Development of CVD Diamond Beam Monitors at cyrogenic and room temperature for LHC, CNGS and ATLAS

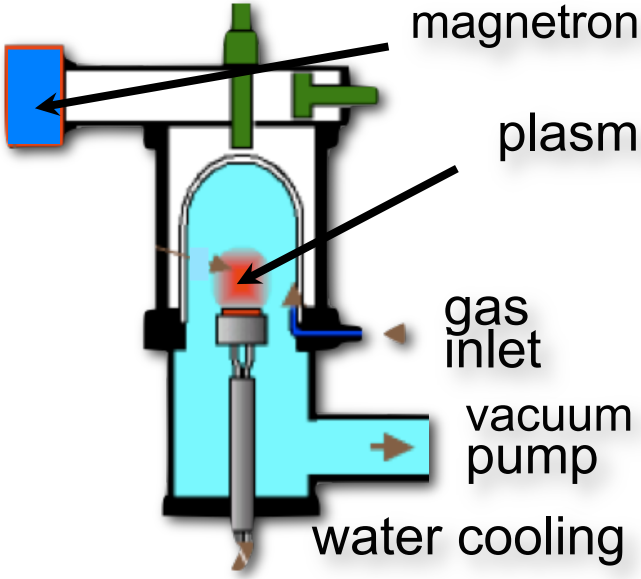
H. Pernegger/CERN

On behalf of B.Dehning, D. Dobos, V. Eremin, Ch. Gallrapp, E. Griesmayer, E. Gschwendtner, F. Hügging, H. Jansen, H. Kagan, N. Wermes

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



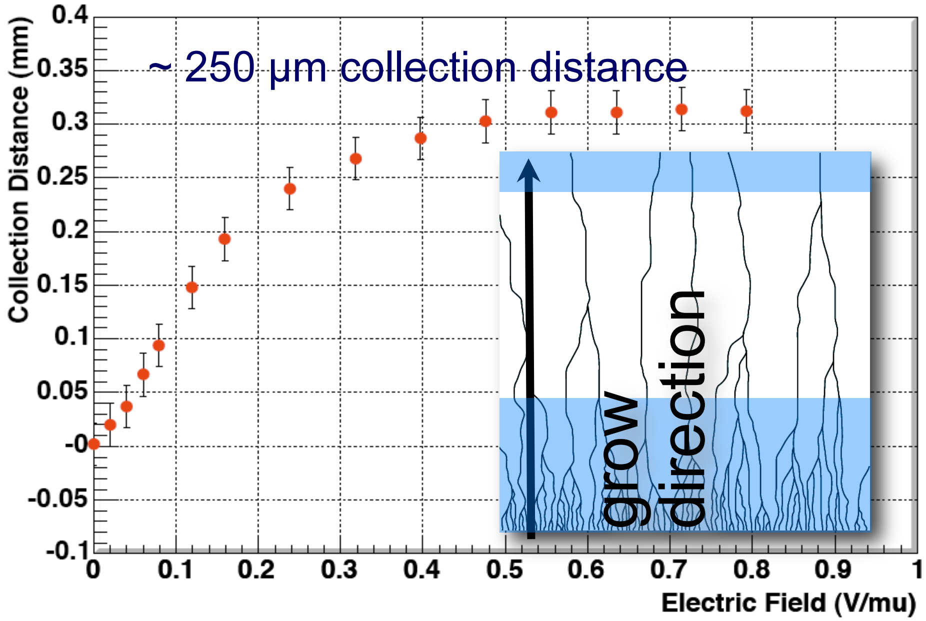
Metallization

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

Types of CVD diamonds

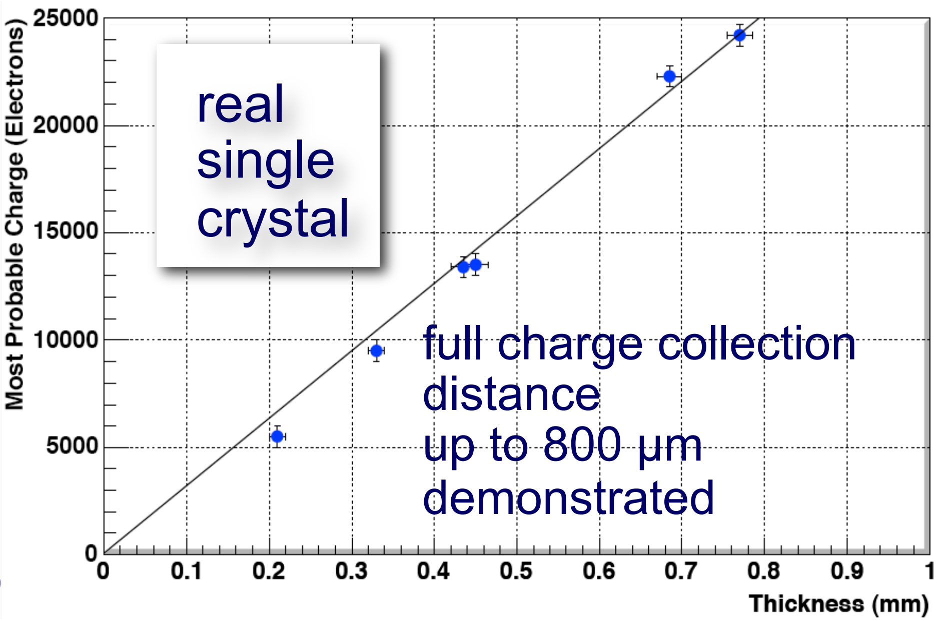
polycrystalline (pCVD):
Fast and short signal (~2ns FWHM) :
Use for optimal double-pulse resolution

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



~ 250 μm collection distance

grow direction



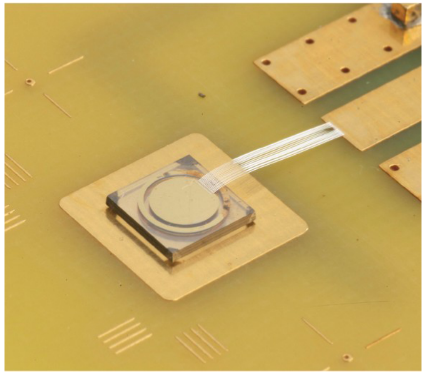
real single crystal

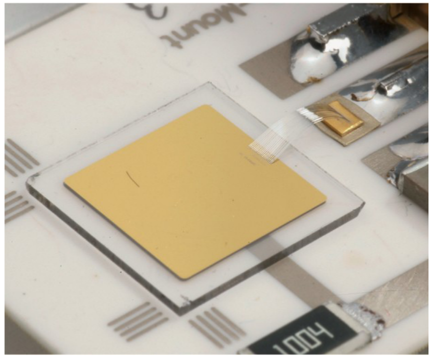
full charge collection distance
up to 800 μm
demonstrated

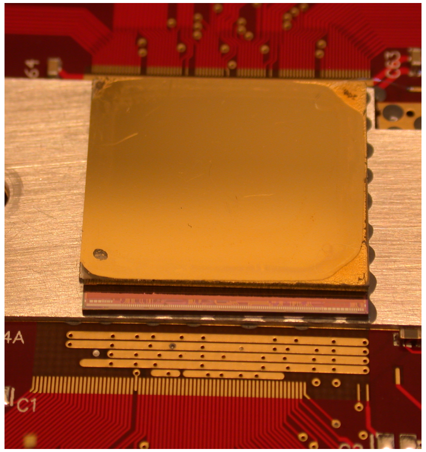
Diamond Beam Monitors

- Large Pad Diamond Beam monitors
  - Large pads (typically 1cm2) for the measurement of high-flux beam or losses
  - Fast current amplifiers and readout (typical 1-2ns rise time)
  - Measure beam intensity
  - Resolve time structure of beams
  - Examples: LHC beam monitors, CNGS muon detector

- Diamond Pixel Detectors
  - Typically 10-20k channels per module with pad sizes of O (50x250 μm) and module size 2x2 cm2
  - 25ns charge amplifier and LHC-time structured readout
  - Measure hit position (~10μm resolution), particle tracking and charge (time-over threshold)
  - Used for luminosity measurements in ATLAS and CMS
  - Examples: ATLAS Diamond Beam Monitor







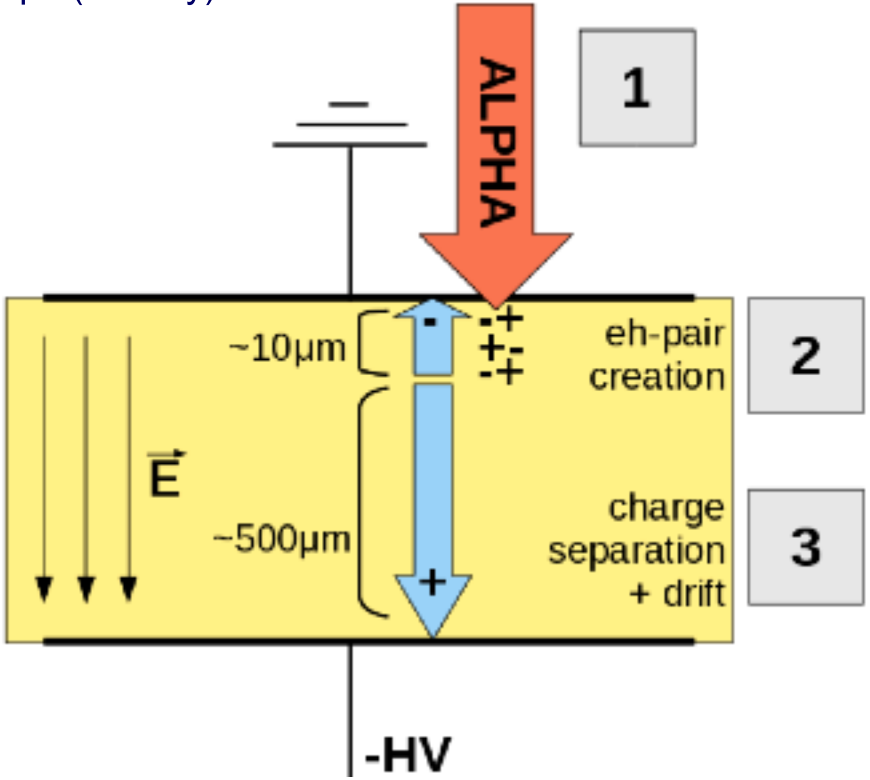
Charge carrier properties in diamonds

- **Understand basic signal collection & trapping mechanisms in diamonds**
  - **At room temperature**
  - **At cryogenic temperature**
- Transient-Current-Technique
  - Well established technique to measure transport properties and fields in solid state detectors
- 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

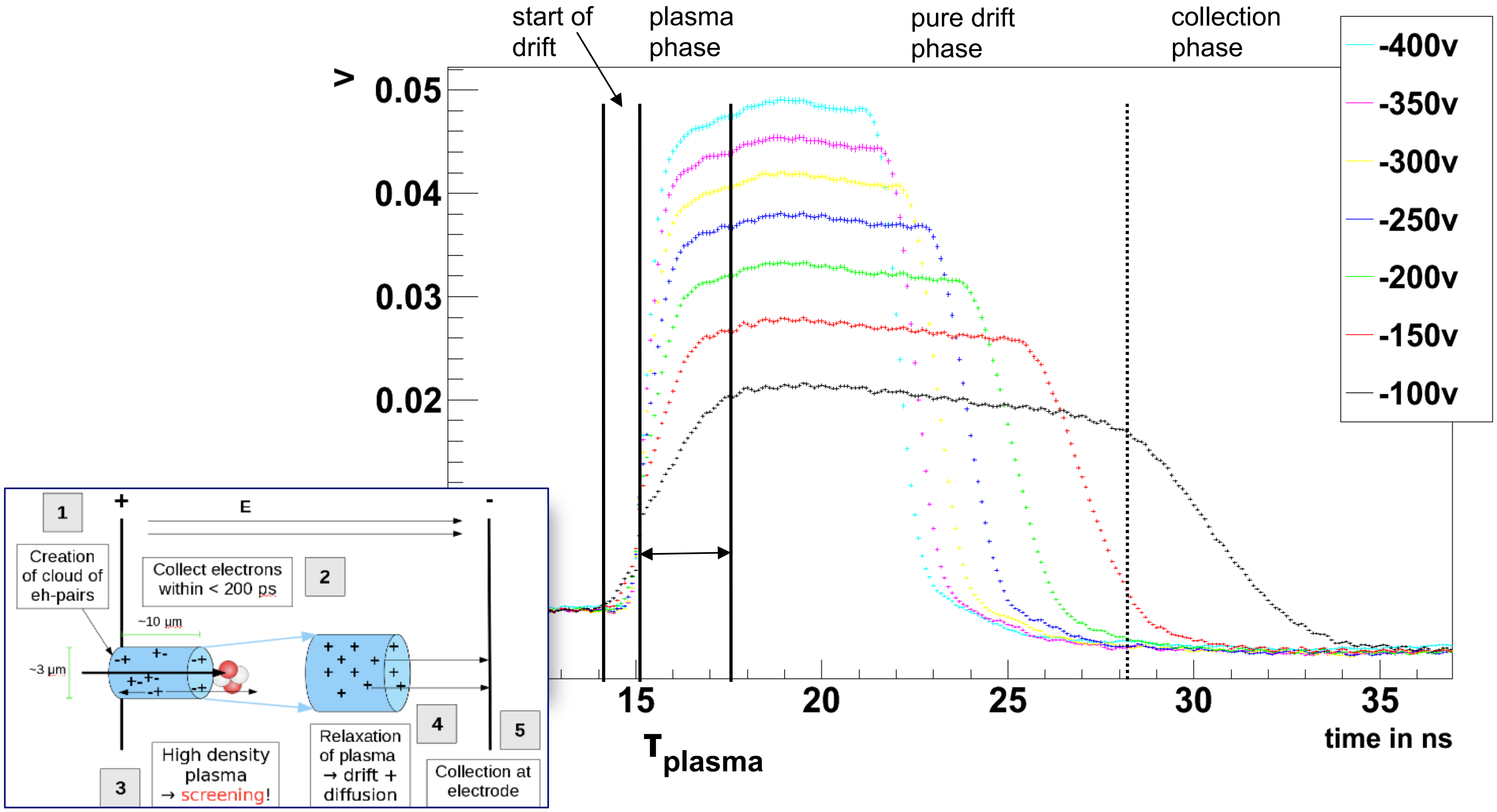
→ Pos. (neg.) bias → Measure e^- (h^+)

