Charge carrier properties in diamonds at low temperature

TCT measurements down to 60K

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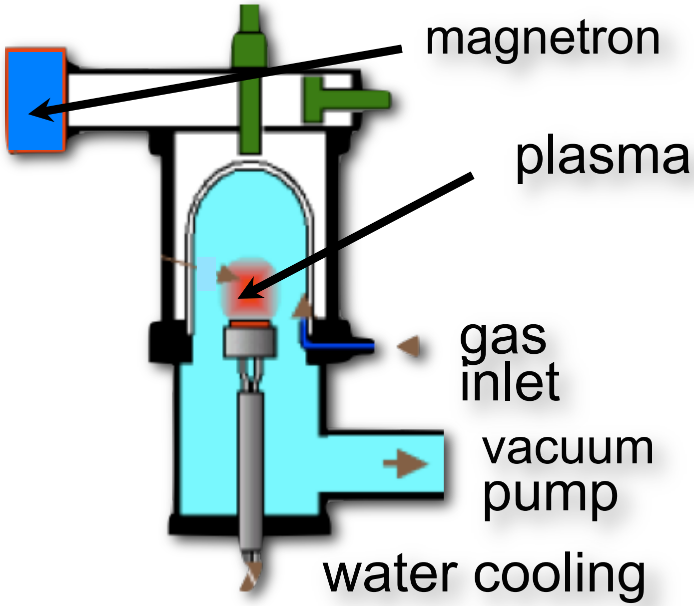
Why Diamonds

- High band-gap (5.5 eV)
  - Low leakage current after irradiation
  - High breakdown field (operate at large fields for fast signals)
- Low dielectric constant (5.7)
  - Low detector capacitance
  - Low noise
- High displacement energy (43 eV)
  - Radiation hard

- Cons: high ionization energy per e-h-pair (13.6 eV)
  - Lower signal than silicon
  - ~36 e-h / micrometer path length

Microwave CVD Plasma Reactor



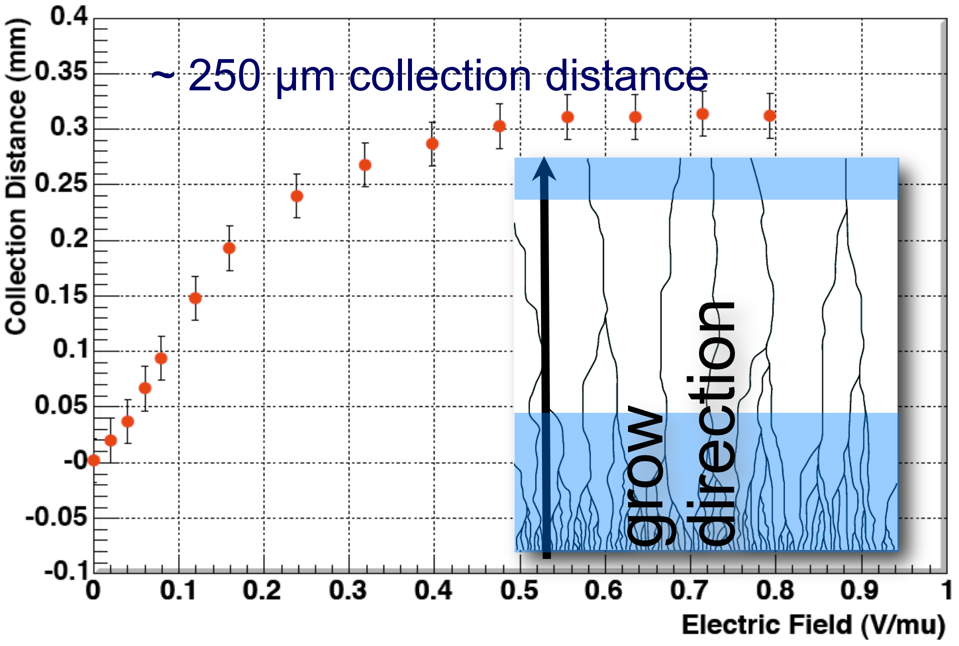
Metallization

☑ No doping needed
☑ Metal contacts (pads, strips, pixels) sputtered or evaporated
☑ Can be stripped off and redone

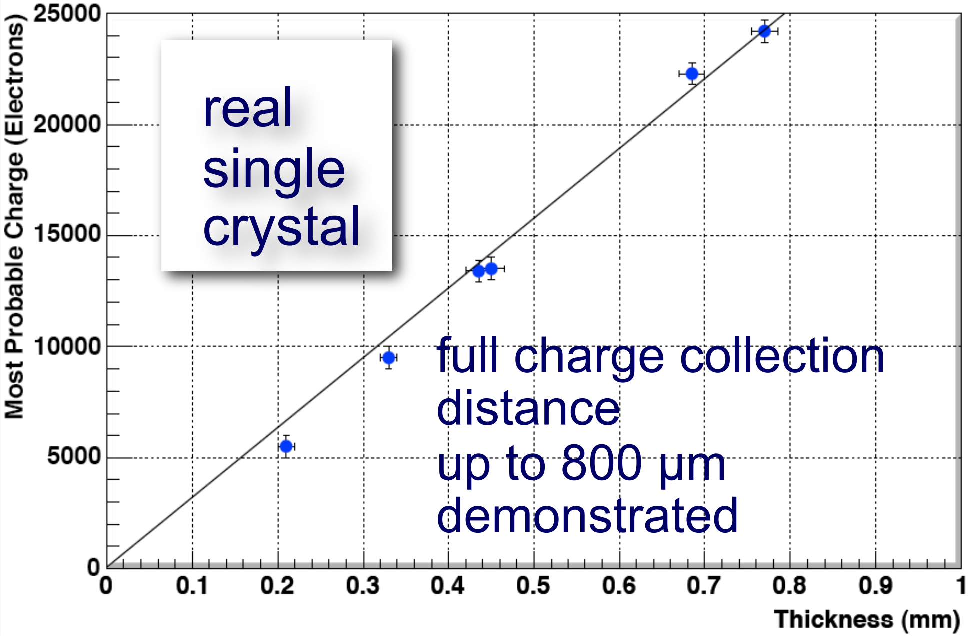
Types of CVD diamonds

polycrystalline (pCVD):
Fast and short signal (~2ns FWHM) :
Use for optimal double-pulse resolution

single crystal (scCVD):
Fast signal with full charge collection:
(~7ns FWHM)
Use for best signal-to-noise on MIP muons



~ 250 µm collection distance

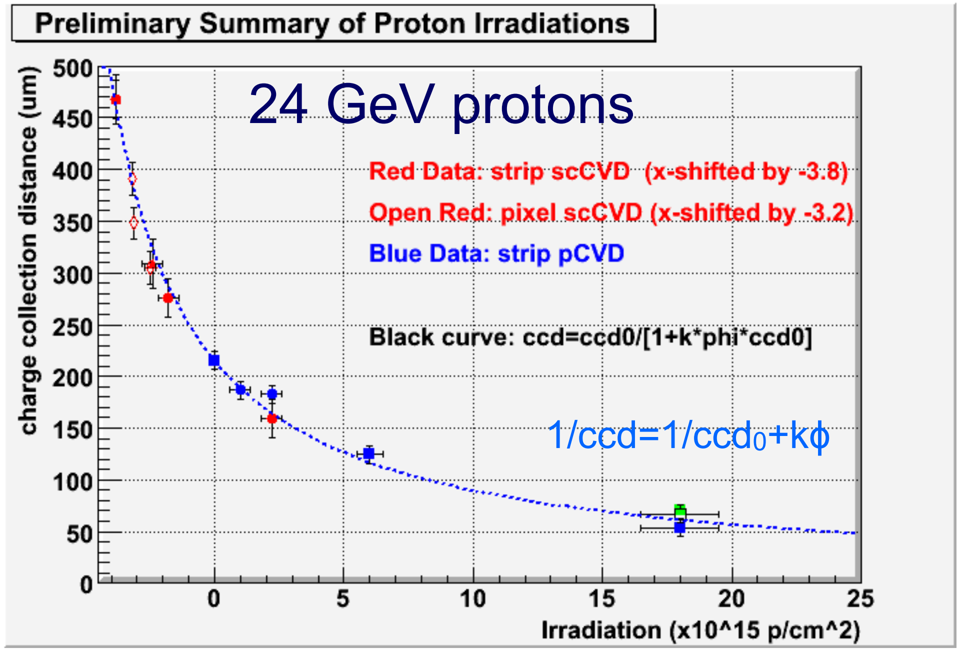


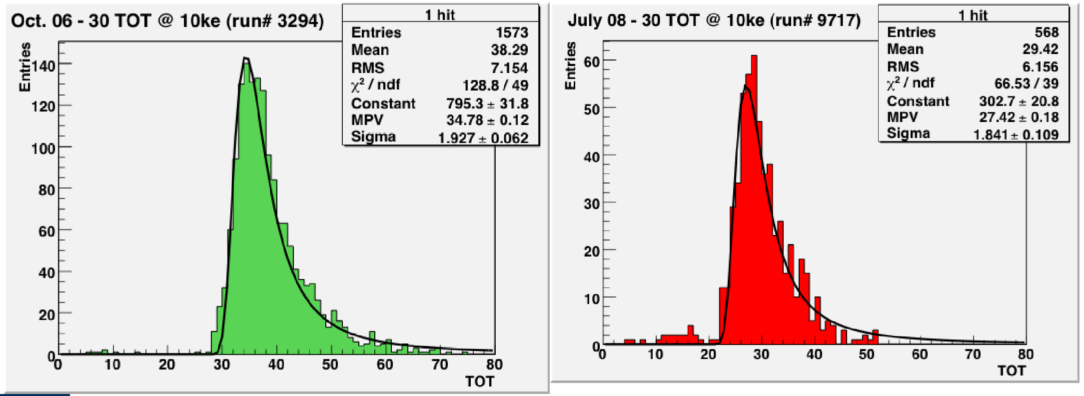
real single crystal

full charge collection distance
up to 800 µm demonstrated

Radiation hardness

- Studied with pCVD and scCVD diamonds as pad, strip and pixel detectors
- E.g. Signal on scCVD pixel with FEI3 before & after irradiation (0.7x10^{15} p/cm^{2})





- Before irradiation
  - Threshold ~ 1700e-
  - Signal MPV ~ 11540e- @400V
- After irradiation
  - Threshold ~ 1470 e^{-}Signal MPV ~ 9025e- @800V

Diamonds in PH-ADE Group & ATLAS

- PH-ADE has been active in the development of diamonds as tracking detectors since > 15 years
- Key-driver of developments in the context of LHC experiments has been the CERN RD42 collaboration
  - Better quality diamonds – high charge collection distance
  - Radiation hardness
  - Development of CVD strip and pixel detectors
  - Development of CVD pad detector for beam monitoring

- Example of applications of CVD diamonds in our group
  - ATLAS Beam Conditions Monitor and BLM
  - ATLAS Diamond Pixel Detector (DBM)
  - MERIT : high flux application
  - LHC loss monitors: See Erich's talk

