Diamond Detectors

Properties, Performance,
Future Applications, R&D

Properties of Diamond Detectors

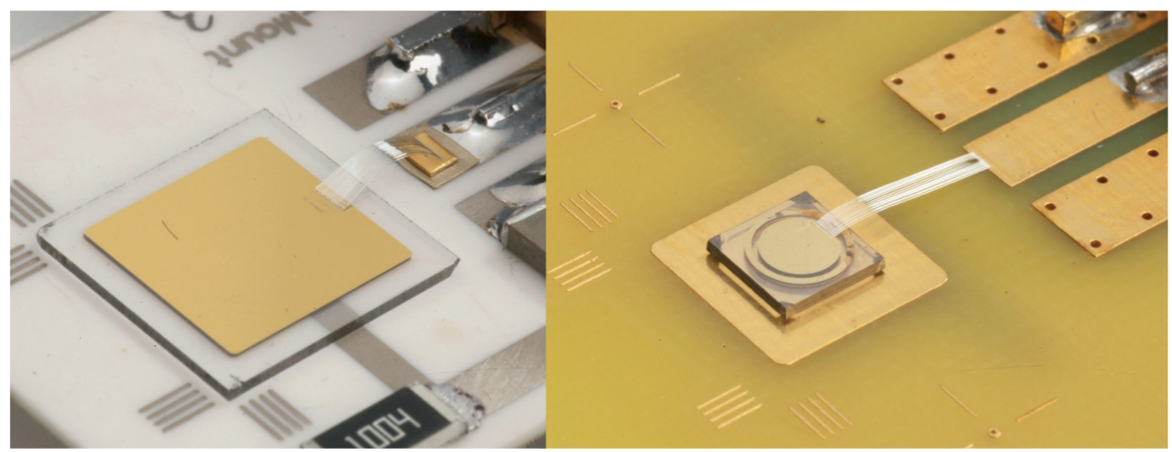
Why Diamond

Pros:

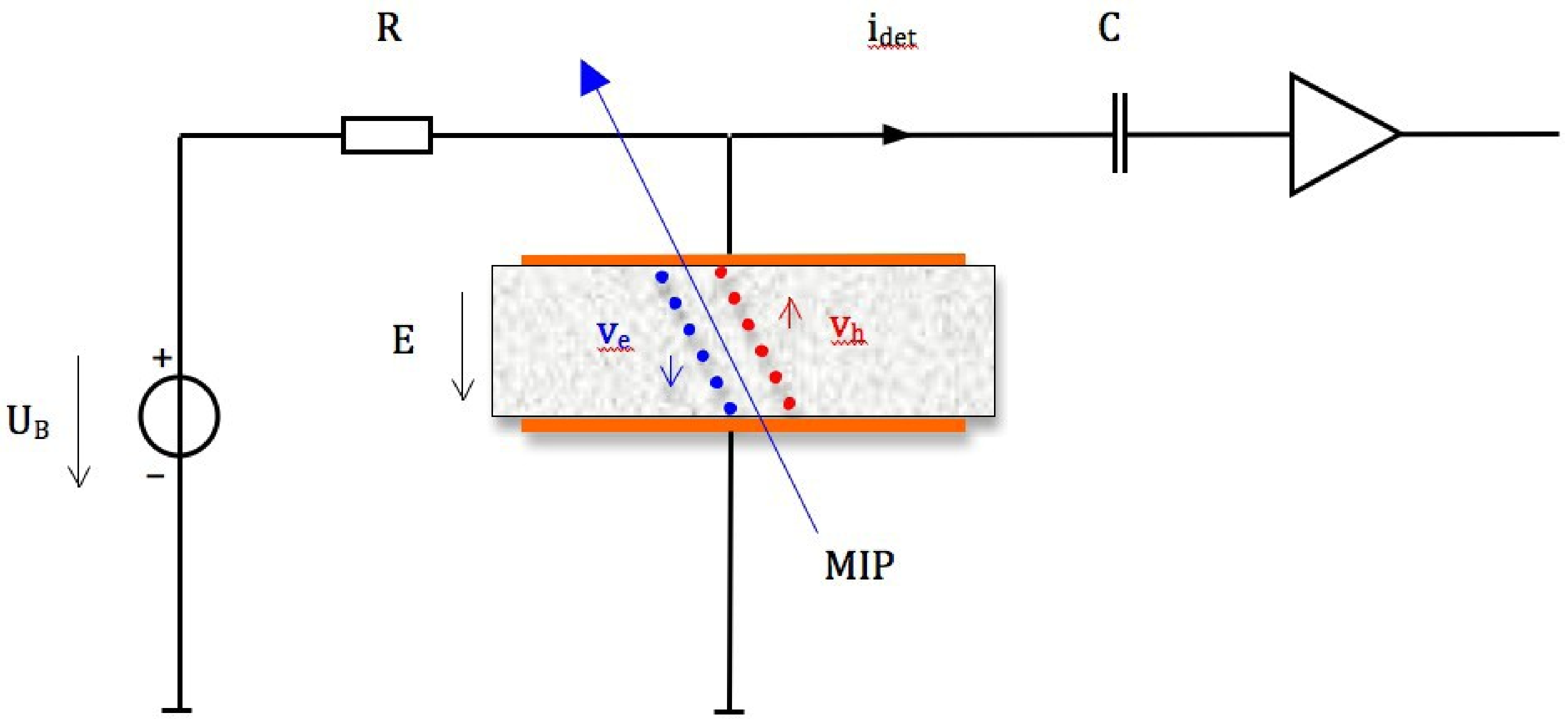
- High band gap (5.5 eV)
  - → Very high breakdown field > 1e7 V/cm
  - → Very high resistivity > 1e11 Ωcm
    - → Large area
  - → Very low leakage current ~ few pA
- Low dielectric constant (5.7)
  - → Low capacitance → Low noise
- High displacement energy (43 eV/atom)
  - → Radiation hard → No replacement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

Cons:

- High $E_{pair\text{-}creation}$ (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



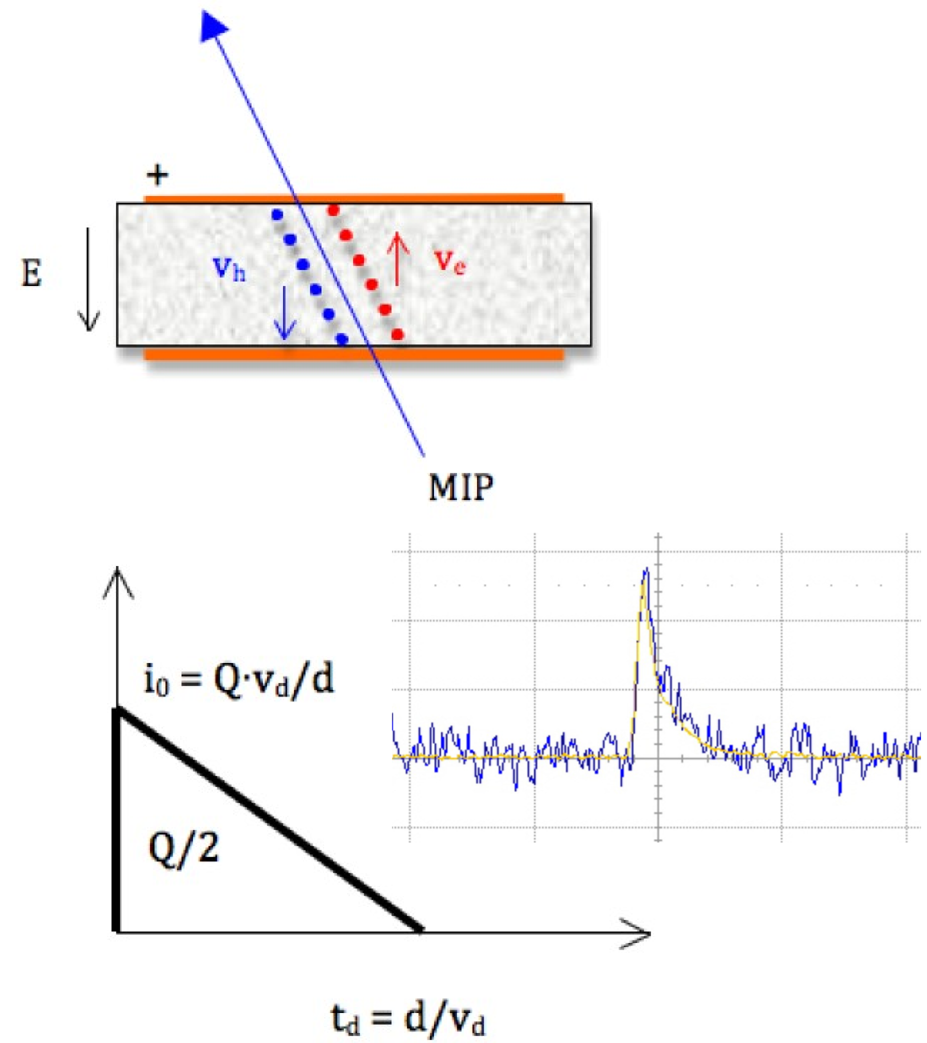
- Diamond is solid state ionization chamber

