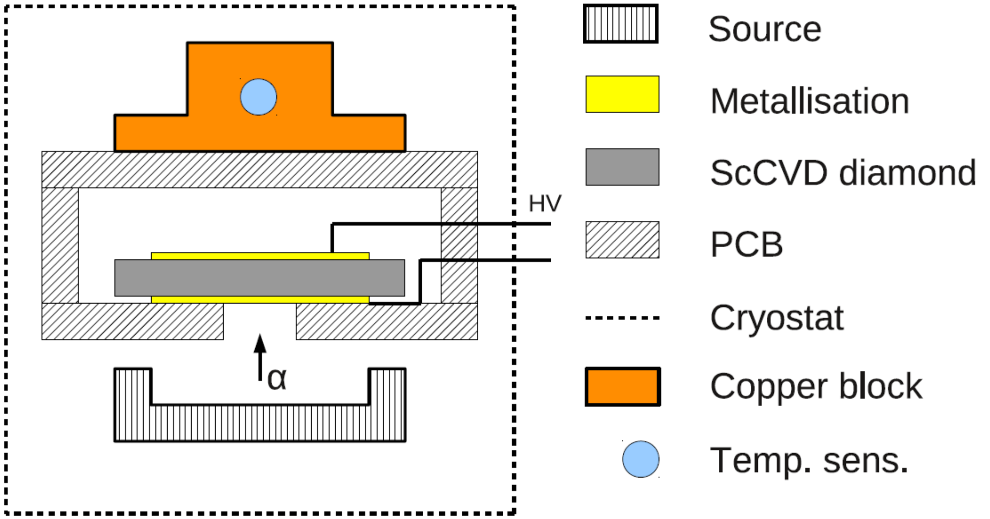
$$i(t)=Q(t)v(t)/d$$



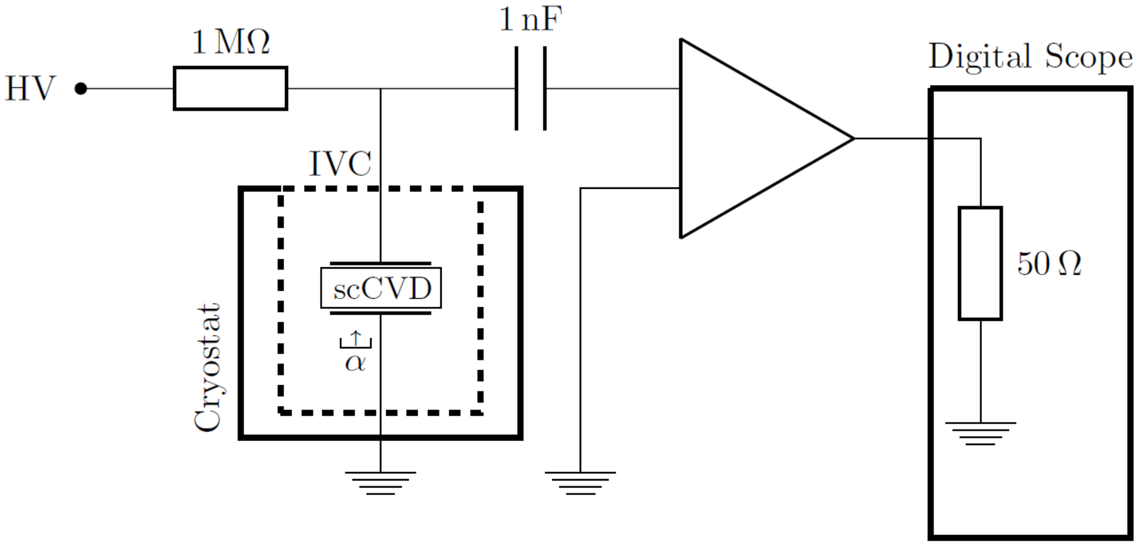
- Sensor + Sensor holder:



Sample size: 5x5 mm^2, 500 µm



- Circuit schematics:



The Cryostat

- Outer chamber:

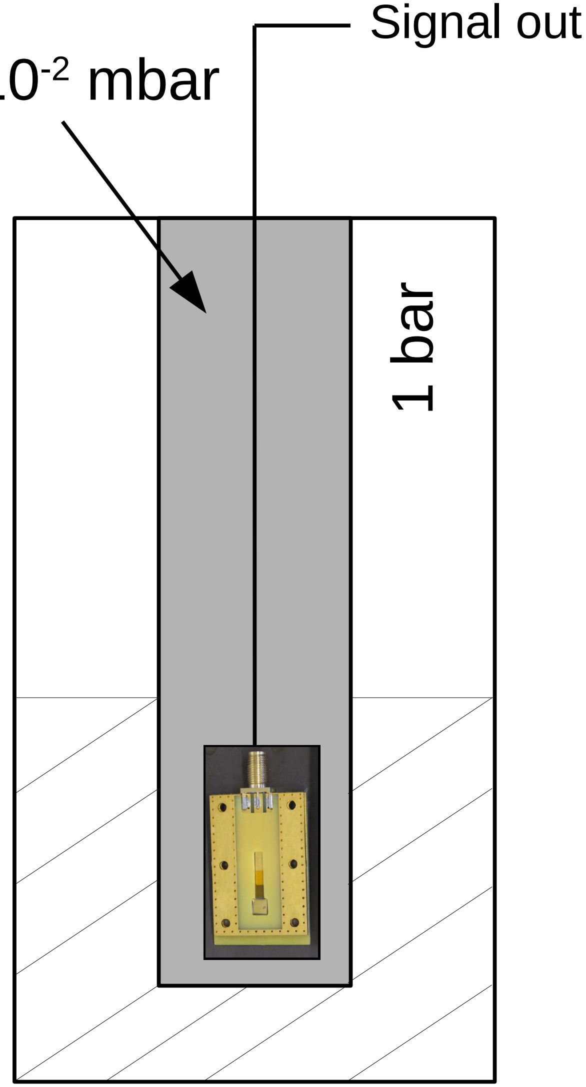
  - liquid helium
  - pressure = 1 bar for T ≥ 4.2 K
  - pressure few mbar for T = 1.6 K

- inner vacuum chamber:

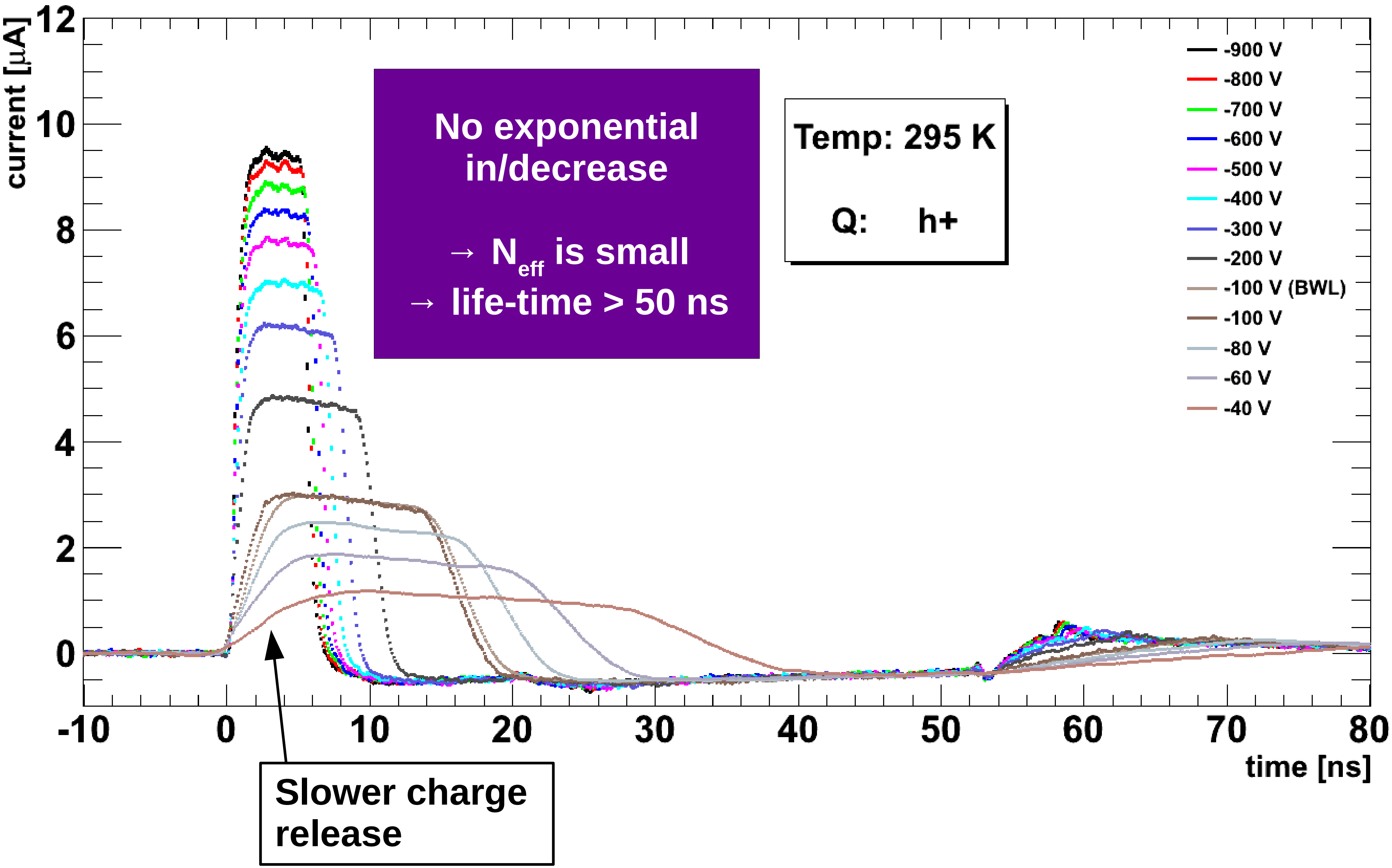
  - helium gas @ few 10^{-2} mbar
  - where the sensor is

    → almost no energy loss of the αs
    → high breakdown voltage
    → good thermalisation

5x10^{-2} mbar



TCT Pulses at RT: Holes

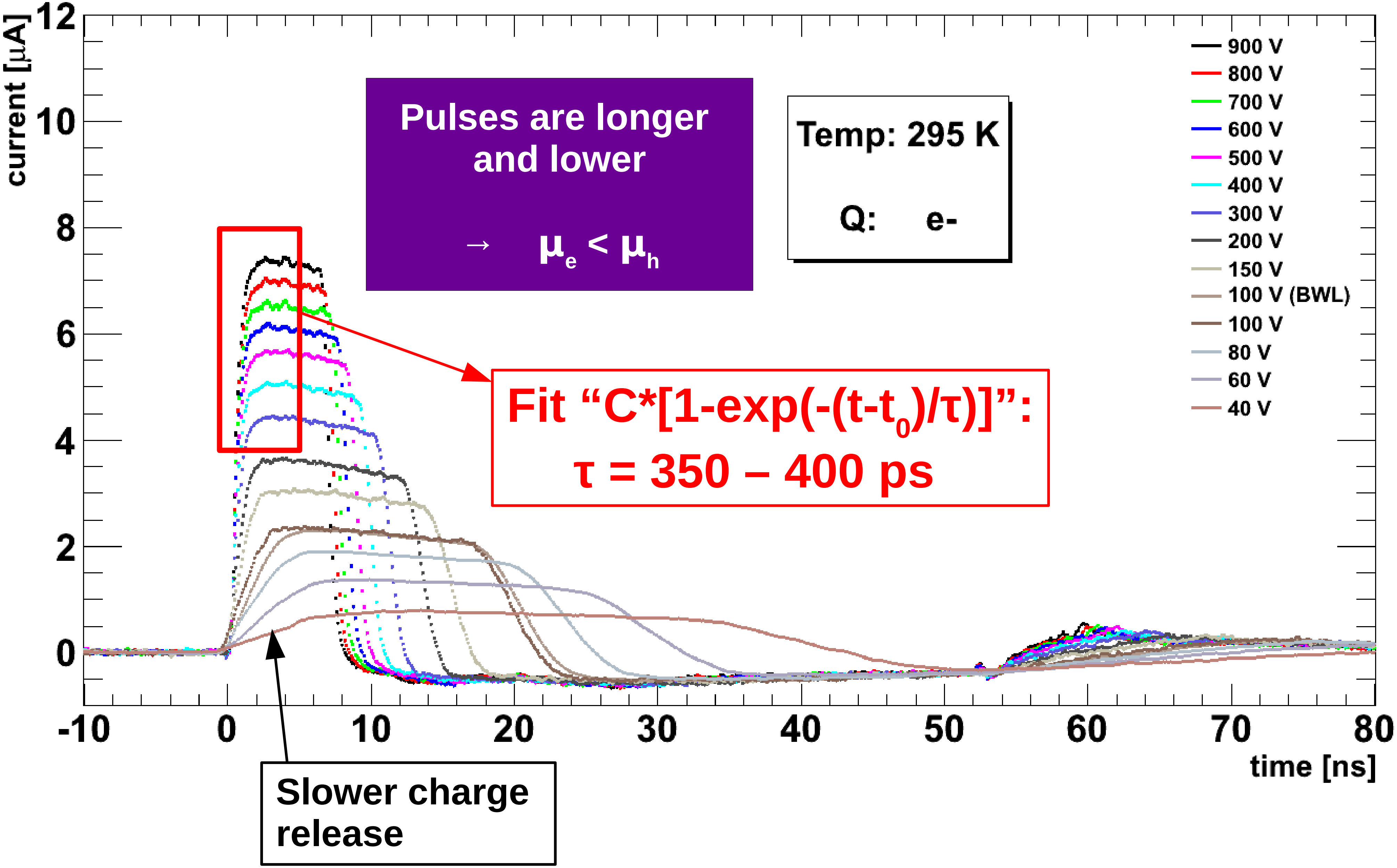


No exponential in/decrease

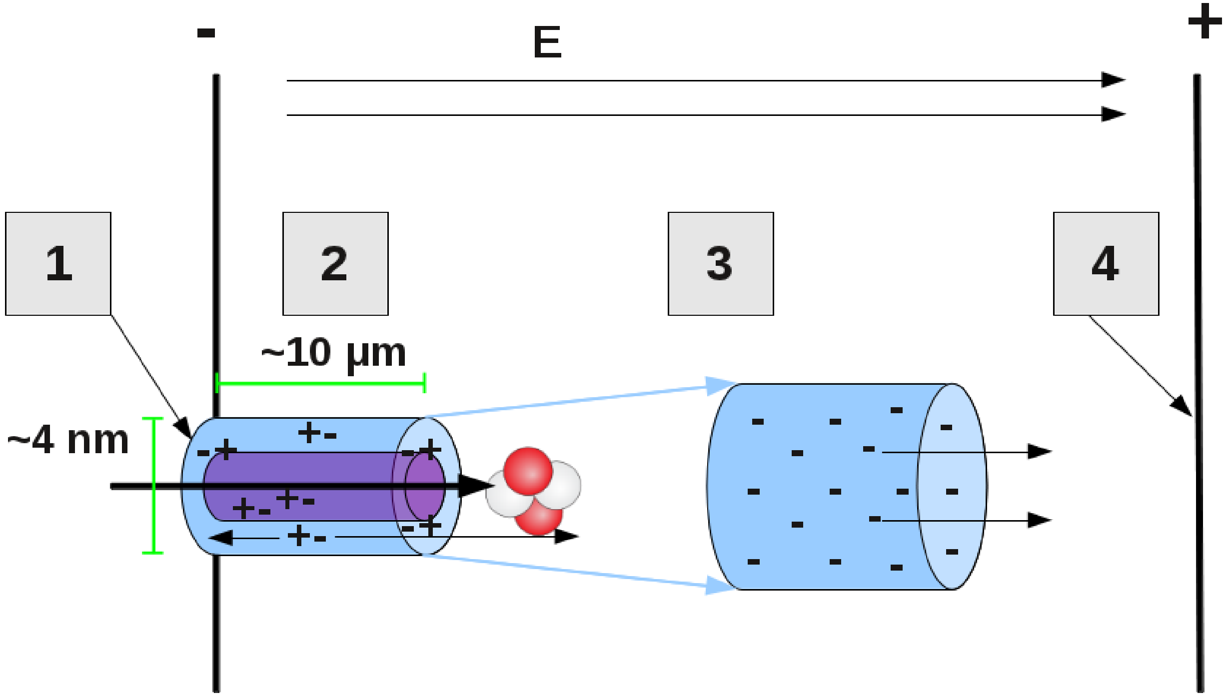
→ N_{eff} is small

→ life-time > 50 ns

TCT Pulses at RT: Electrons



The Plasma



1 Creation of eh-pair cloud

2 Hot, high density plasma → cooling via phonon transport (~100ps)

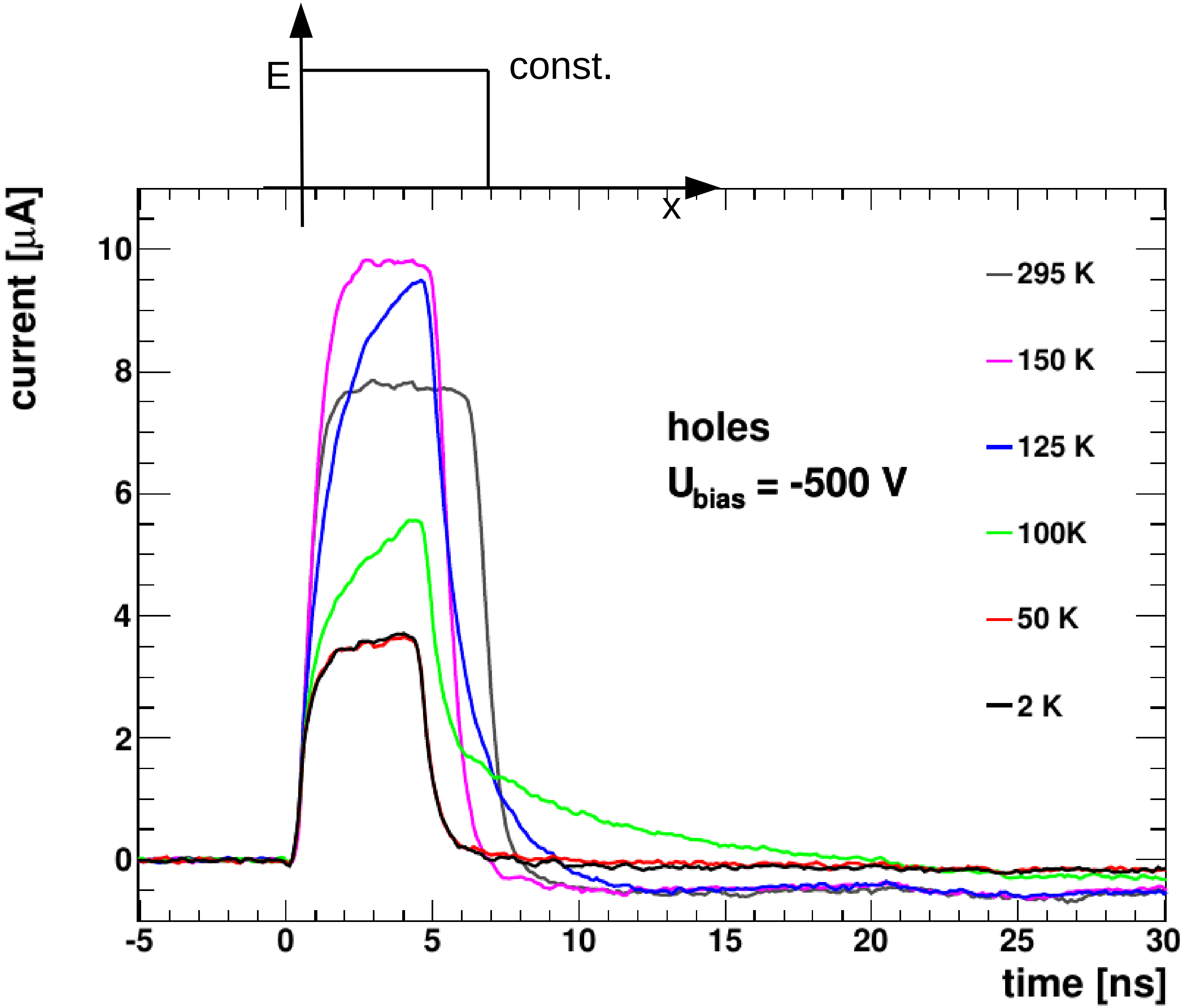
3 drift + diffusion (ns)