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

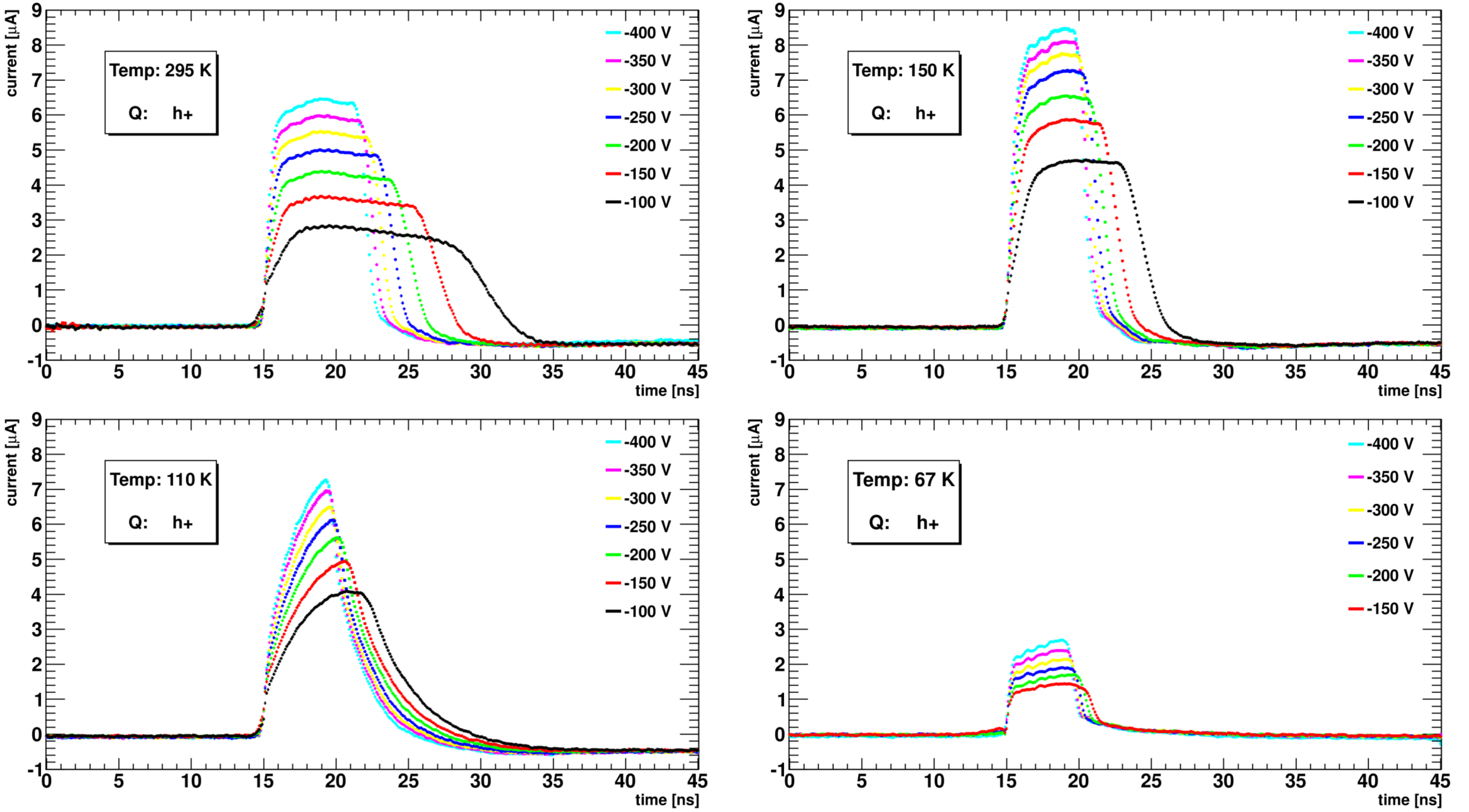
→ Use broad-band 3 GHz scope (LeCroy)



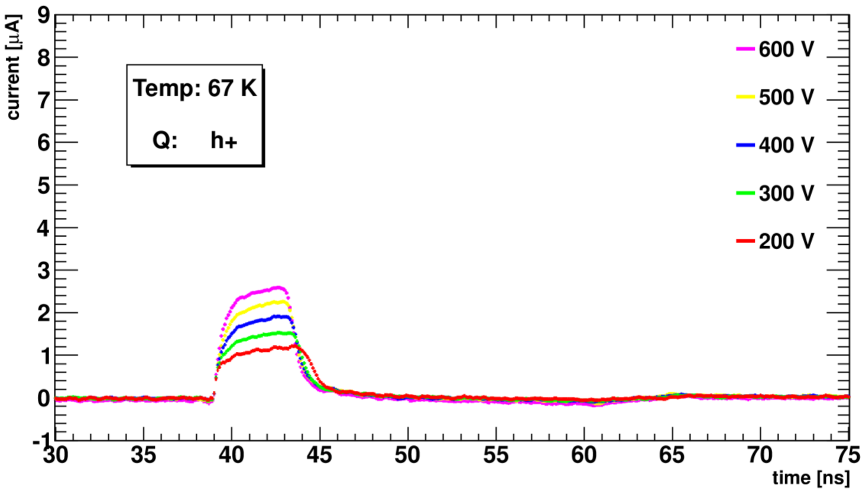
Different phase of charge drift (@ Room Temp.)

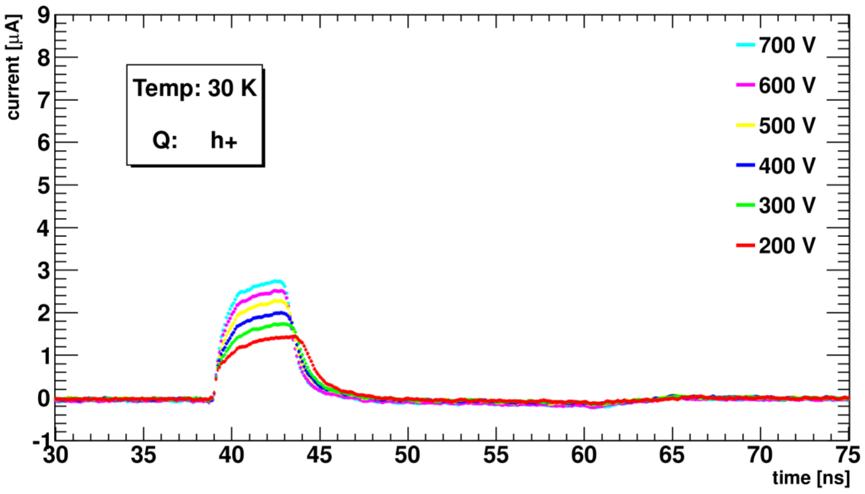


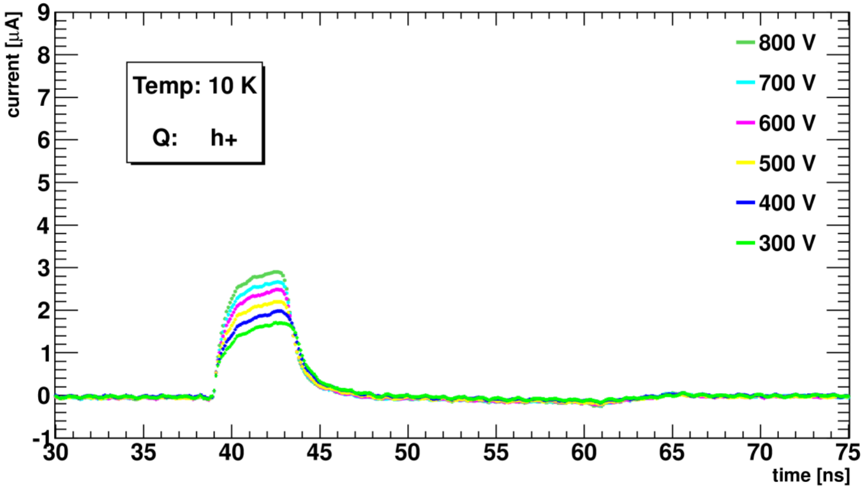
Temperature dependence: From RT…

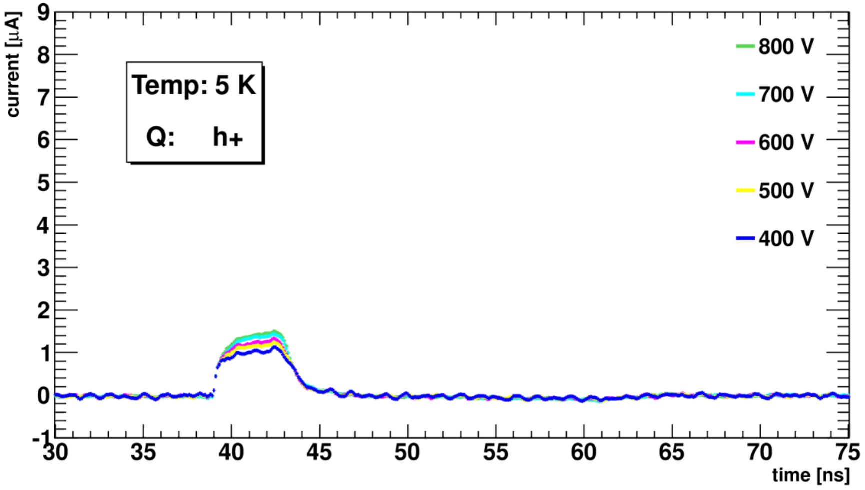


… down to cryogenic temperatures



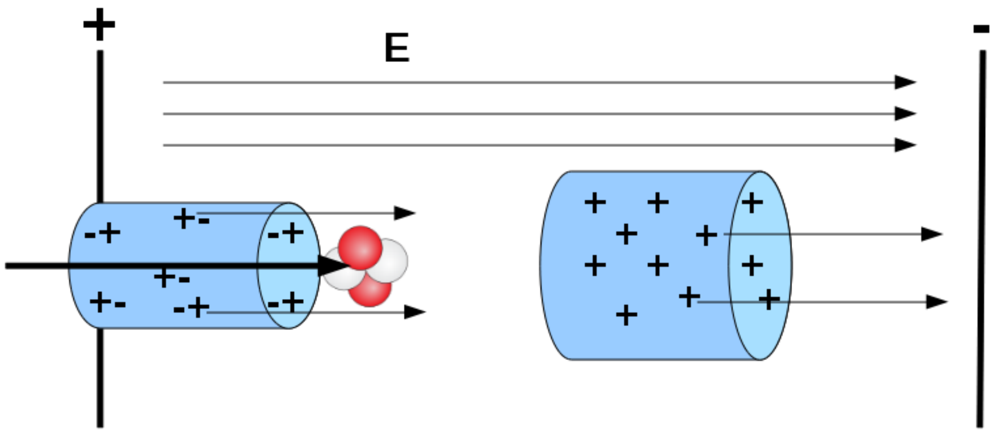


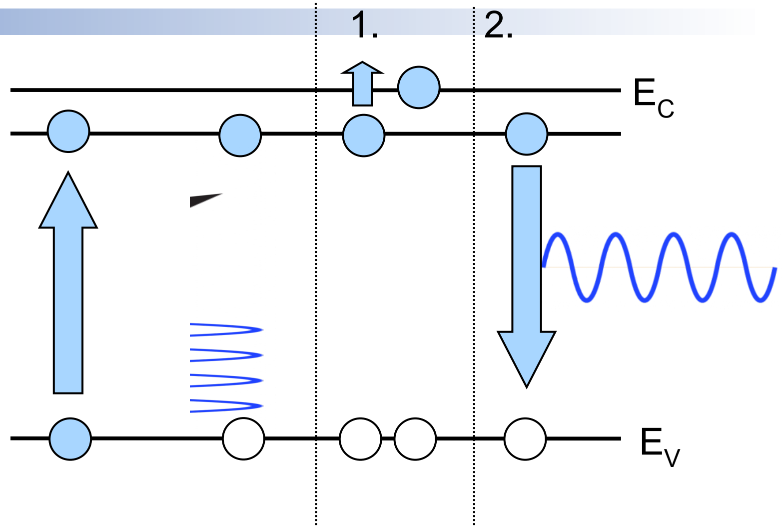




Electrons show same charge reduction

Within the Plasma...





1. dissociation
2. recombination

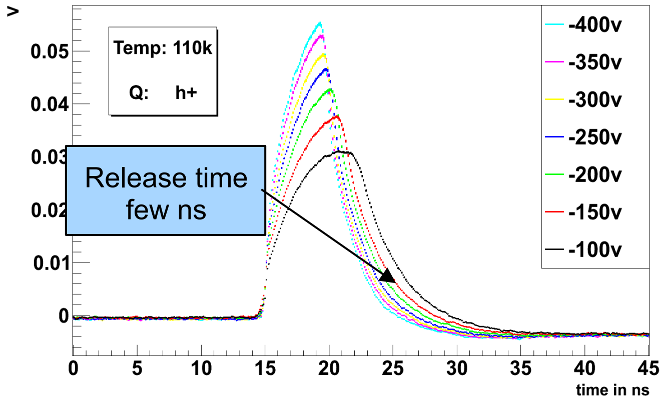
Below ~150 K:

- Field-free region within plasma cloud
  → charges being retained
  (formation of exciton?)
  → increased recombination
- Release charges if E_{act} / kT large enough
- THIS IS NOT TRAPPING DURING DRIFT!
- Same behaviour for e- and h+ !

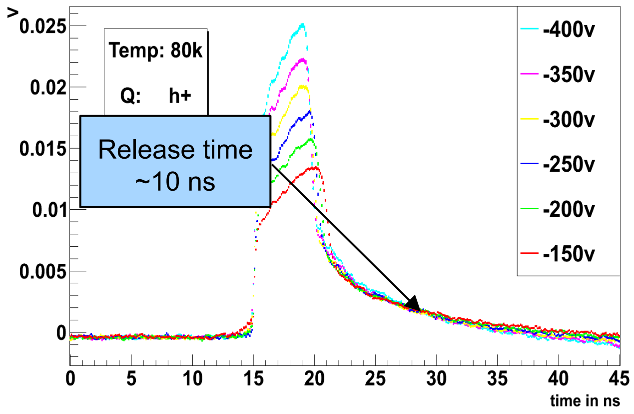
From Ramo-Theorem:

$$i_{(t)} = i_{inner}(t) + i_{outer}(t)$$

Integrated Charge & Release time versus temperature

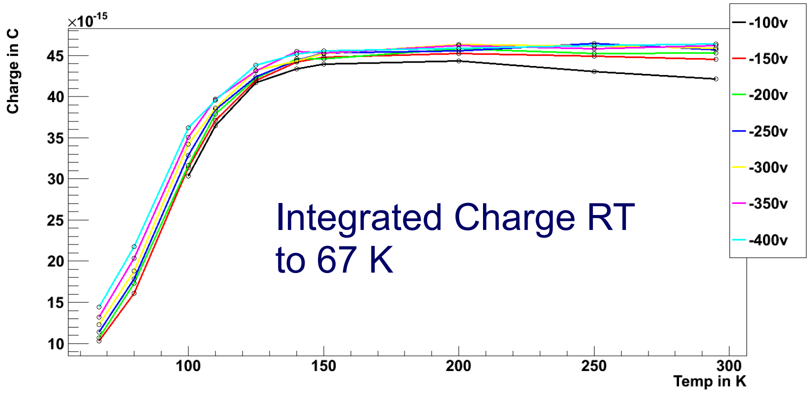


Release time few ns

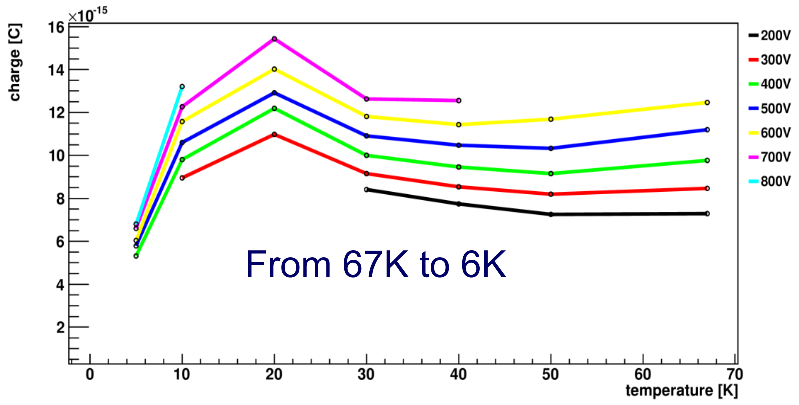


Release time ~10 ns

Sanity check:
corrected charge = 50 fC
4.6 MeV alpha (coating of source!)
→ Pair creation energy = 14.7 eV
→ Literature: 13.5 eV
→ OK