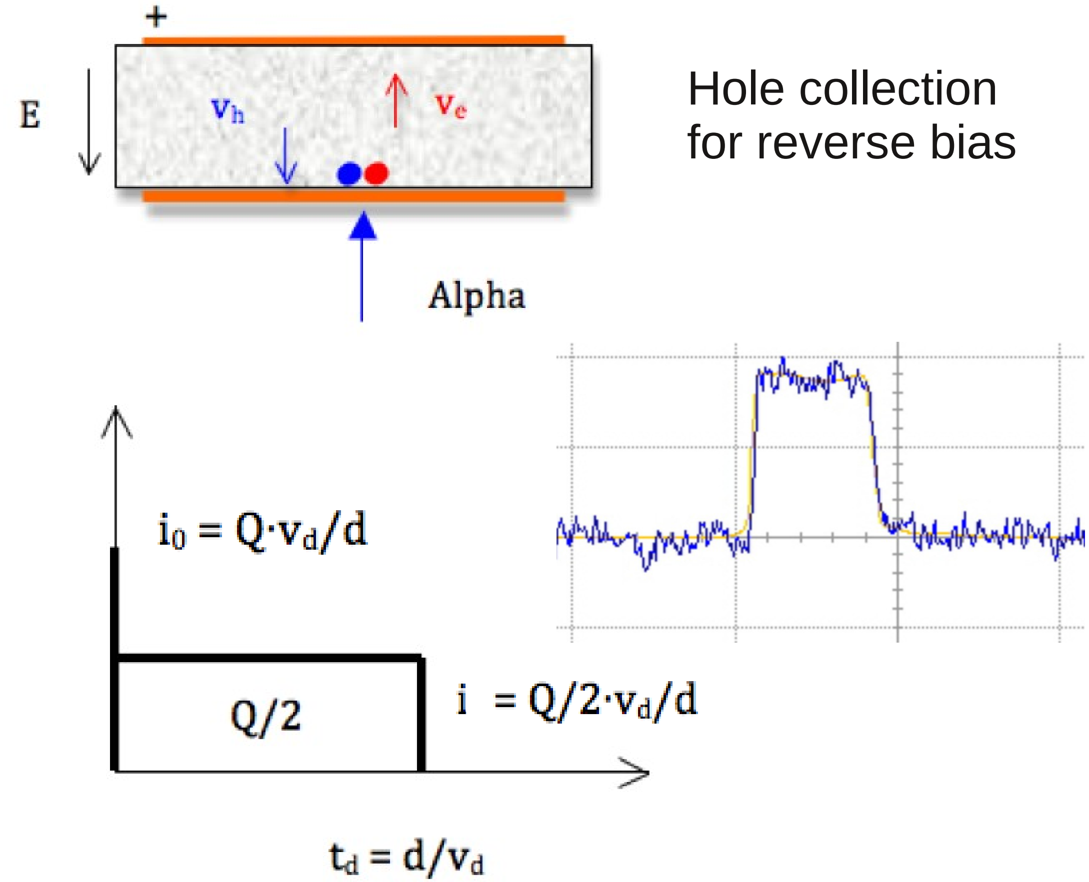


Courtesy
CIVIDEC

Modes of Operation

- Counting Mode
- Calorimetric Mode





Hole collection
for reverse bias

Courtesy
CIVIDEC

- pCVD Diamond:

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

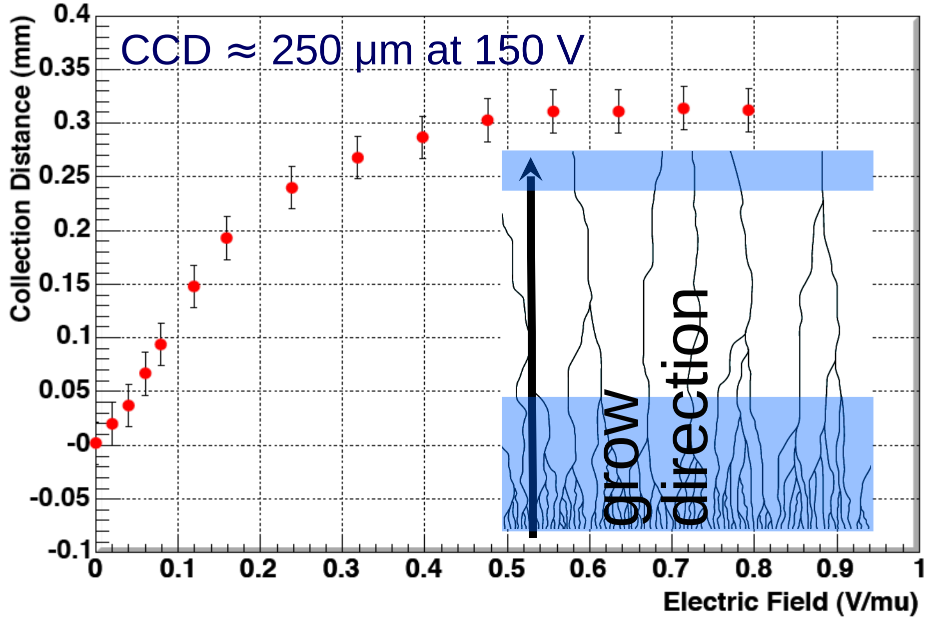
  optimal double pulse resolution
  charges lost at trapping centres

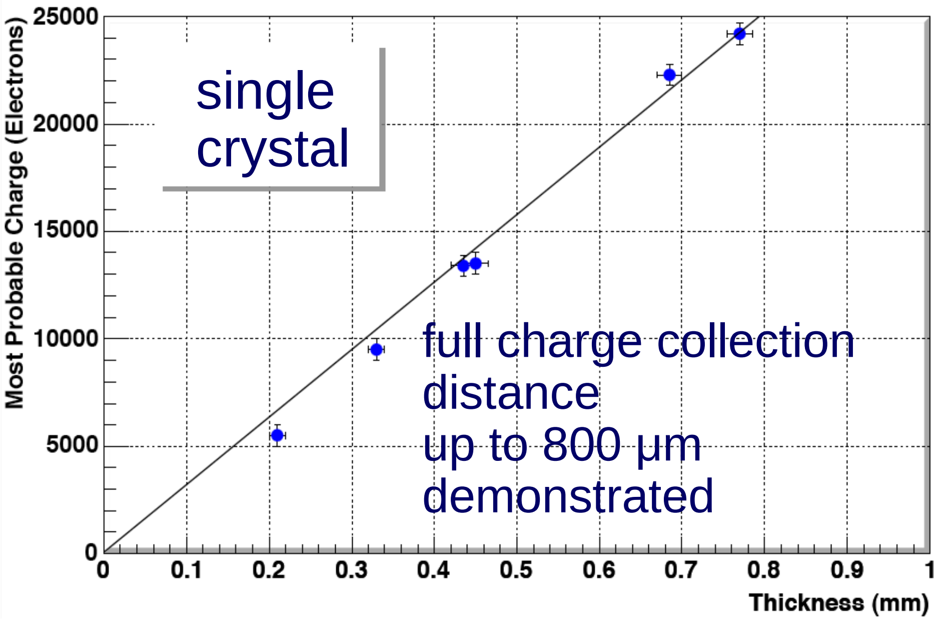
- scCVD Diamond:

  short signal
  ~5ns FWHM @ 1V/um

  optimal Signal-to-Noise ratio
  lower trapping centre concentration

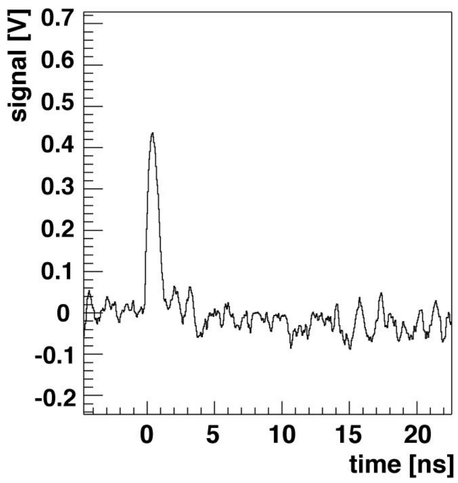
$$CCD = d * Q_{sig}/Q_0$$



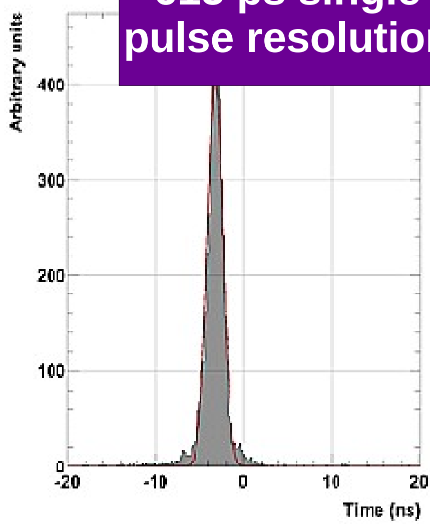


Time resolution

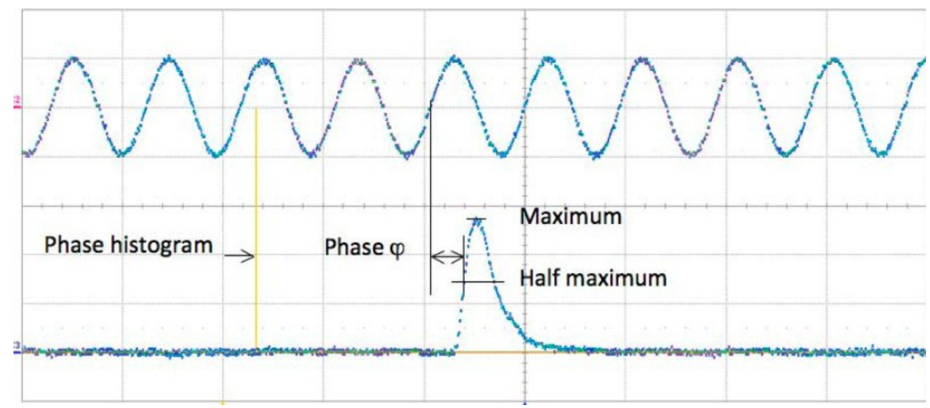
- Measure 200 MeV protons for Proton Therapy