4 Collection at electrode

- αs produce high density charge cloud
- Outer charges screen inner ones only in very early phase of the plasma
  → E-Field penetrates plasma after 100 ps or so
- E-Field influences “inside” to “outside” fraction

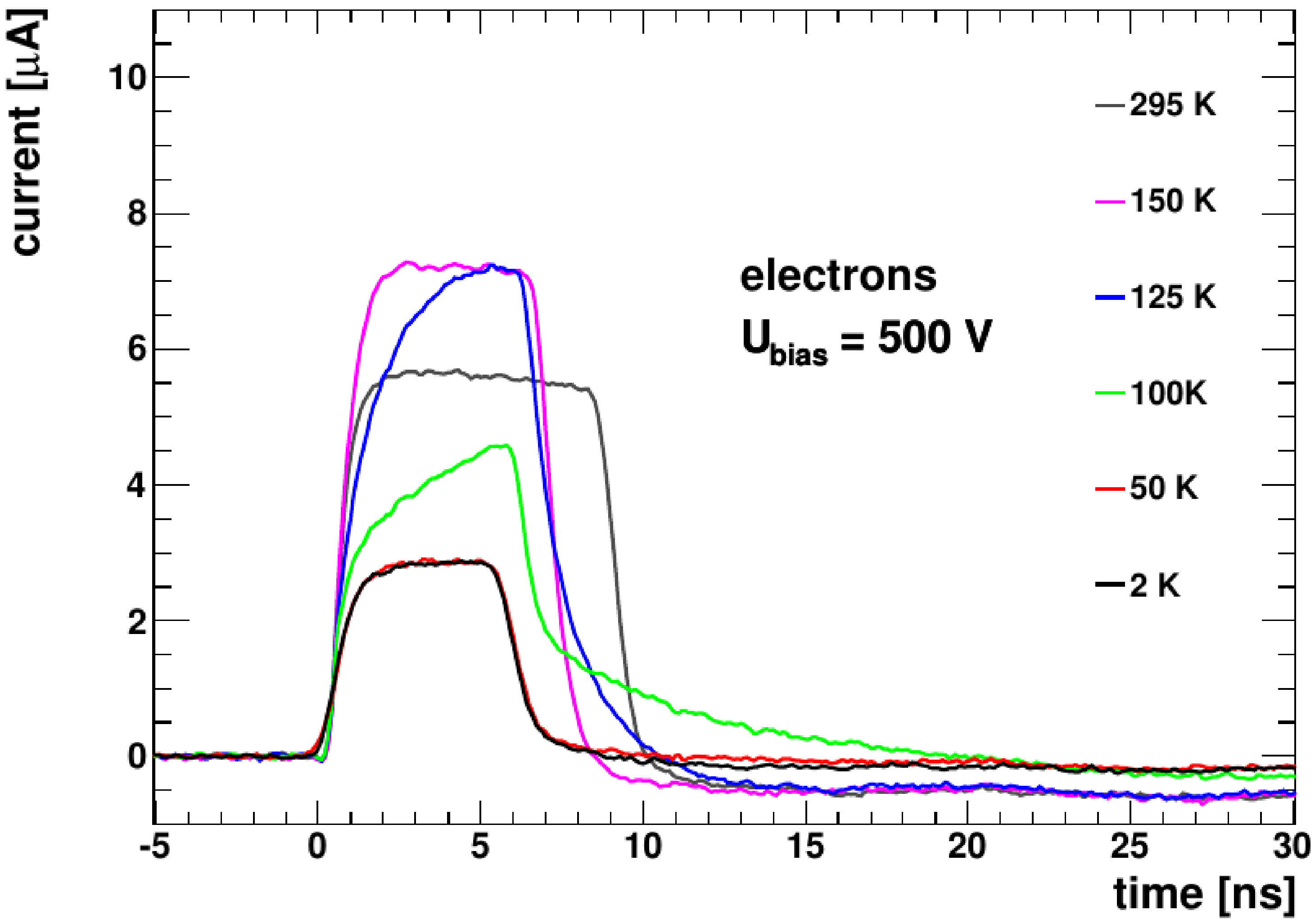
$$\rho_{cloud} \approx \frac{3.5 \cdot 10^5 \, pairs}{(2\,\mathrm{nm})^2 \pi \, 10\,\mu m} \approx 10^{21} cm^{-3}$$

TCT Pulses at Various Temperatures

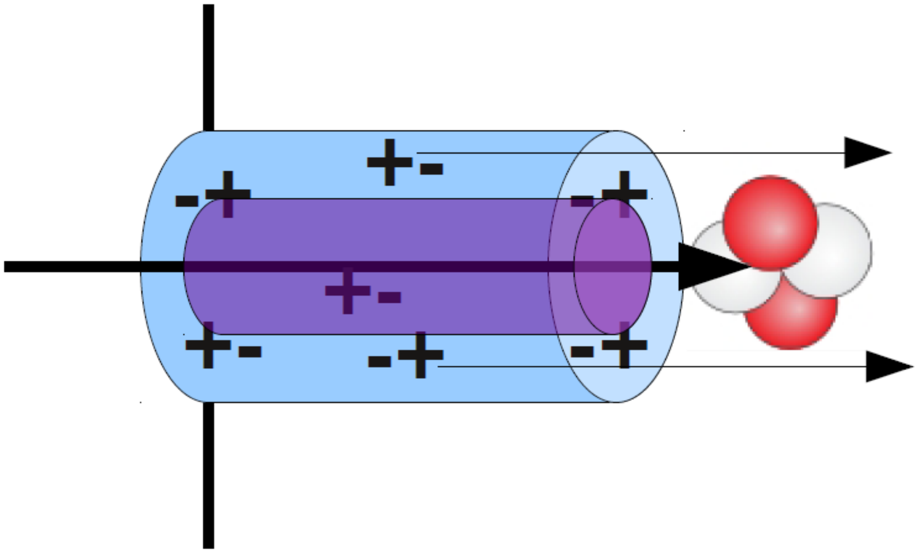


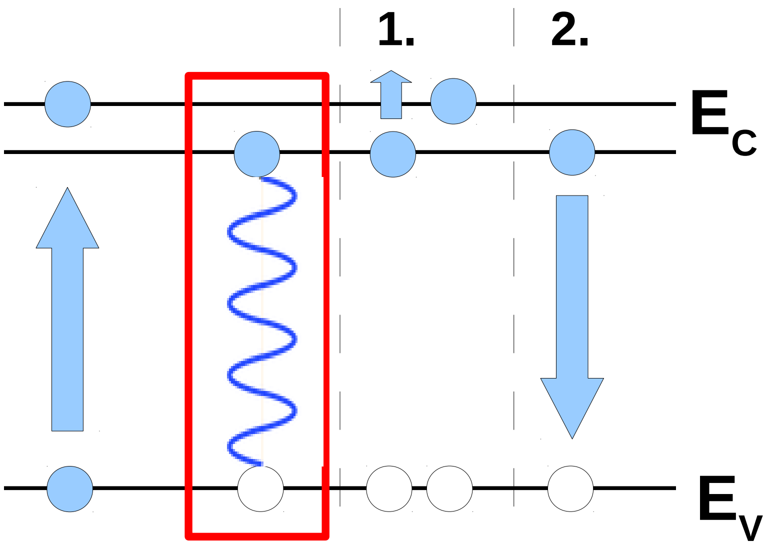
Verified for three samples, two metallisations !

TCT Pulses at Various Temperatures



The Plasma again





- Always collect "outer" charge
- Fraction inner to outer
  → E-Field dependent

Exciton "Decay-modes":
1. dissociation
2. recombination

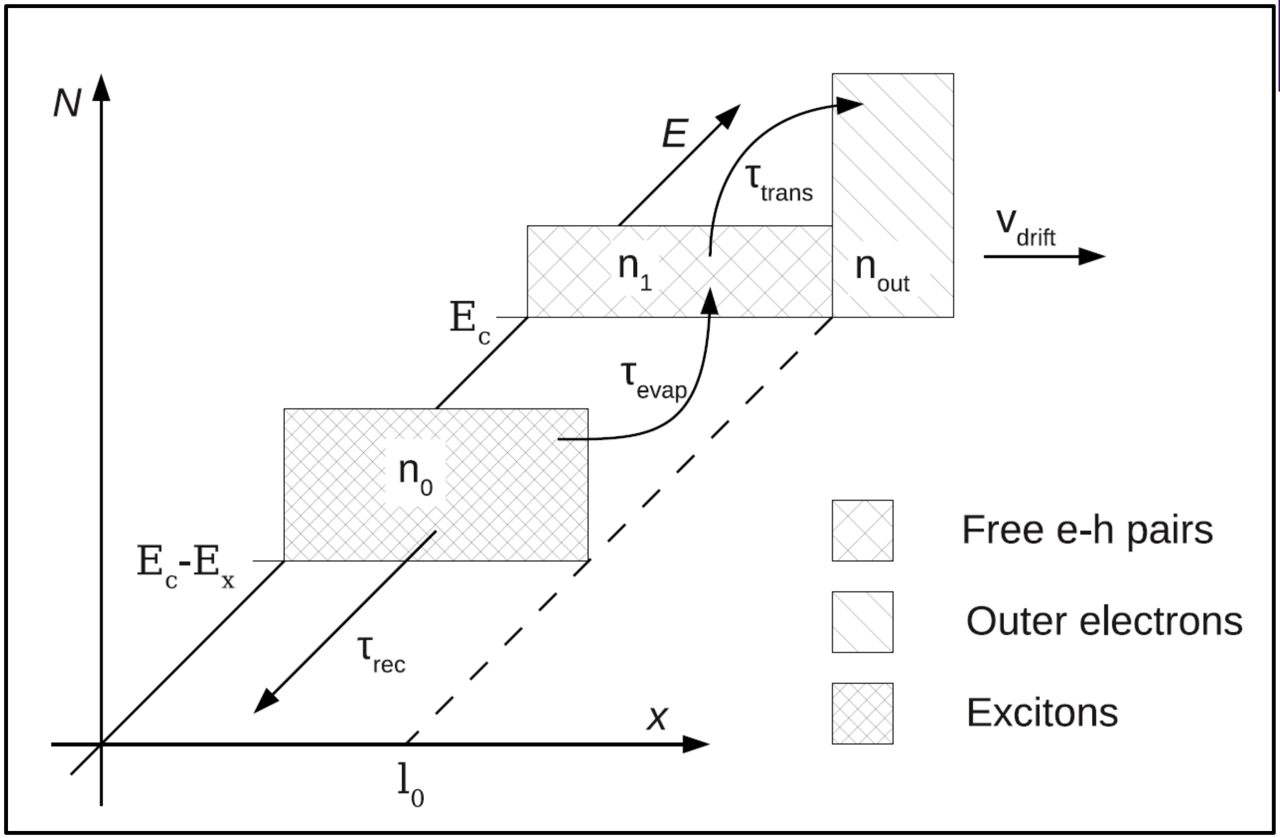
- "Inside": Thermal equilibrium between excitons and free e-h pairs
- Charges are released with $\tau_{evap} \sim \exp(E_X / kT)$
  → charges being retained, thermal lifetime 100 ps (RT) to 100 us
  → recombination time (~2ns) important for T < 150 K

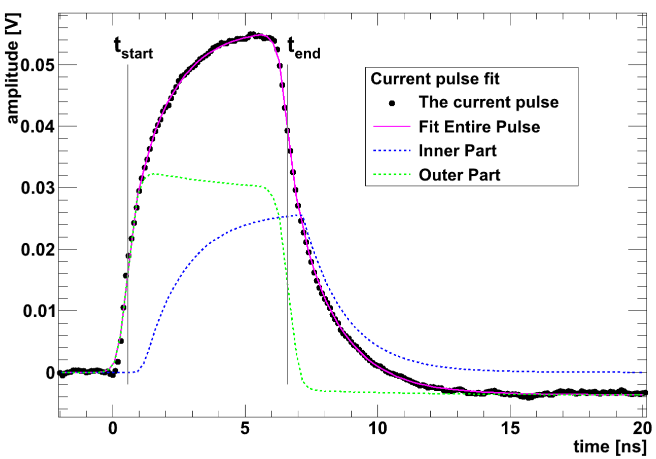
The Model

- Creation of excitons and subsequent ionisation or recombination
- If ionised, charges are transported

Two competing processes: τ_{rec} vs τ_{evap}

$$\frac{1}{\tau} = \frac{1}{\tau_{\rm rec}} + \frac{1}{\tau_{\rm evap}}$$

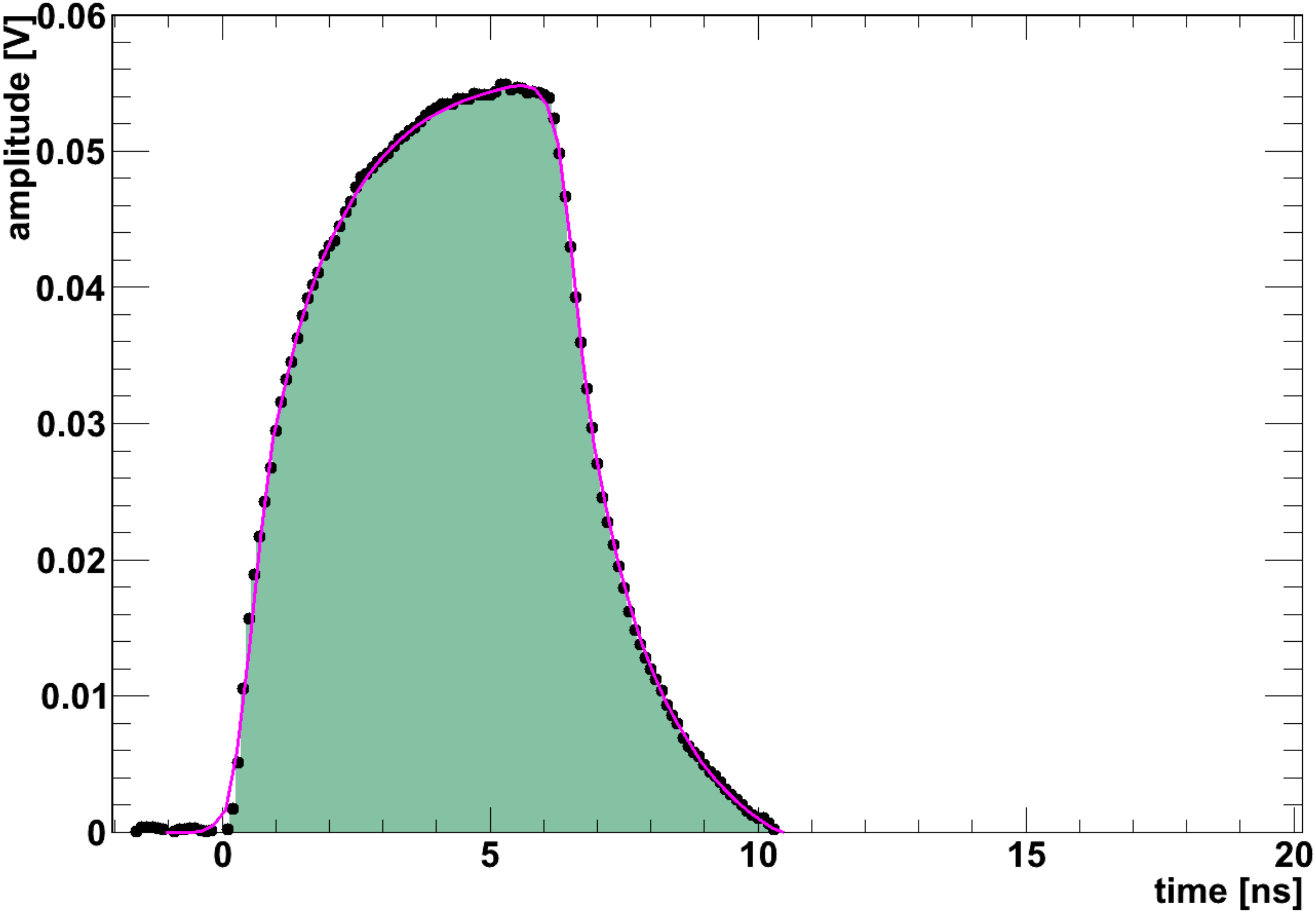




$$n_{\rm out}(t) = n_{\rm out}(0) + n_0(0)\frac{\tau}{\tau_{\rm evap}}\left(1 - \exp\left(-t/\tau\right)\right)$$