Development

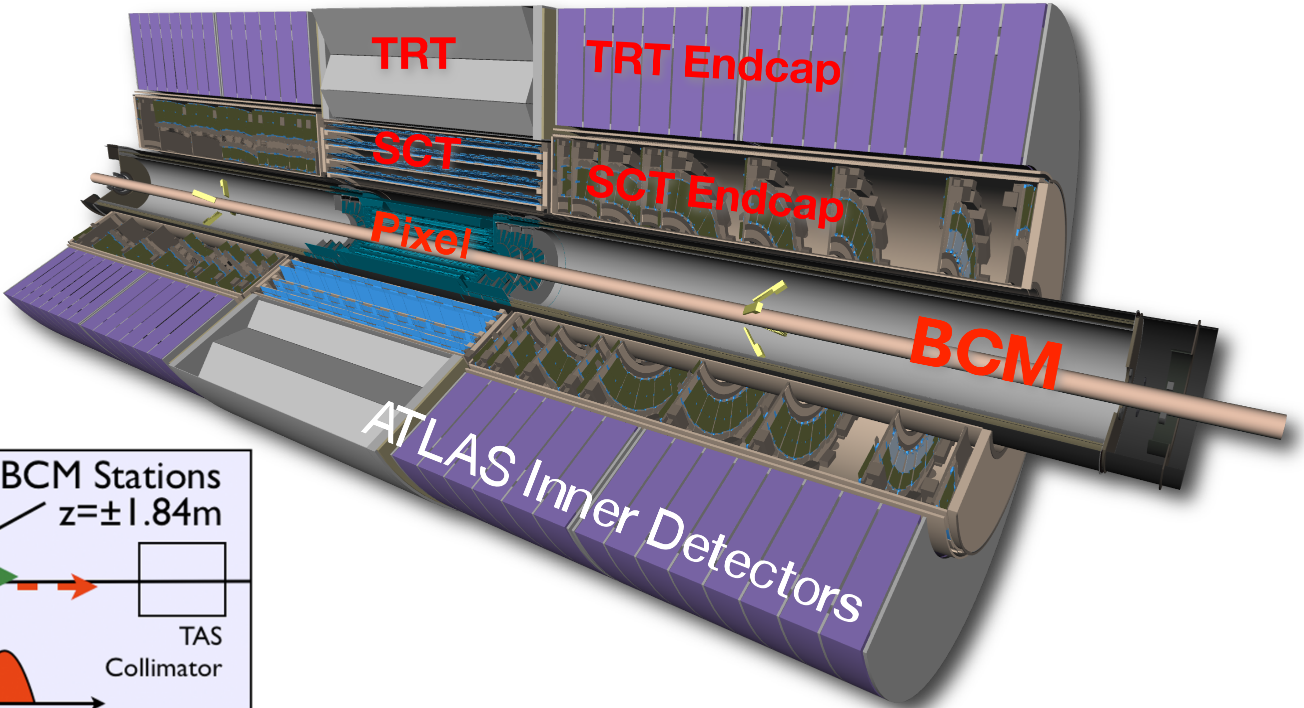
- Developed in research collaboration between **academic collaborations** and **specialized industry**
- **RD42 collaboration**
- **ATLAS Diamond Pixel Collaboration**

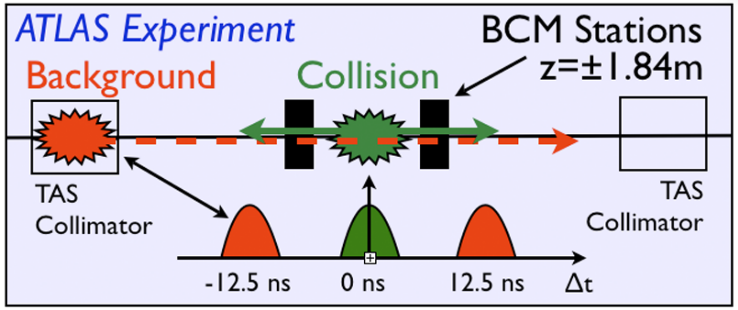
- Diamond Detectors Ltd, UK
- II-VI Incorporated, USA
- CIVIDEC, Austria

ATLAS Beam Conditions Monitor

- Monitor collisions and beam background simultaneously near ATLAS IP through TOF measurements
- Fast time resolution and bunch-by-bunch analysis

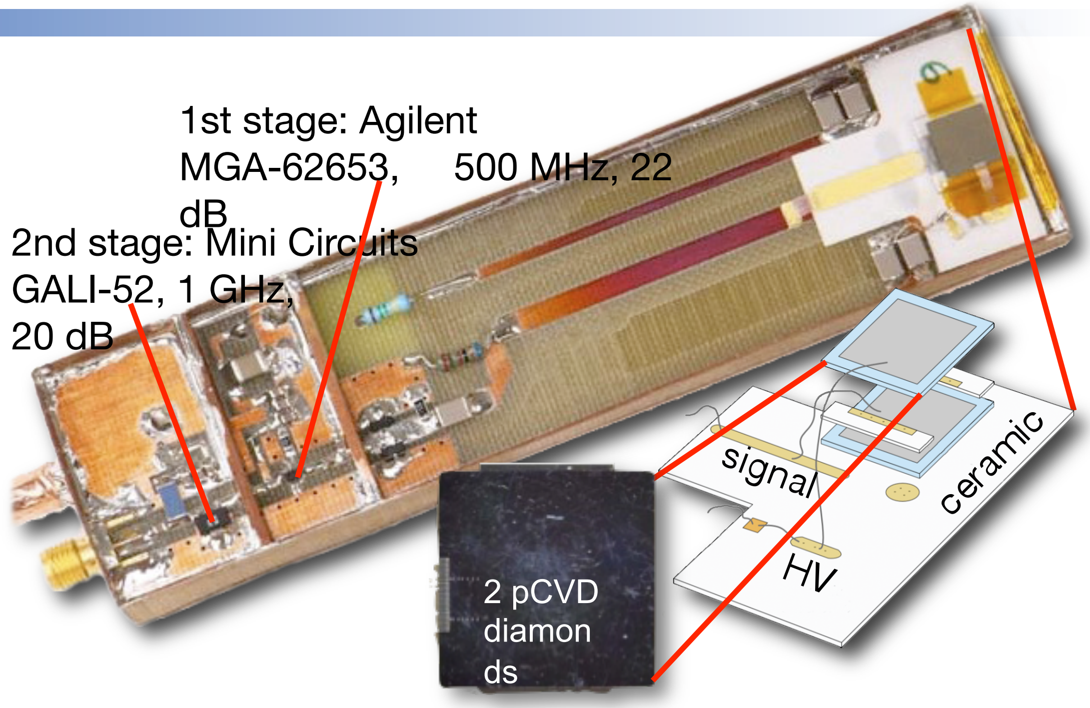
- 4 detectors each side (C & A)
- Positions: X+, Y+, X-, Y-



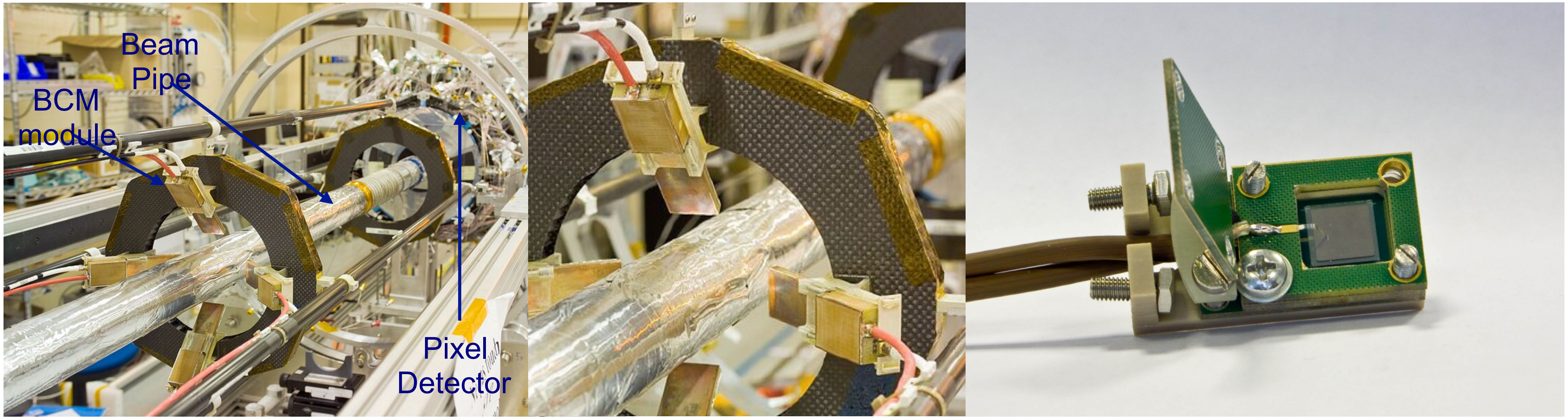


Fast beam monitoring with BCM

- Optimized for fast signal response for single MIPS to response details of bunch structure
  - 2 pCVD diamonds (8x8mm2 active)
  - Rise time ~ 1ns, FWHM ~3ns
  - Time resolution ~500ps

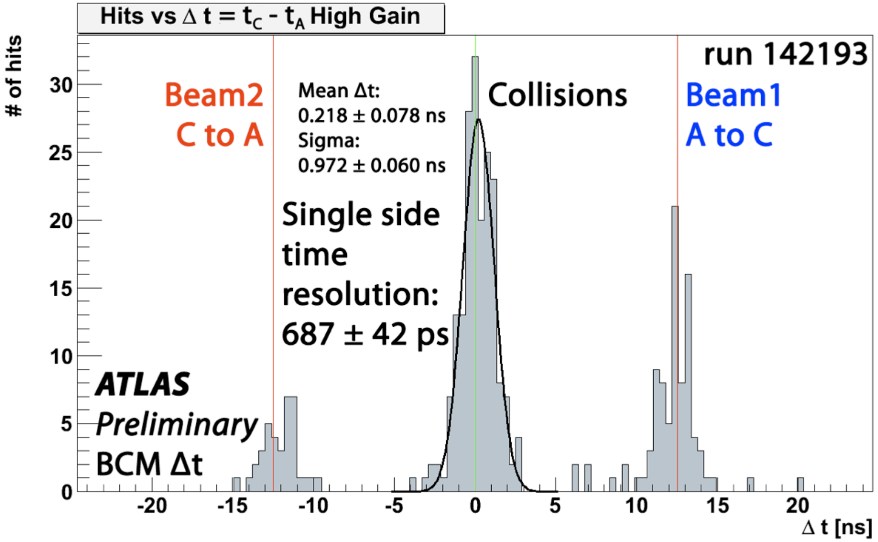


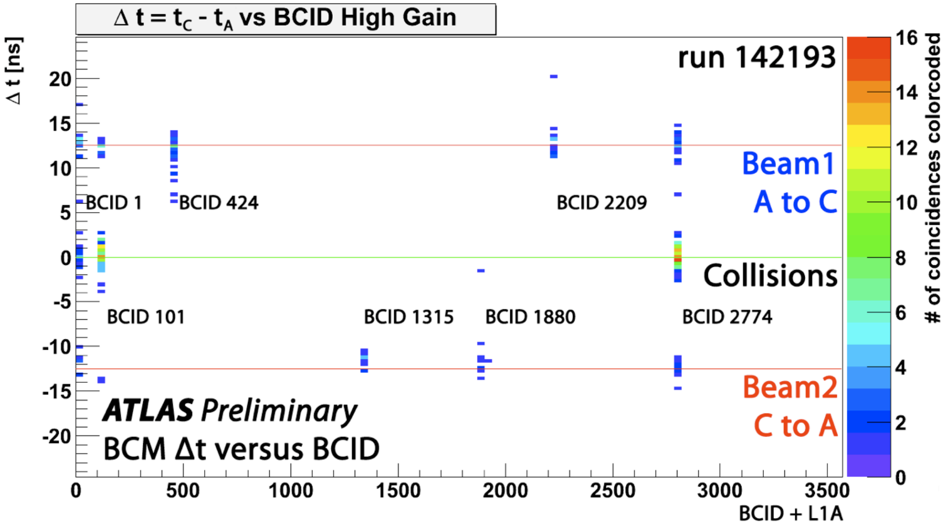
- Beam monitoring through diamond current:



Resolve and analyze LHC bunch structure

- Bunch-by-bunch analysis of LHC collisions and background





- Collisions = ΔT ~ 0
- A-to-C/C-to-A single bunch background ~ ΔT = +/- 12ns

- **Colliding bunches** in BCID 1, 101 & 2774
- **Single bunches** 424, 1315, 1880 & 2209 collide in ALICE & LHCb

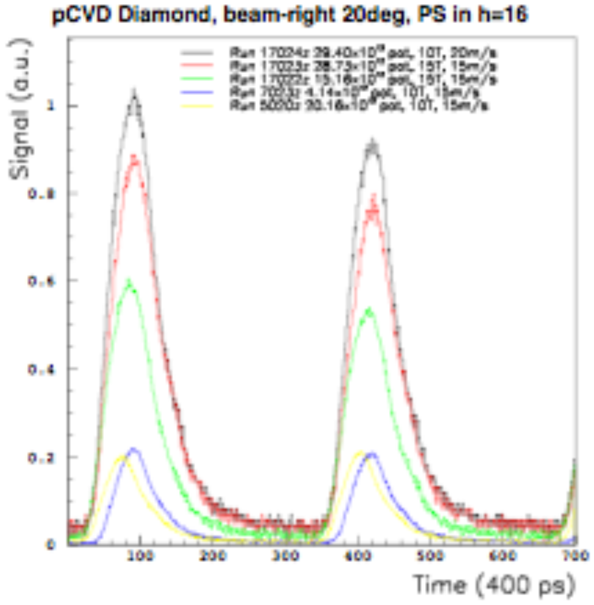
High-flux example: MERIT

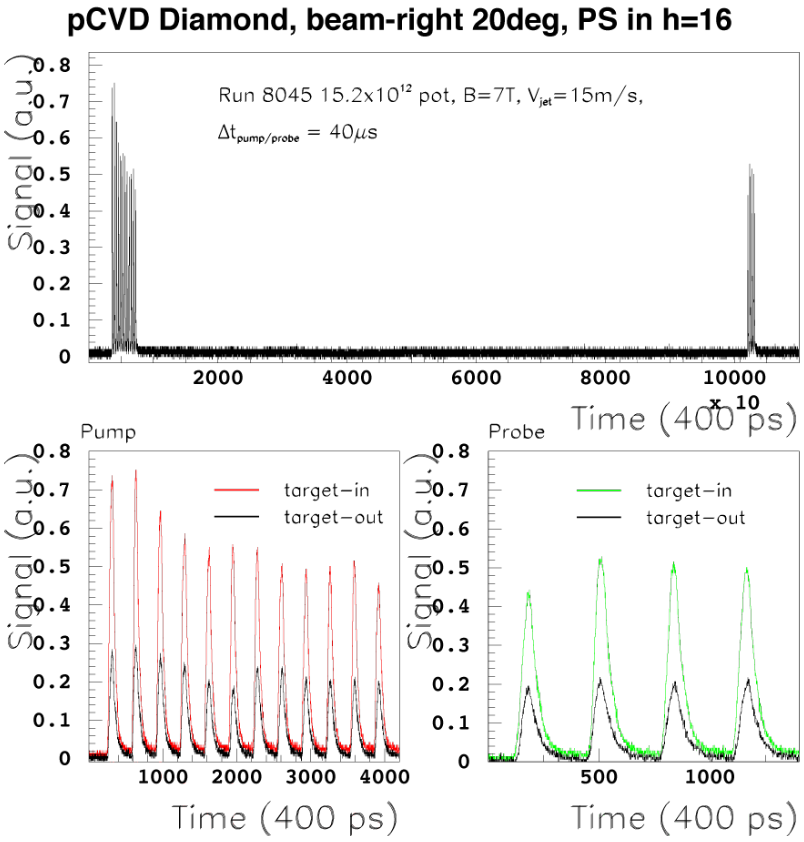
- MERIT – design of mercury jet target for neutrino factories or muon colliders
- High intensity (0.2 to 30x1012 proton/pulse) on free mercury jet target in 15T solenoid
- Use pCVD diamonds to measure resulting flux of particles/pulse

- 5 pCVD diamonds around target region to measure flux of secondaries and their relative distribution
- Enormous signals:
- ~ up to 5x107 part/cm2/pulse
- Diamond current signal up to 1.6 A (use attenuators, not amplifiers … !)

Diamonds in MERIT

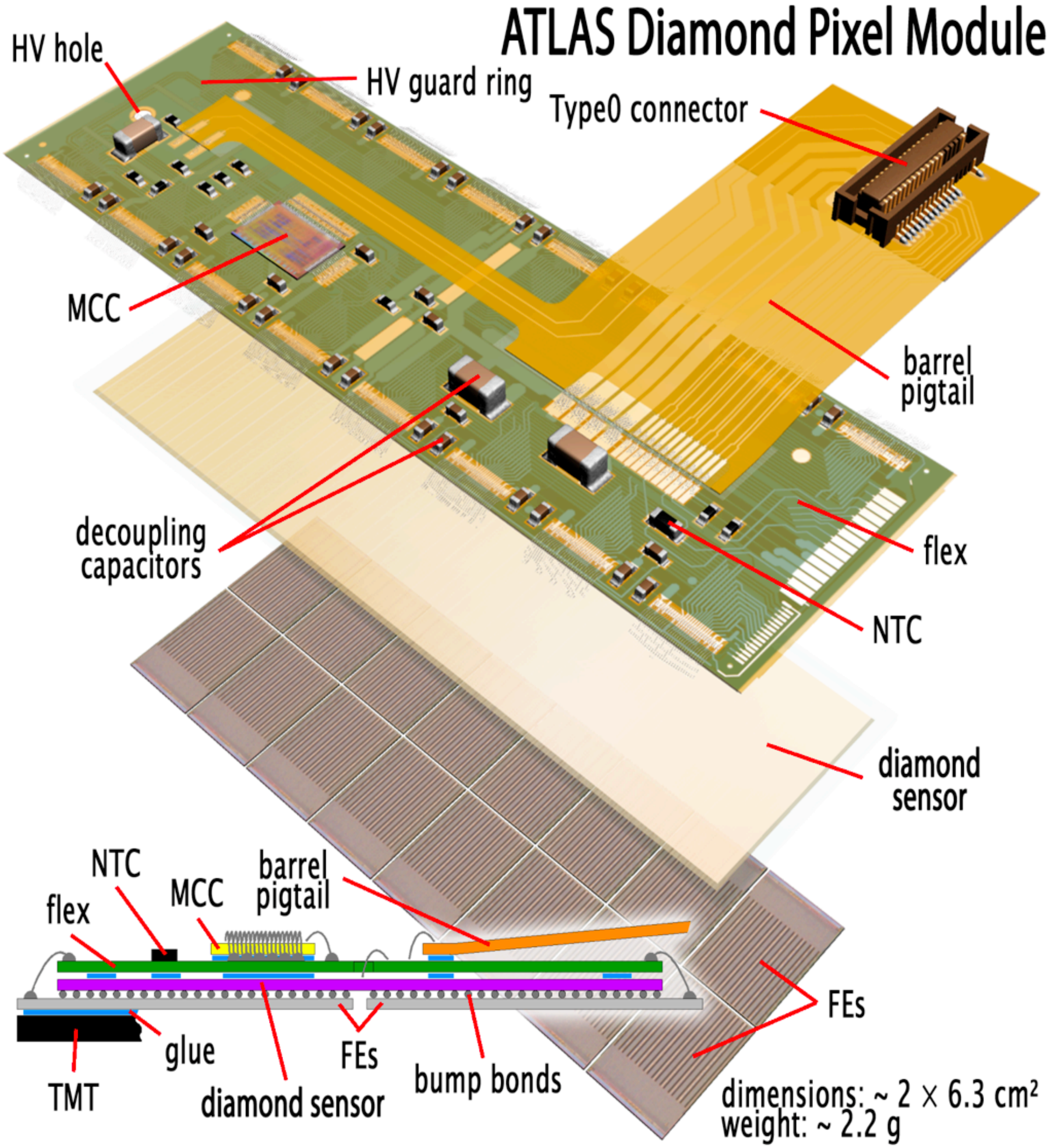
- Diamond response to pulse trains of PS pulses on mercury target
  - Tested different target conditions (jet velocity, magnetic field,…)
  - Tested how target gets disrupted by sudden impact of beam

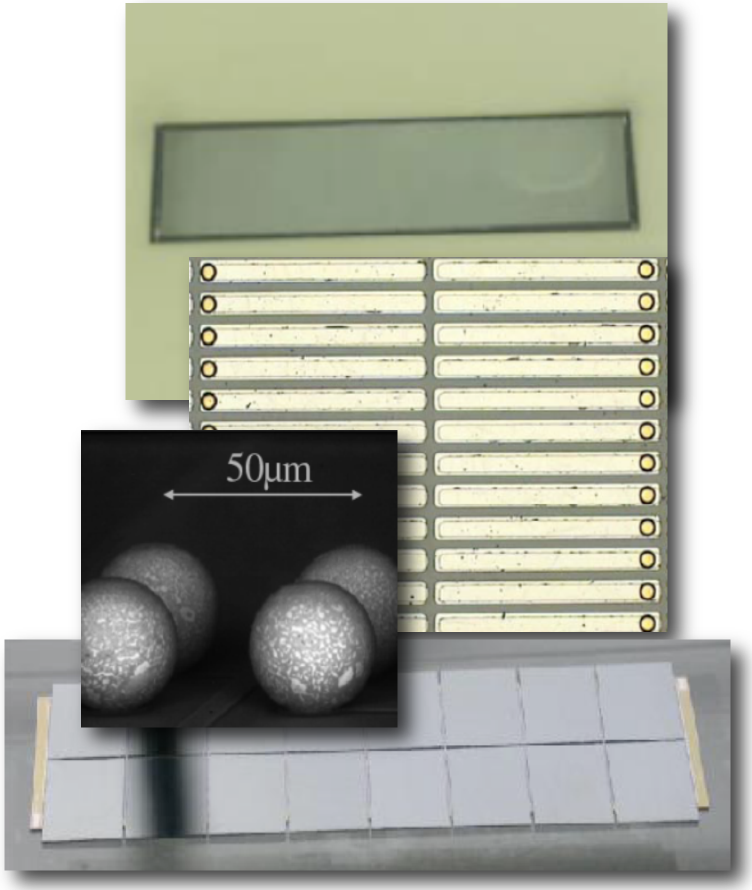




- **Result**: no reduction of particle flux for bunch train operation up to 350μs suitable for operation of a 4MW proton driver at a neutrino factory