Integrated Charge RT to 67 K



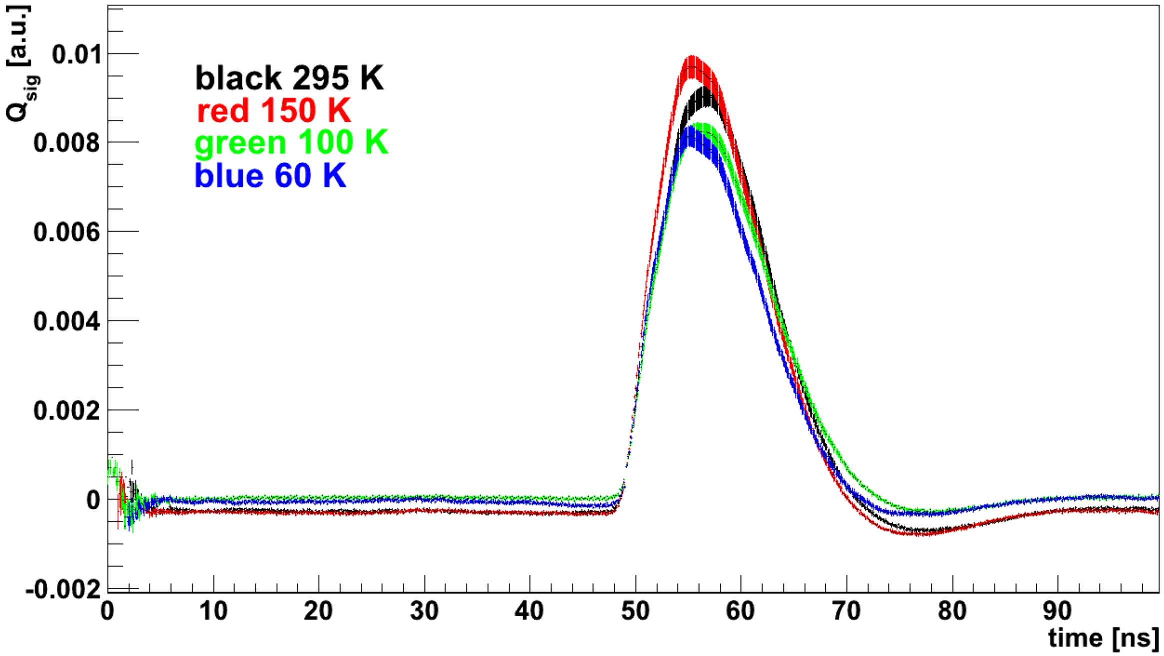
From 67K to 6K

- Charge constant in range 150 K to 300 K
- Steep drop from 140K down to 67 K → gradual increase of plasma associated with “retaining” and recombination

- Integrated charge doesn't drop to zero at 50 K

Difference to MIPS:

- It all depends on the charge deposition density…
- With Highly Ionizing particles and short range, plasma leads to a reduction of measured charge at low temperatures
- How about MIPS
  - Measured cosmic muons on diamonds at different temperatures

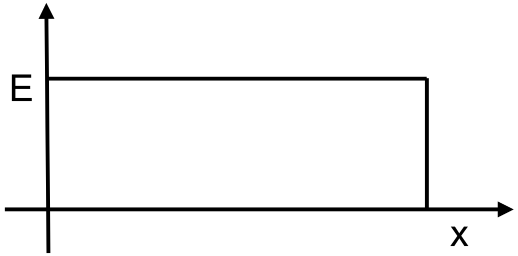


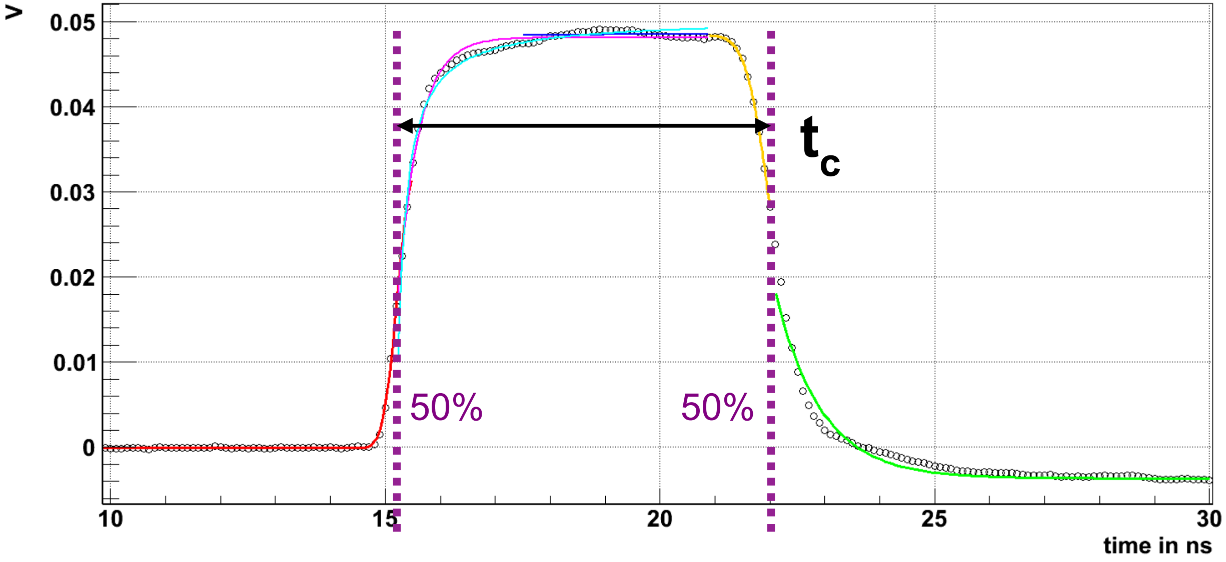
- Measurement with Charge Amplifier
- No significant reduction of charge observed due to lower density of charge deposition (track traverses bulk)

Mobility - Analysis of TCT Pulses

- Four phases:

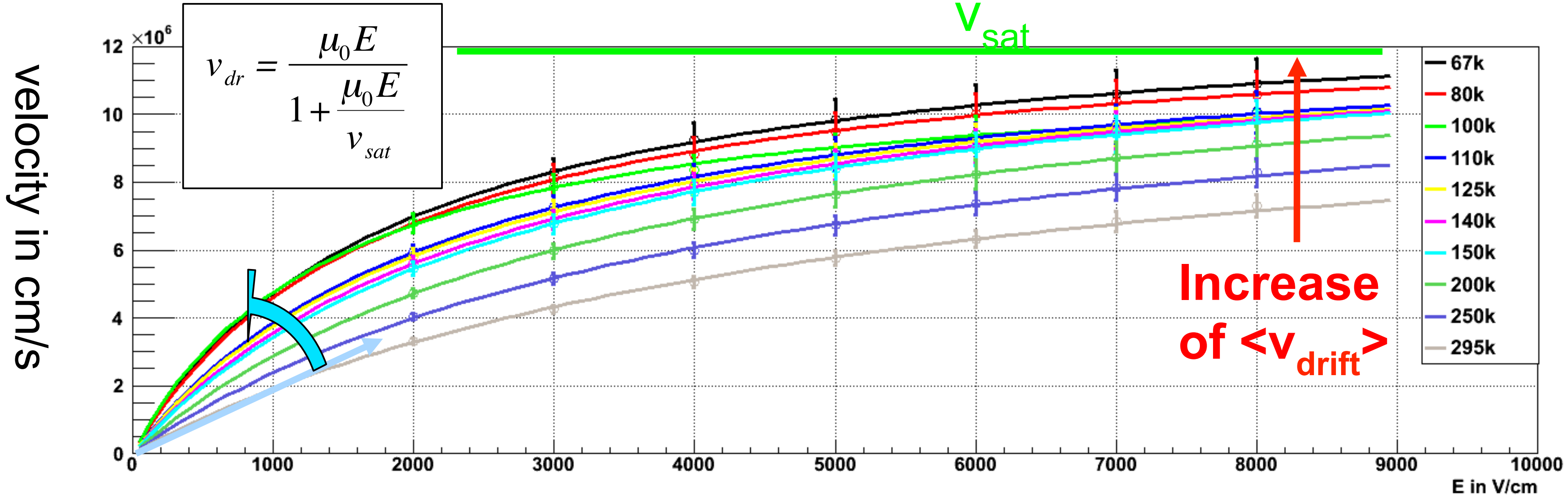
1) Start of drift
2) Current saturation
3) Collection at electrode
4) Tail





- 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
- Integral -> total charge

Hole Drift Velocity



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

Fits yield:

Room temperature:

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

$$v_{sat}^{295K} = 11.8 \cdot 10^6 \pm 0.8 \cdot 10^6 cm/s$$

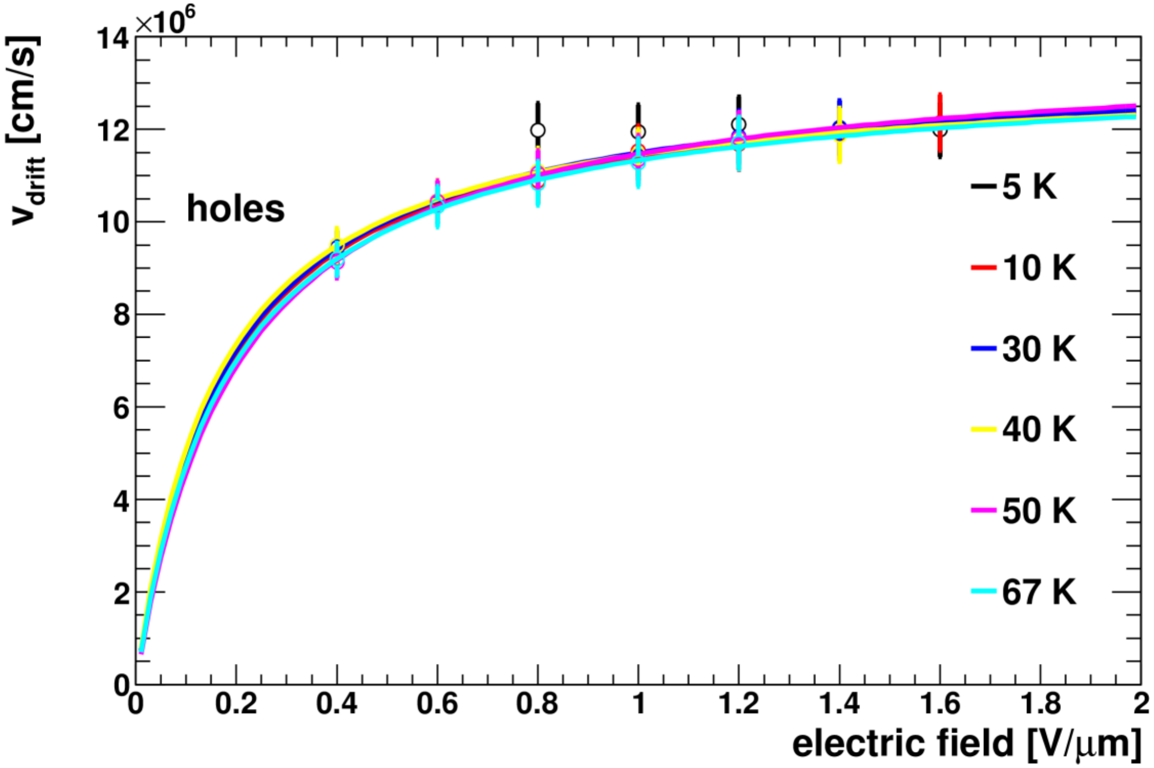
At 67 Kelvin:

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

$$v_{sat}^{67K} = 13.4 \cdot 10^6 \pm 1.4 \cdot 10^6 cm/s$$

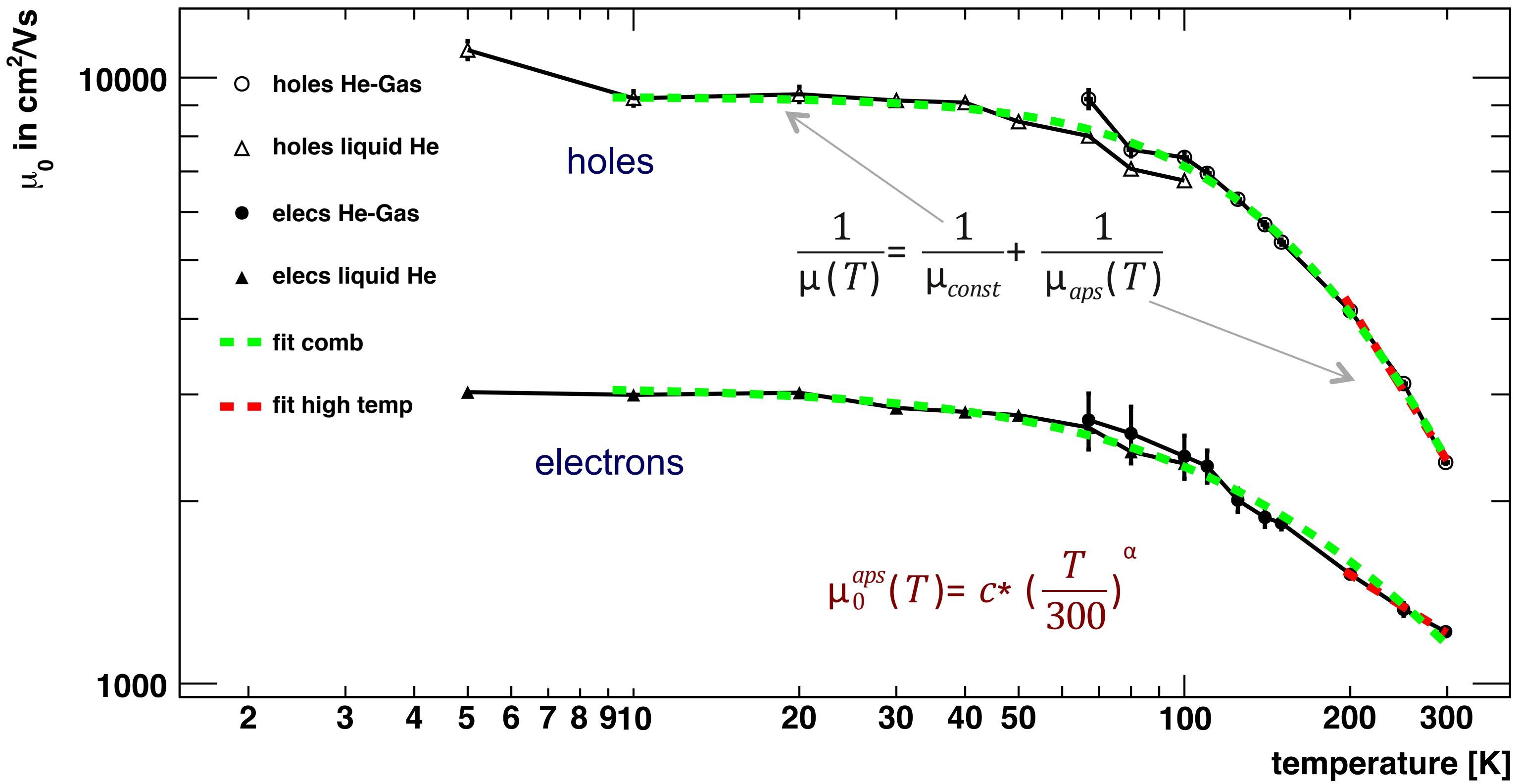
- Mobility μ_h and avg. drift velocity $<v_{drift}>$ at RT as expected
- μ_h increases down to 67 K (→ $<v_{drift}>$ increases as well)
  → no onset of impurity scattering
- v_{sat} ~ constant with temperature