Analysis of TCT Pulses

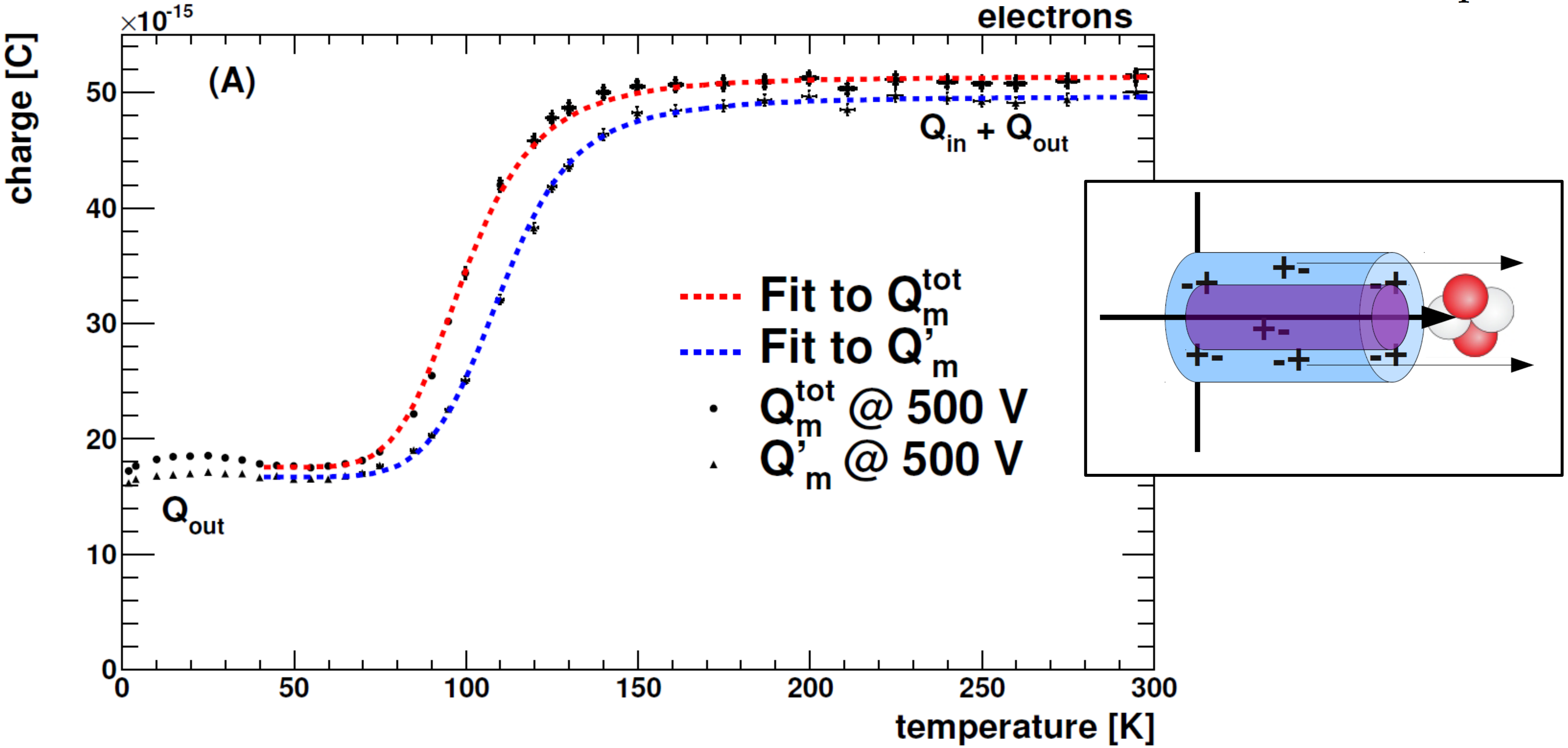
- Calculate integral of pulse:



Integrated Charge

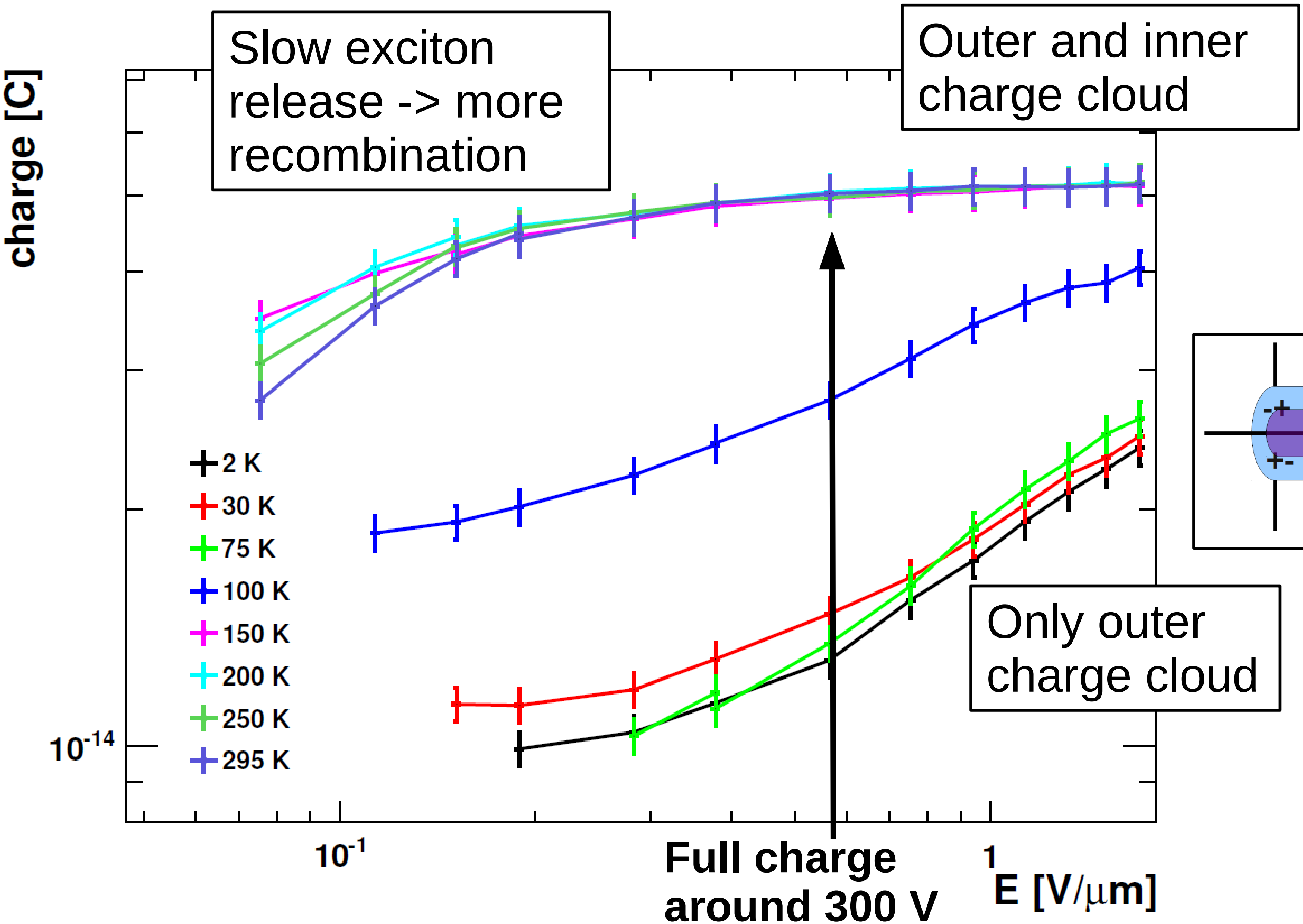
- Integrate $n_{out}(t)$ over t, fit model to the integral of pulses over T :

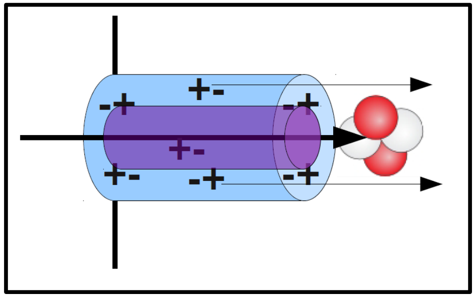
$$Q_{\text{out}} + \frac{\tau_{\text{rec}}}{\tau_{\text{rec}} + \tau_{\text{evap}}} Q_{\text{in}}$$



Integrated Charge

- Charge as function of E-field:





Integrated Charge

- For T> 150 K:

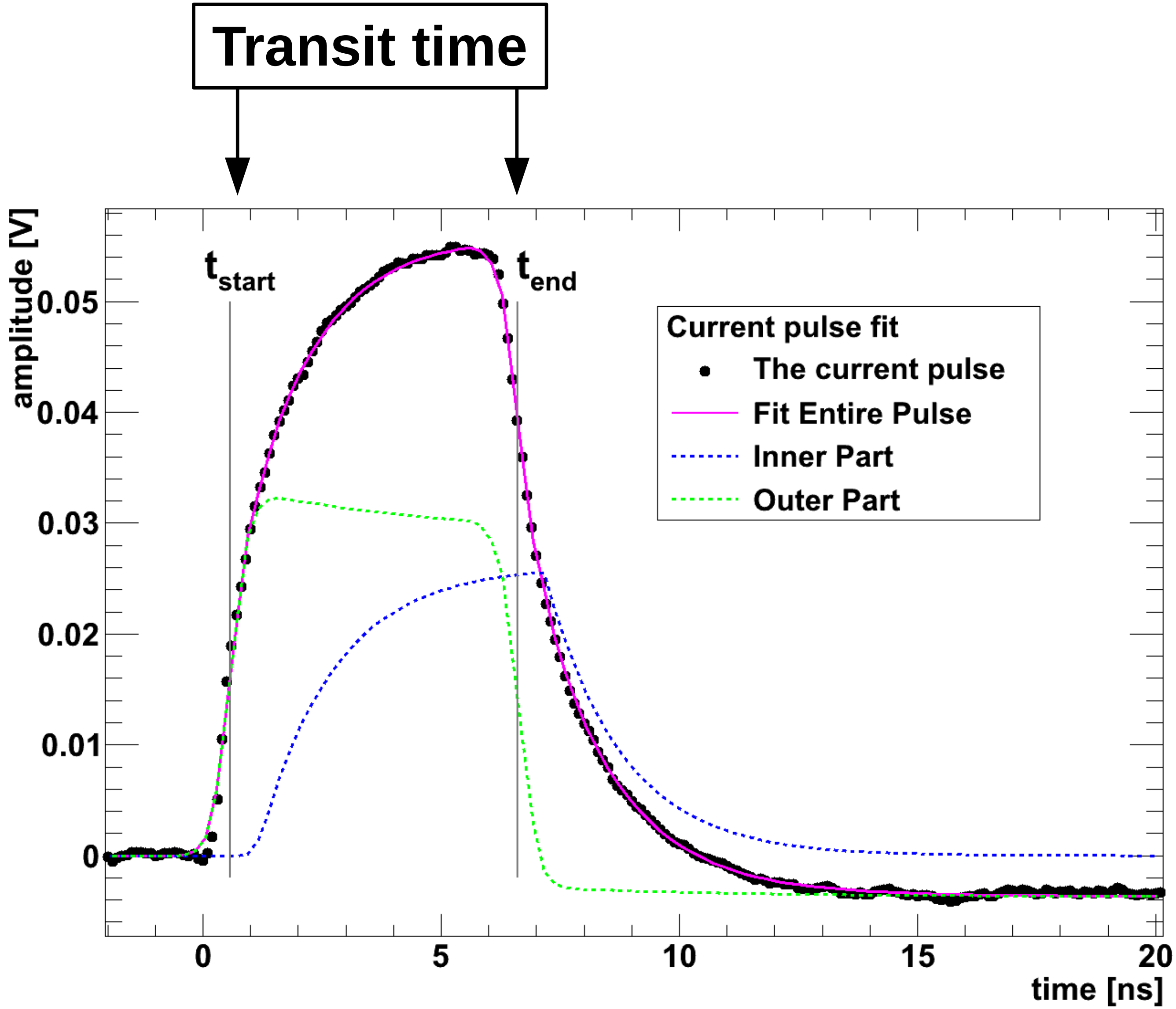
  - Full charge at 300 V
  - Recombination leads to charge
    loss for |U| < 300V, why?
  - NO TRAPPING DURING! See flat pulses.
    Q-E behaviour not dominated by CCD ($\tau_{trap} \approx 1us$)
  - This is charge recombination in the early plasma
  -> Dominant charge loss mechanism in high-quality,
    unirradiated scCVD diamond

- For T < 80 K:

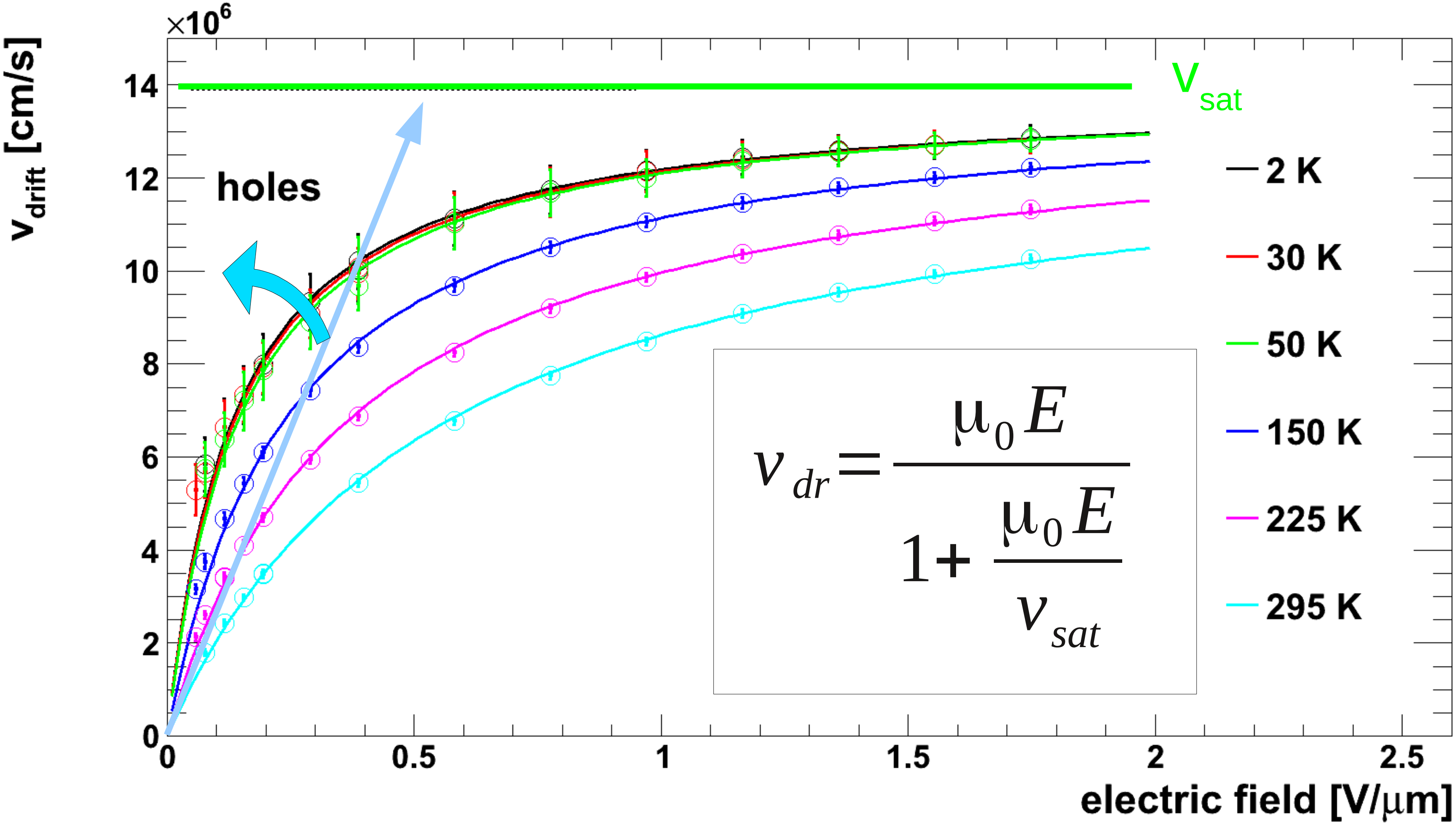
  - ALL inner charges recombine
  - only measure outer charges
  - See how "outer" part grows with field strength
    -> sensitive to physical processes
      within first ~100 ps of the plasma!