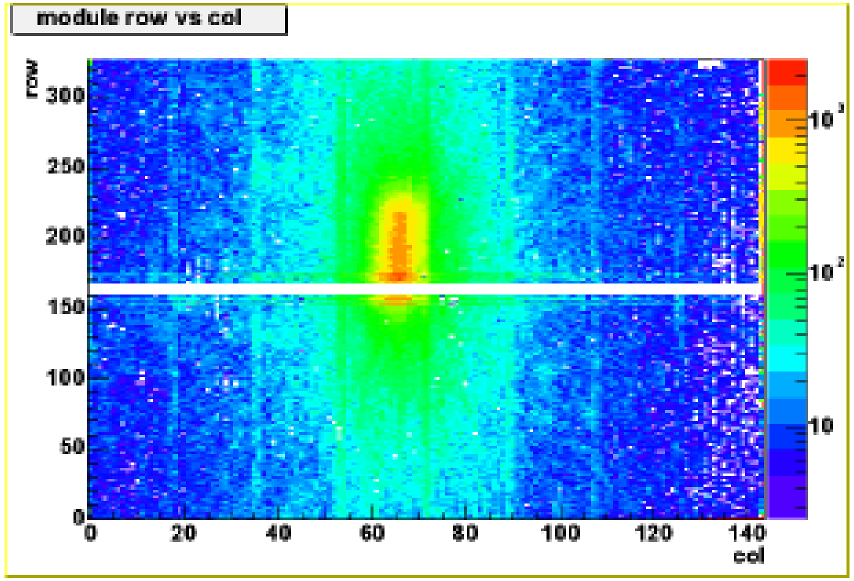
Diamond Pixel Module

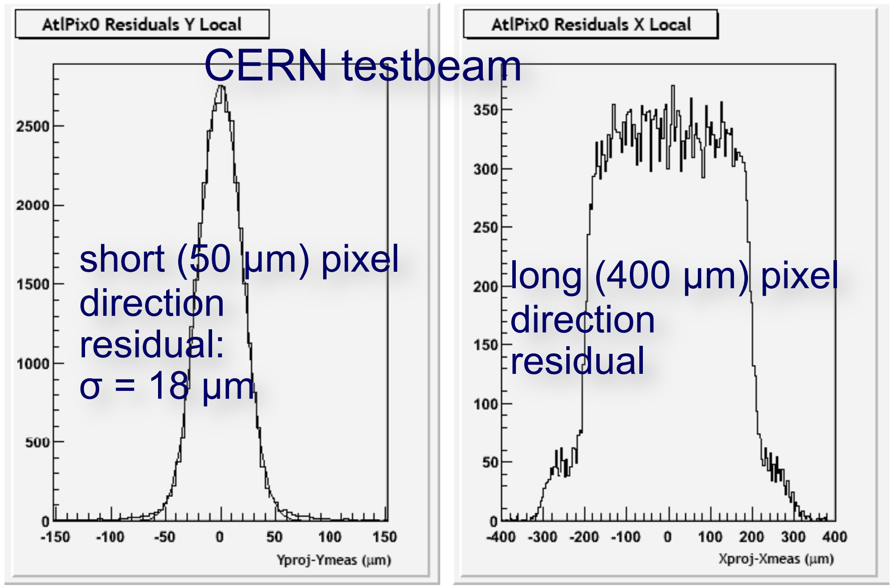




- 800 μm pCVD diamond
- 50×400(600) μm pixels
- 16 ATLAS FE-I3 chips
- active area: 61×16.5 mm^2

pCVD Diamond Pixel Module





CERN testbeam

short (50 µm) pixel direction residual: σ = 18 µm

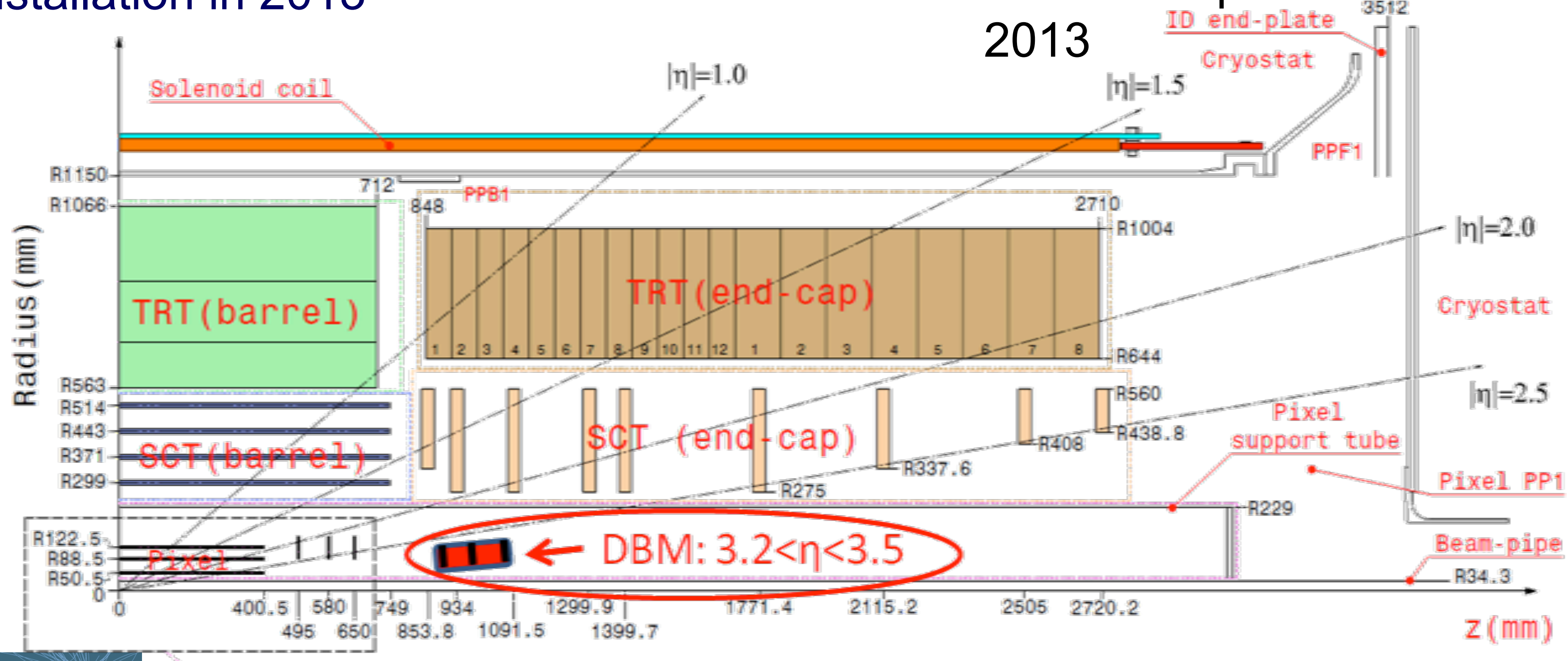
long (400 µm) pixel direction residual

- residuals show expected behavior: 18 µm → unfold telescope resolution → 14 µm as expected from 50 µm/√12
- 97.5% efficiency in DESY TB lower limit due to scattered tracks (4 GeV electrons)
- Excellent threshold ~ 1450 e- threshold
- Pixel noise ~ 136 e-)

ATLAS Diamond Beam Monitor

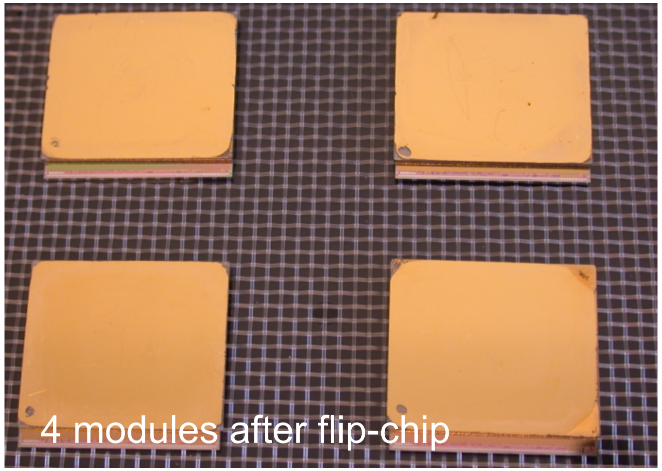
- Spin-off from diamond bid for IBL
- 24 diamond pixel modules arranged in 8 telescopes around interaction point
  - Bunch by bunch luminosity monitoring
  - Bunch by bunch beam spot monitoring
- Installation in 2013

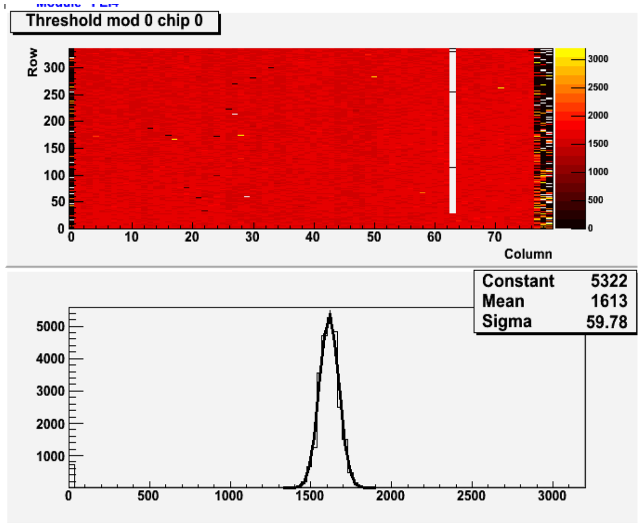
- Proposed during last months as add-on to IBL
- ATLAS decision expected soon
- Contingent on pixel services replacement in 2013

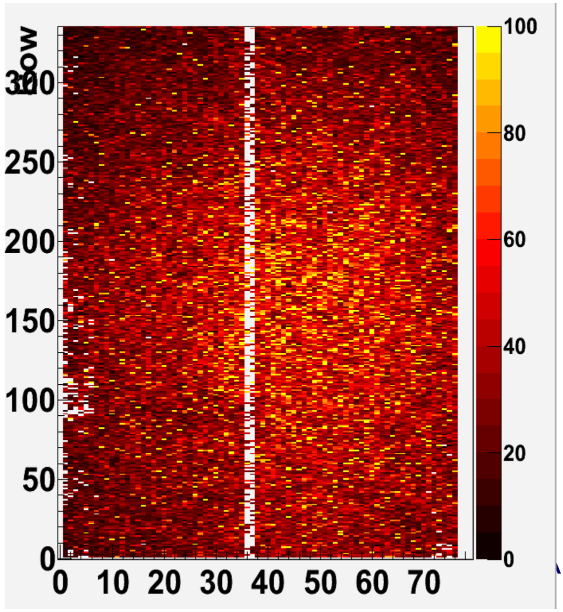


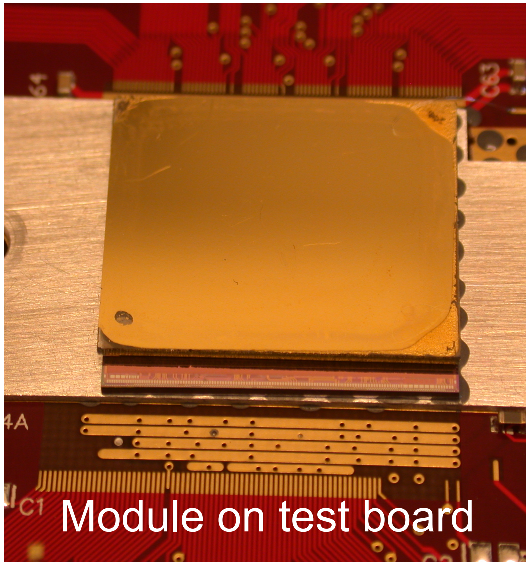
DBM first modules

- Four DBM modules built at IZM
  - 21x18 mm^2 pCVD from DDL
  - FE-I4 ATLAS IBL pixel chip
  - 336x80 = 26880 channels, 50x250 µm^2
- Largest ASIC/diamond flip chip assembly!