Hole Drift Velocity at low temperatures



- Drift velocity and mobility remains about constant for < 67 K
- This is expected from non-ionized impurity scattering

Mobility vs. Temperature



$$\frac{1}{\mu(T)} = \frac{1}{\mu_{const}} + \frac{1}{\mu_{aps}(T)}$$

$$\mu_0^{aps}(T) = c * \left(\frac{T}{300}\right)^{\alpha}$$

- 300 K to 200K: mobility increases as acoustic phonon scattering decreases: $\alpha = -1.535$, $\mu_0 = 2316$ cm^2/Vs
- 50 K to 10 K: mobility stays ~const.
  -> scattering dominated by non-ionized impurity scattering

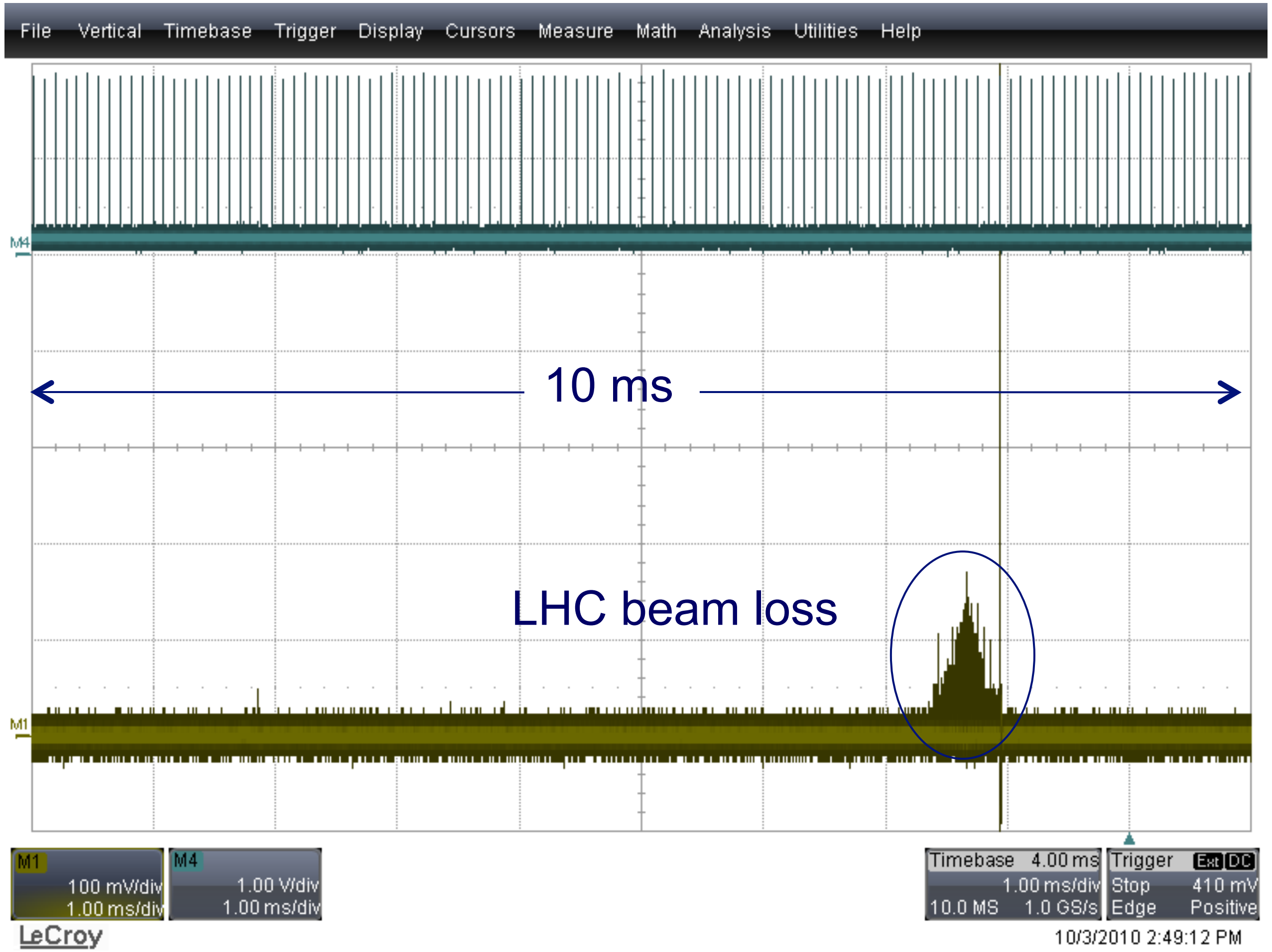
Beam Monitors at LHC and CNGS

- CERN SPS and LHC currently operates diamond beam monitors, which are developed in collaboration between CERN BE, PH and CIVIDEC
- Installed near LHC collimator to measure beam losses in collimator

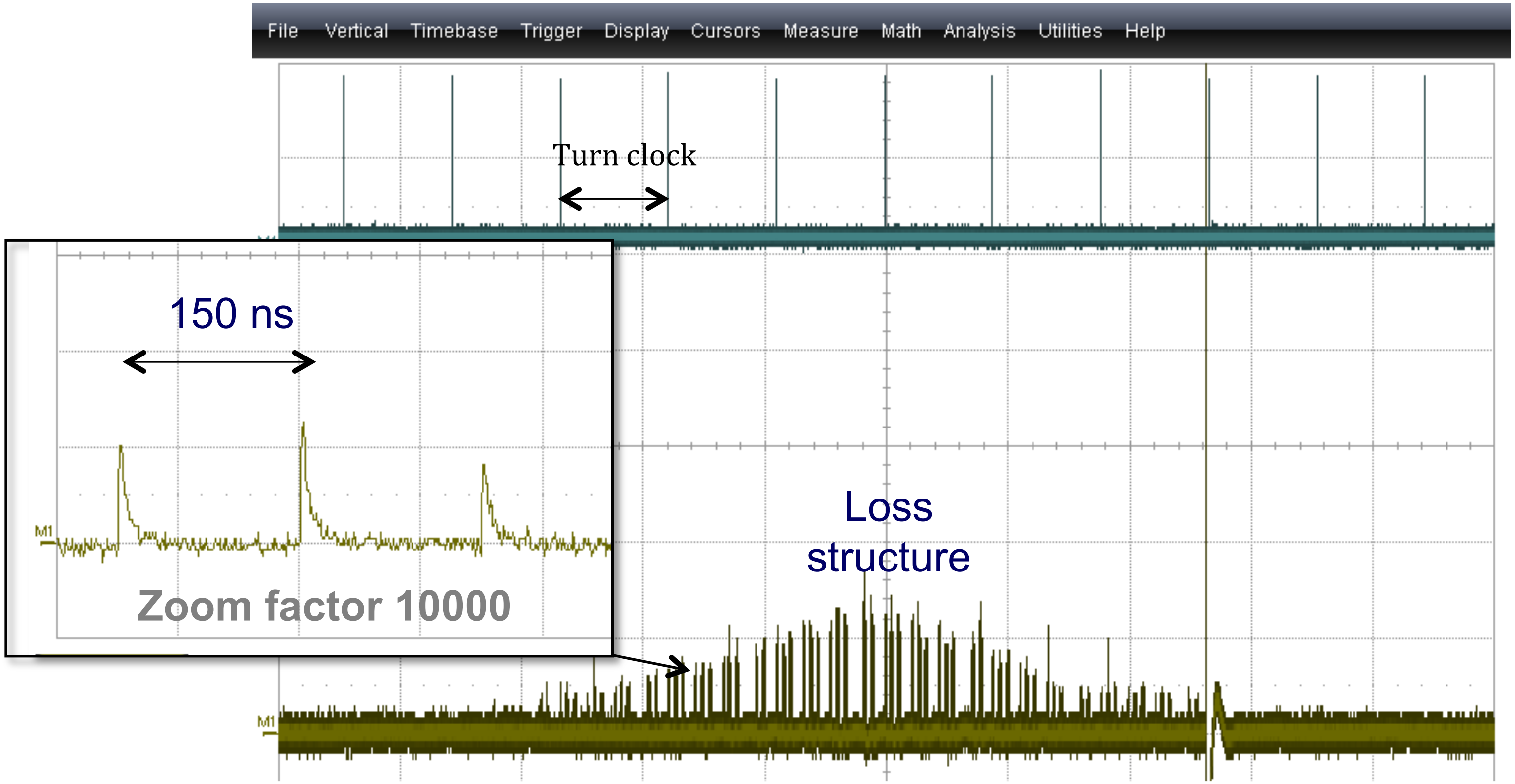
- pCVD with 8x8 mm2 pad and readout using 2GHz broadband amplifiers
- Benefit from fast signal response of diamonds to resolve time structure of losses

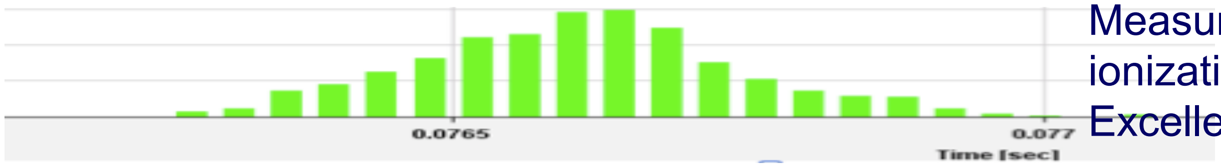
Diamond BLM at LHC collimator

- Provide high-time resolution monitoring of losses



Factor 10 zoom



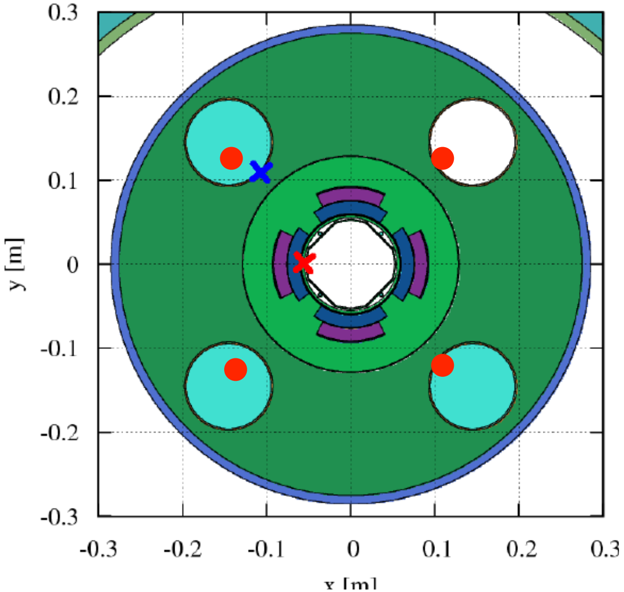


Measurements with ionization chambers. Excellent agreement!

Diamonds as Beam Loss Monitor at 2K

- New LHC quadropol

New LHC quadrupole magnet



● Location of detectors

Initiating of beam abort trigger

Specs

low temperature of 1.9 K (superfluid Helium)

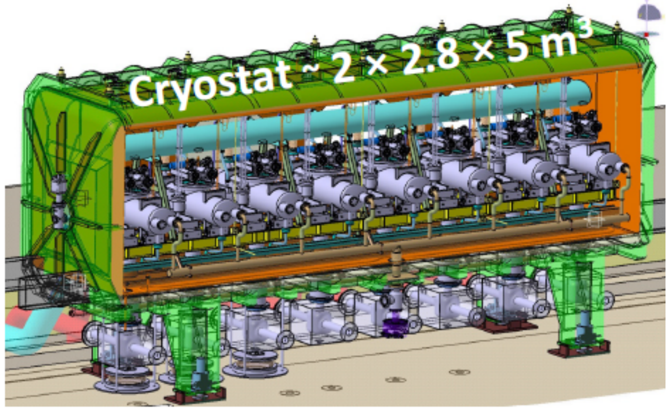
- radiation of about 1 MGy in 10 years

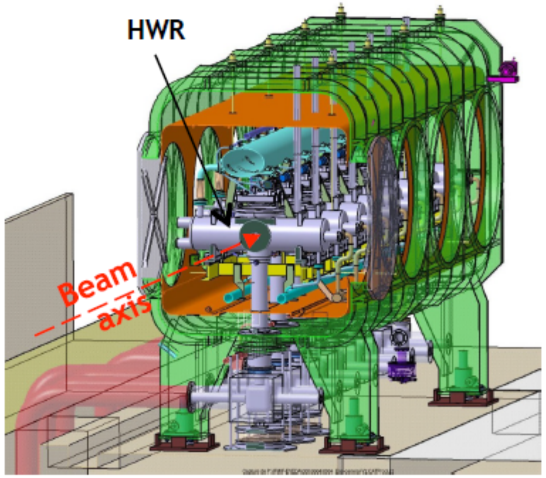
magnetic field of 2 T

pressure of 1.1 bar, withstanding a fast pressure rise up to about 20 bar

- Linearity between 0.1 and 10 mGy/s
- Detector response faster than 1 ms
- Stability, reliability and availability: afterinstallation no access possible