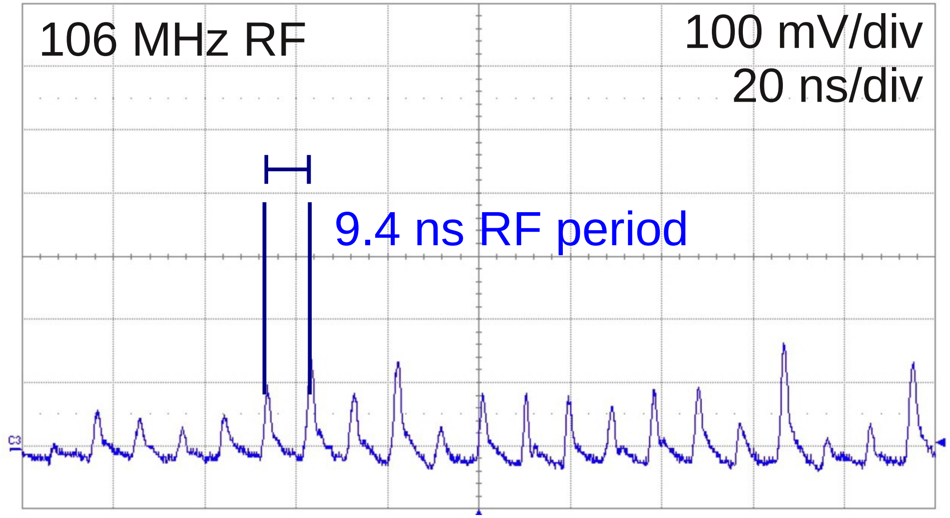
615 ps single pulse resolution



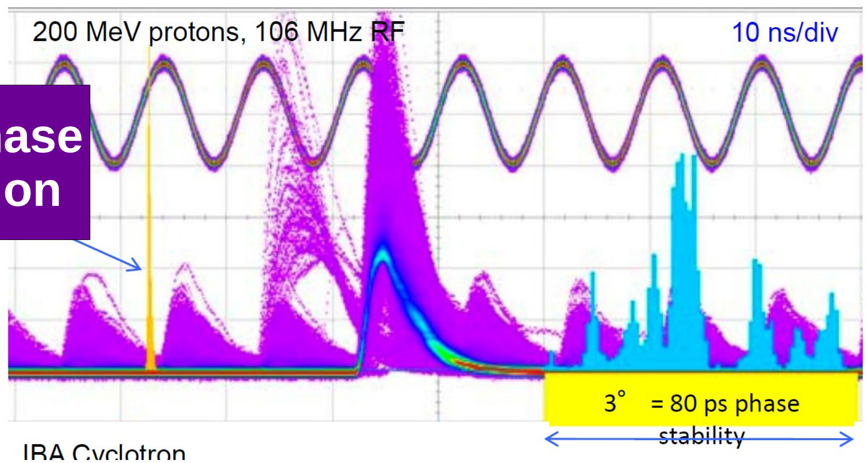
- Phase measurement



- Beam structure

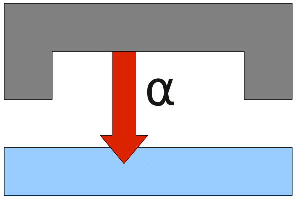


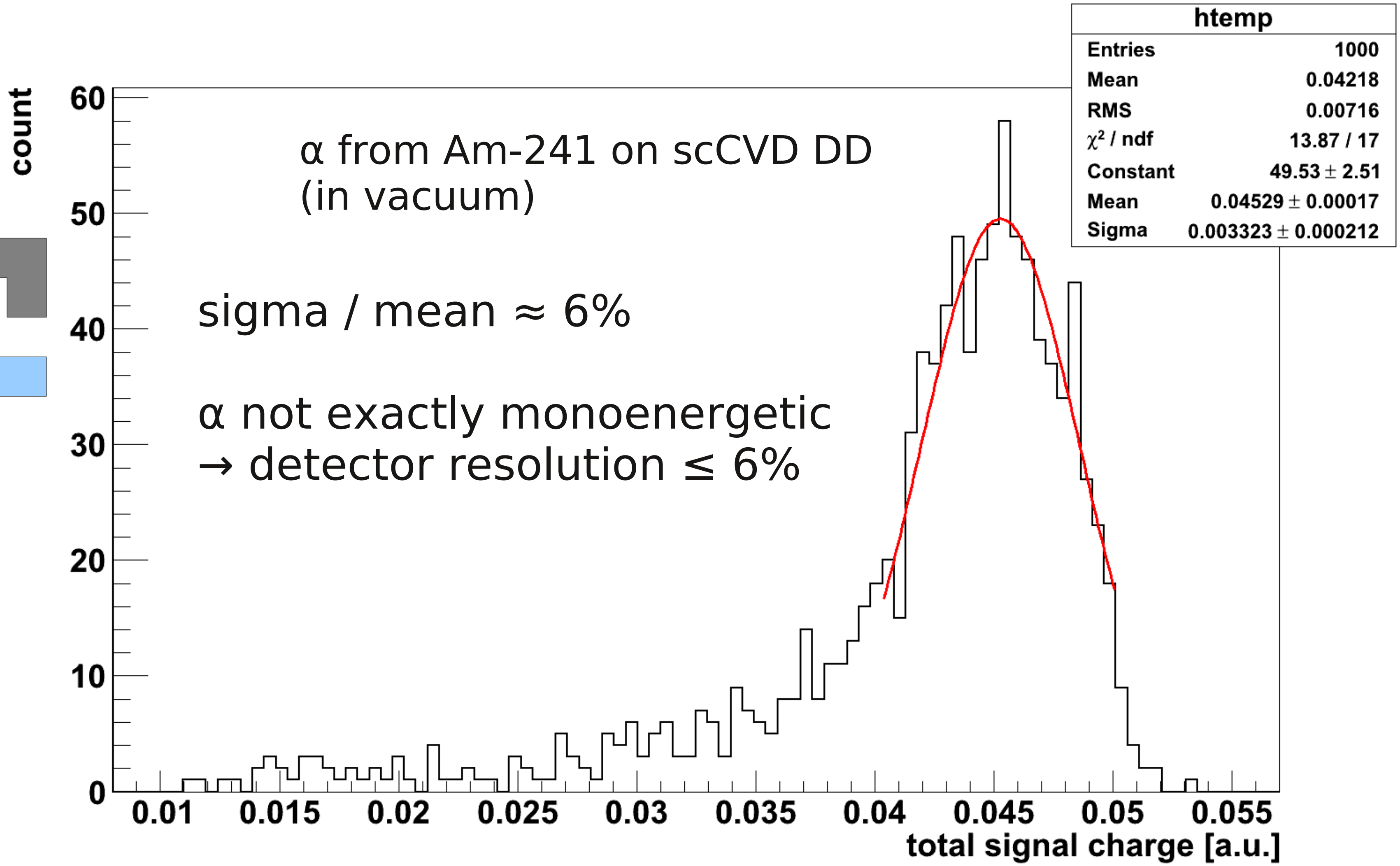
10 ps phase resolution



Energy resolution of scCVDs

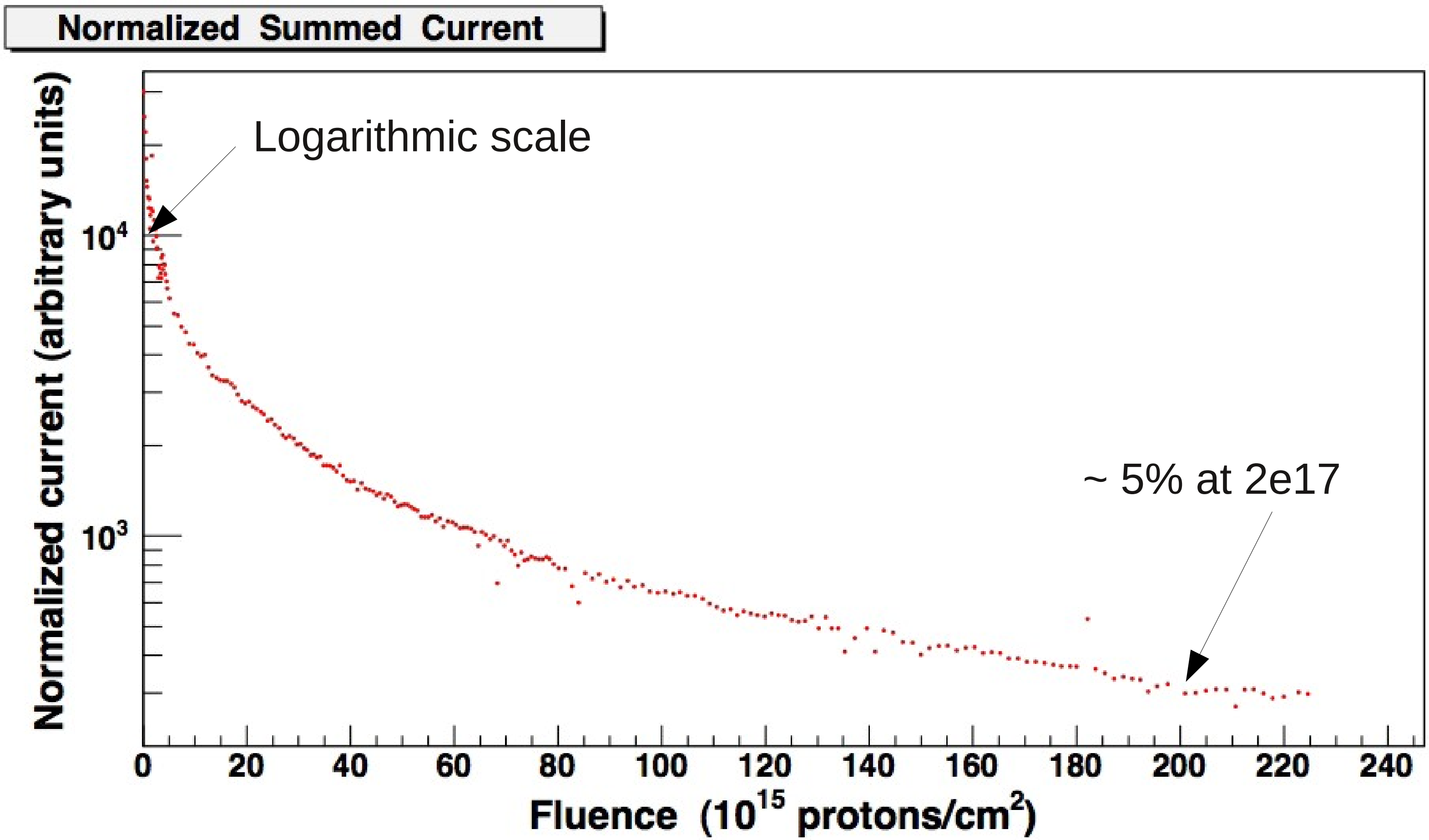
- Distribution of measured total signal charge