4 modules after flip-chip



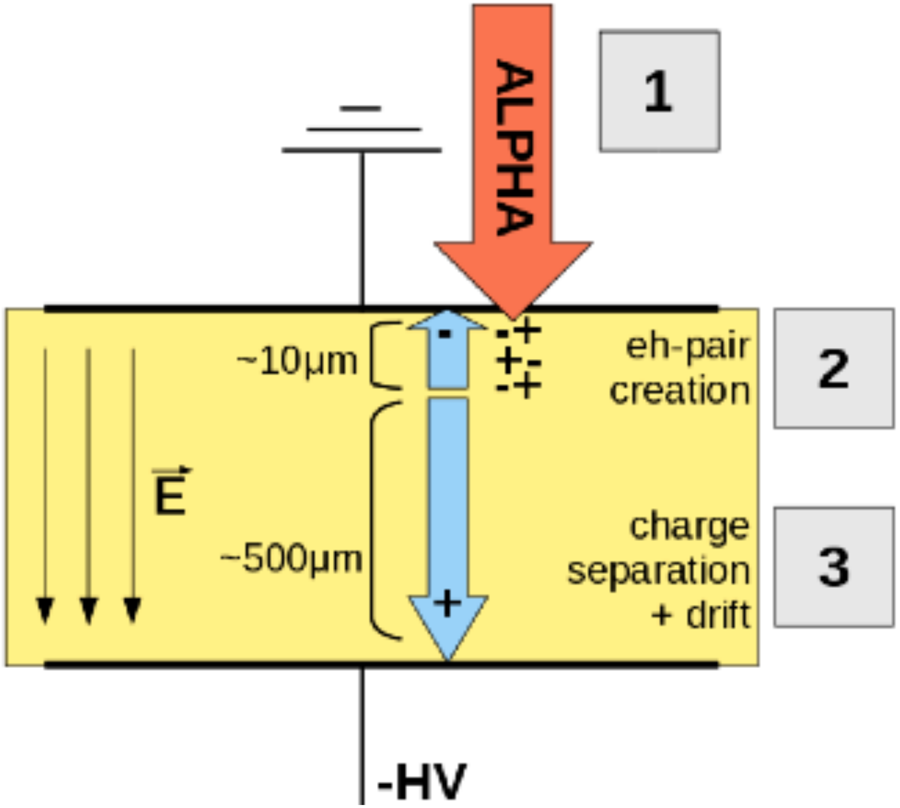



Module on test board

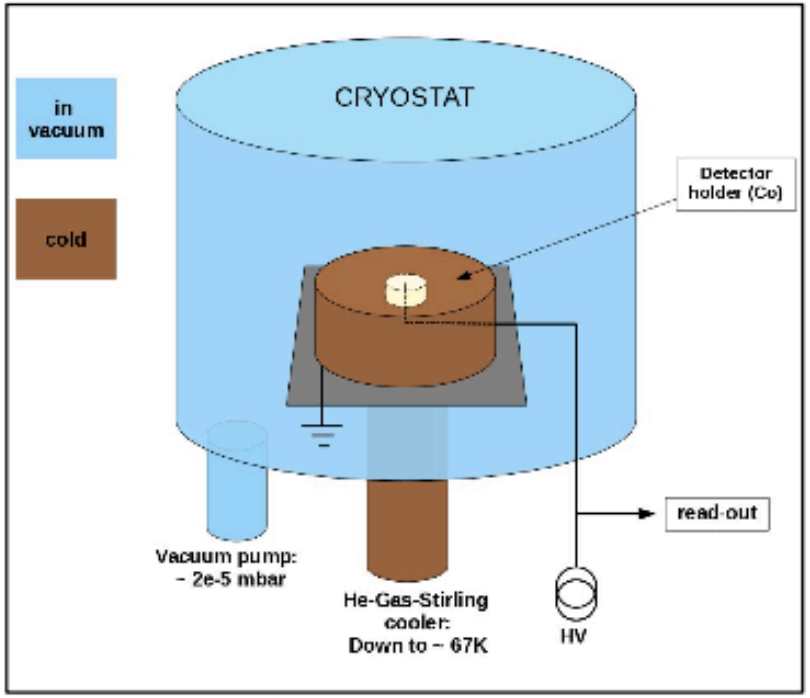
Transient current technique

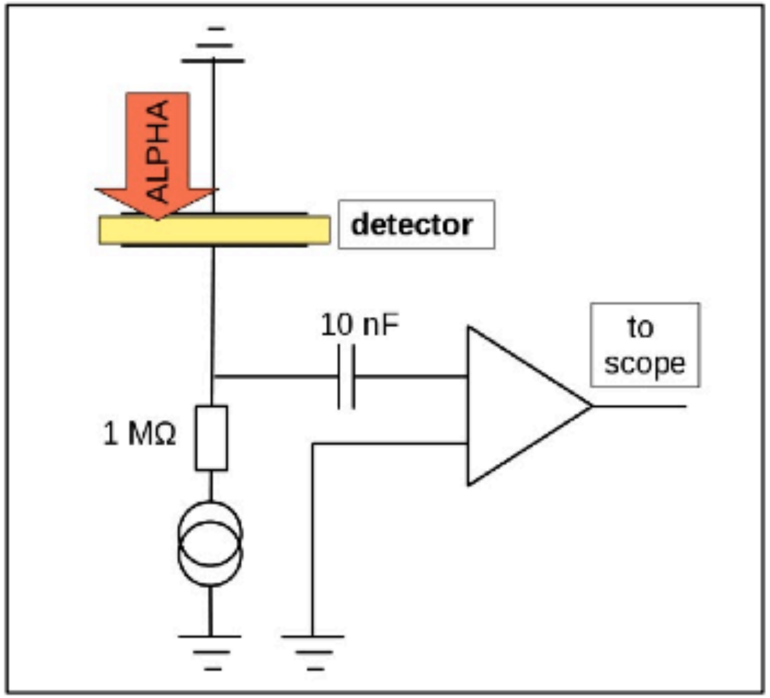
- In parallel to developing, constructing and operating detector systems we focus on RD on diamonds
- **Understand basic signal collection & trapping mechanisms in diamonds**
- Measure the drift of charges through diamond bulk
- Allows to characterize charge carrier properties relevant for detector operation
  - Drift velocity, mobility
  - Charge trapping, de-trapping and lifetime
  - Field configuration

- **The following slides are the research topic & results of Hendrik Jansen for his PhD Thesis**

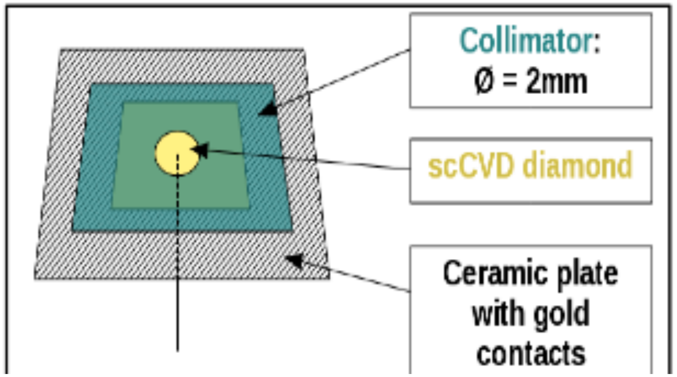


Setup – Many thanks to RD39 !

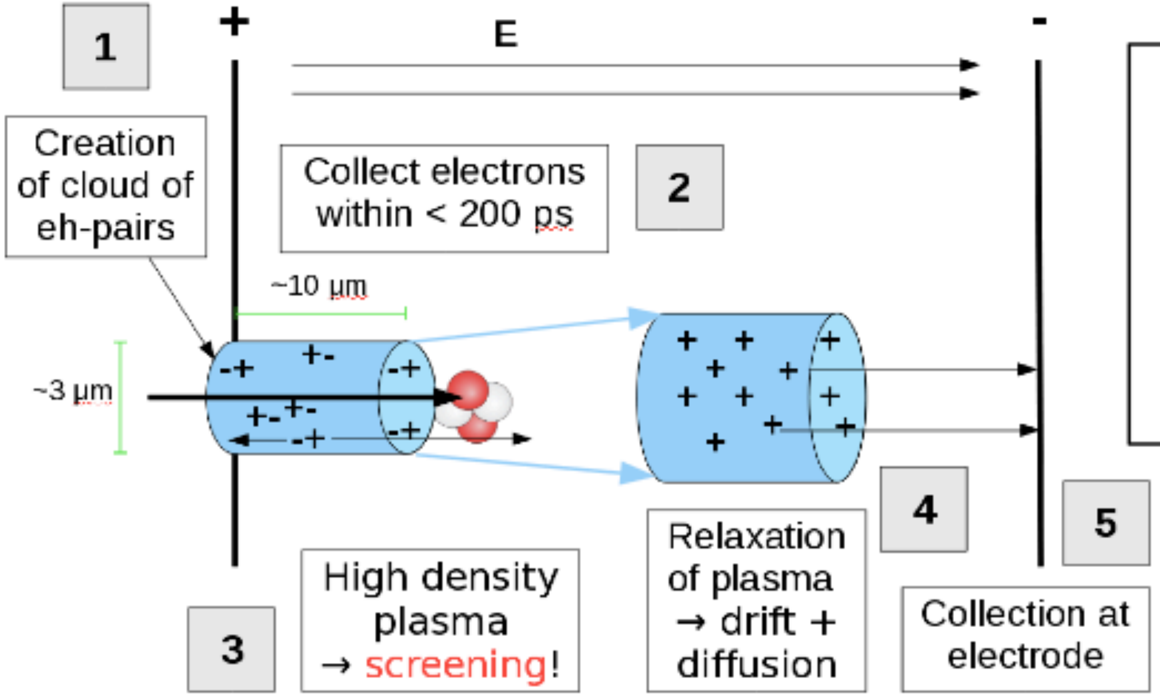




- **FACTS:**
  - → TCT in vacuum
  - → Temp: 65 K - 300 K, bias ≤ 600 V
  - → Read-out from HV-side
  - → Use collimator (avoid edge-effects)