- IFMIF (LIRA) & ITER

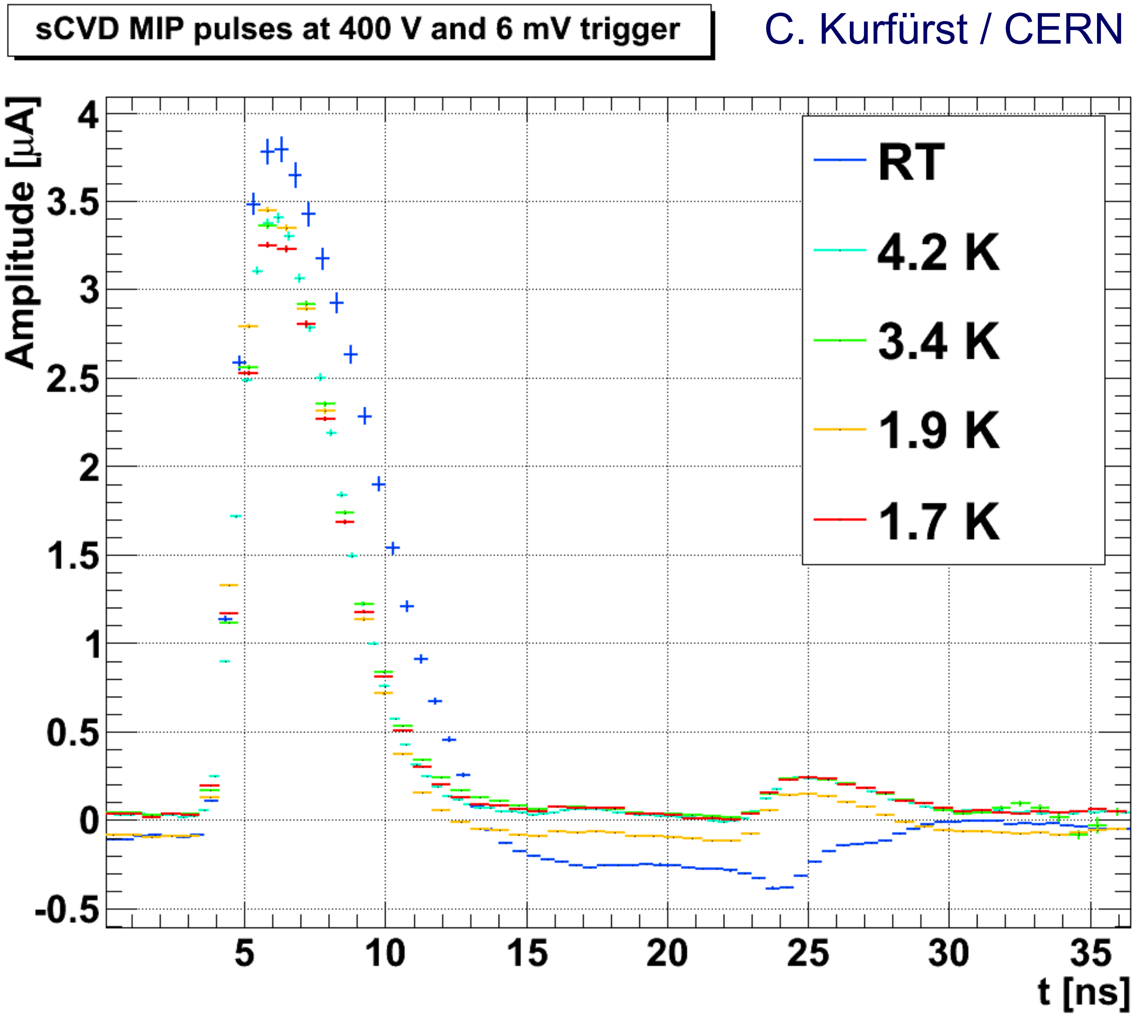




Steering of beam to minimize energy deposition in cavity (Courtesy J. Marroncle)

BLM at 2K

- To allow for precise measurement of losses: integrate BLM in cold mass of magnets: diamonds operate as BLM at 1.9K

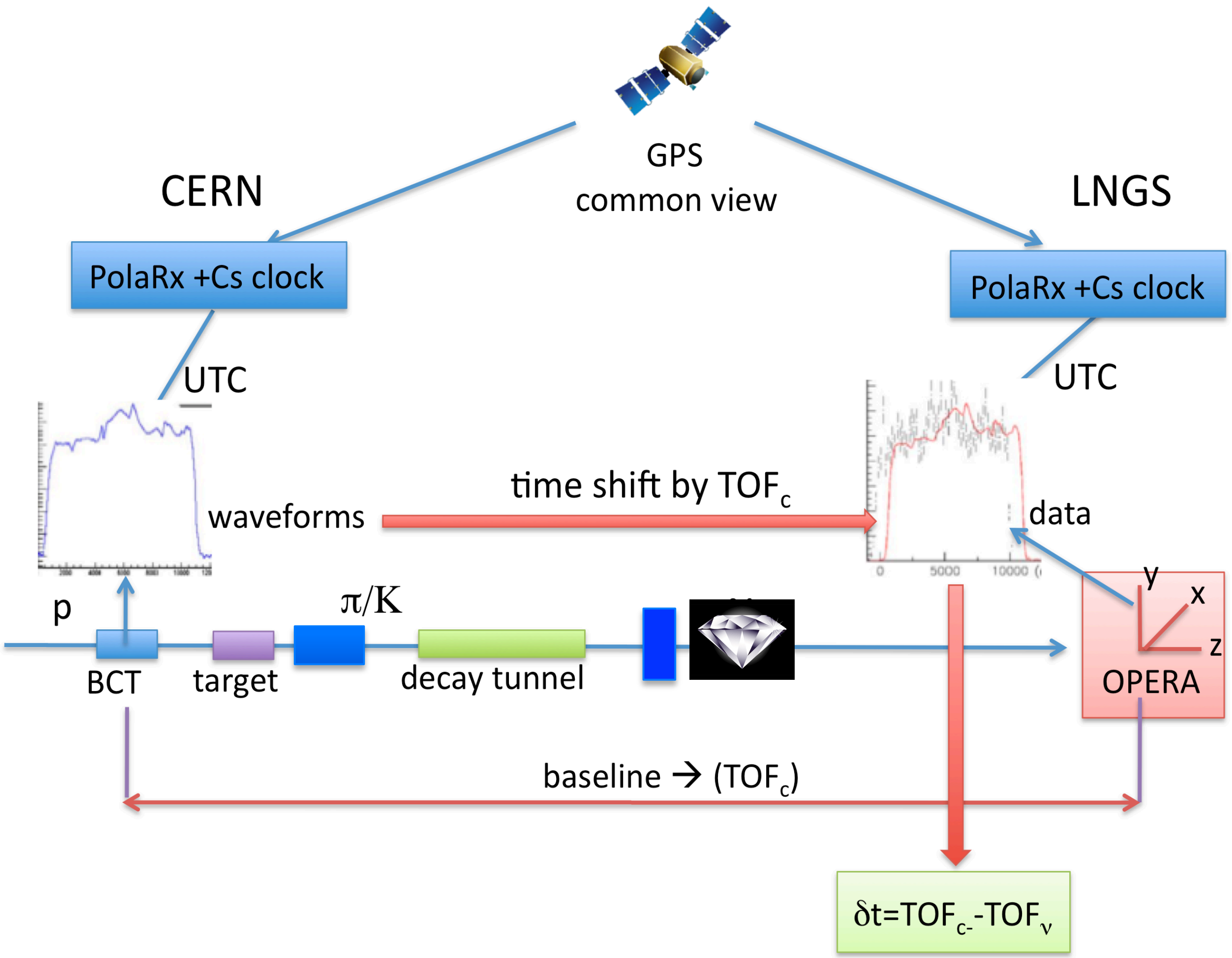


C. Kurfürst / CERN BE

- Carry out first test beam measurements at cryogenic temperatures
- Diamond Beam monitors with scCVD (like the ones used in TCT measurements)
- Use charge sensitive amplifiers

Diamond at CNGS

- Existing muon detectors determine beam profile & intensity
- “Start” signal: time structure of proton beam measured by Beam Current Transformer (BCT)



GPS
common view

CERN

LNGS

PolaRx +Cs clock

PolaRx +Cs clock

UTC

UTC

waveforms

time shift by TOF_c

data

p

π/K

BCT

target

decay tunnel

OPERA

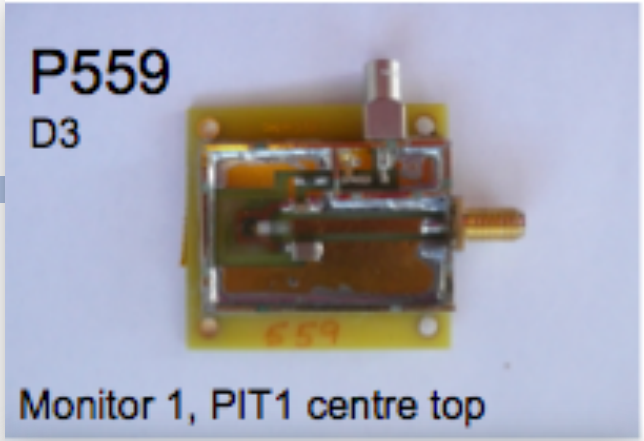
baseline → (TOF_c)

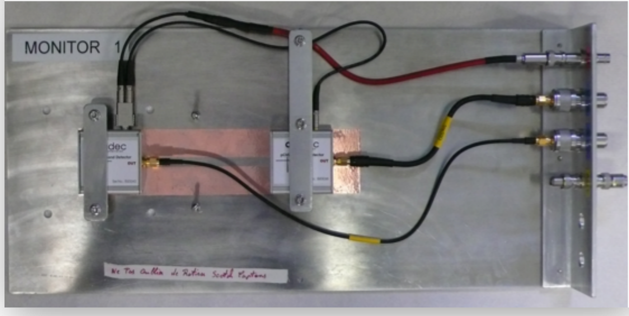
$\delta t = TOF_{c} - TOF_{\nu}$

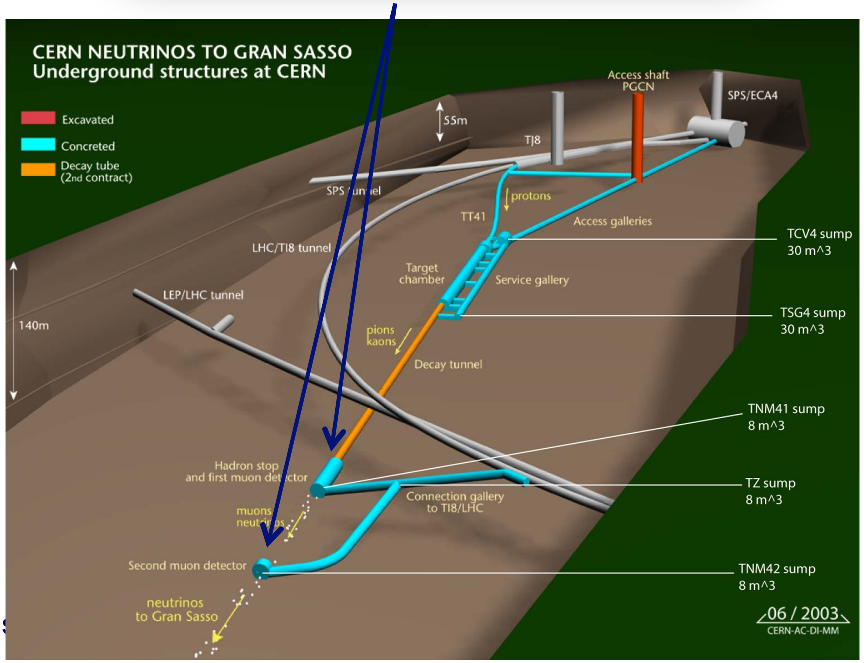
Diamonds at CNGS

- Goal is to provide an independent measurement of the time-structure of the muon beam to verify ToF and TOD in secondary beam line
- Compare to the BCT measurement of the proton beam

- Installed 6 pCVD and scCVD diamonds
  - Beam intensity high (up to 5x10^5muons in bunched beams and 2.5x10^7/10us)
  - Installed in beam center and edge in two muon pits
  - Therefore record diamond signal directly without amplifier

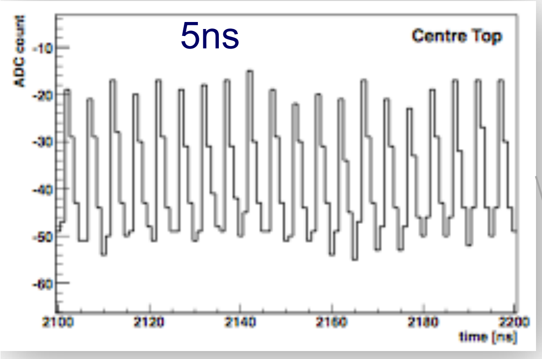


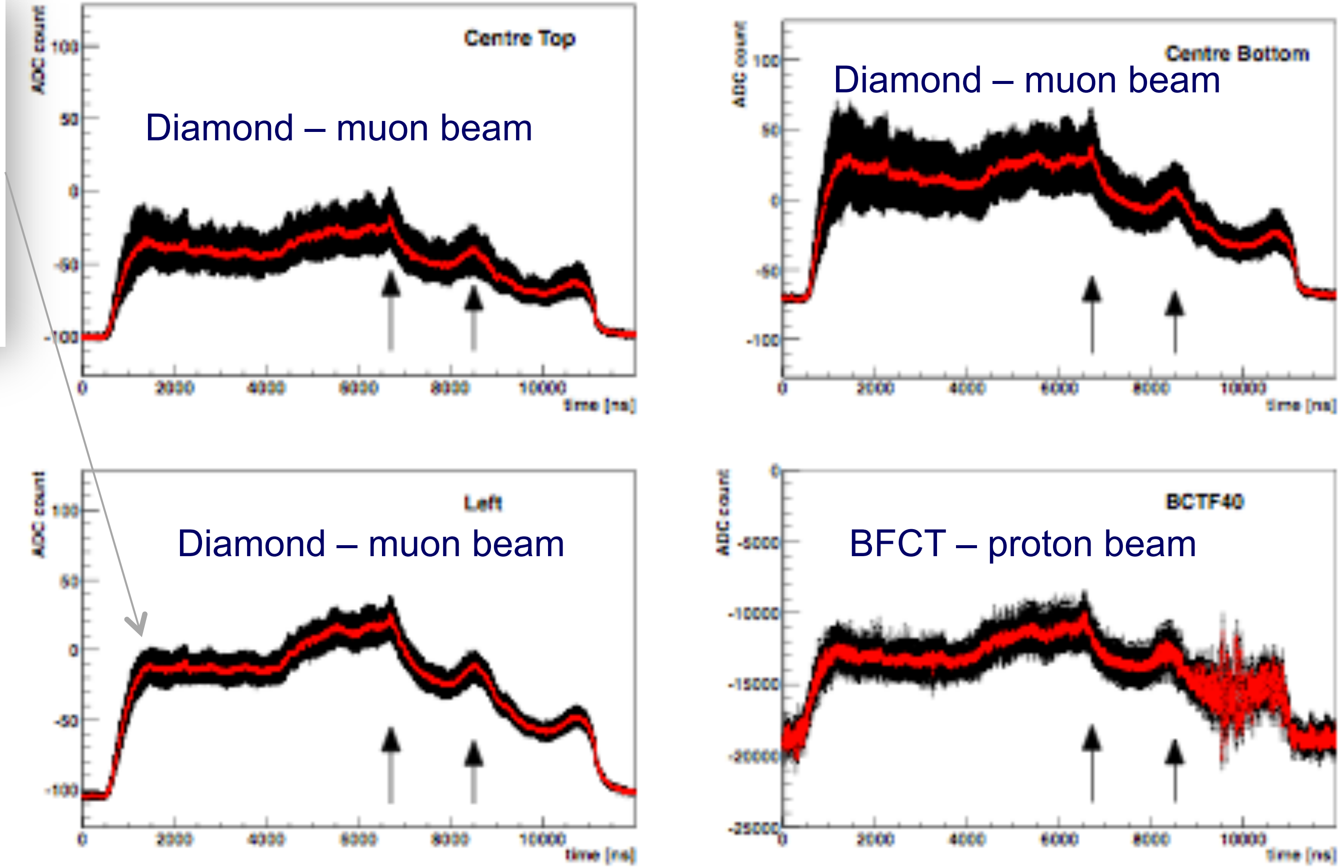




Diamond signal from muon beam

- Record extracted muon beam profile (12μs) in diamond stations
- Verify CNGS timing and confirmation of BCT signal through TOF measurement to muon pit with precision of ~ 1.5ns