Radiation hardness

- Samples radiated up to 2.25e17 cm^{-2} with 500 MeV protons



JInst 6:P05011,2011

Performance of Diamond Detectors

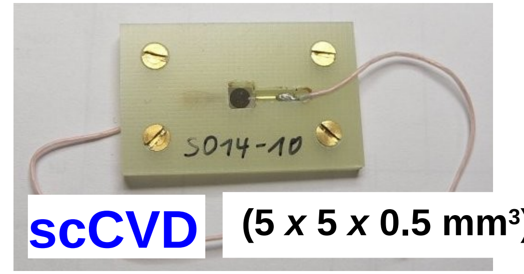
The CMS BCM1F

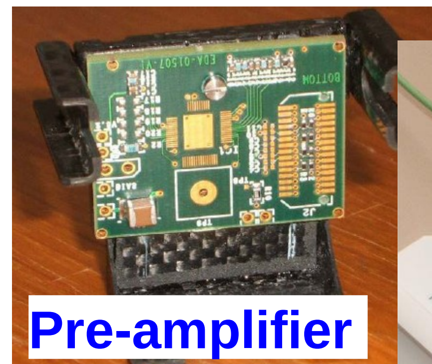
Tasks and requirements :

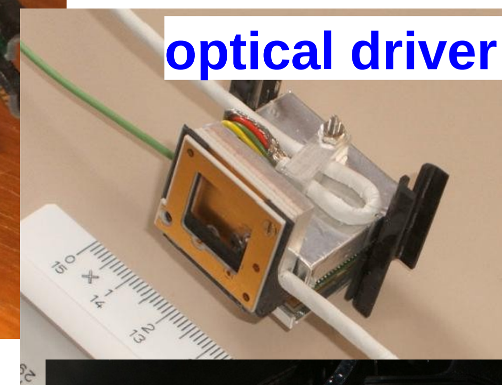
- Monitoring and protection
- MIP detection, low power, radiation hard
- Feed back BGND levels to LHC
- Instantaneous luminosity to CMS

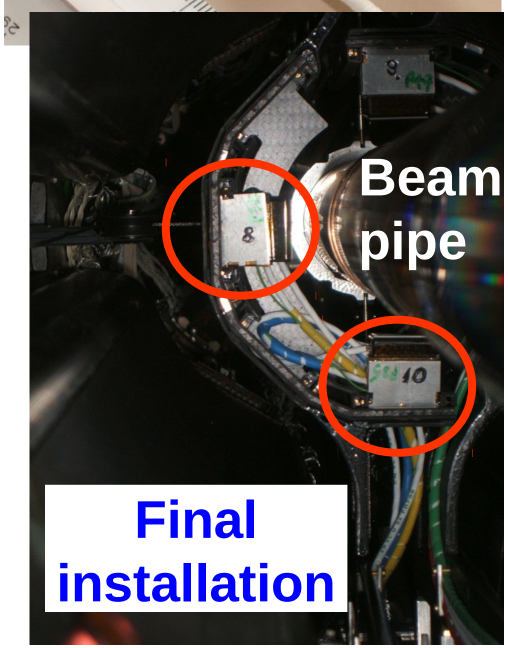
Design:

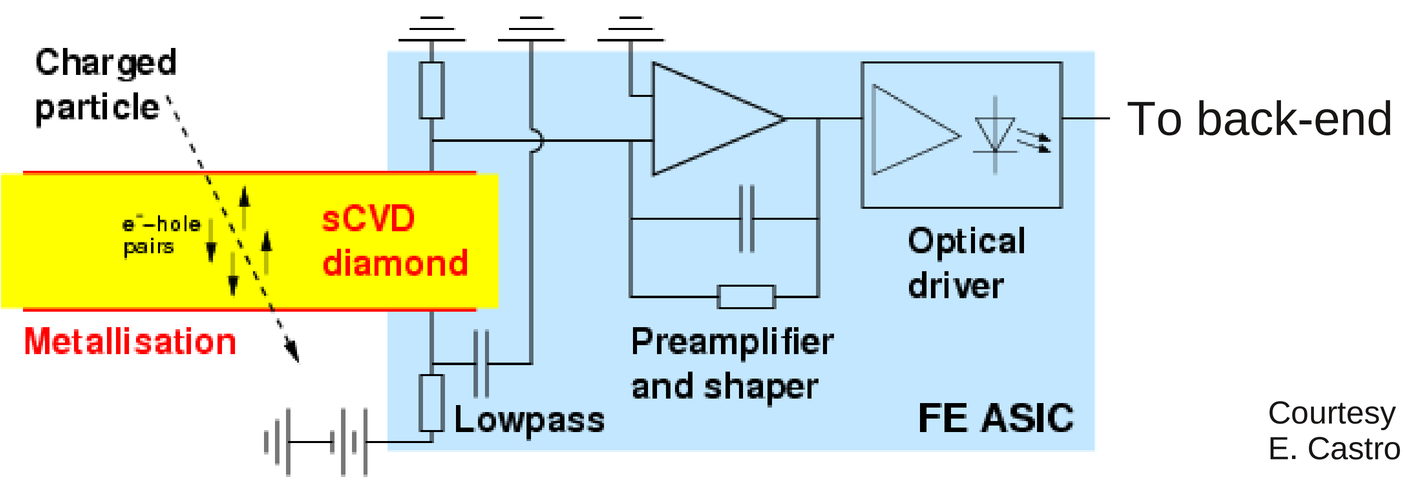
- 4 scCVD Diamond sensors on each side











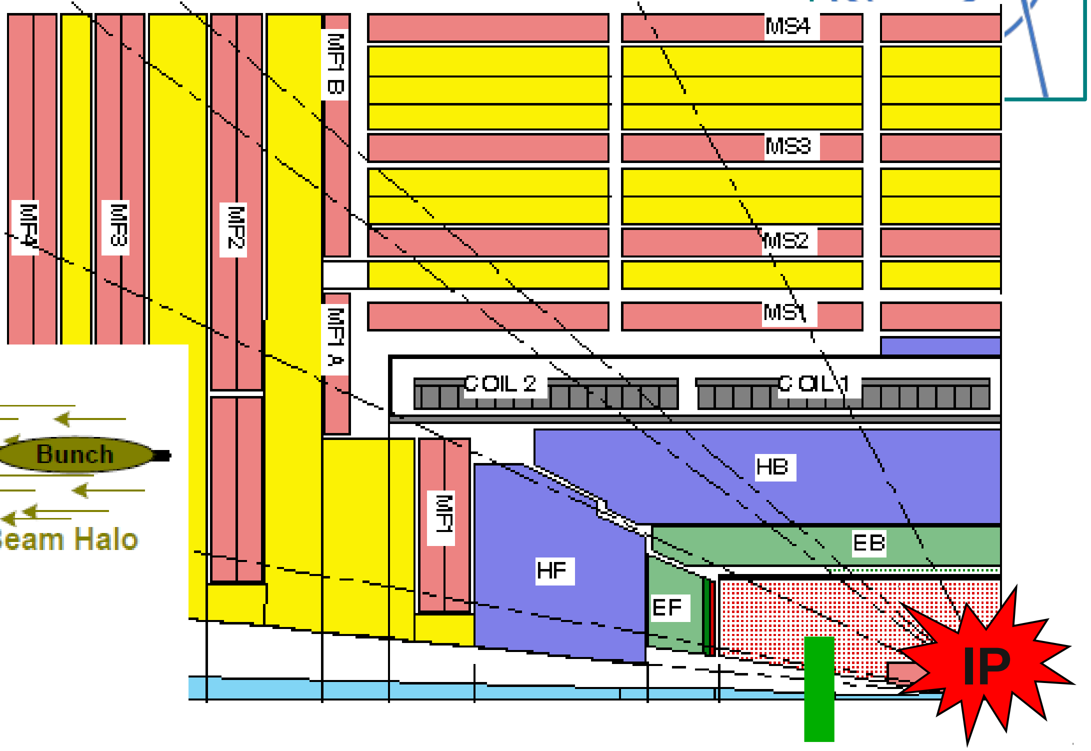
Courtesy E. Castro

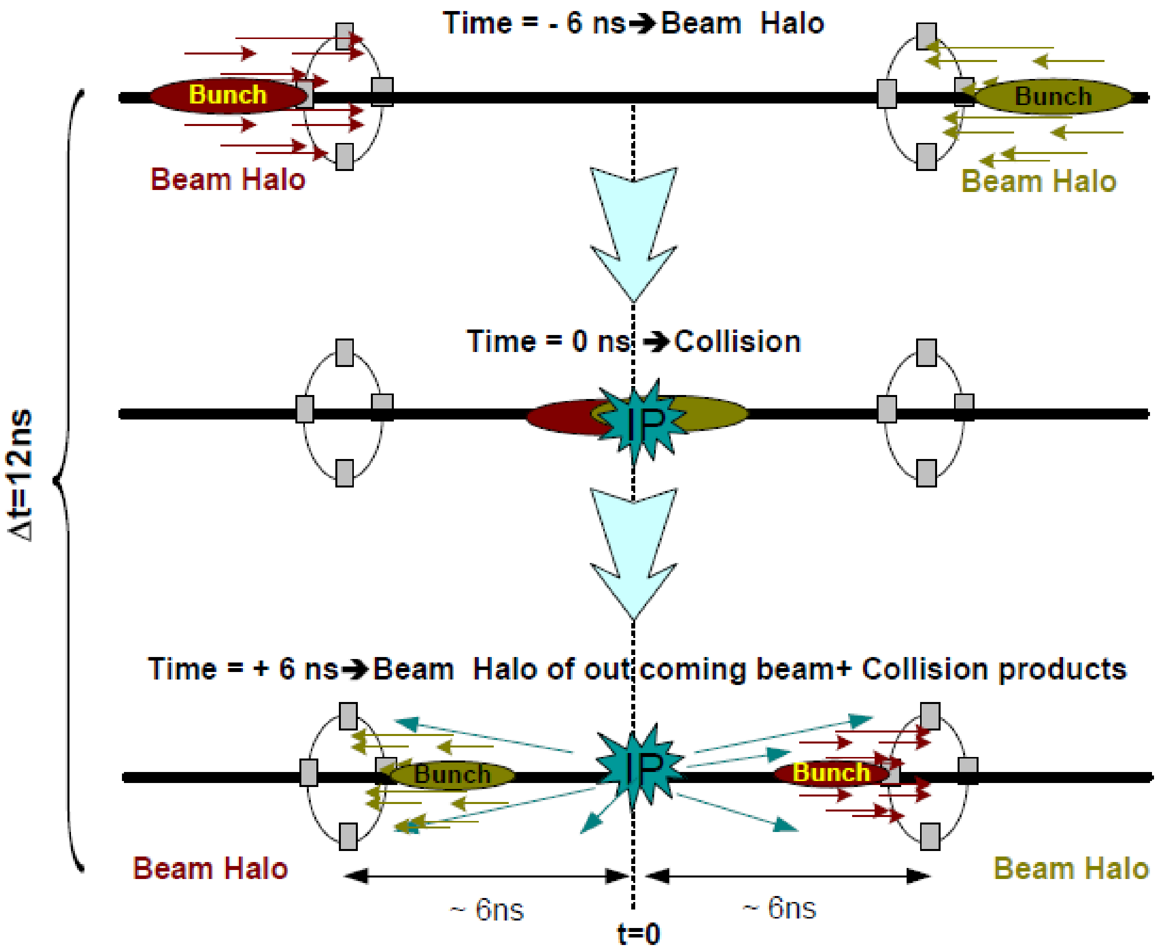
The CMS BCM1F

- Location:

  r = 50 mm

  z = ± 1.8 m (~6.25 ns)