Energy deposition and Plasma



1
Creation of cloud of eh-pairs

2
Collect electrons within < 200 ps

3
High density plasma → screening!

4
Relaxation of plasma → drift + diffusion

5
Collection at electrode

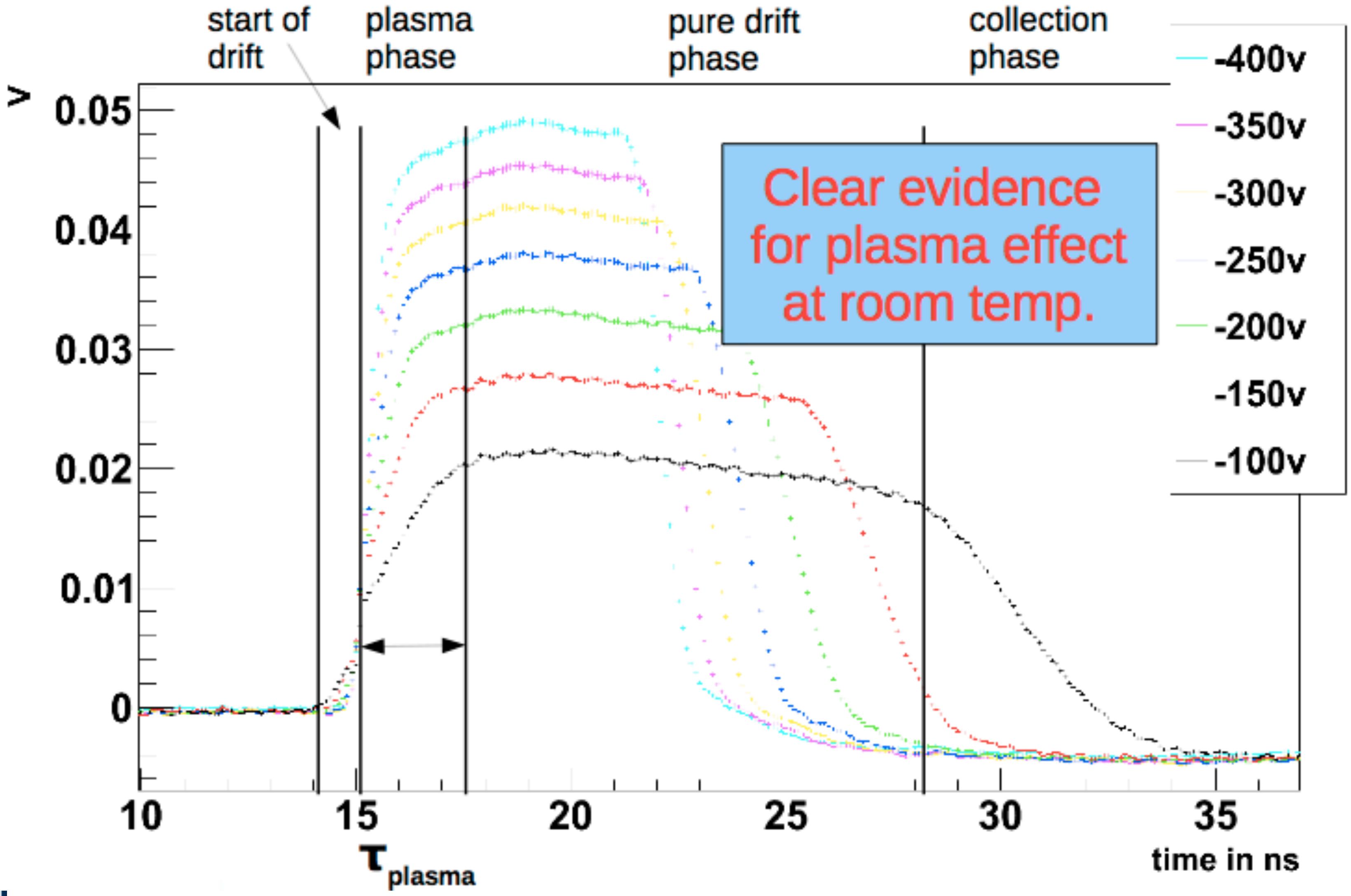
From Ramo-Theorem:

$$i(t)=Q(t)E_w v(t)$$
$$=\frac{1}{d}\sum_i q\,v(t-t_i^{start});$$
$$v(t)=0 \quad for \quad t<0$$

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

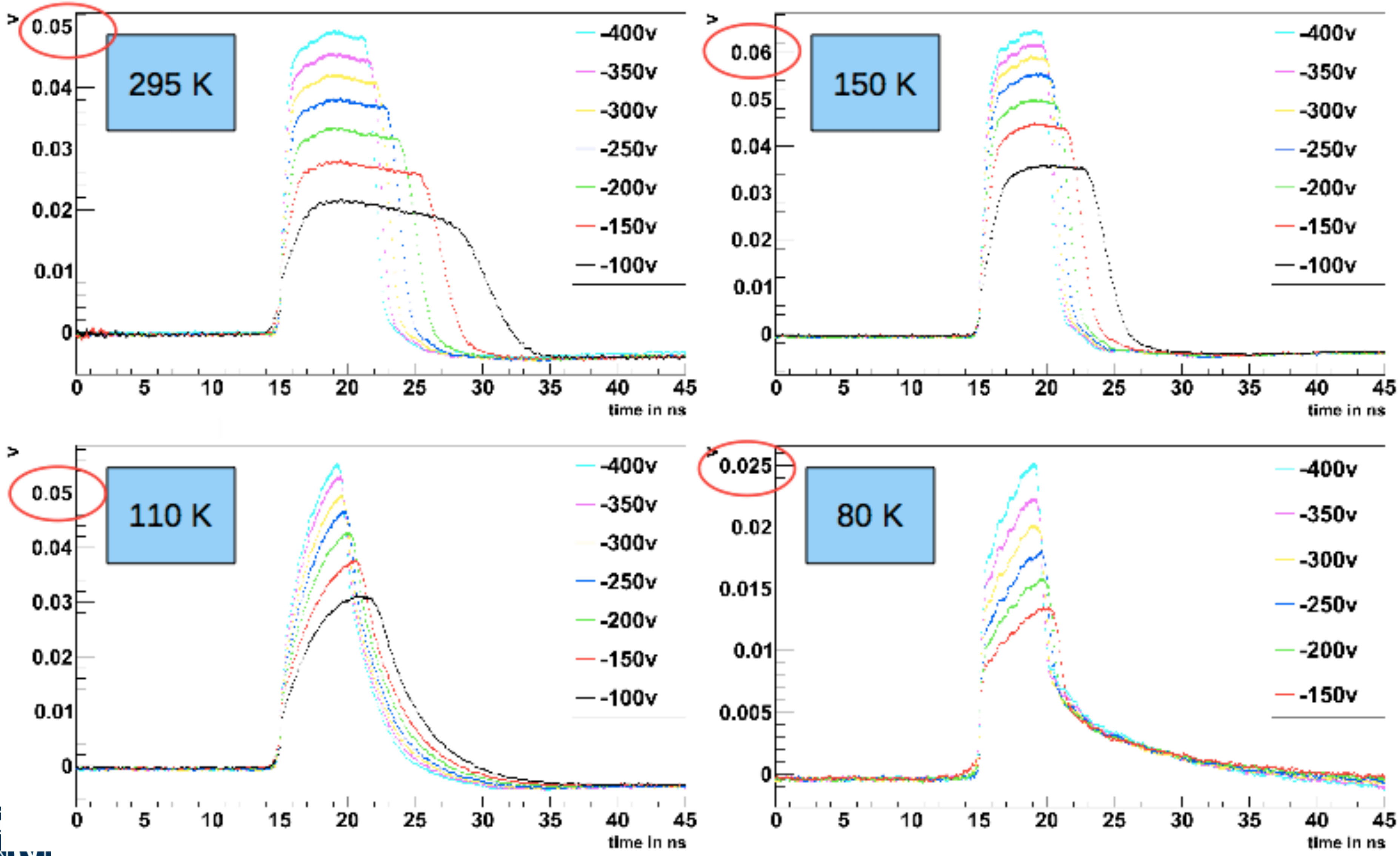
$$\rho_{cloud}\approx\frac{4\cdot 10^5\,pairs}{(3\,\mu m)^2\pi\,20\,\mu m}$$
$$\approx 10^{15}\,cm^{-3}$$

Different phase of charge drift (@295K)



Clear evidence for plasma effect at room temp.