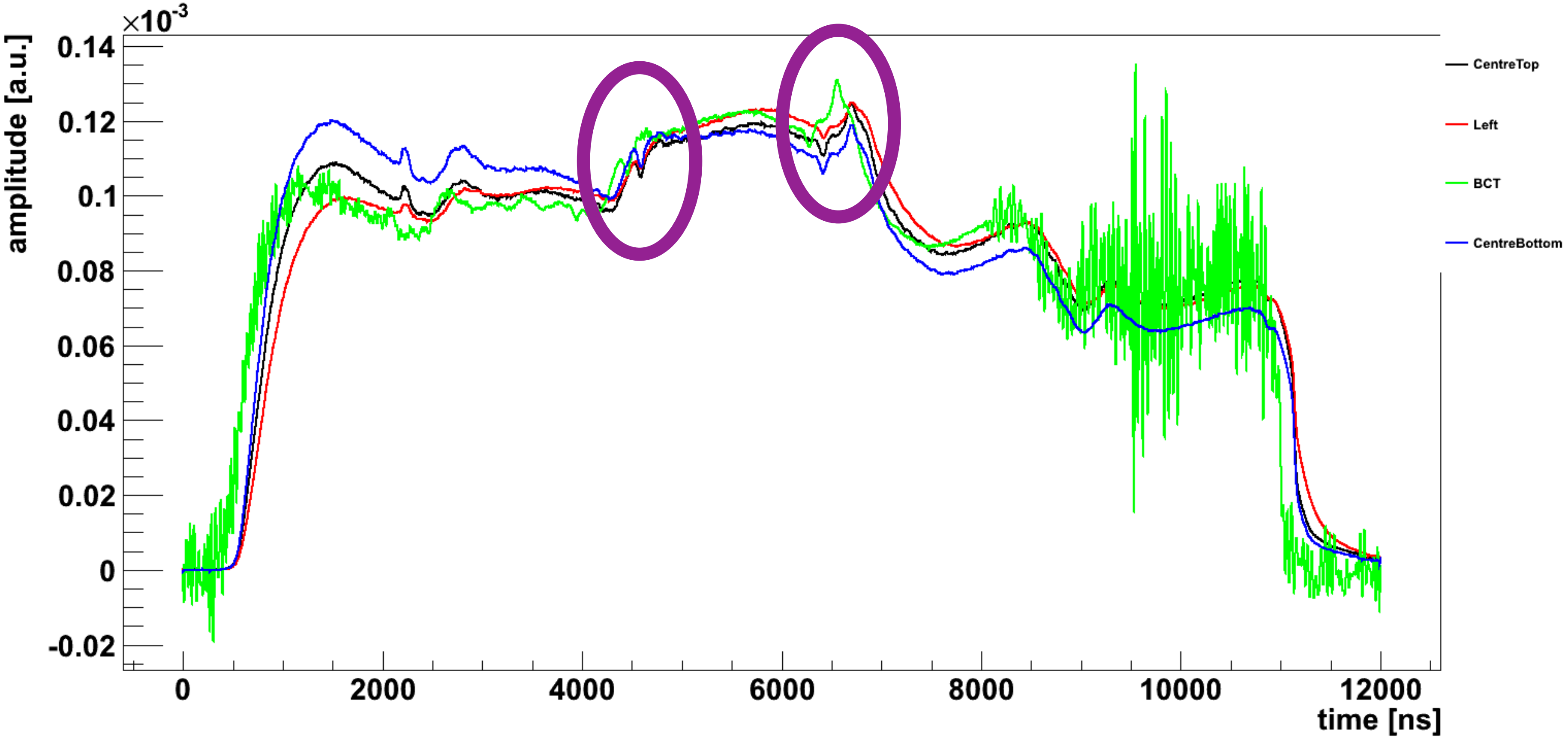
Diamond stations

Can clearly resolve 5ns SPS RF structure in muon beam

SNR of 65 to 80 (cf BCT ~11)

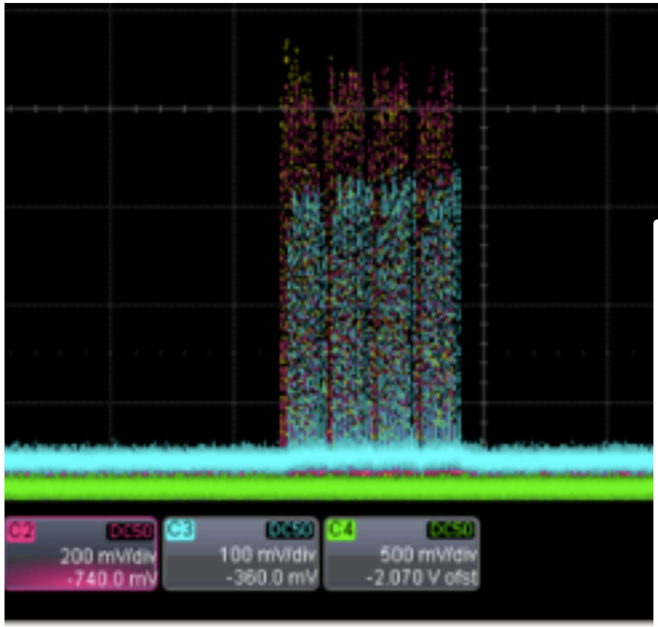
TOF measured by diamond

- Measure TOF from BCT to muon pits (DD and BCT signal agree well)
- Measured TOF agrees with calculated to ~1.3ns.



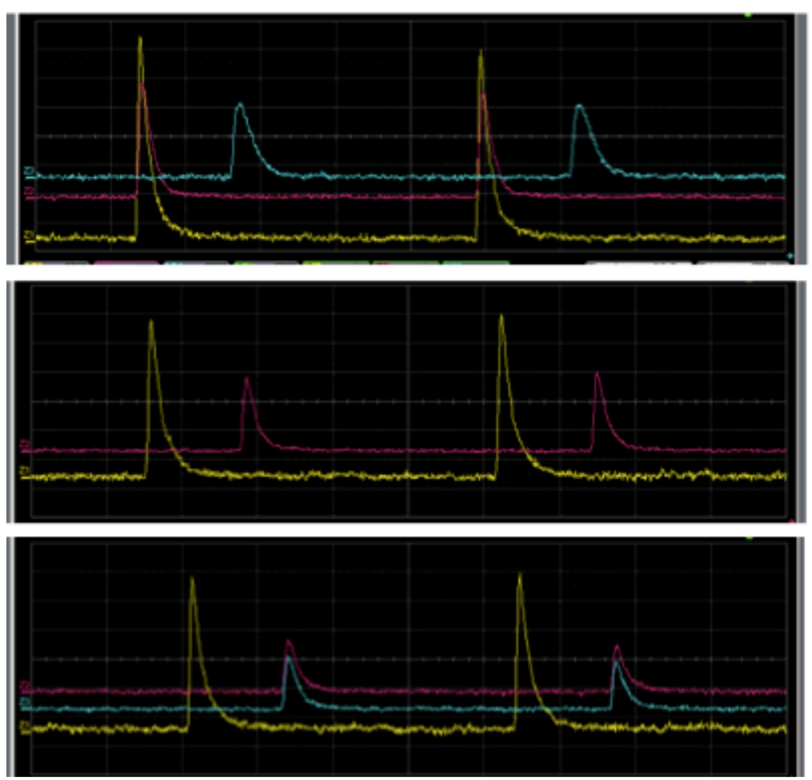
Bunched beam at CNGS as seen in diamonds

- First measurements in 2012 of bunched muon beam to Gran Sasso



11ns/div

Diamond response ~1.6V
at 5x105 muon/pulse



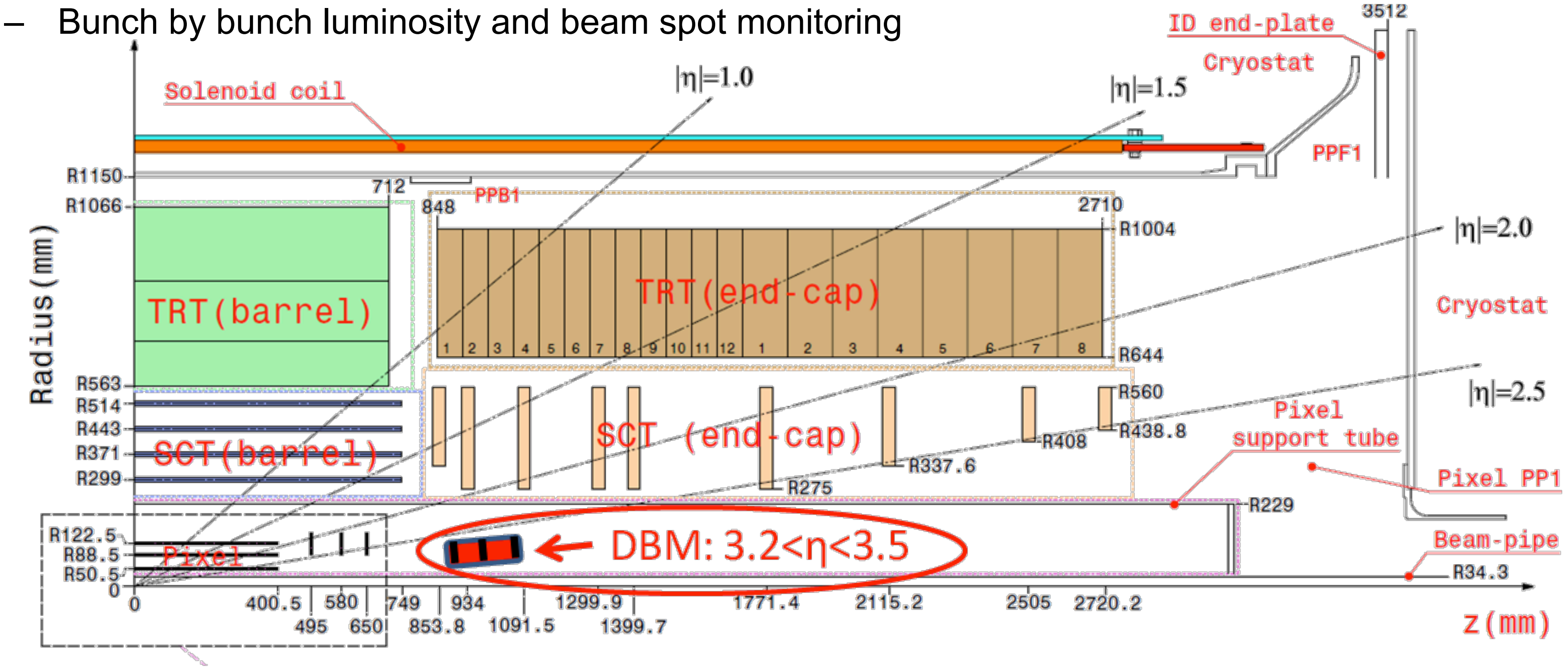
Ella, d3
Henri, 9x9
Lucas I 20x20

Greta 8x8
Lucas II 9x9

Greta 8x8
Max 9x9 + 20dB
Henna 9x9 + 20dB

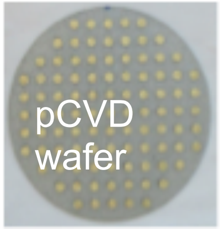
ATLAS Diamond Beam Monitor

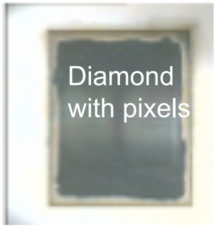
- ATLAS already operates Diamond BCM system to monitor beam conditions near IP
  - See Poster by A. Gorisek
- **New Diamond Beam Monitor System:**
- 24 diamond pixel modules arranged in 8 telescopes around interaction point
  - Bunch by bunch luminosity and beam spot monitoring
- Diamond pixel modules in forward region:
- Track reconstruction in 8 telescopes to monitor collision & back ground



DBM first modules

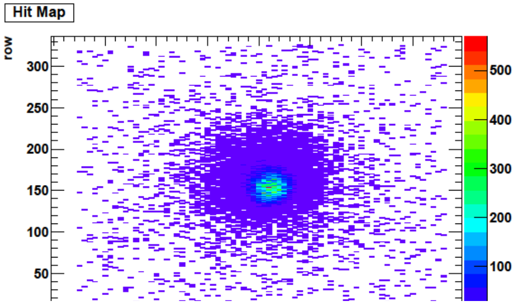
- See Poster by F. Hügging & N. Wermes
- DBM modules built at IZM
  - 21x18 mm^2 pCVD from DDL
  - FE-I4 ATLAS IBL pixel chip
  - 336x80 = 26880 channels, 50x250 μm^2
- Lab Tests with Sr90 source

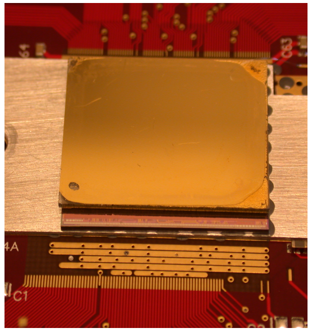


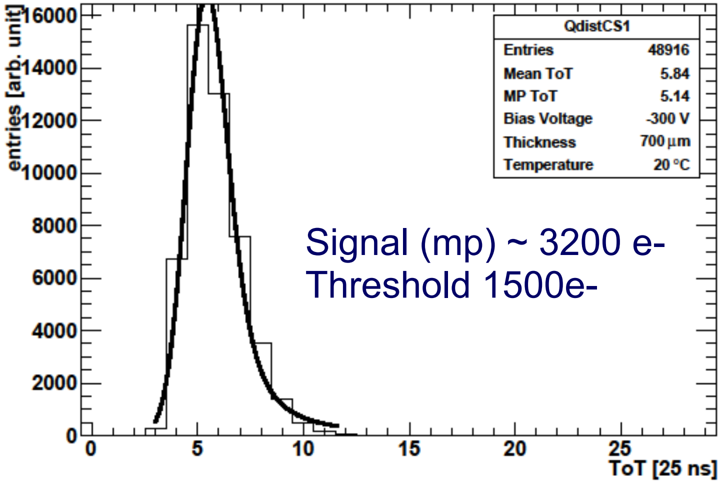


Sr90 Source scan with external trigger
HV metallization to the edge of the sample
Bias voltage 300V (700um sample)

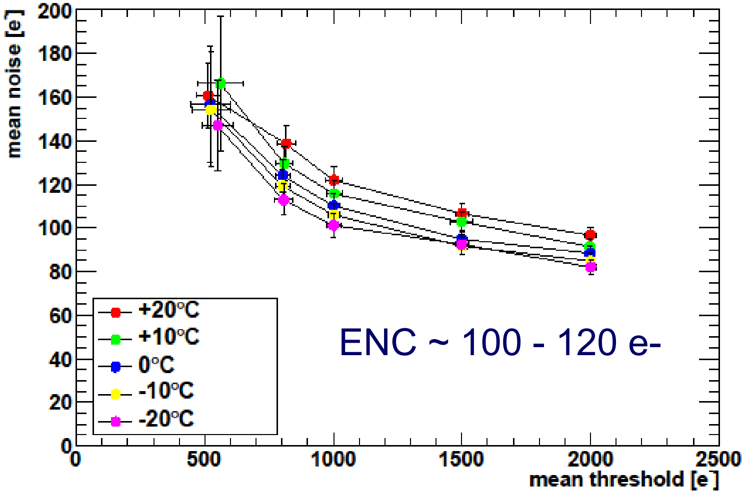
Thresholds of less than 1000 e- possible