Analysis of TCT Pulses

- Fit rectangular (2- Erfc(t)) – (2- Erfc(t-t'))
  + exponential (1-exp(-t/τ)) - (1 - exp(-(t-t')/τ))



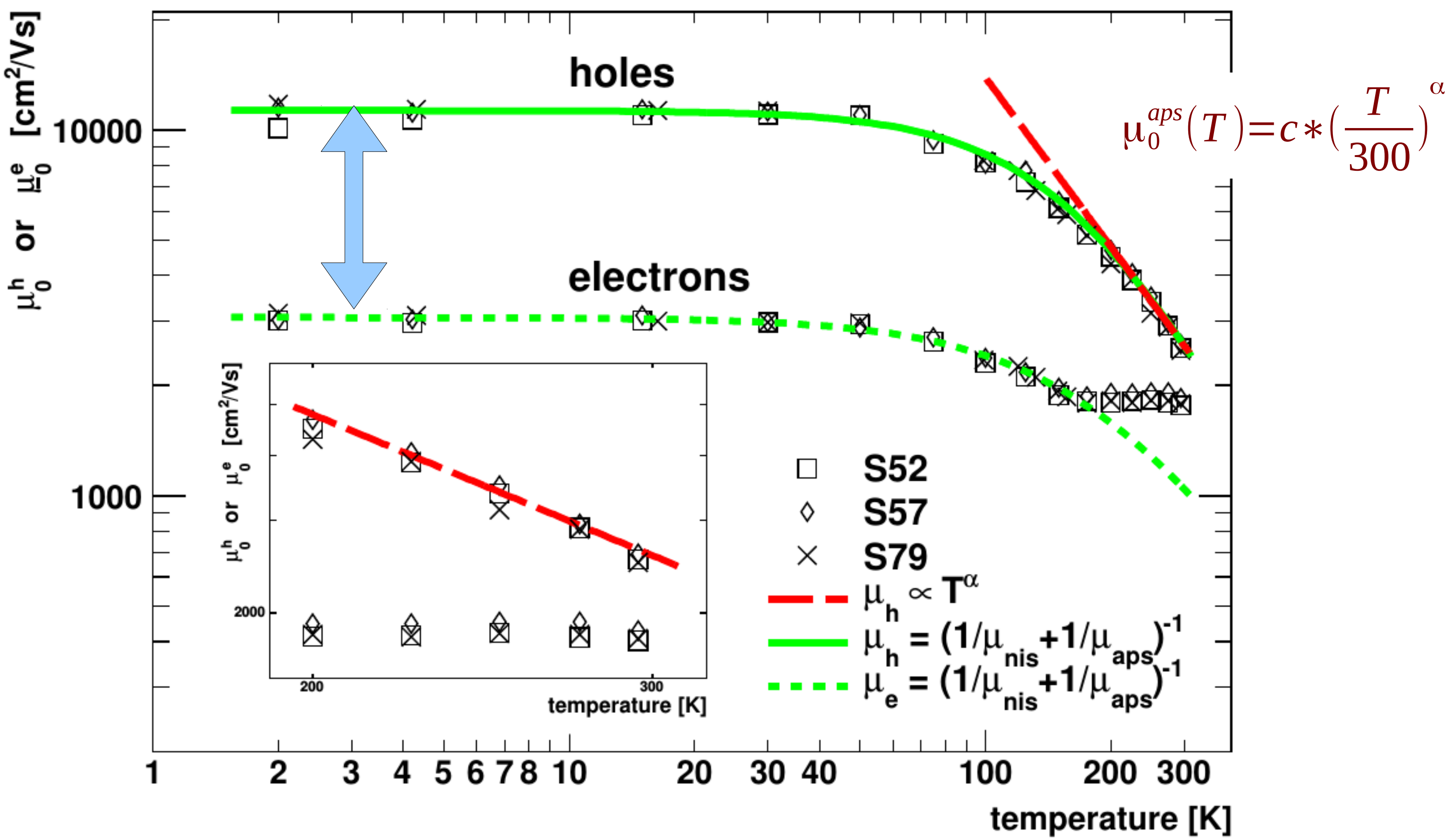
Hole Drift Velocity



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

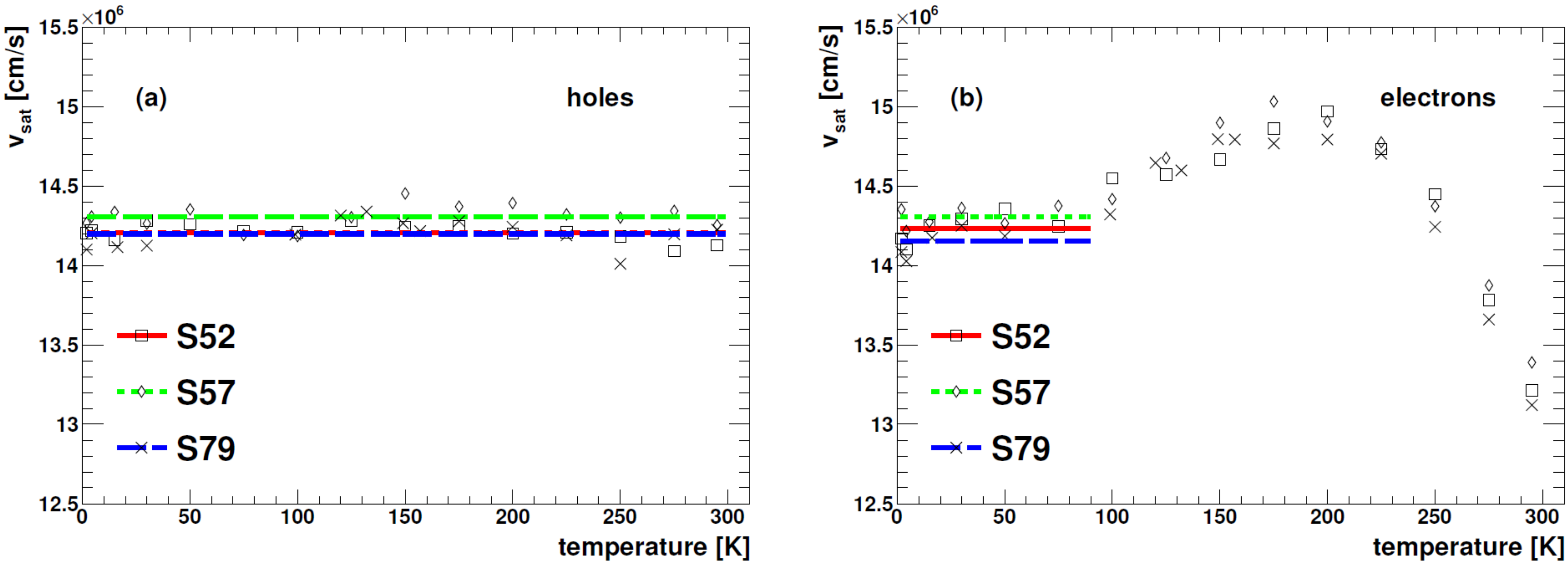
- μ_h increases with decreasing T down to 2 K
- v_{sat} ~ constant with temperature @ 14e6 cm/s

Mobility vs. Temperature



- Holes: For 300 K <T< 200K the mobility increases as acoustic phonon scattering decreases: $\alpha = -1.49$, $\mu_0 = 2400$ cm²/Vs
- 50 K to 10 K: mobility stays ~const.
  -> scattering dominated by neutral impurity scattering

Saturation velocity



- Holes: v_{sat} ~ constant with T , low T limit: 14e6 cm/s
- Electrons: v_{sat} has certain dependence, low T limit: 14e6 cm/s

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Mobility vs. Temperature

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Temperature dependence of charge carrier mobility in single-crystal chemical vapour deposition diamond

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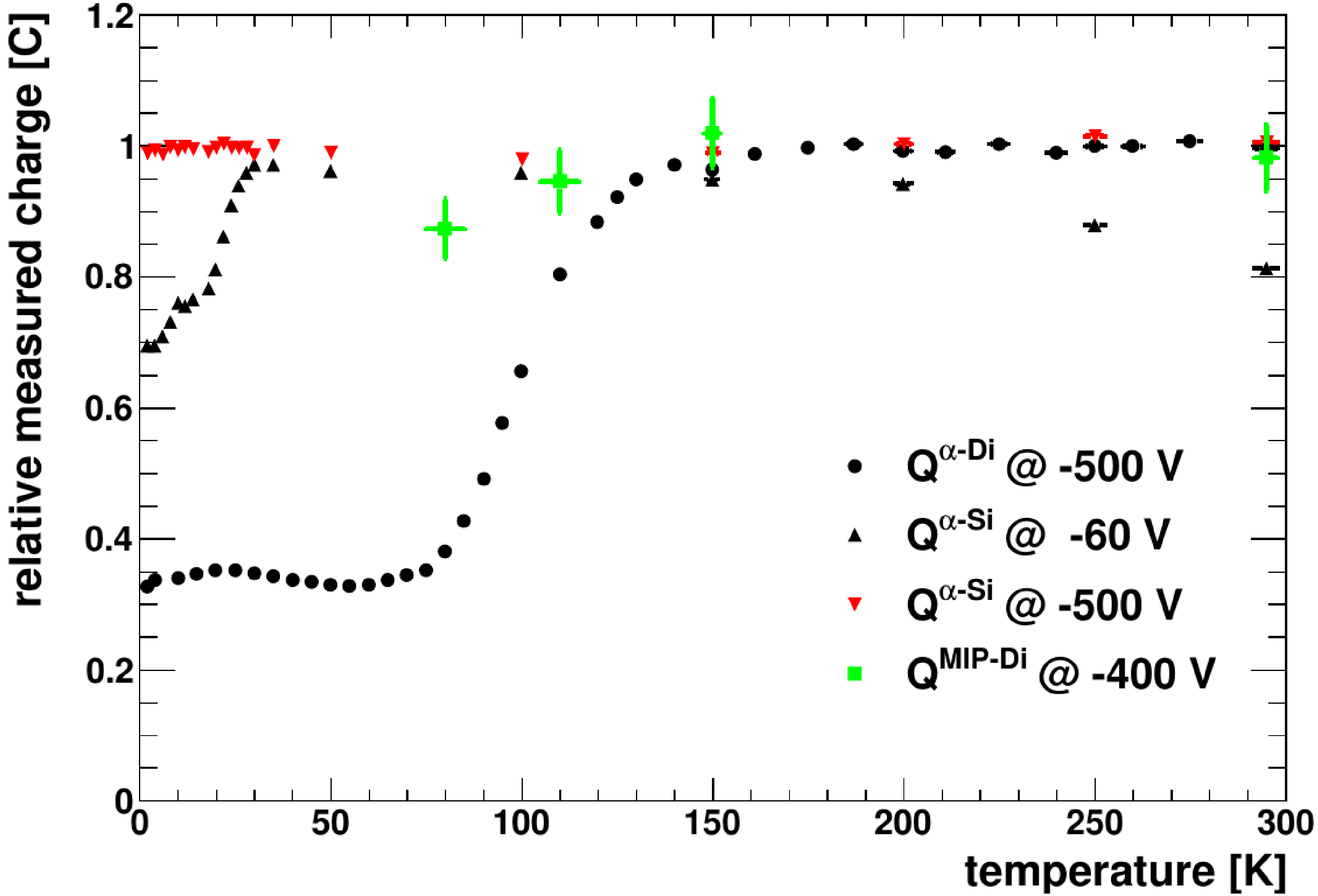
View Map

(Received 25 February 2013; accepted 8 April 2013; published online 6 May 2013)

Comparison with Silicon

- $\tau_{evap} \sim \exp(E_X / kT)$!

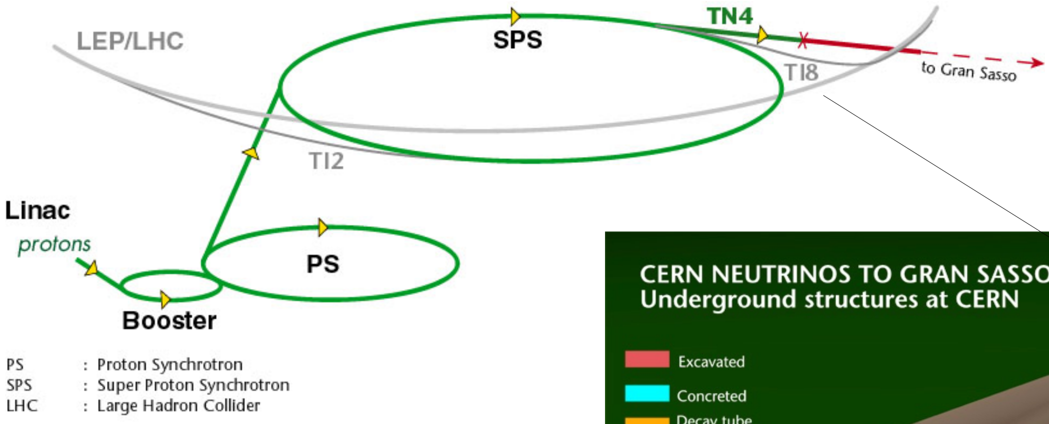


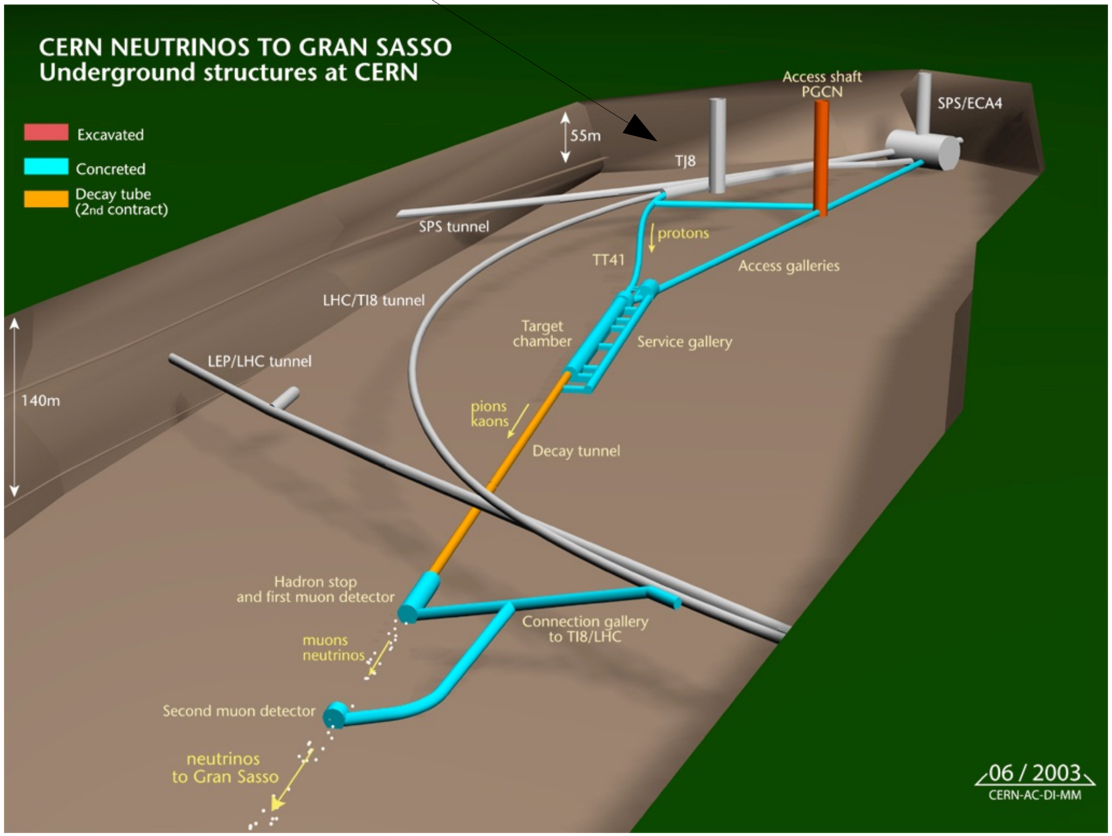
Conclusion from cold measurements

- Diamond detects radiation even at 2 K
- Charge collection is function of the temperature:
  → full charge at T > 150 K
  → collection of 'outer charge only' for T ≤ 75 K
- Creation of excitons by alpha particles in the diamond
  → maybe implications even at room temperature?
  Surface recombination, etc.
- First diamond mobility measurement down to 2 K
- Further reading:
  - H. Pernegger et al., JAP 97 (7) (2005) 073704.
  - C. Erginsoy, Phys. Rev. 79 (1950) 1013–1014
  - H. Jansen et al., Physics Procedia 37 (2012) 2005
  - H. Jansen et al., JAP 113 173706 (2013)

Usage of CVD Diamond at CNGS

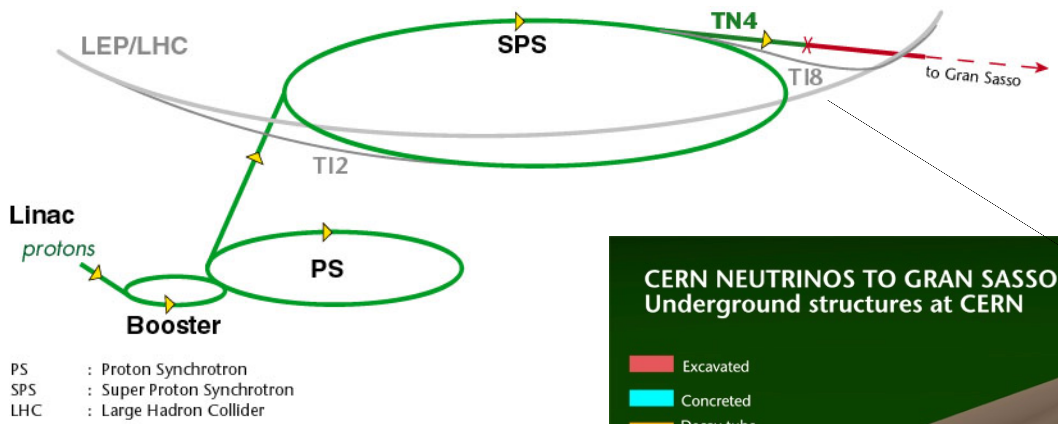
- Where?