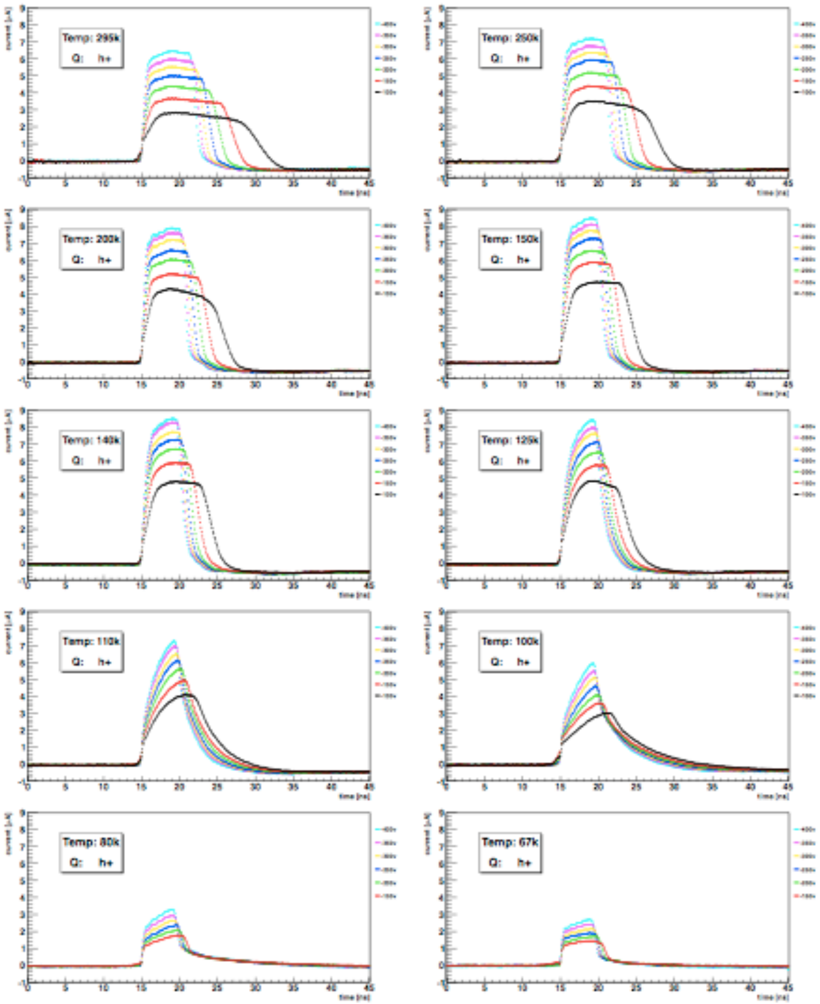
Temperature dependance



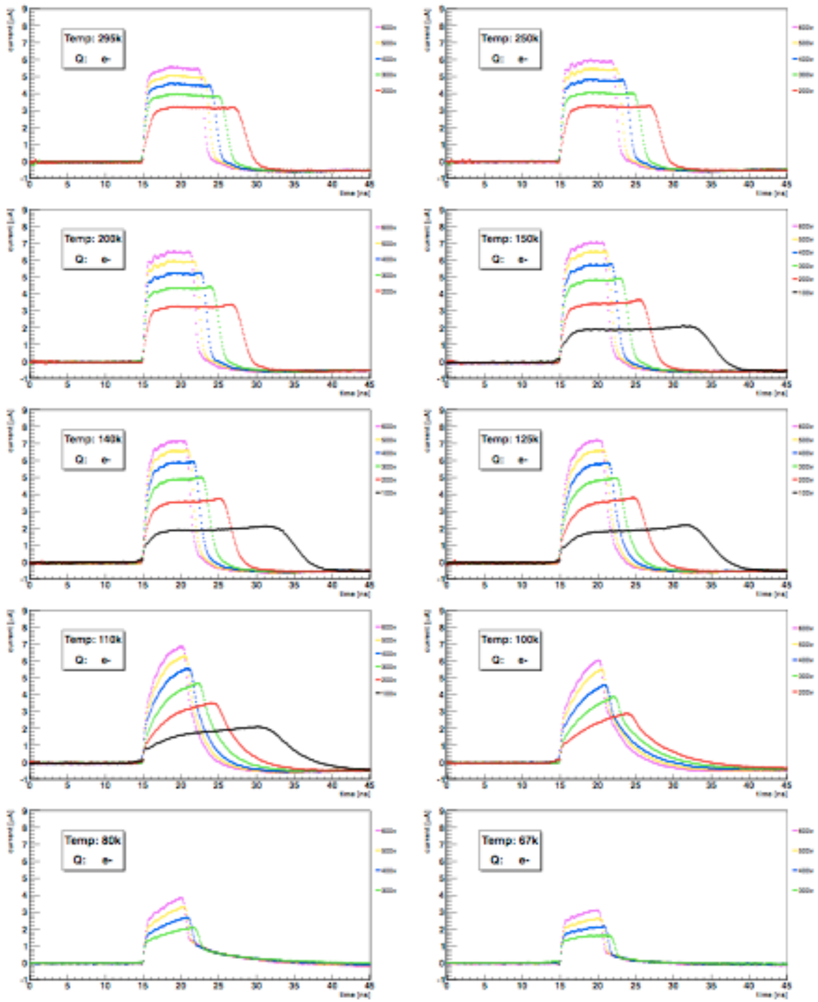
Holes & Electrons

Preliminary

- Holes



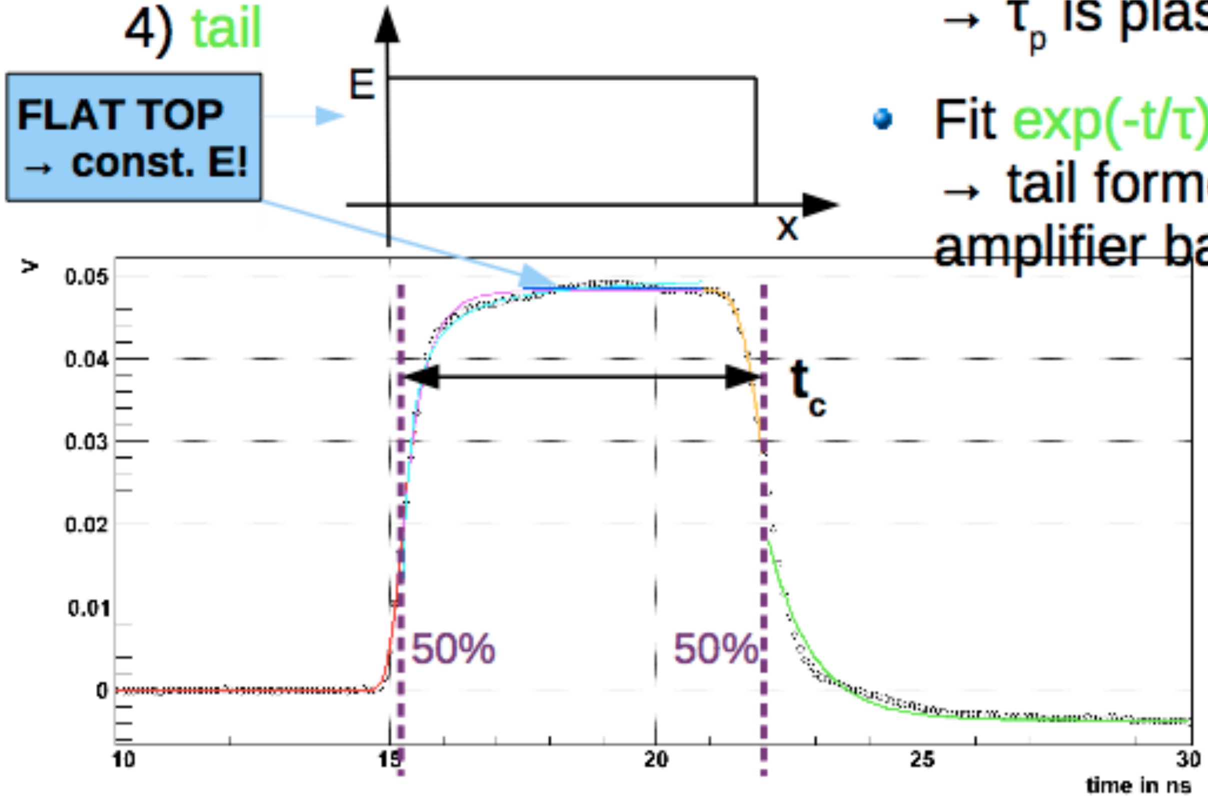
Electrons



Analysis of TCT pulses

- Four phases:

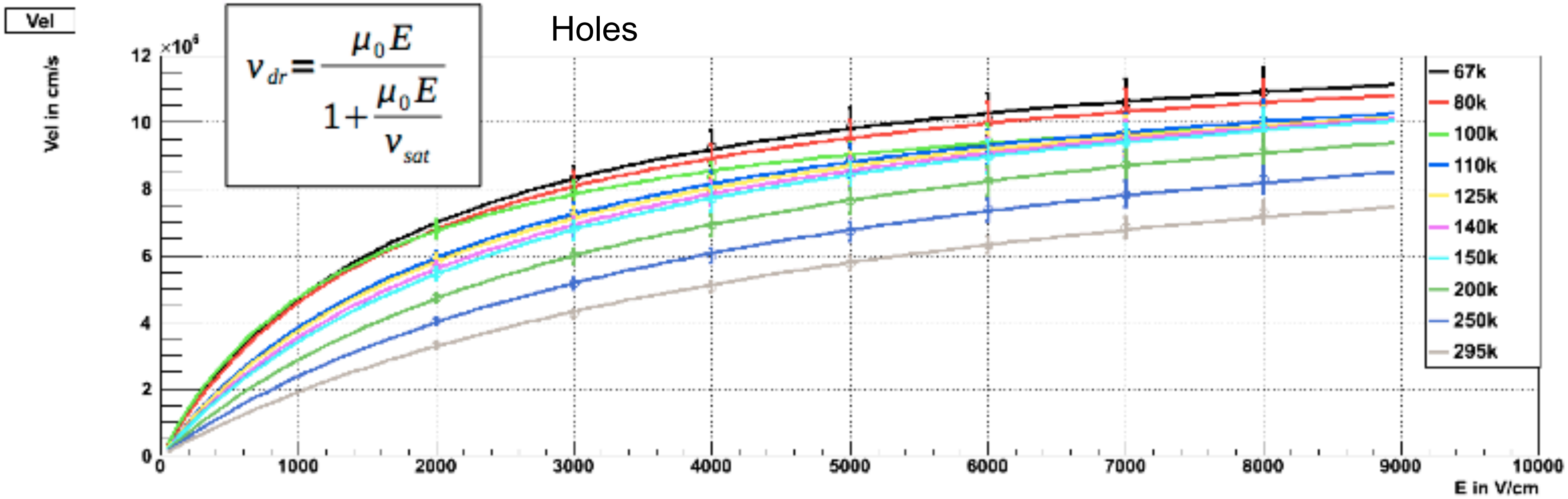
  1) start of drift
  2) current saturation
  3) collection at electrode
  4) tail



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

Mobility and Drift velocity



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

Fits yield:

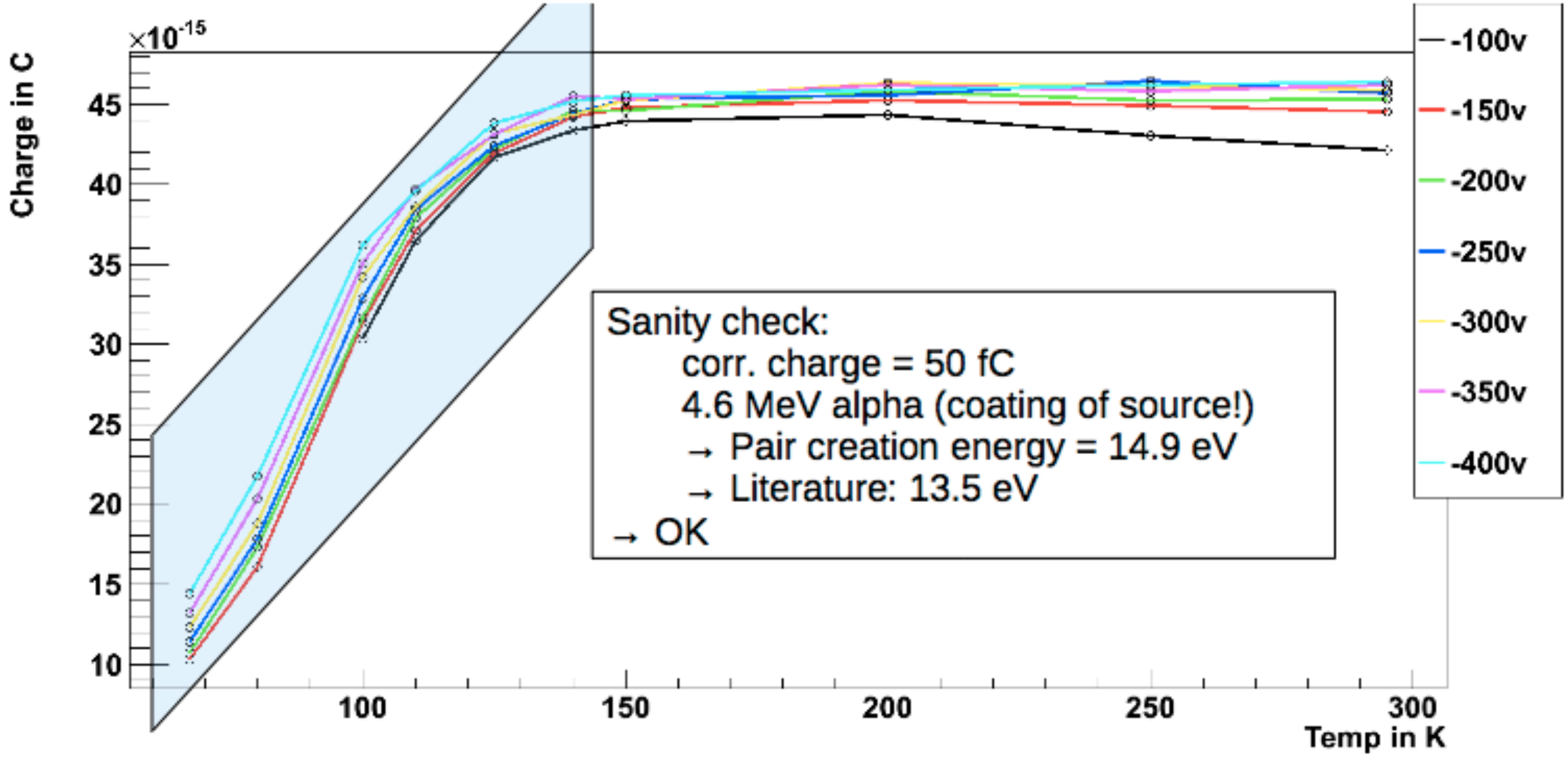
$\mu_{0,h}^{295\,K}= \quad \pm \quad cm^2/Vs$ $\qquad$ $\mu_{h}^{67\,K}=7300\pm1850\,cm^2/Vs$