Signal (mp) ~ 3200 e-
Threshold 1500e-



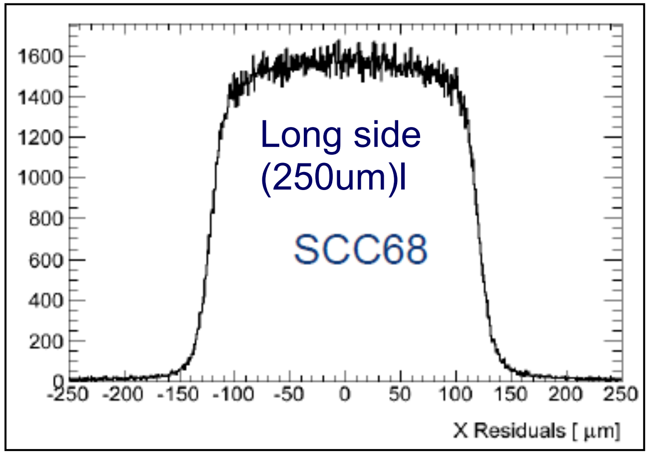
ENC ~ 100 - 120 e-

module after flip-chip on test board

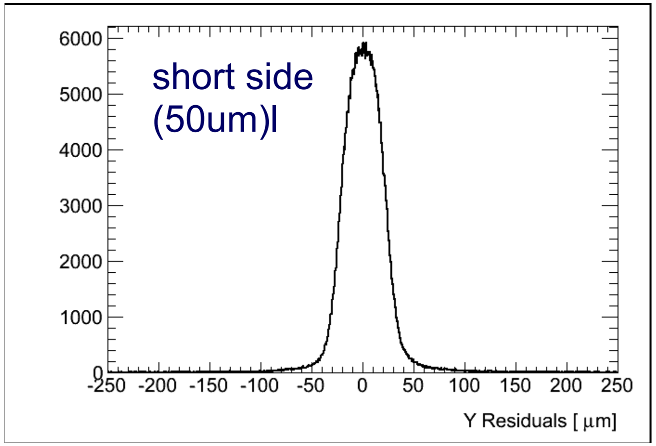
ATLAS DBM Modules in testbeam

- First test beam results with FEI4+ diamond sensors in 2011 (CERN) and 2012 (DESY)

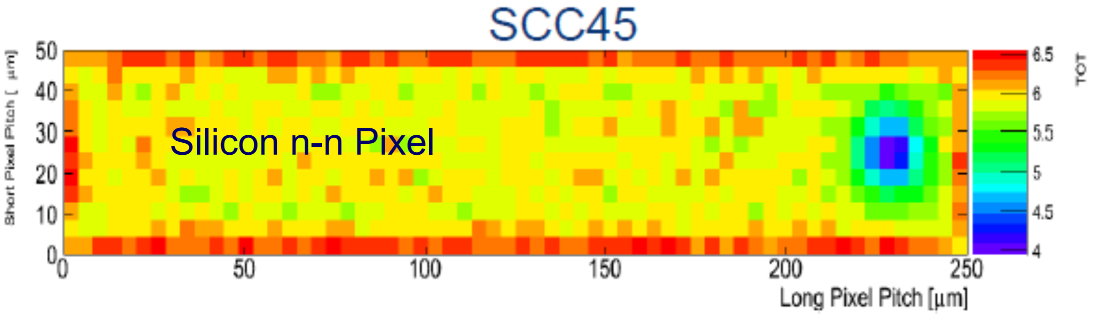
Residual


Long side (250um)l

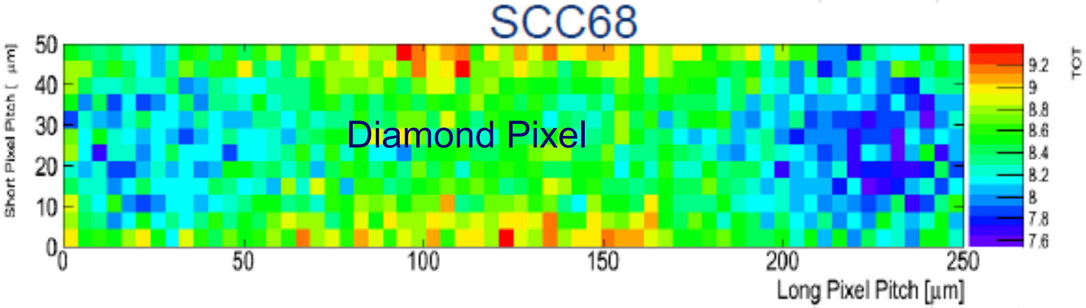
SCC68


short side (50um)l

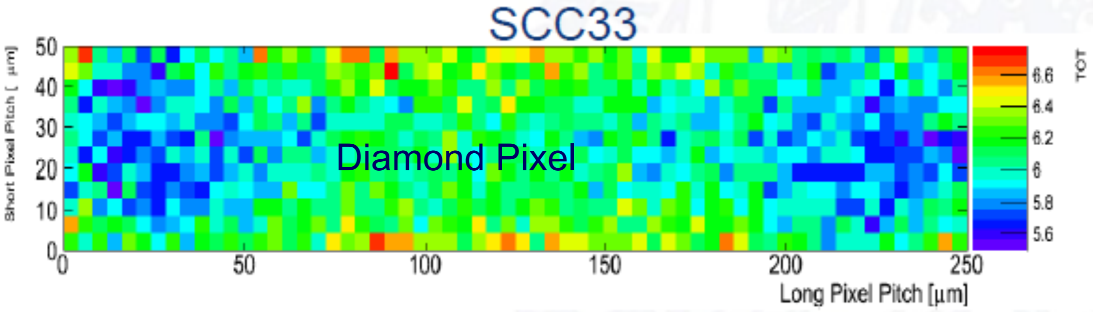
Time over threshold vs. hit position X/Y


SCC45

Silicon n-n Pixel


SCC68

Diamond Pixel


SCC33

Diamond Pixel

Summary

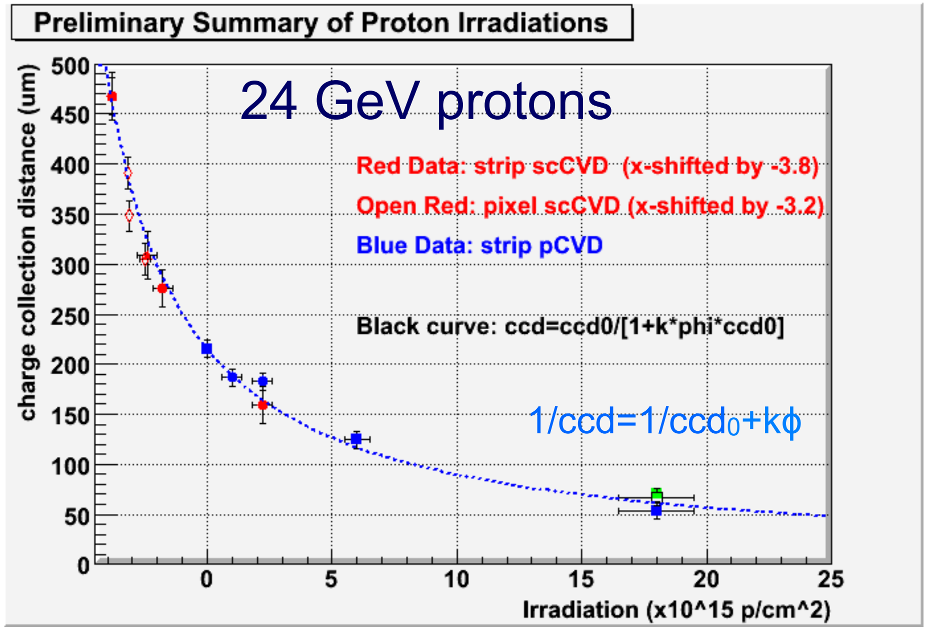
- Diamonds have a good track record as beam monitors in applications from single –particles to very high flux

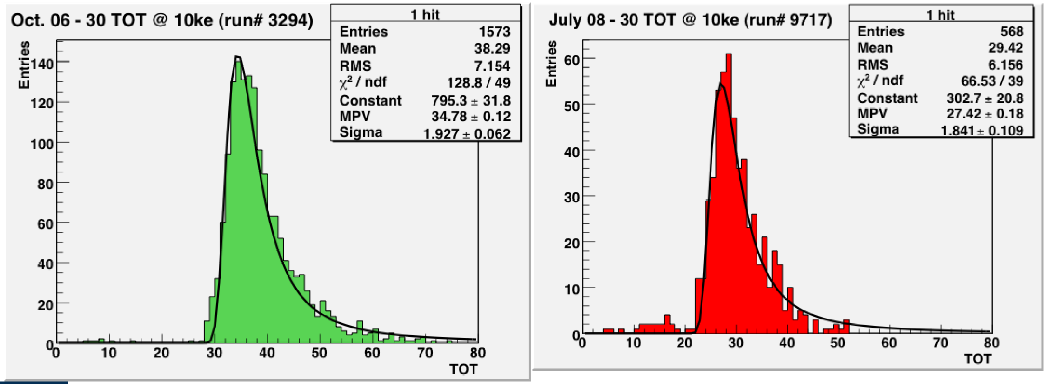
- They are compact enough for many beam (loss) monitoring applications
- BLM benefit from the fast signal, high time-resolution and radiation hardness
- Started to investigate diamond as beam monitors for cryogenic applications
- Shown applications for
  - LHC monitoring: resolve beam losses and provide diagnosis for beam aborts
  - CNGS: monitor muon beam to verify CNGS timing
  - ATLAS: new diamond pixel detector for luminosity measurments

Backup slides

Radiation hardness

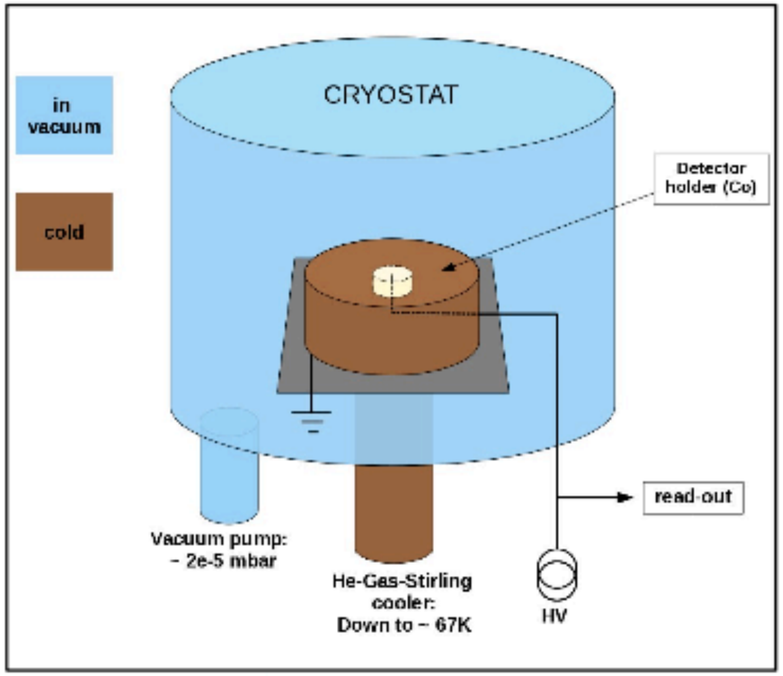
- Studied with pCVD and scCVD diamonds as pad, strip and pixel detectors
- E.g. Signal on scCVD pixel with ATLAS-FEI3 before & after irradiation (0.7x10^{15} p/cm^2)

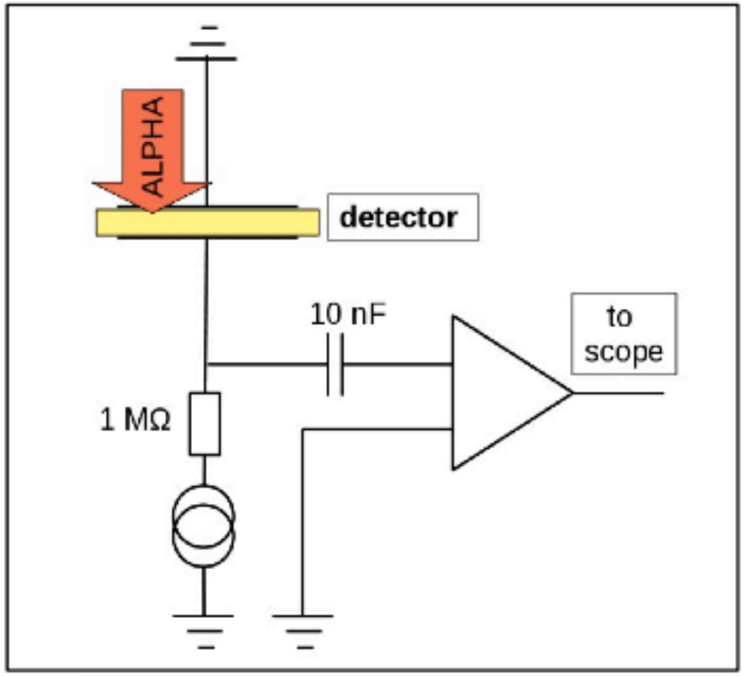




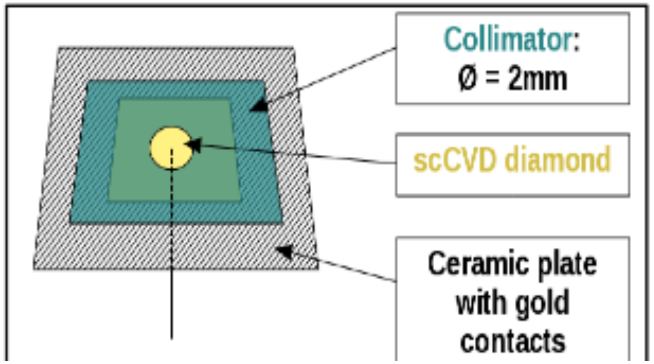
- Before irradiation
  - Threshold ~ 1700e-
  - Signal MPV ~ 11540e- @400V
- After irradiation
  - Threshold ~ 1470 e$^-$Signal MPV ~ 9025e- @800V

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)



The Set-up

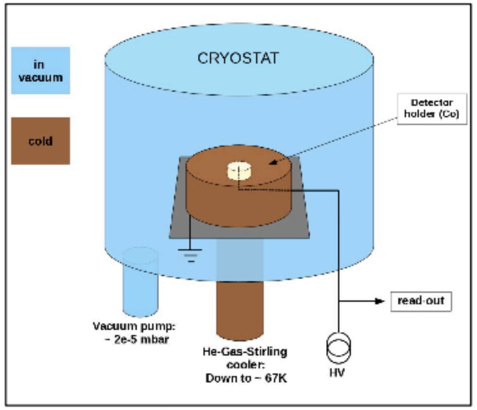
- Two different set-ups used:

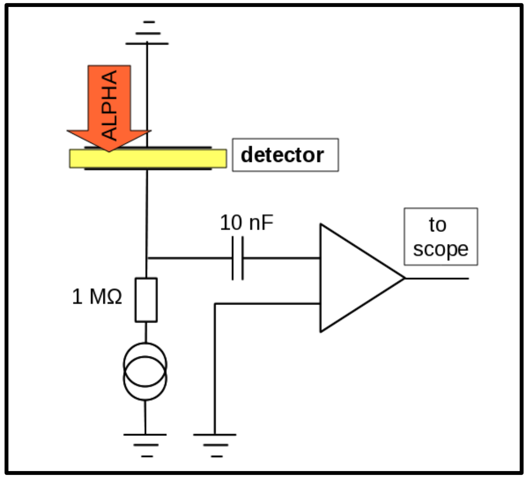
  - Helium Gas cooling + vacuum
    - → RT down to 67 K
    - →irradiate from LV side