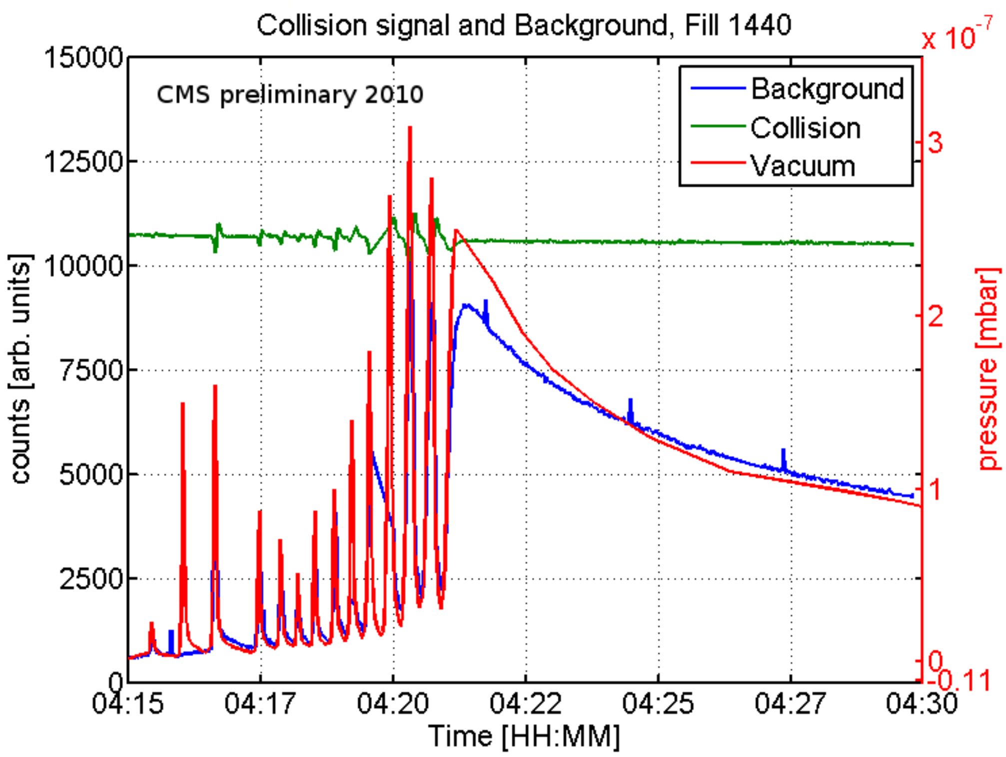


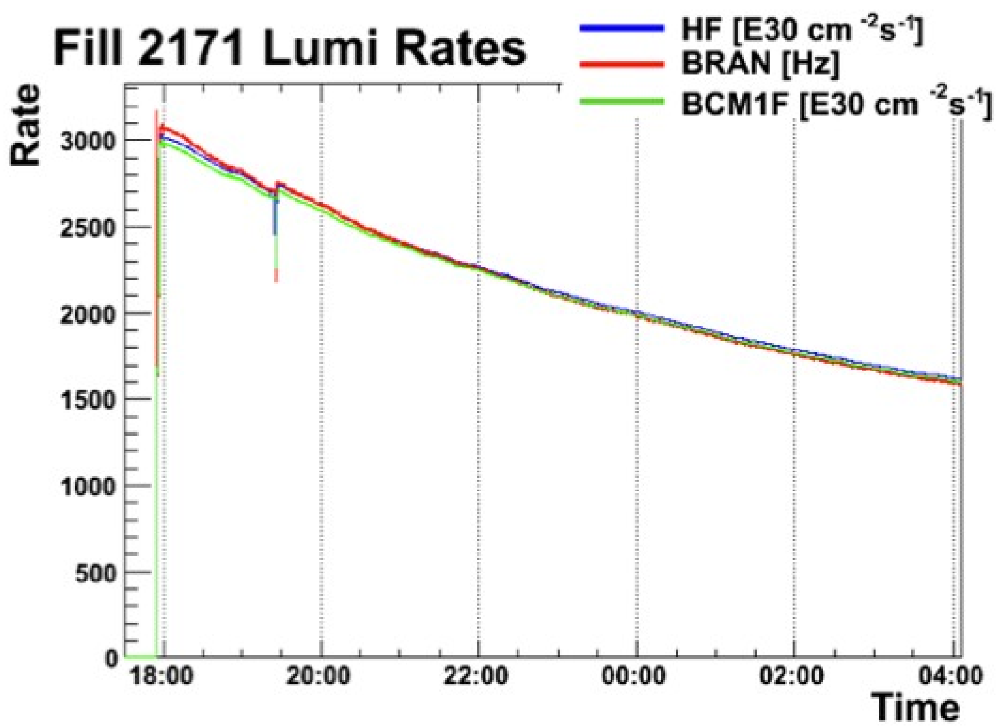


Courtesy
E. Castro

The CMS BCM

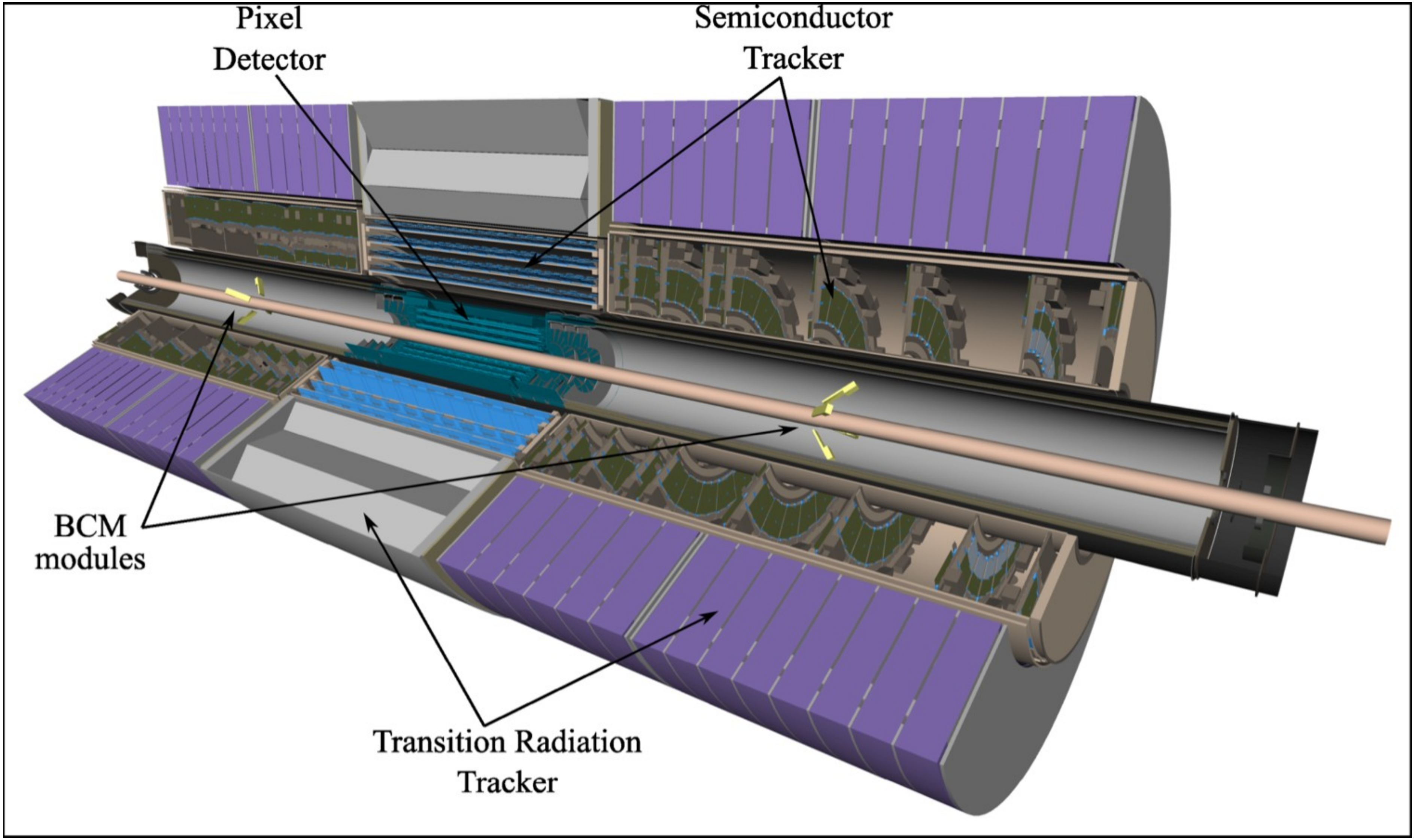
- Measure halo and collision rate
- Measure instantaneous luminosity
- Studies ongoing to extract bunch-by-bunch lumi



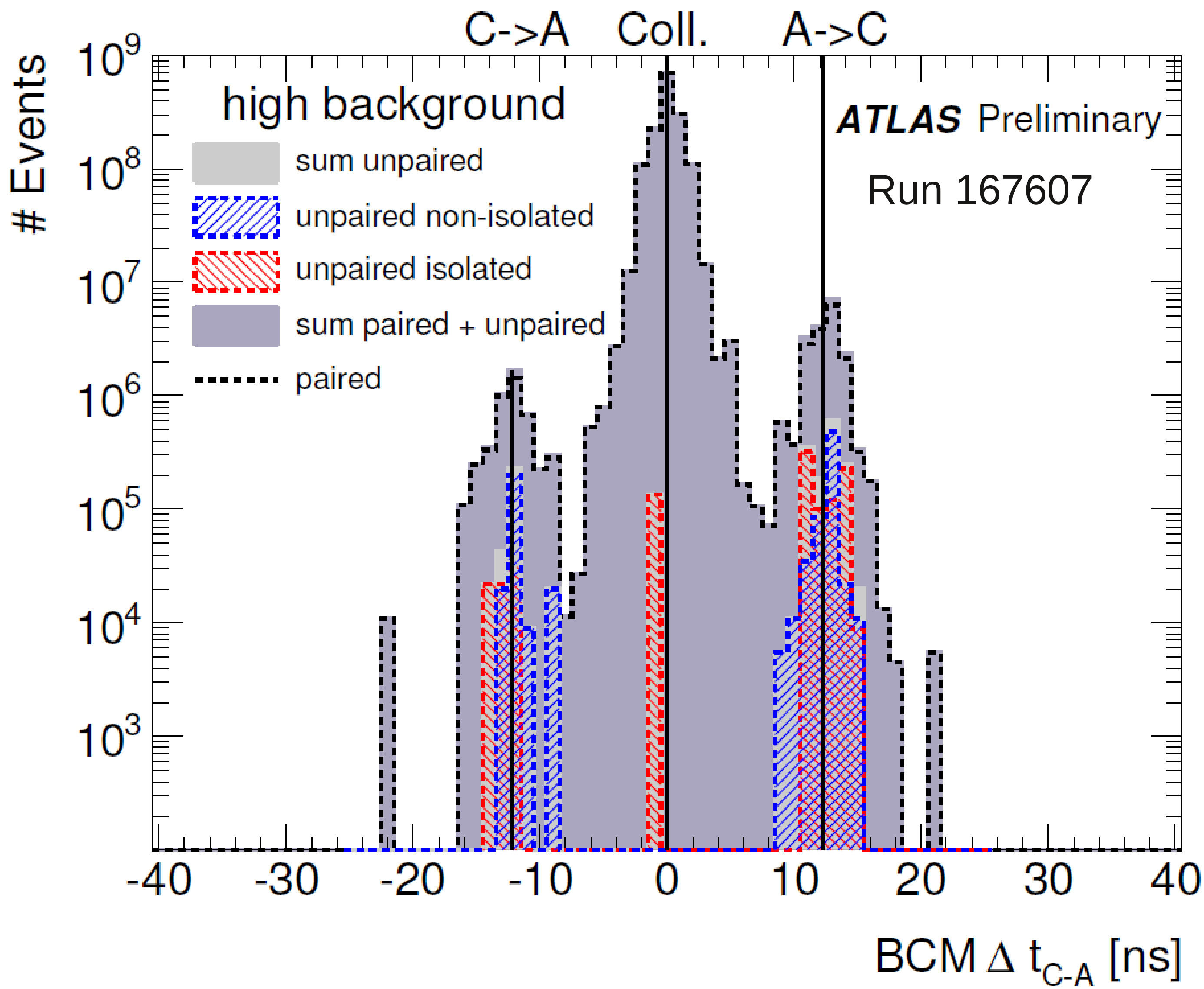


Courtesy
E. Castro

ATLAS BCM

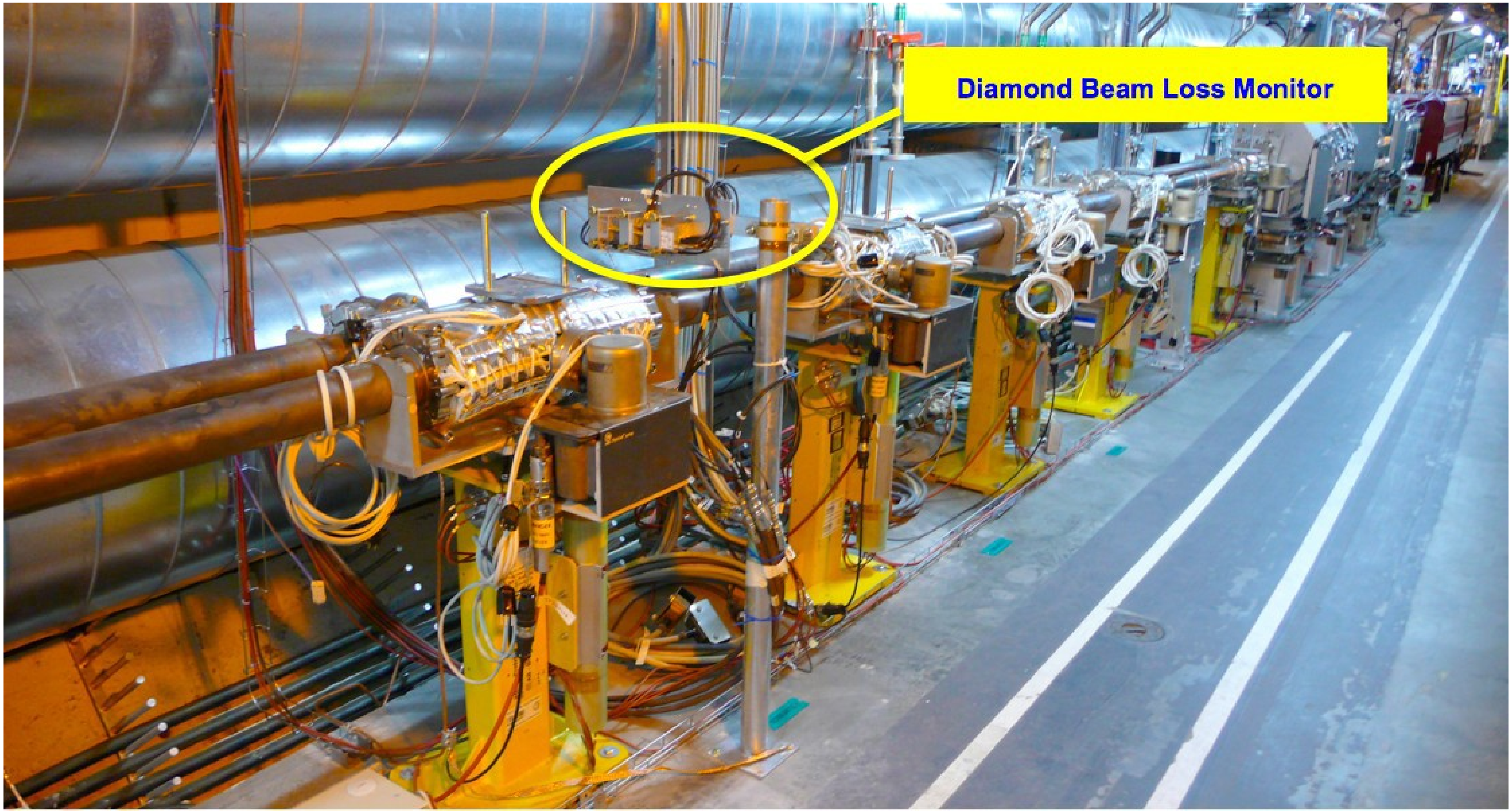

Pixel Detector
Semiconductor Tracker
BCM modules
Transition Radiation Tracker

- Similar location, but pCVDs, ultra-fast electronics



LHC Diamond BLM

- Record "Post Mortem" data after beam dump (among other functionalities)
- 6/10 installed