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

- Mobility and velocity at RT as expected
- μ_h increases down to 67 K

  → no onset of impurity scattering
- v_{sat} ~ constant with temperature

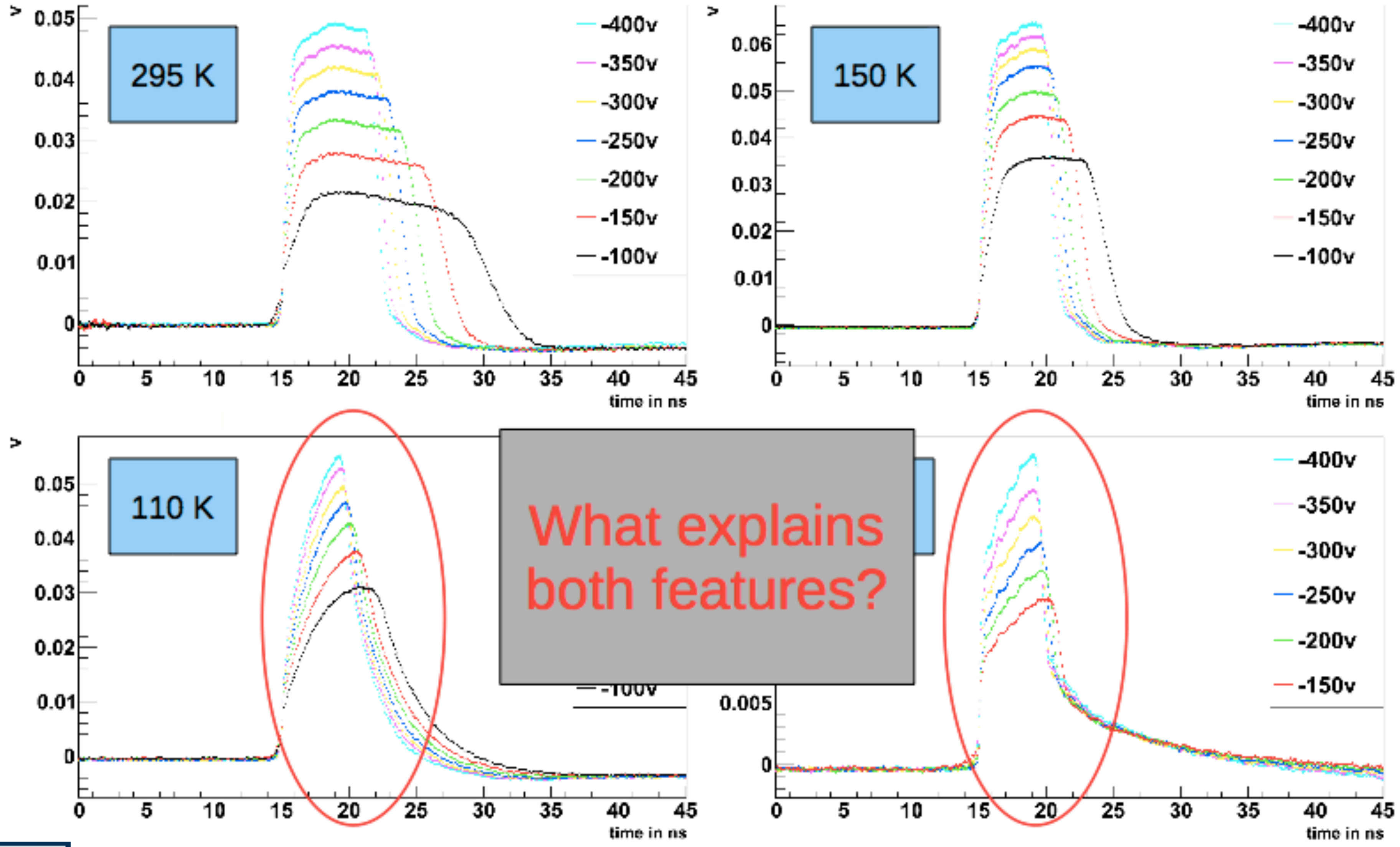
Integrated Charge



Sanity check:
corr. charge = 50 fC
4.6 MeV alpha (coating of source!)
→ Pair creation energy = 14.9 eV
→ Literature: 13.5 eV
→ OK

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

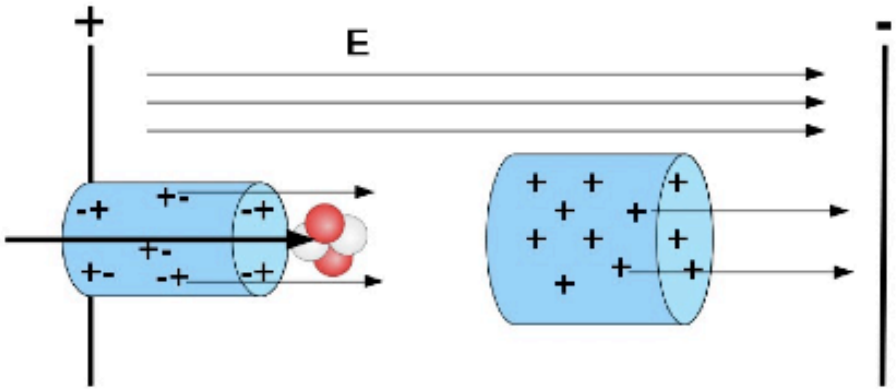
What can explain signal reduction and tail? (speculation!)

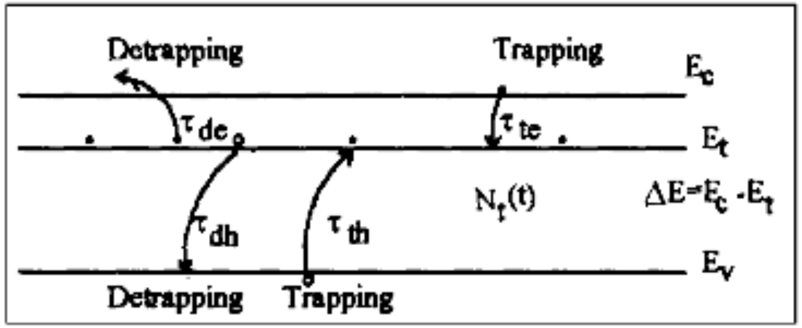


What explains both features?

Plasma behaviour at low temperatures

- Trapping and De-trapping at low temperatures





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!

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

from Ramo-Theorem:

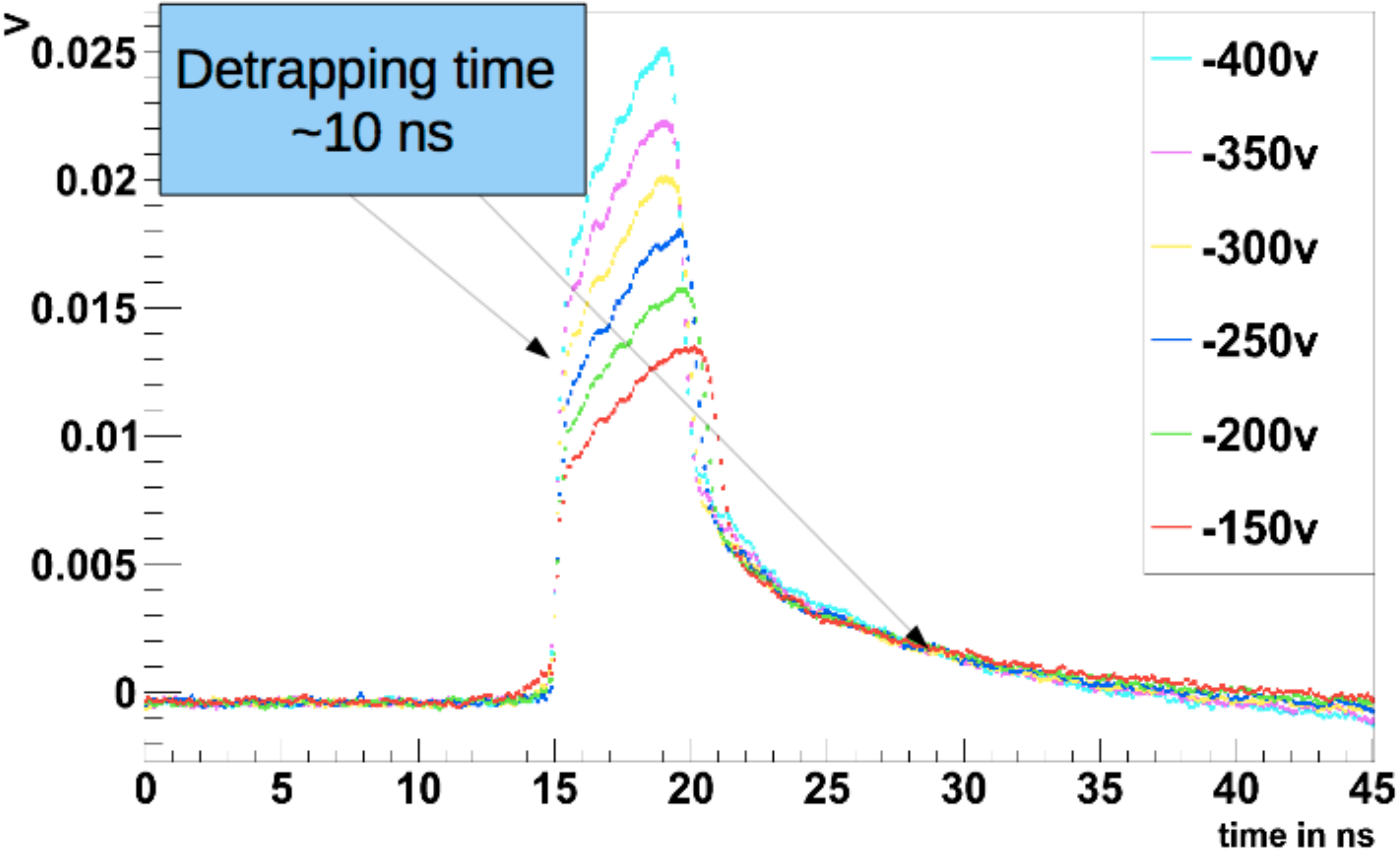
$$i_{(t)} = i_{non-trapped}(t) + i_{released}(t)$$

$$= \sum_i \frac{q_{not-trapped}}{d} v(t - t_i^{start})$$

$$+ \sum_i \frac{q_{released}}{d} v(t - t_i^{detrap});$$

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

Detrapping at 80K


Detrapping time ~10 ns

Is this relevant for Cryo-BLM – what next ?

- For beam monitoring energy deposition is significantly lower than alpha's ionization density, therefore only the trapping/detrapping **during drift** is relevant (**no plasma**).

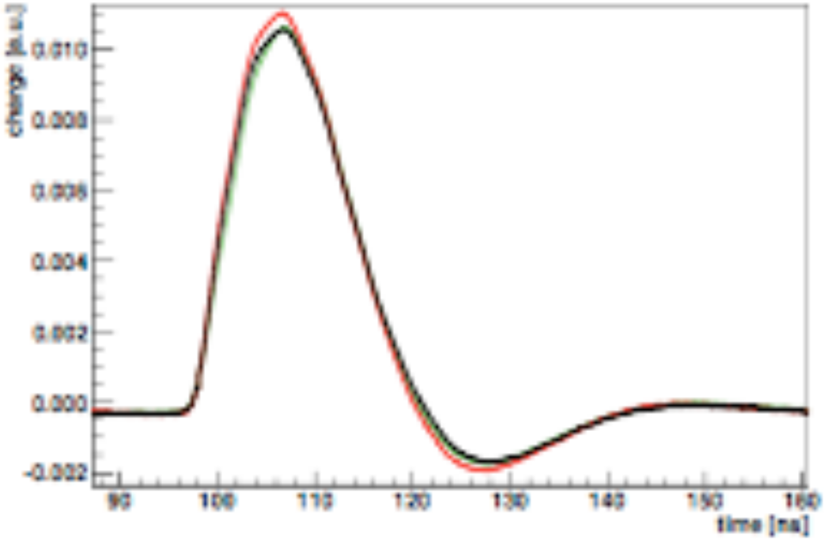
- This is consistent with the fact that we see nice testbeam pulses at 2K (see Christoph's talk)

- **Investigate charge trap levels**: have carried out **TSC measurements** in Florence (Many thanks to Mara Bruzzi, R. Mori. M. Scaringella!) – Analysis of data is on-going

- Next step: measure signal with **MIP equivalent +** Integrator electronics as function of temperature

Cosmics in diamonds at low temperatures

- Very preliminary !
- Measurements at 295K,150K,67K with Cosmics (MIP) and integrator
- No sign of charge loss at low temperatures



Summary

- Diamonds have a good track record as beam monitors in applications from single –particles to very high flux
- They are compact enough for a Cryo-BLM
- Diamonds are (relatively) easy to operate and reliable in operation (“>10 years locked away)
- The possible application of diamonds as beam loss monitors at 2K at LHC sparked our interest to investigate their behaviour at low temperatures in collaboration with Bernd & Erich & Christoph