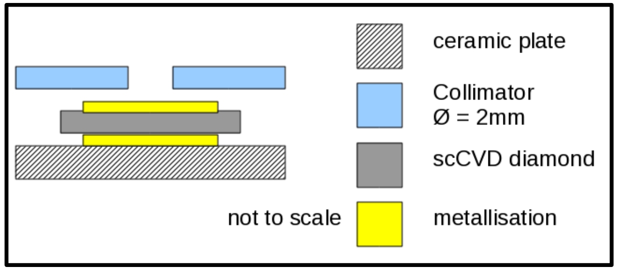
  - Liquid Helium cooling
    - → down to 1.9 K
    - → but He gas environment
    - → irradiate from HV side

- Two set-ups render cross-checks possible

- Only the Liquid Helium set-up has been used in p-beam

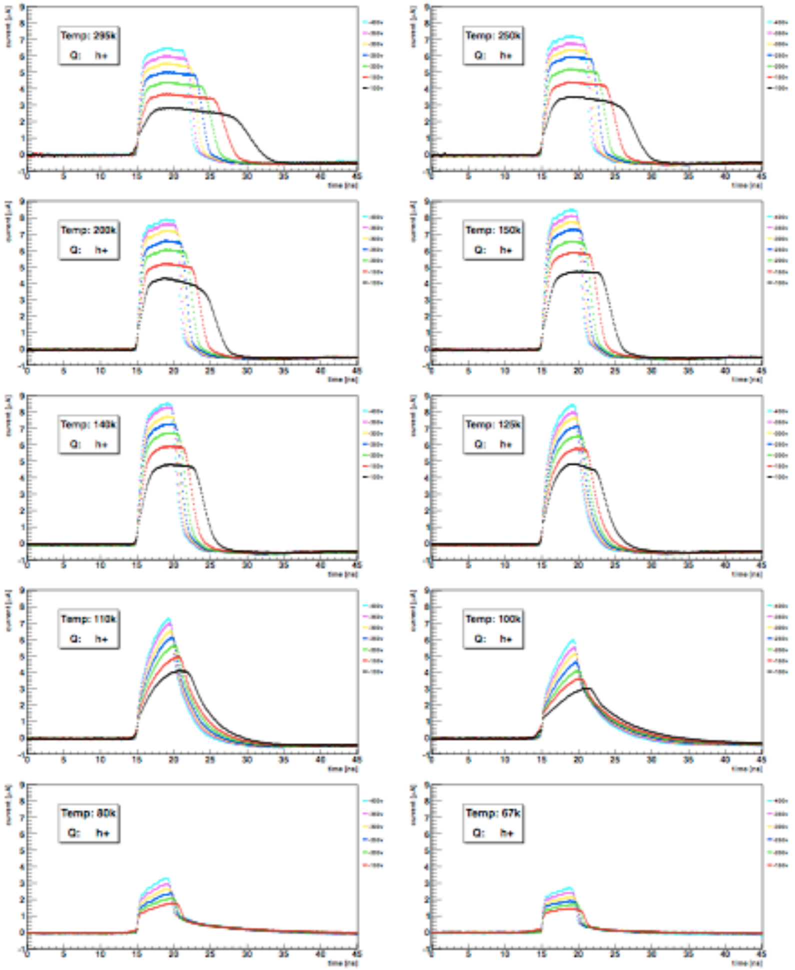




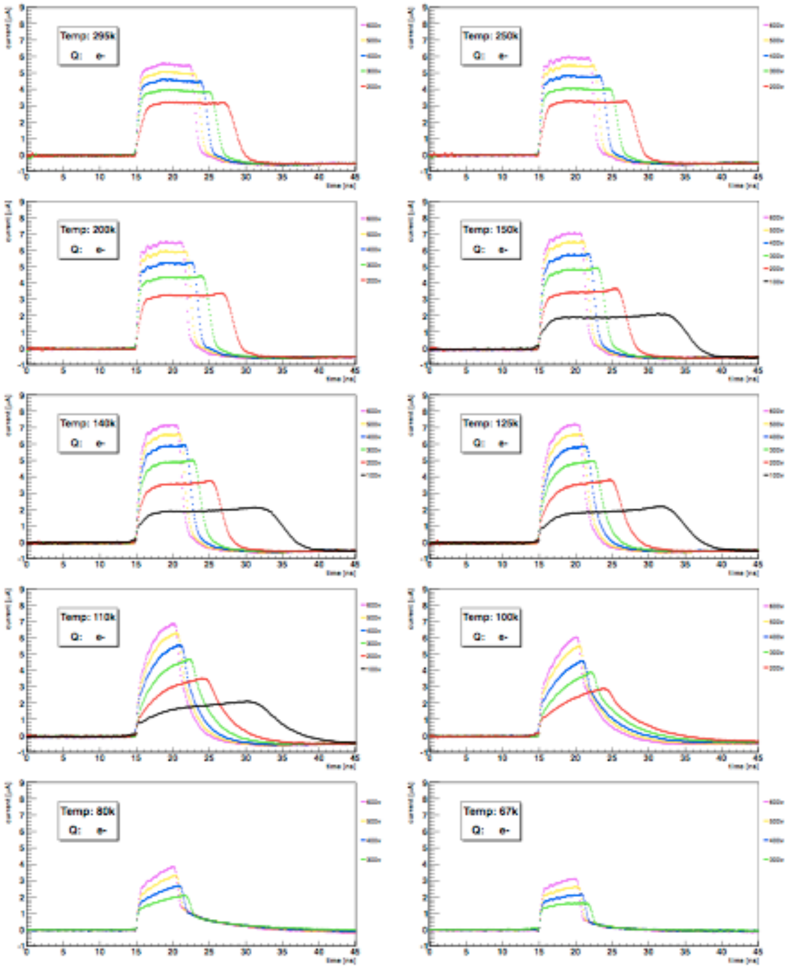


Holes & Electrons

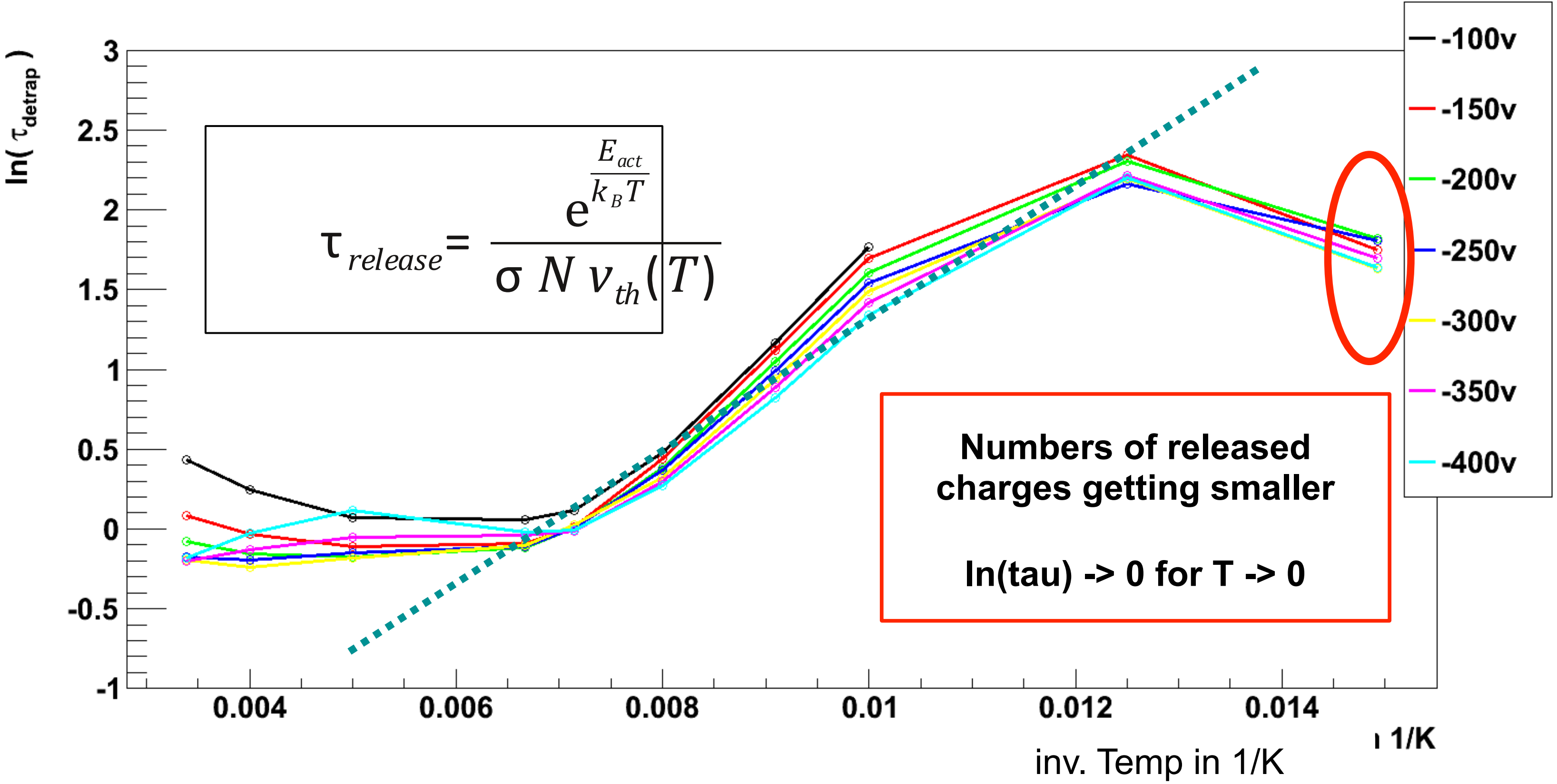
- Holes



Electrons



Release Time Constant



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

Numbers of released charges getting smaller

ln(tau) -> 0 for T -> 0

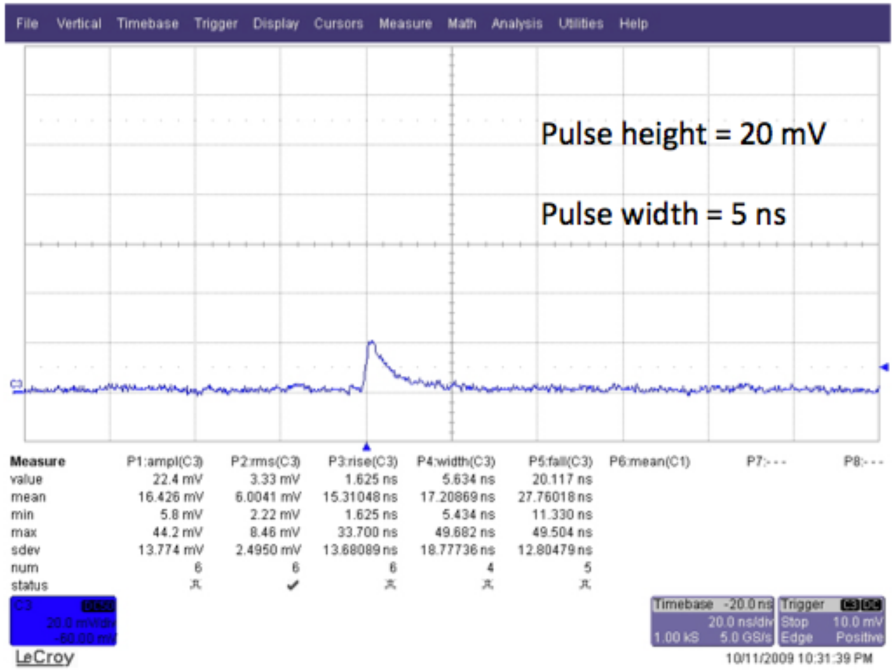
Plot ln(τ_{dt}) vs 1/T, do line fit: $E^{h}_{act} \approx 40\,\mathrm{meV} \pm 10\,\mathrm{meV}$

→ binding energy of excitons to Boron impurities, coincidence?

→ investigate if shallow traps are present using Thermally Stimulated Current technique

Diamond BLM at SPS

- Response single particle losses and bunch trains at SPS
- Monitor losses at SPS
- Can clearly resolve 5ns RF structure of SPS



Pulse height = 20 mV

Pulse width = 5 ns

Measure	P1:ampl(C3)	P2:rms(C3)	P3:rise(C3)	P4:width(C3)	P5:fall(C3)	P6:mean(C1)	P7:- - -	P8:- - -
value	22.4 mV	3.33 mV	1.625 ns	5.634 ns	20.117 ns			
mean	16.426 mV	6.0041 mV	15.31048 ns	17.20869 ns	27.76018 ns			
min	5.8 mV	2.22 mV	1.625 ns	5.434 ns	11.330 ns			
max	44.2 mV	8.46 mV	33.700 ns	49.682 ns	49.504 ns			
sdev	13.774 mV	2.4950 mV	13.68089 ns	18.77736 ns	12.80479 ns			
num	6	6	6	4	5			
status	⊼	✓	⊼	⊼	⊼			

C3 20.0 mV/div -60.00 mV

Timebase -20.0 ns 20.0 ns/div 1.00 kS 5.0 GS/s

Trigger C3 DC Stop 10.0 mV Edge Positive

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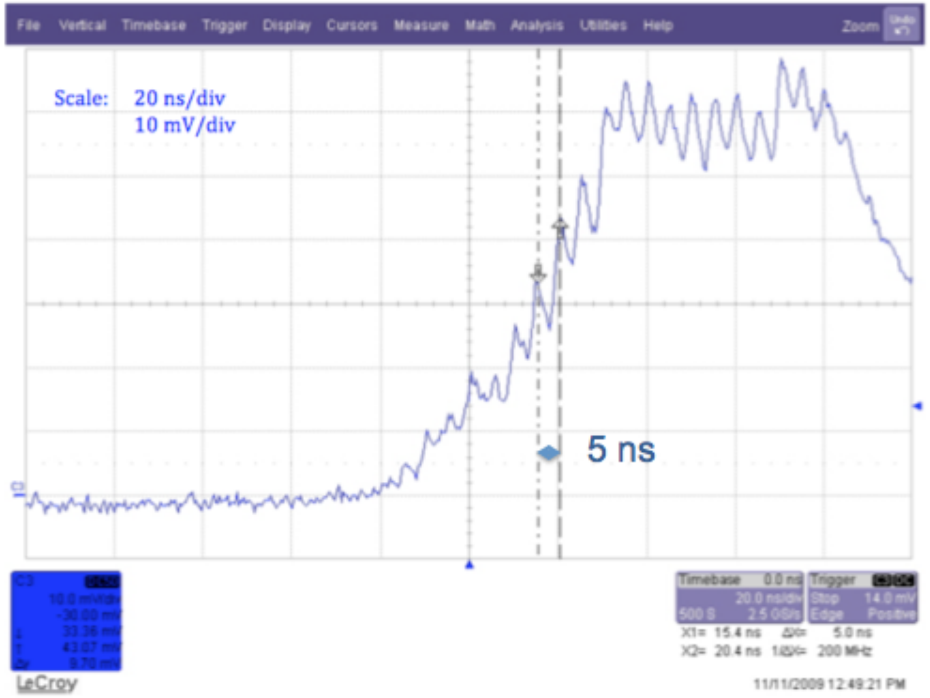

Scale: 20 ns/div
10 mV/div

5 ns

Timebase 0.0 ns 20.0 ns/div 500 S 2.5 GS/s

Trigger C3 DC Stop 14.0 mV Edge Positive

X1= 15.4 ns Δ X= 5.0 ns
X2= 20.4 ns 1/ΔX= 200 MHz

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ATLAS Diamond 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-