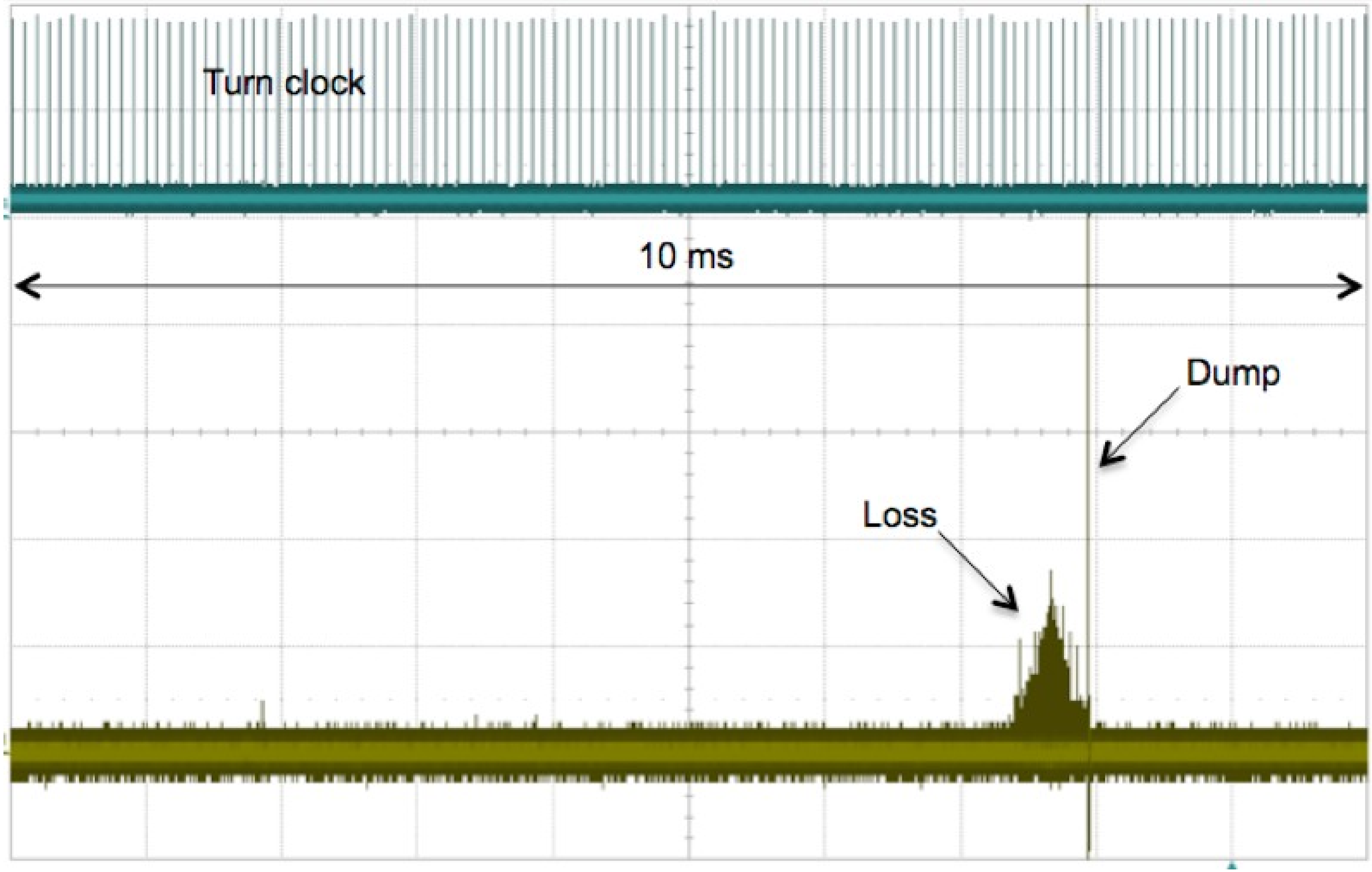


LHC – Collimator Area

Courtesy CIVIDEC

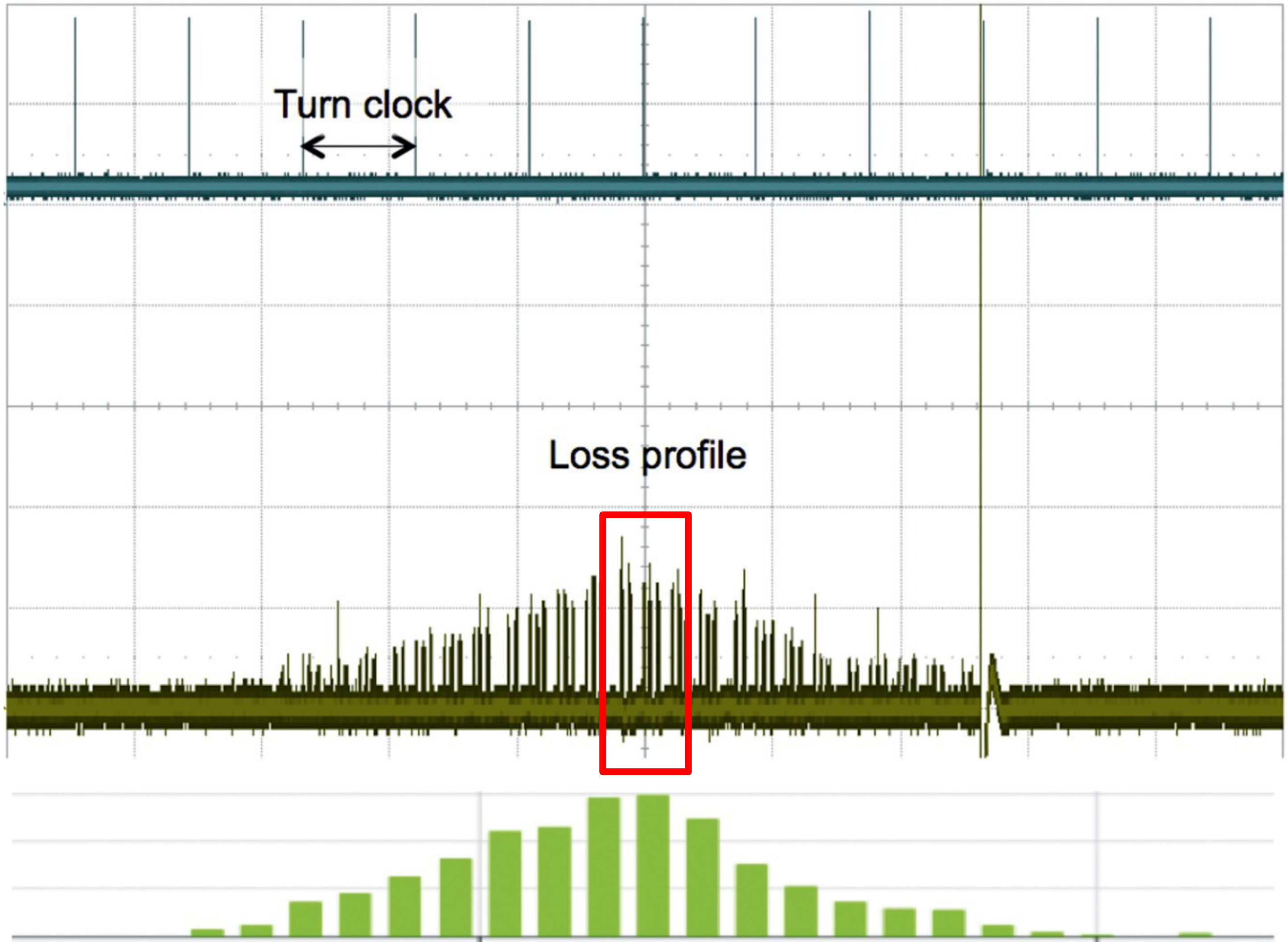
LHC Diamond BLM

- Unidentified Falling Objects (UFOs) seen from time to time
- Create huge losses -> Beam dump