LEP/LHC
SPS
TN4
TI8
to Gran Sasso
TI2
Linac
protons
PS
Booster
PS : Proton Synchrotron
SPS : Super Proton Synchrotron
LHC : Large Hadron Collider

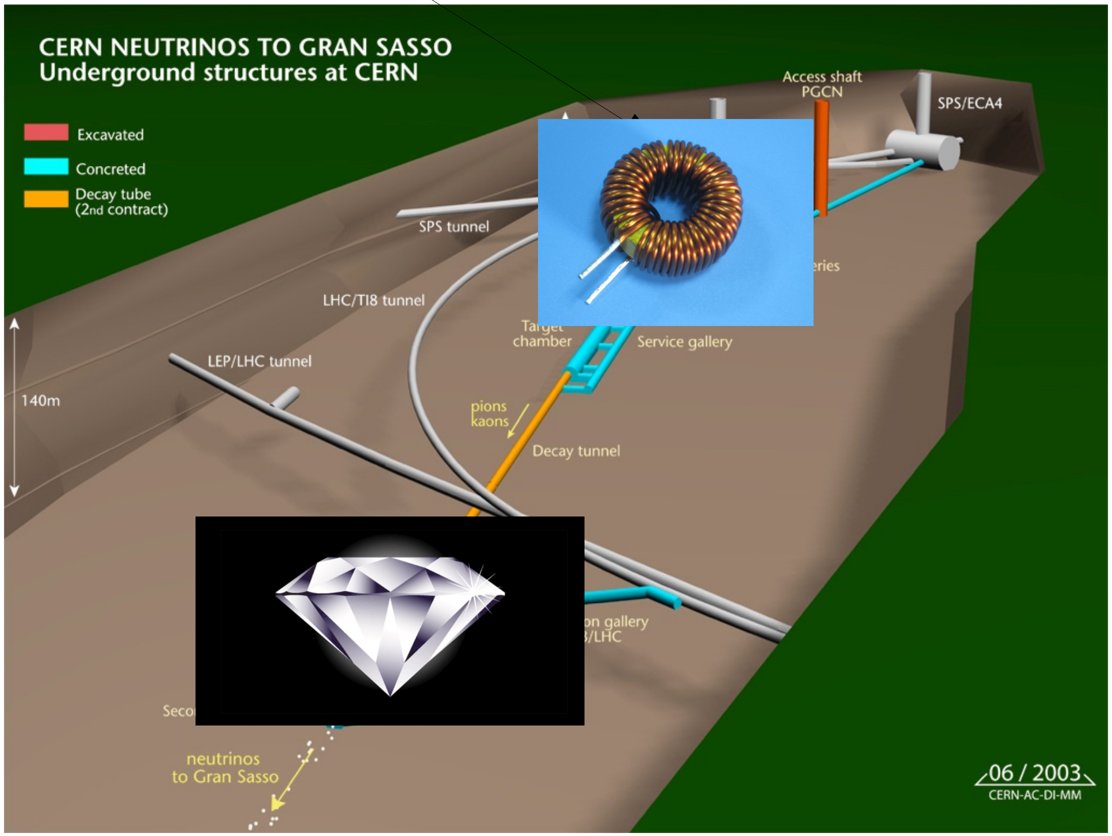

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
Access shaft
PGCN
SPS/ECA4
TJ8
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM

Diamond Detectors at CNGS

- Where?



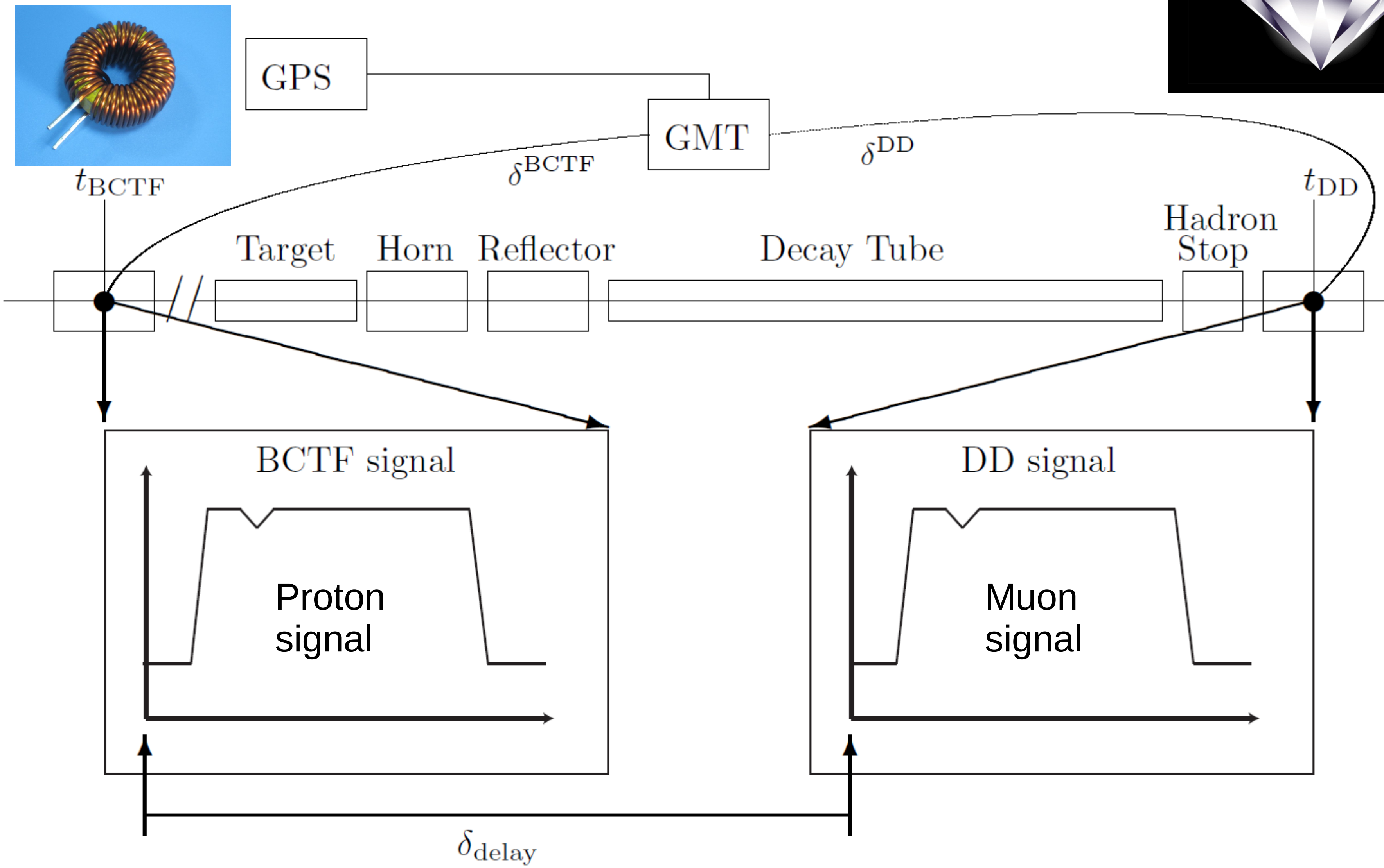
Beam Current Transformer



Diamond Detectors

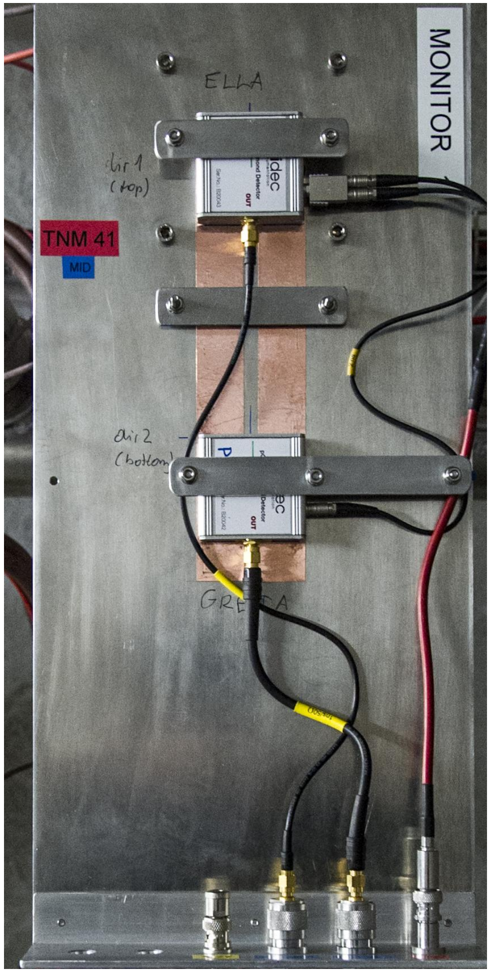
Diamond Detectors at CNGS

- Connection from detectors to Control Room:



Diamond Detectors at CNGS

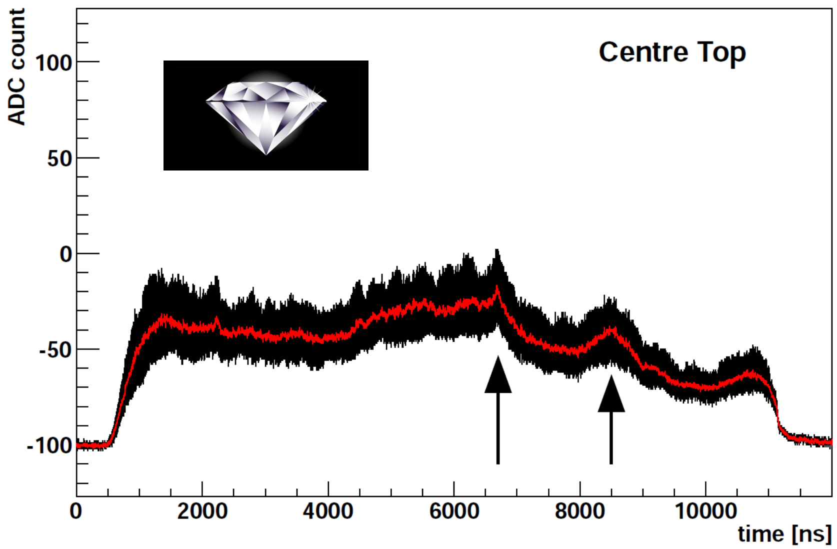
- TNM 41:

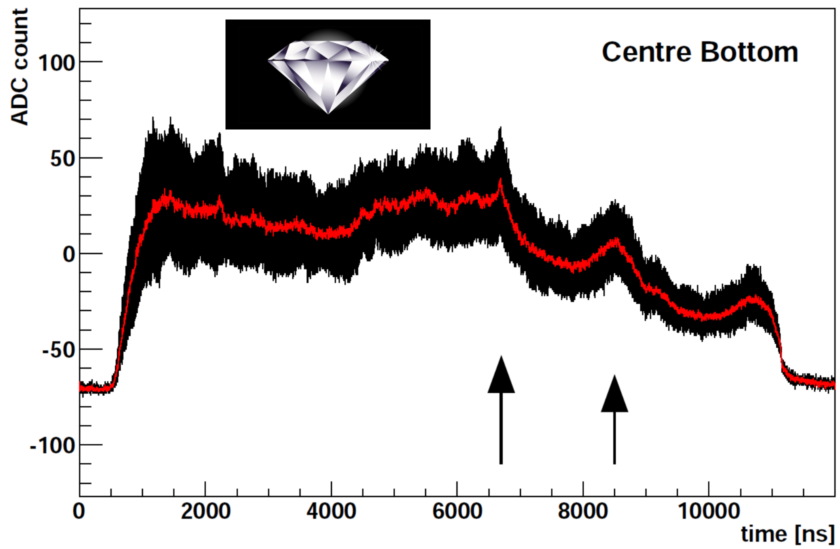


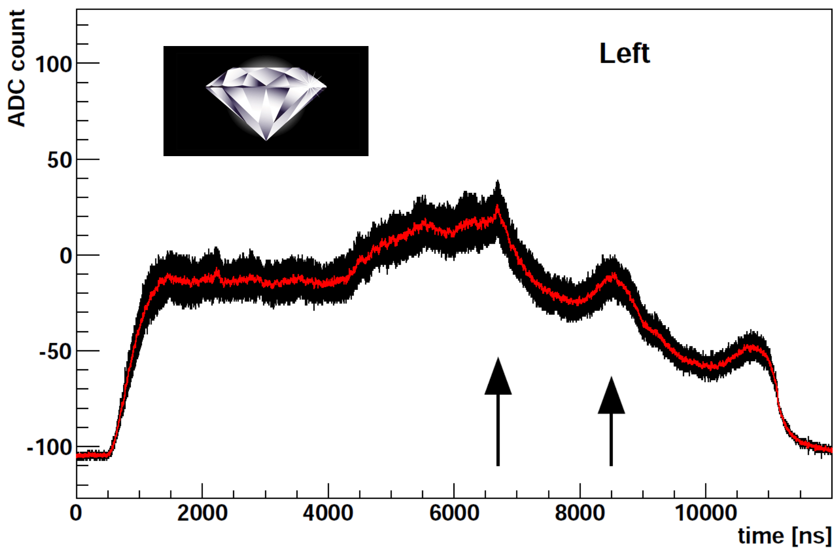
Poly-crystalline CVD diamond detectors:
- 8mm x 8mm
- 500 um thickness
- no amplification, direct scope read-out, 50 Ohm

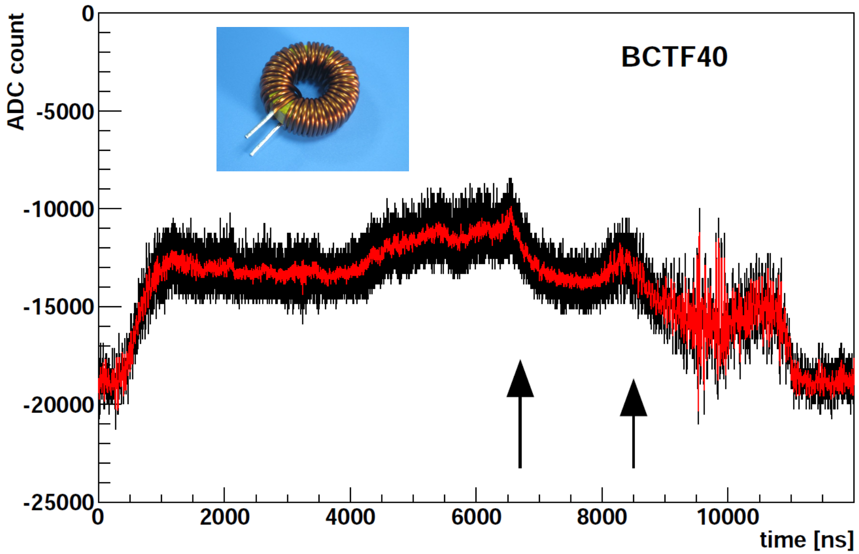
Intensity/Profile Measurements

- From Single Extraction:



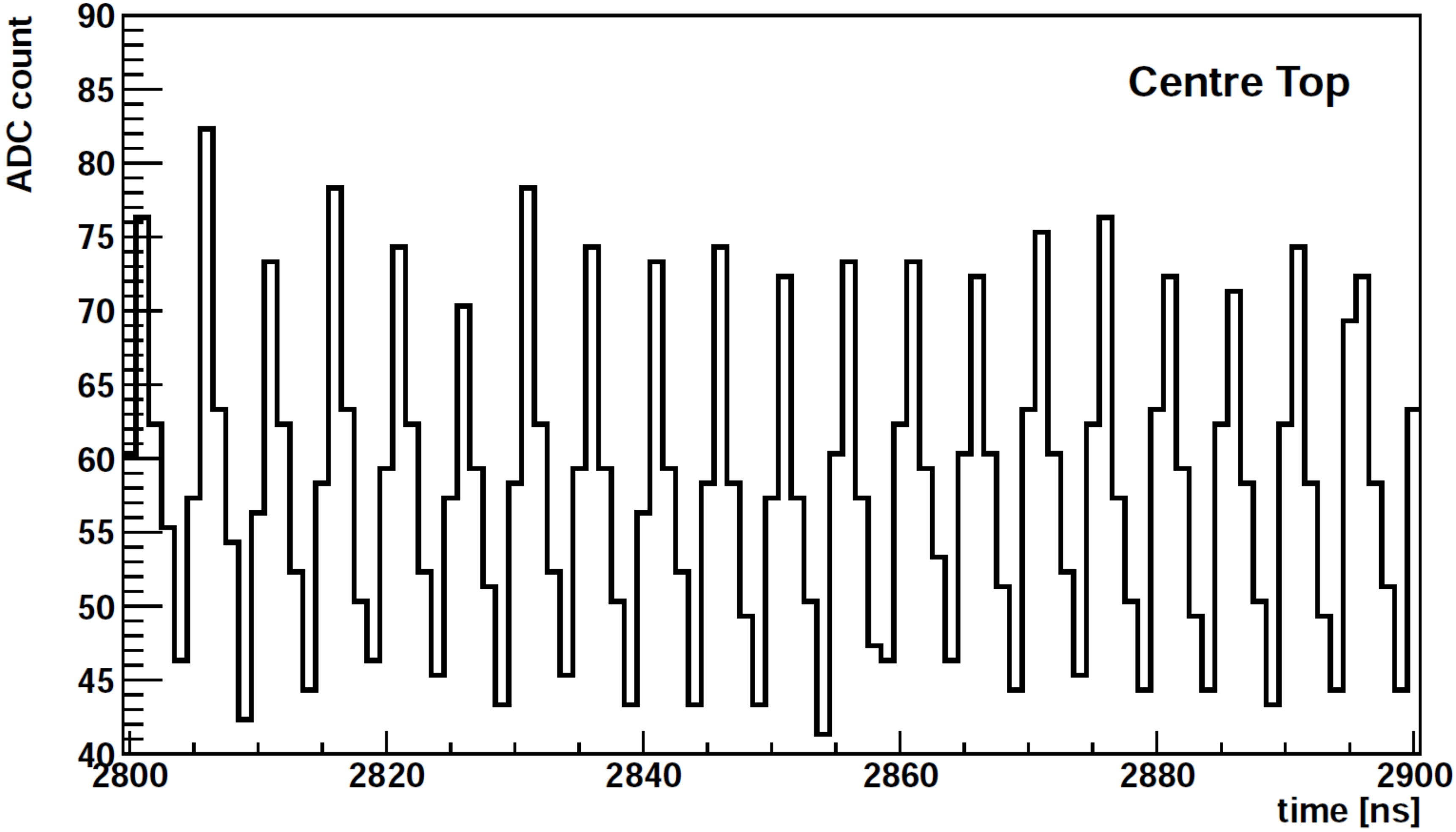






Intensity/Profile Measurements

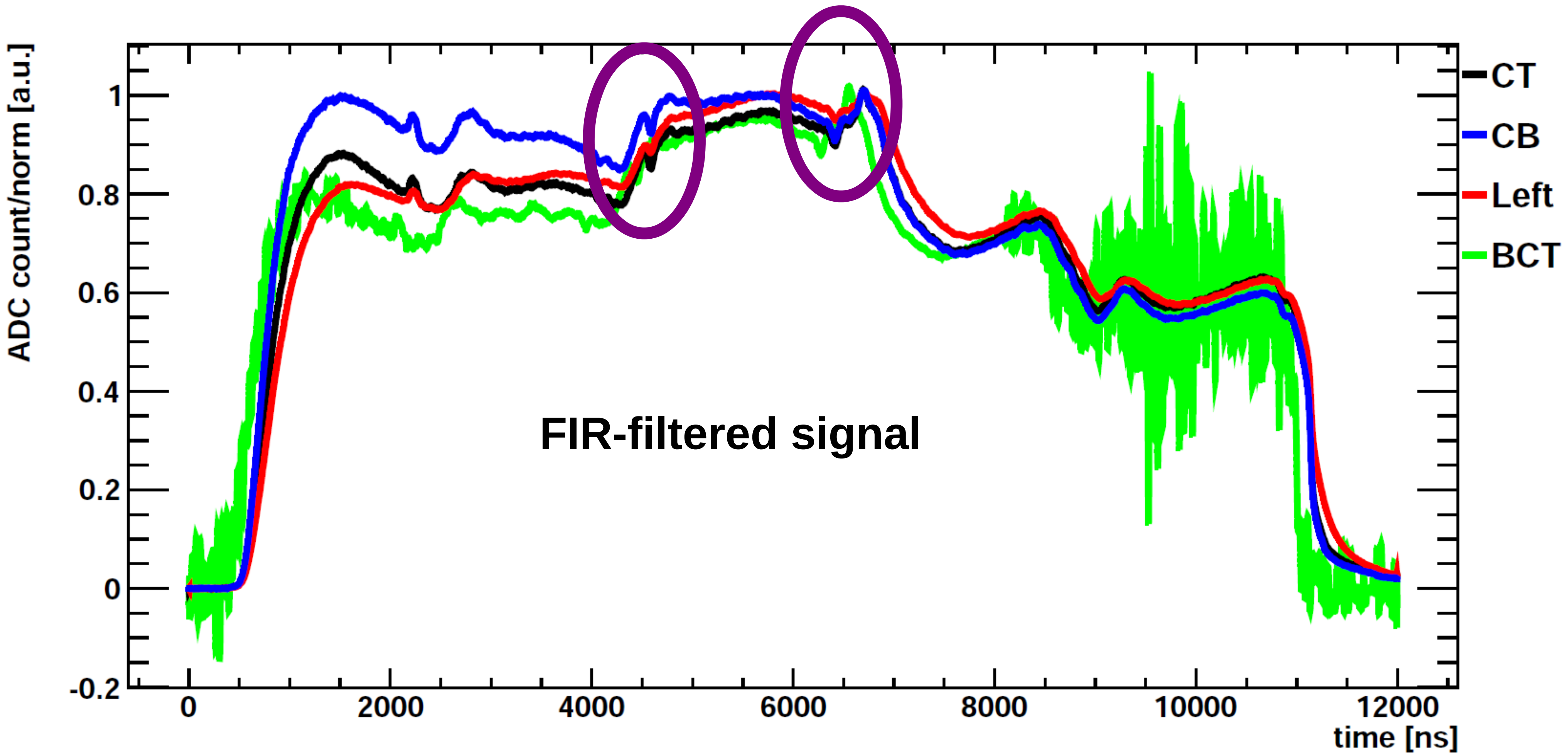
Zoom:



→ 5 ns bunch structure from SPS RF evident

Compare p- to µ-beam structure

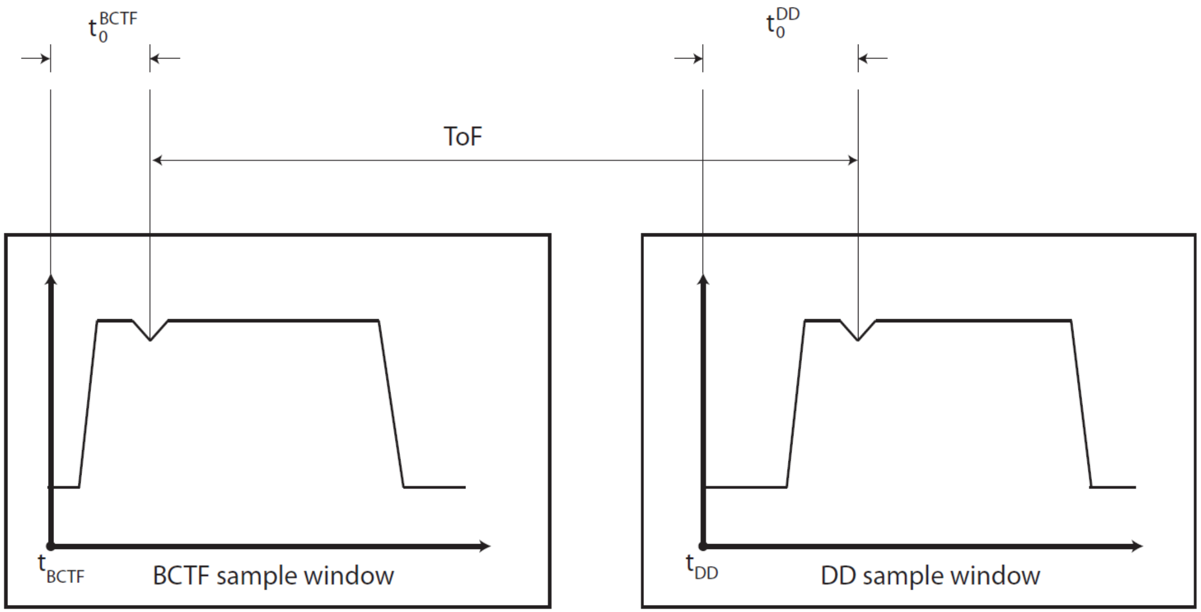
- Signals from BCT and DDs agree nicely
- Even local features show up in both DDs and BCTF



Verification of CNGS Timing

- Measure delays between read-out windows

- Measure timeline offset of signals within read-out window



→ Calculate the Time-of-Flight:

$$\mathrm{ToF}_{\hat{\Theta}_x} = (6205.4 \pm 3.6)\ \mathrm{ns}$$

$$\mathrm{ToF}_{\mathrm{nom}} = \frac{1859.95\ \mathrm{m}}{v} = (6205.3 \pm 2.5)\ \mathrm{ns}$$

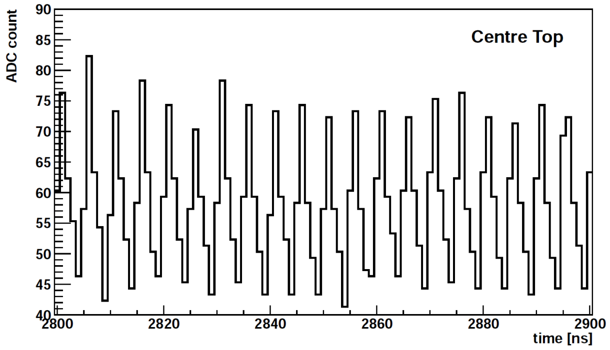
Conclusion

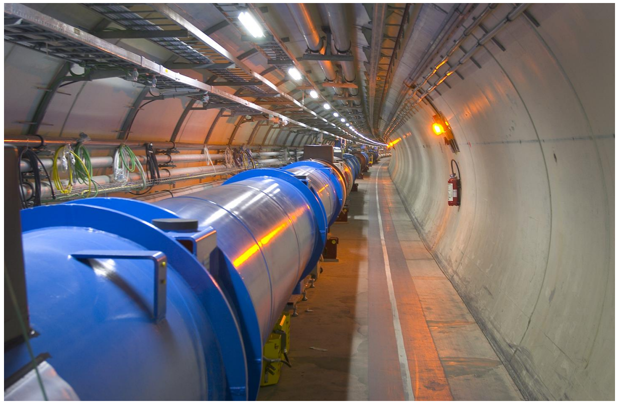
- Diamond is fast:

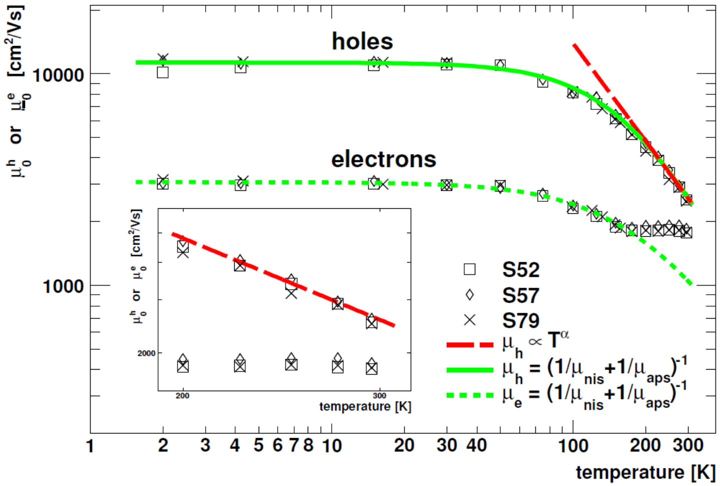
  → Measure individual bunches up to ~200 MHz.

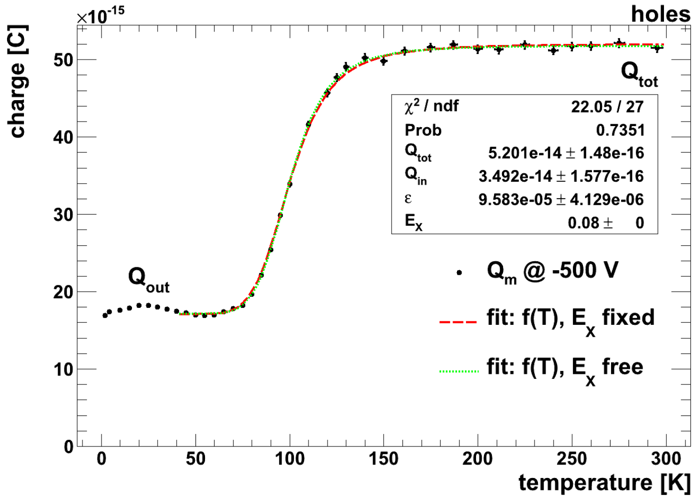
  → Usable as intensity monitor.

- Diamond is usable as cryogenic BLM, just keep in mind T-dependence of mobility and charge yield









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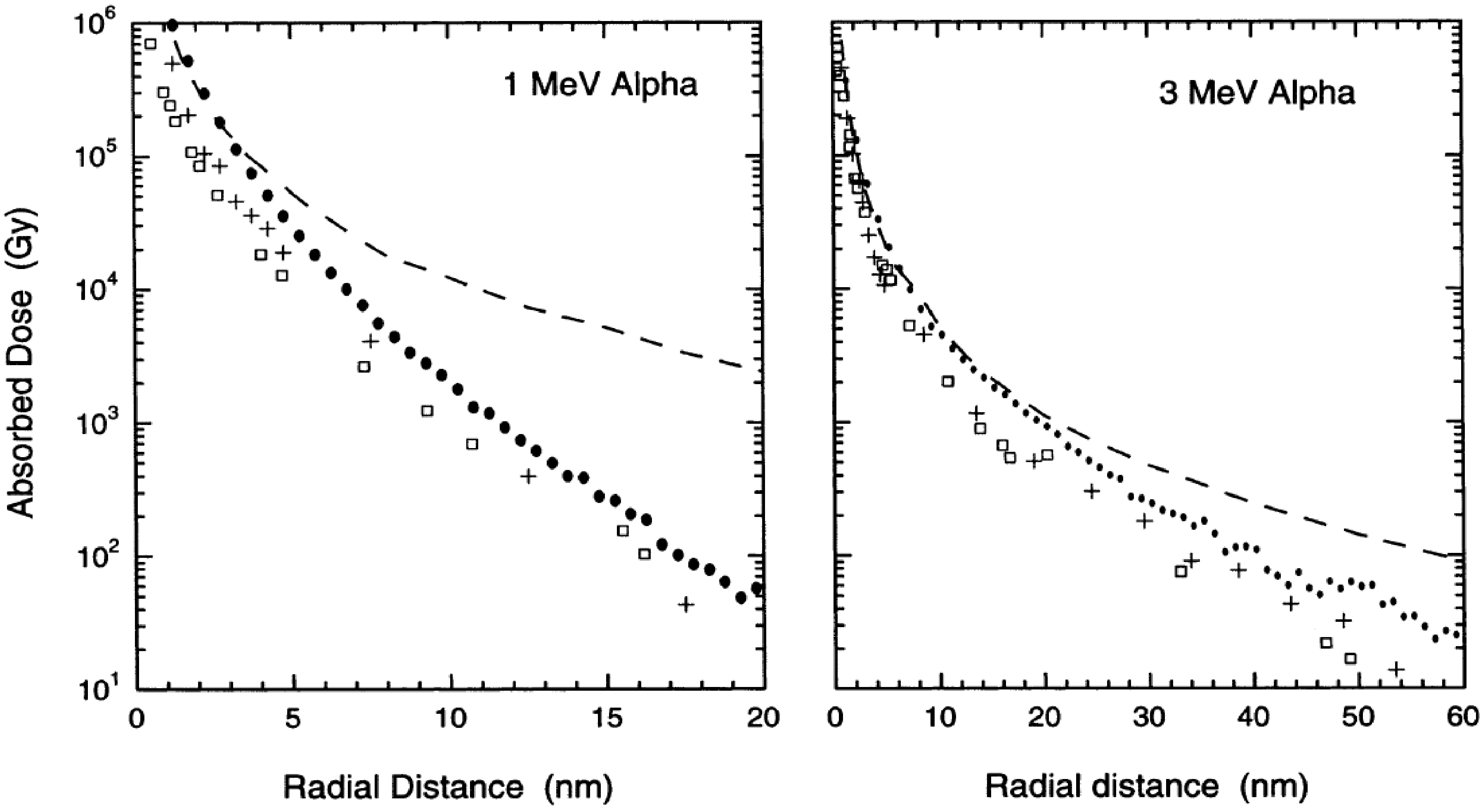
Thomas Eisel and the CryoLab@CERN

Contact:

Hendrik.jansen@desy.ch

Radial Track Size

- Alpha-particles in WATER:
  avg. energy of secondary electrons is 60 eV

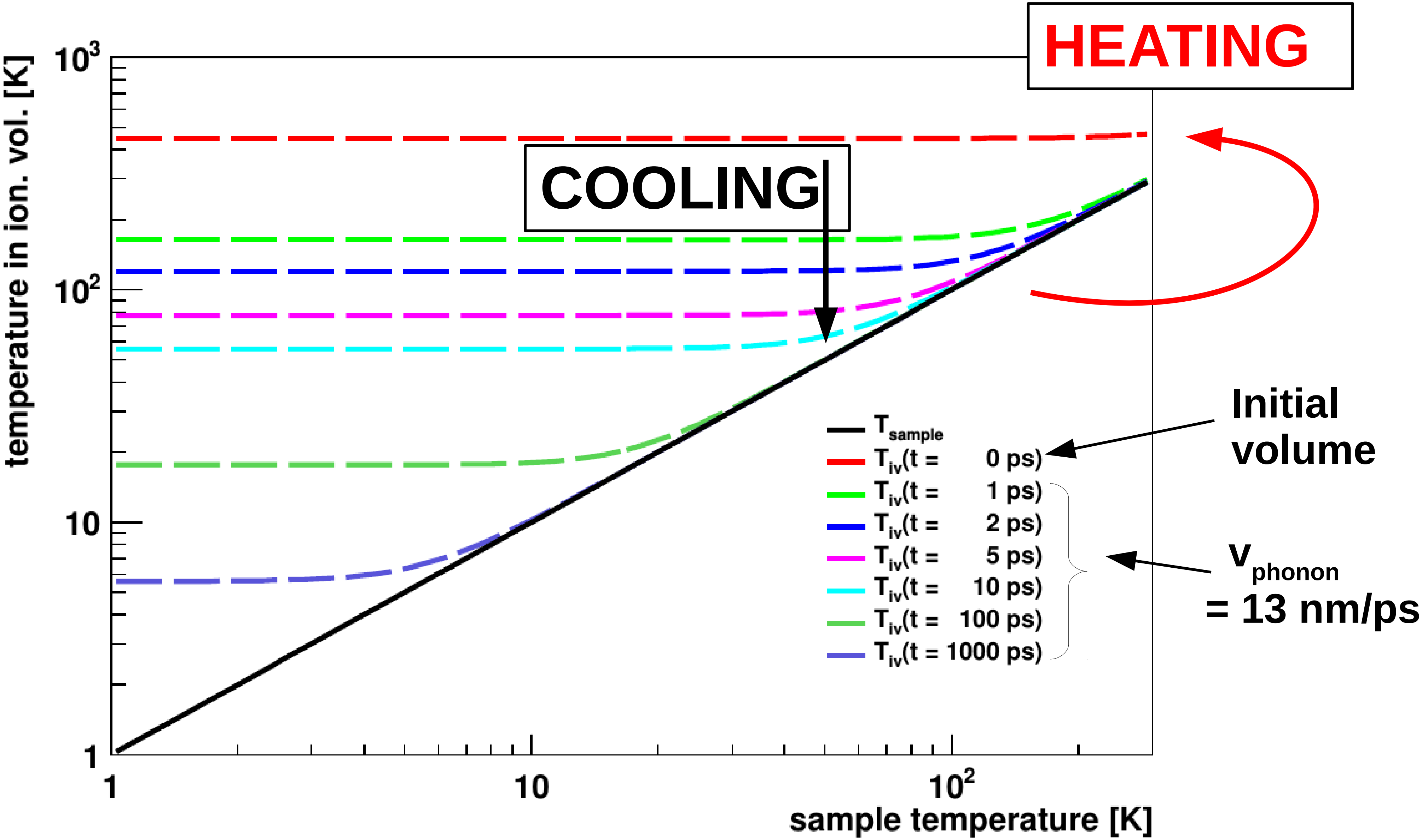


J Phys Chem B, 106 42 (2002) 11055

The Plasma

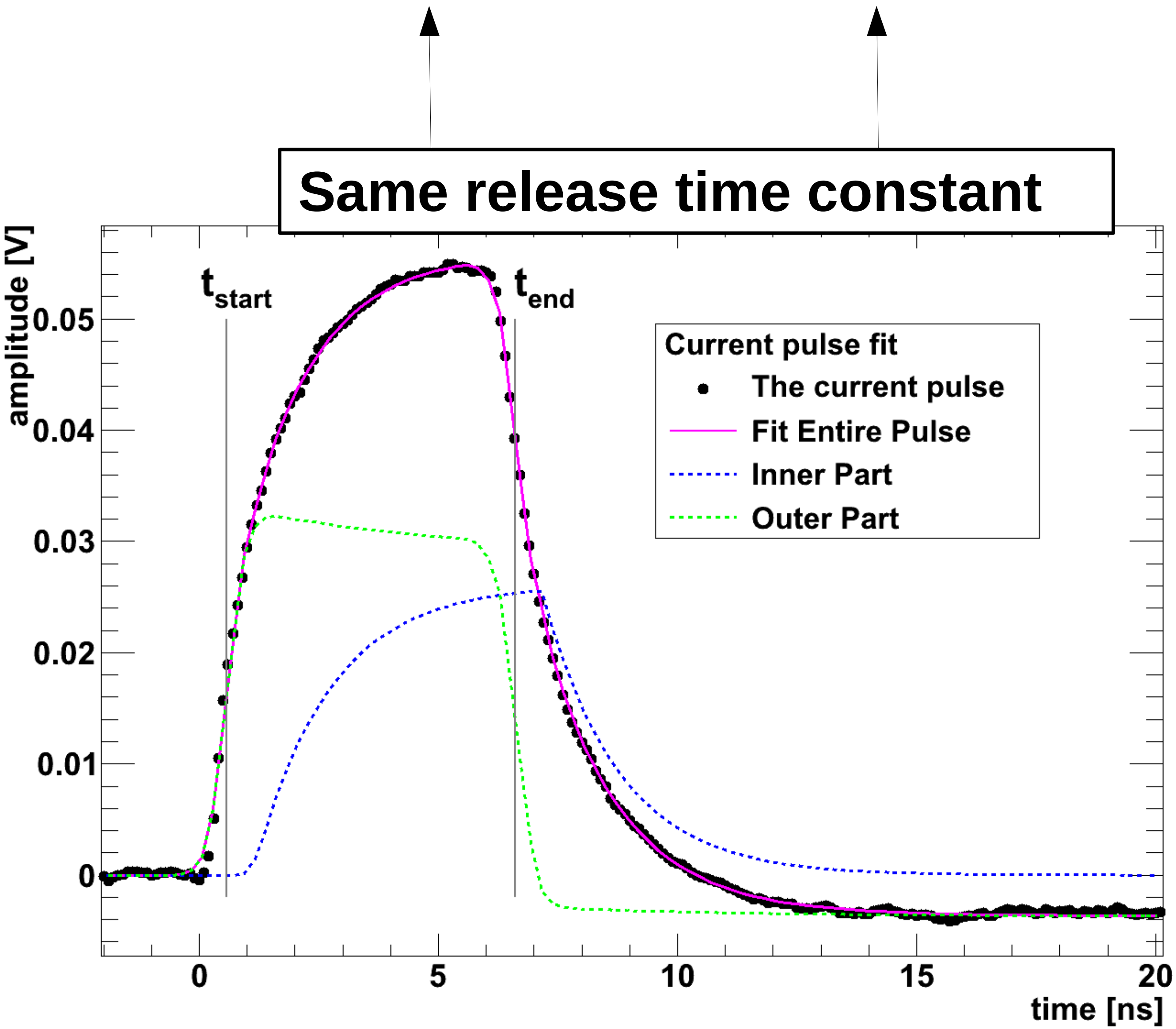
- The alpha-particle heats the ionisation volume!

$c_V \sim T^3$

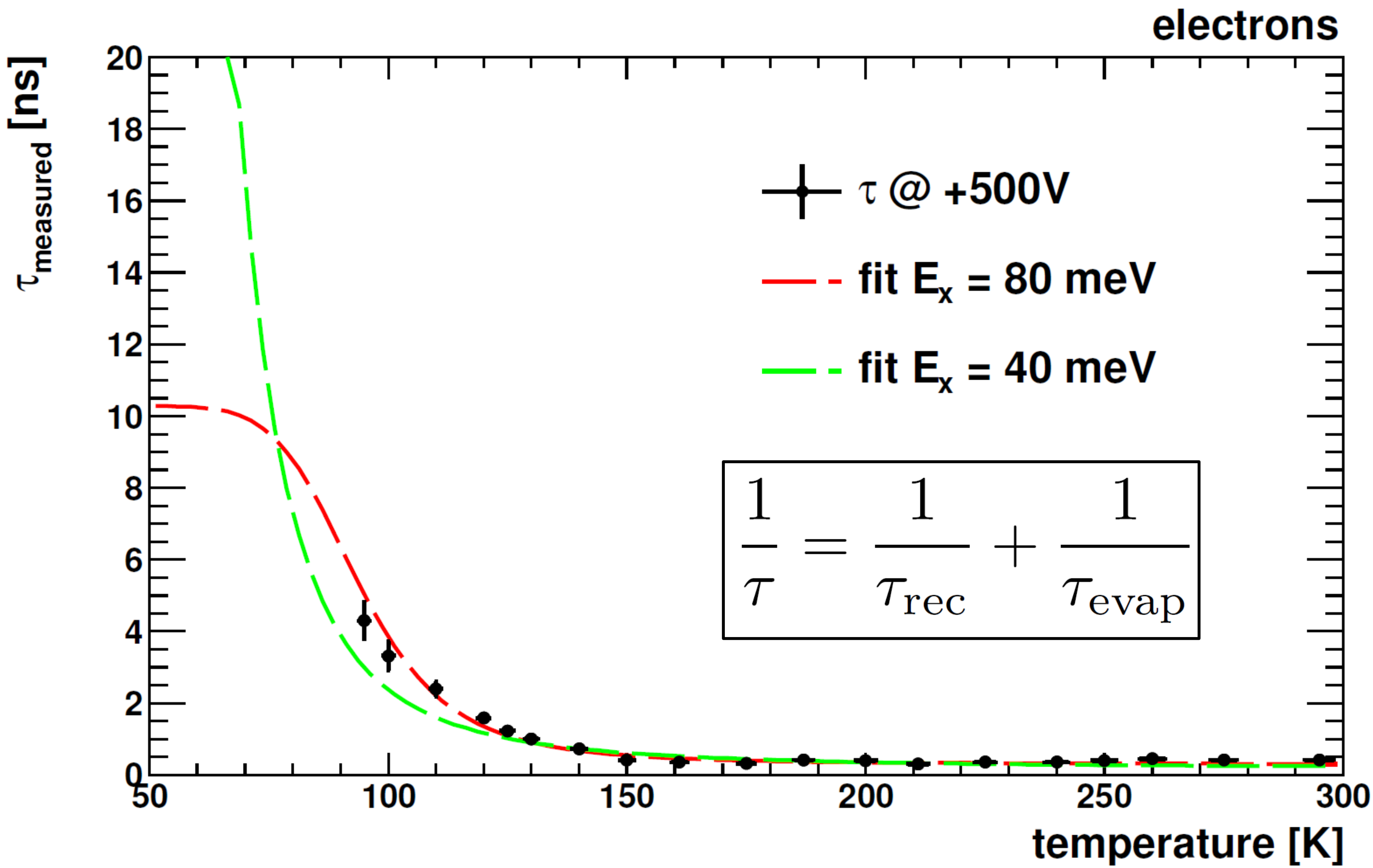


Analysis of TCT Pulses

- Fit rectangular (2- Erfc(t)) – (2- Erfc(t-t')) + exponential (1-exp(-t/τ)) - (1 - exp(-(t-t')/τ))

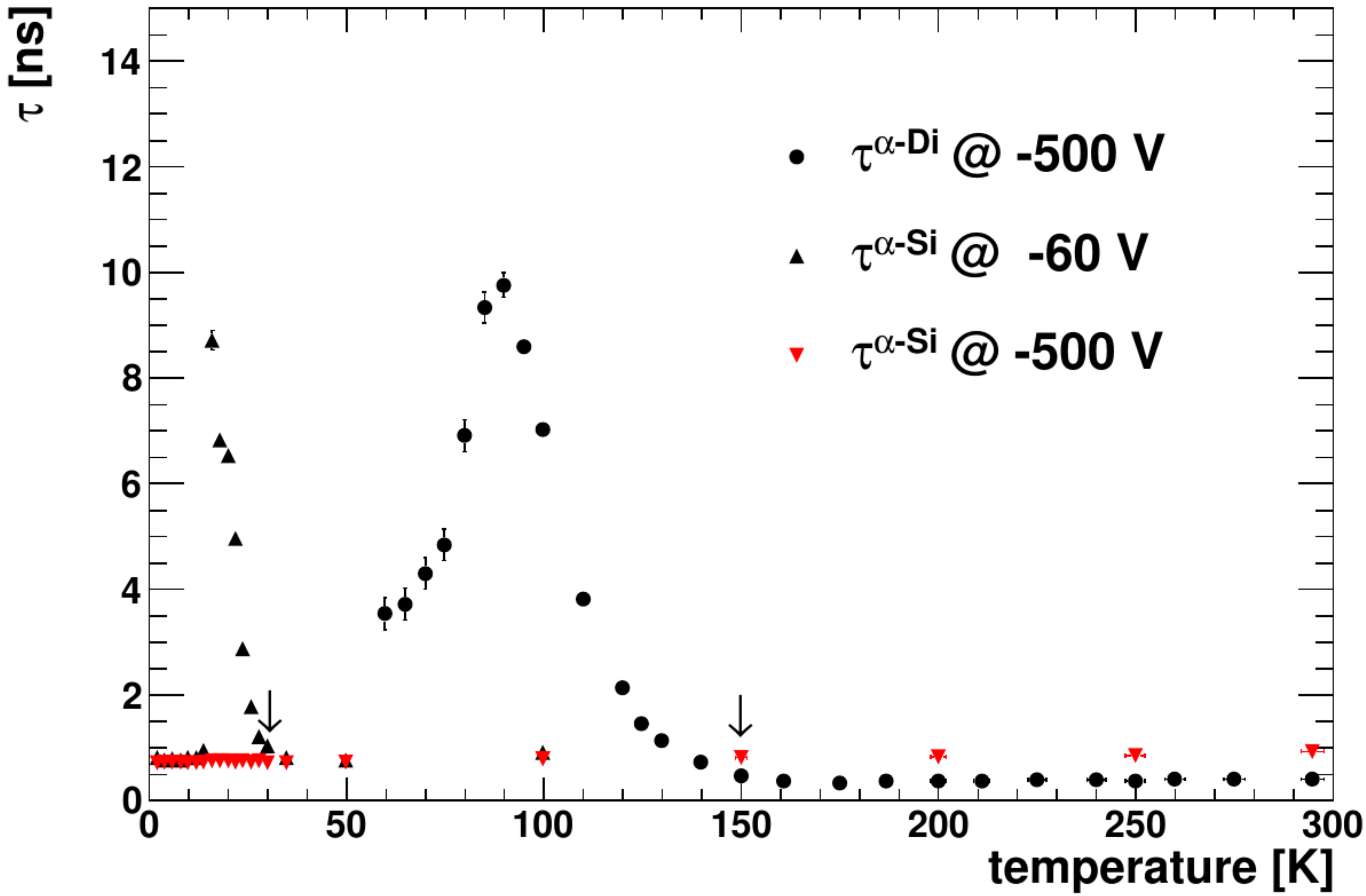


- Plot fitted τ a.f.o. temperature, and fit T-dependent model:



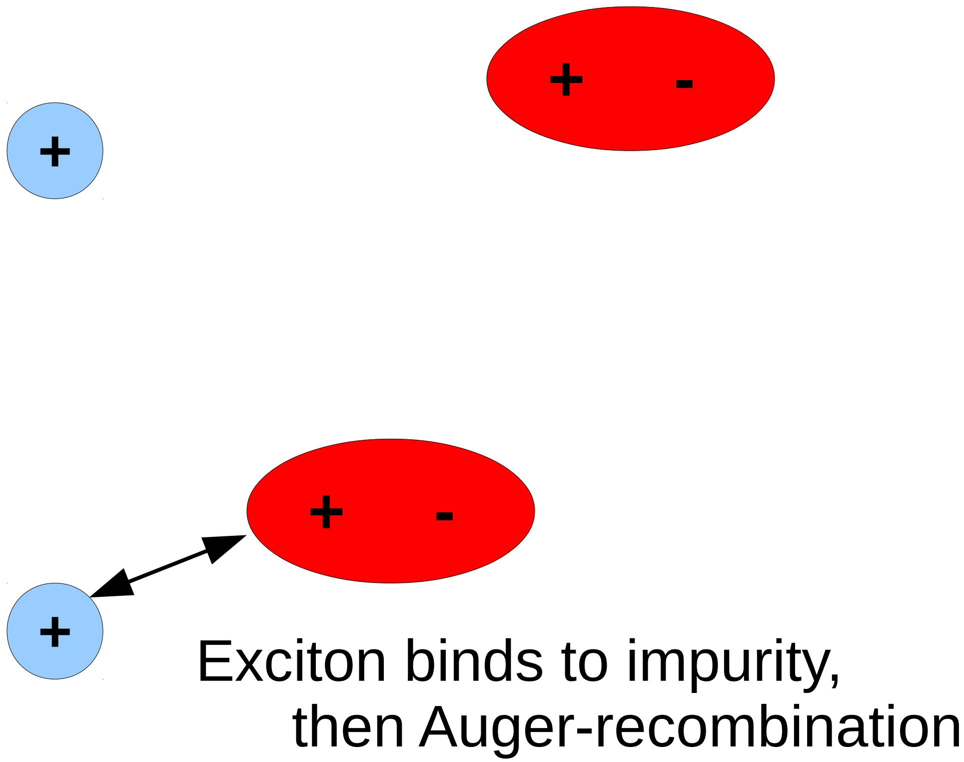
Comparison with Silicon

- $\tau_{evap} \sim \exp(E_X / kT)$!

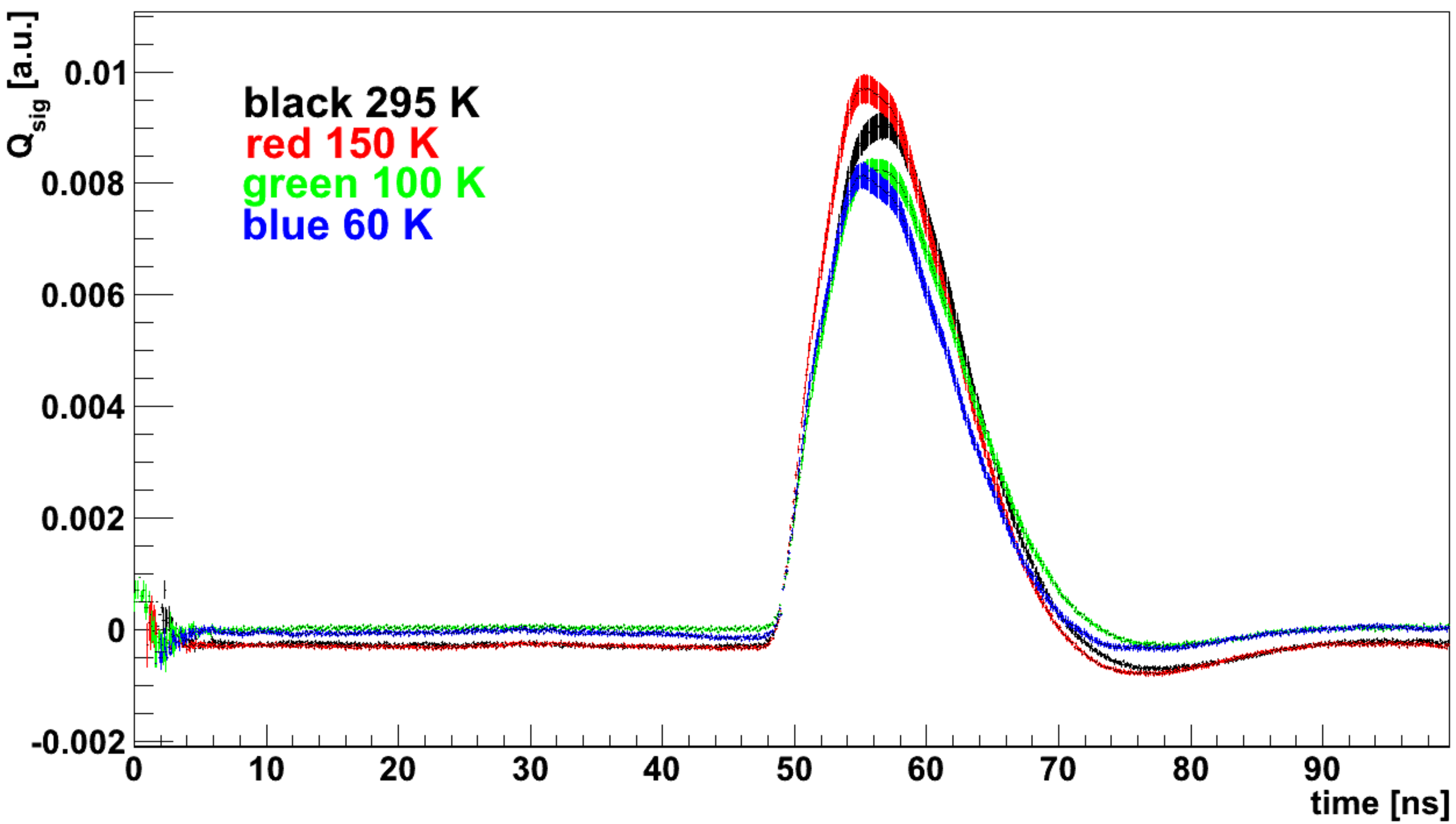


Excitons

- Recombination via impurities

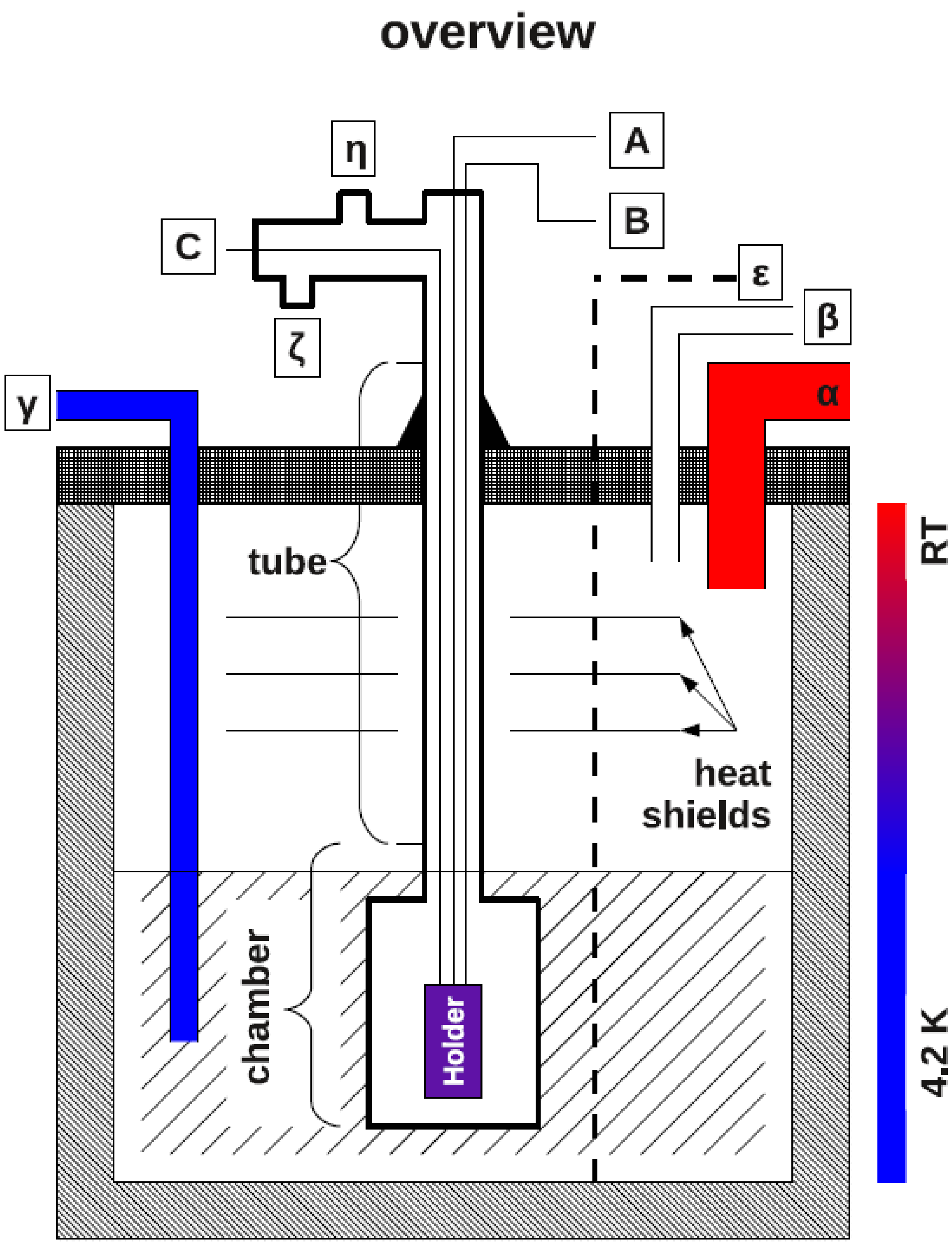


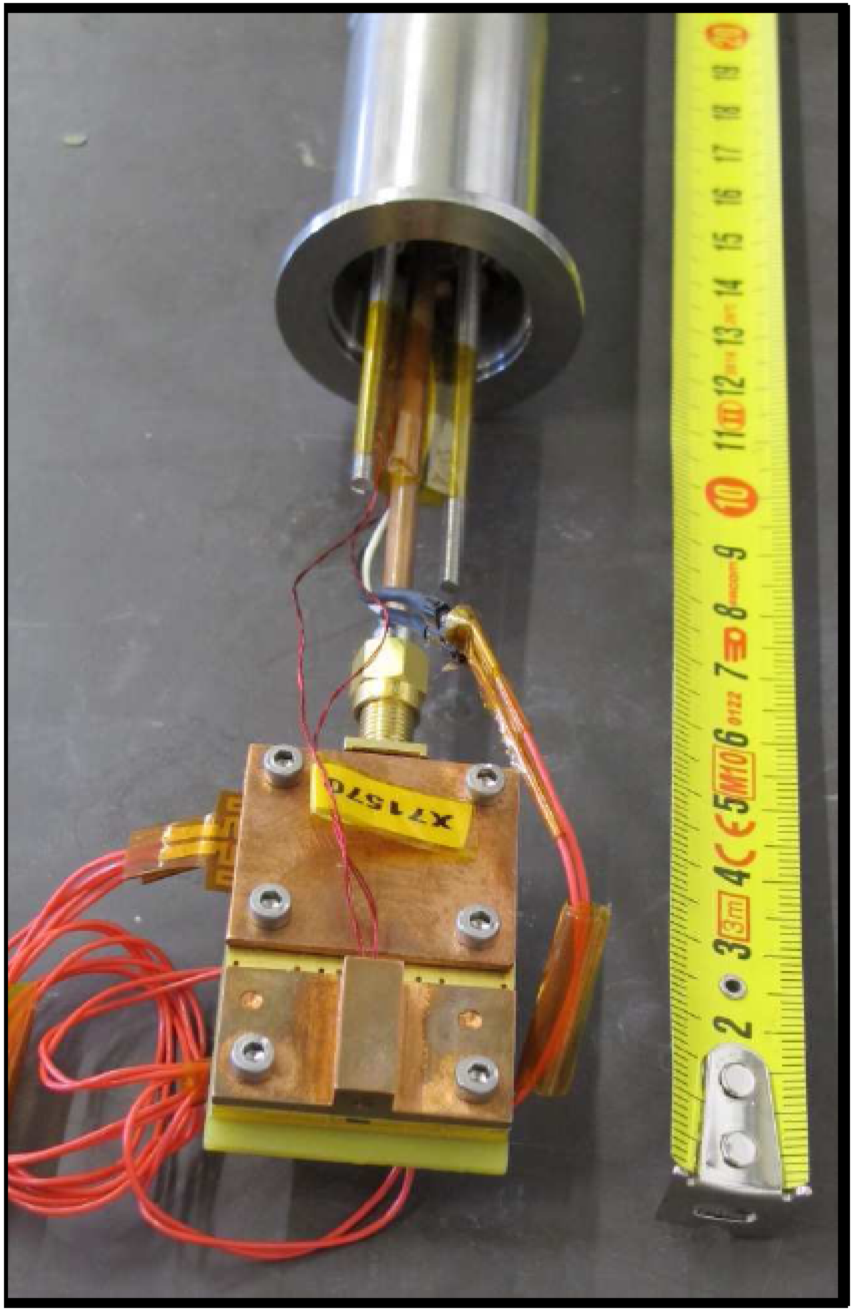
Cosmic Muons



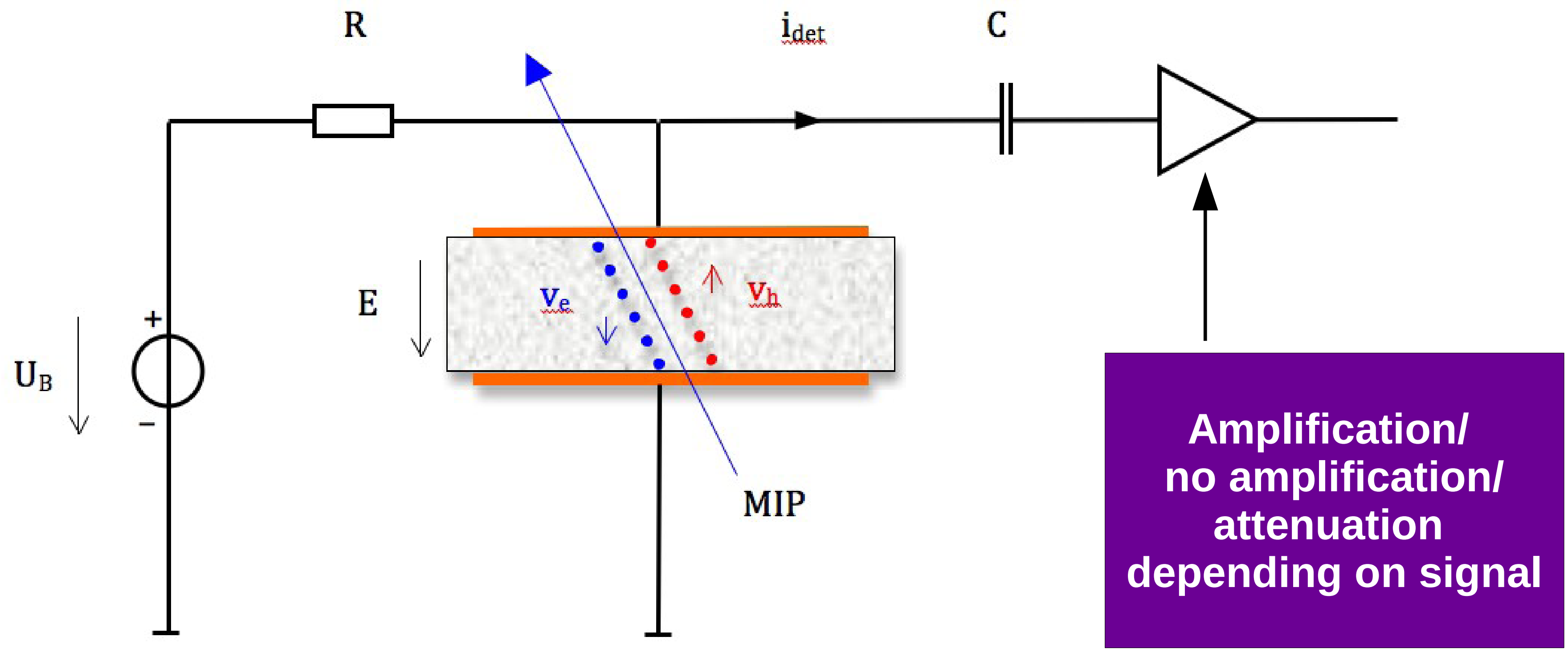
- Use charge-sensitive amplifier here
- Charge degradation much less with MIPs
  - expected due to lower charge density!

Detailed set-up





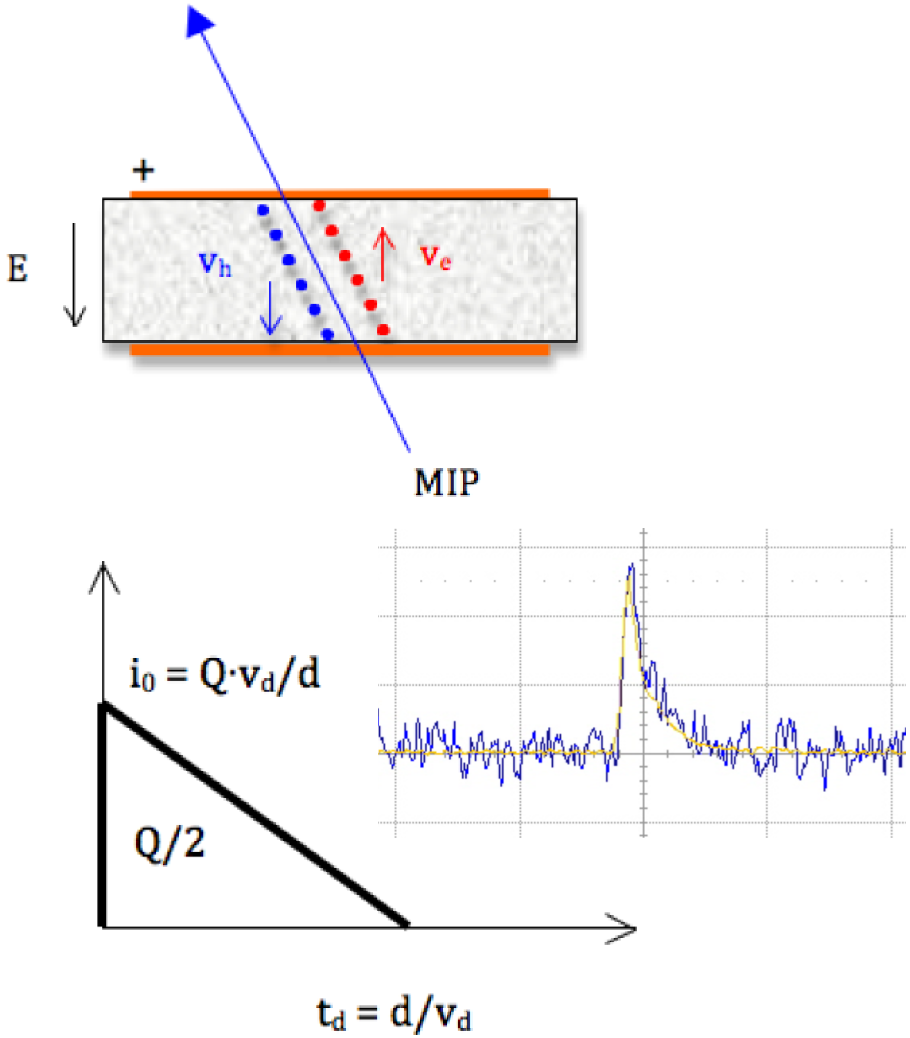
- Diamond is a semi-conductor based, solid state ionization chamber:

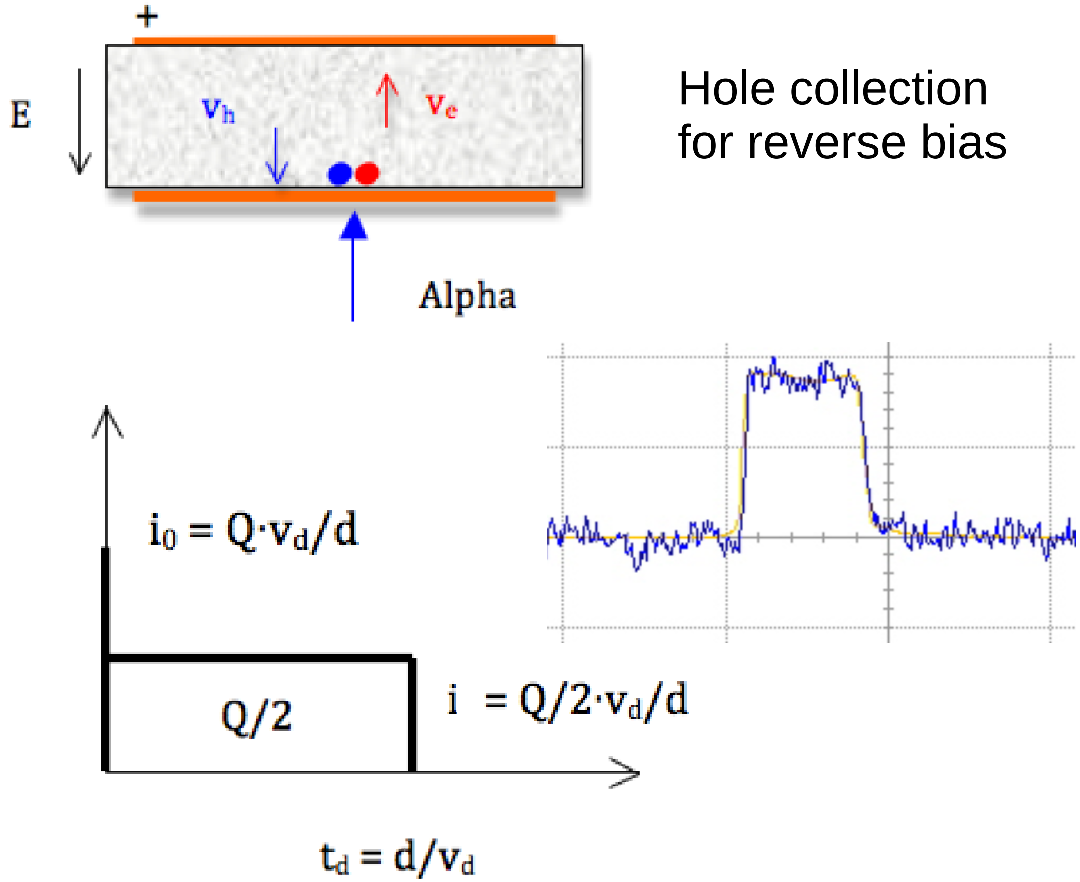


Courtesy
CIVIDEC

Modes of Operation

- Counting Mode
- Calorimetric Mode





Hole collection for reverse bias

Courtesy CIVIDEC

pCVD vs scCVD

- <u>pCVD Diamond:</u>

  very short signal
  ~2ns FWHM @ 1V/um

  optimal double pulse resolution
  charges lost at trapping centres

- <u>scCVD Diamond:</u>

  short signal
  ~5ns FWHM @ 1V/um

  optimal Signal-to-Noise ratio
  lower trapping centre concentration

$$CCD = d * Q_{sig}/Q_0$$