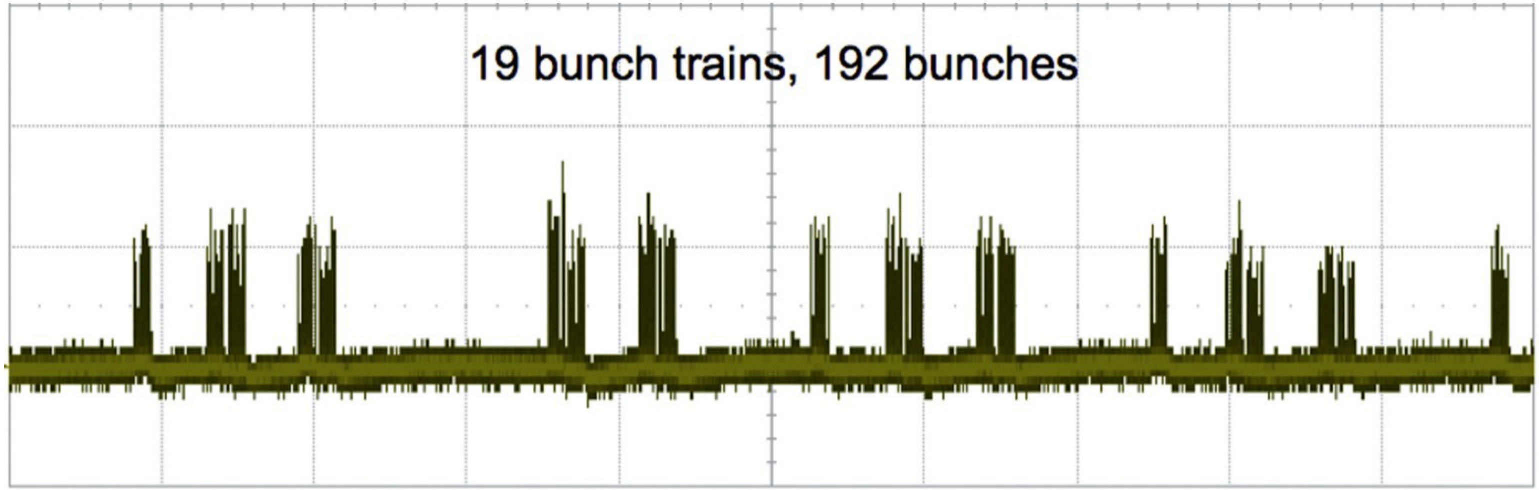
LHC Diamond BLM

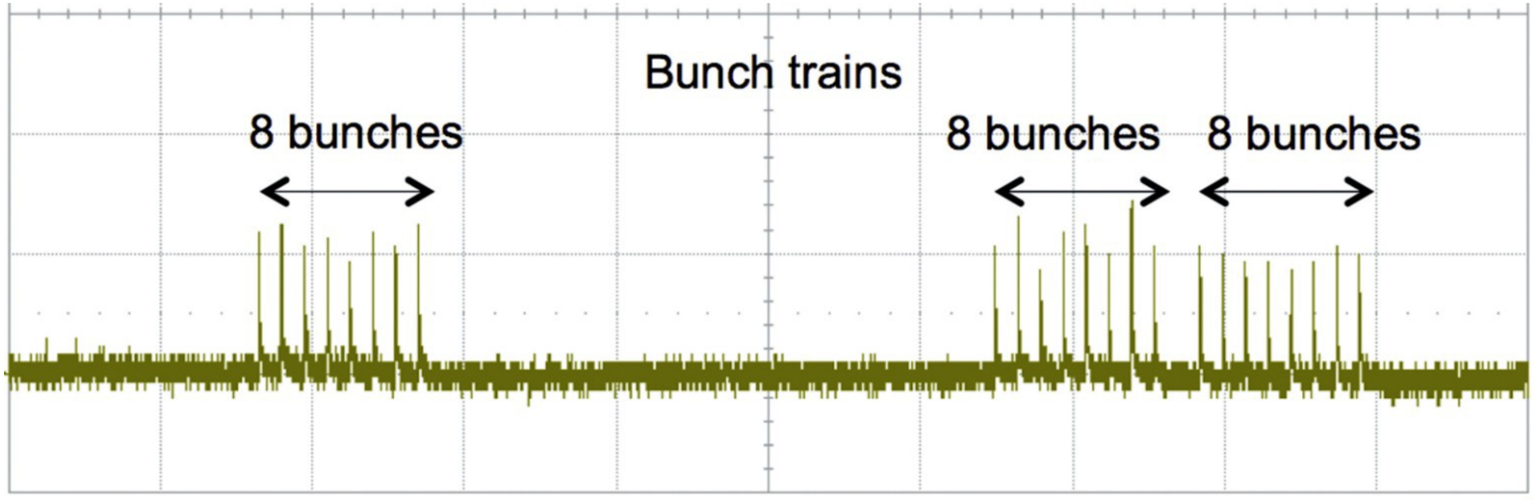
- Fast Diamond BLMs allow closer look at UFOs:



LHC Diamond BLM

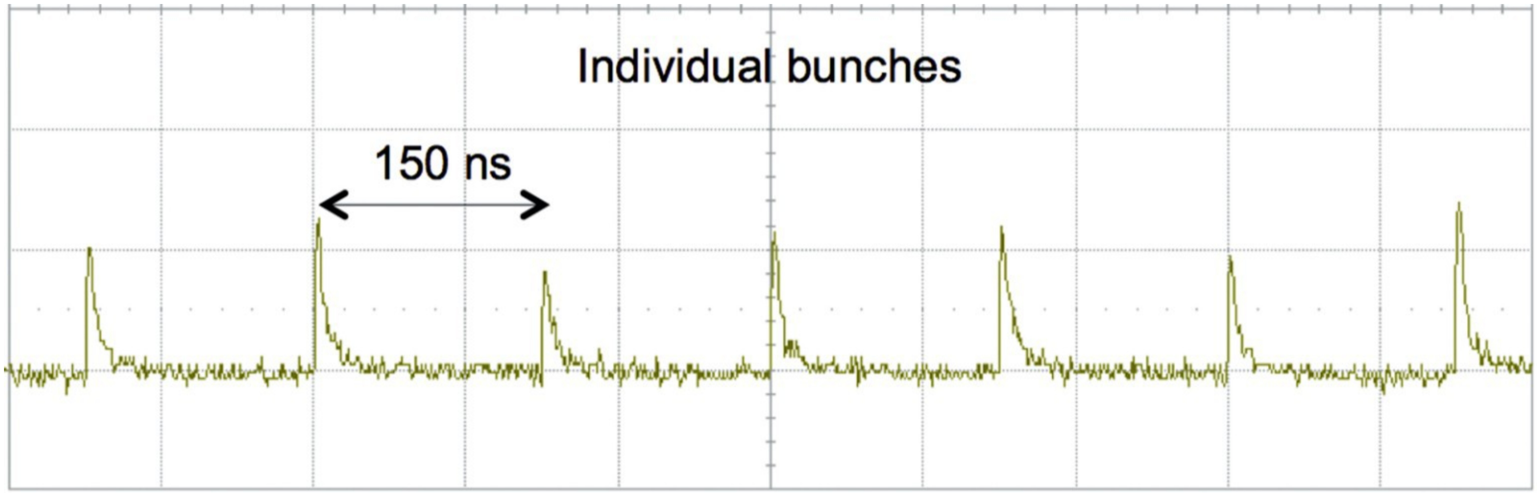
- Closer look at UFOs

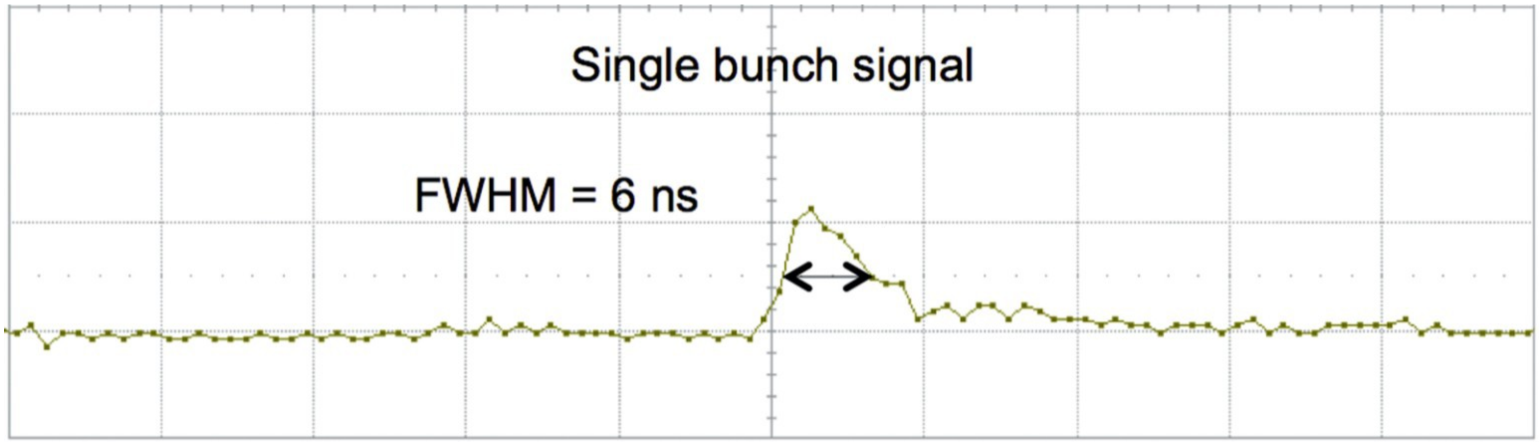




LHC Diamond BLM

- Closer look at UFOs



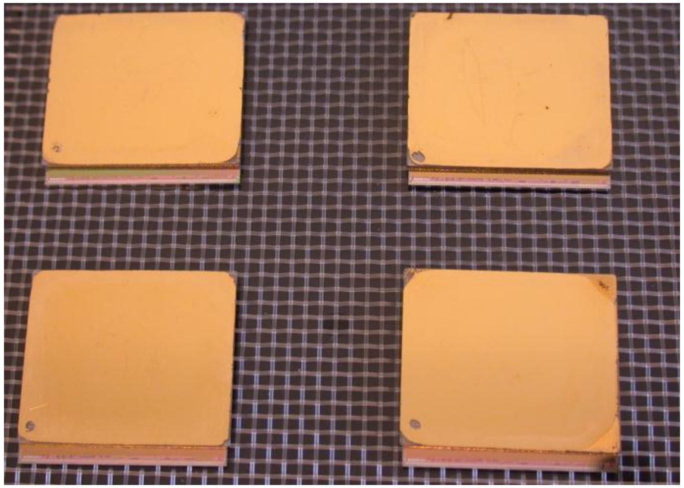


Future Diamond Detectors

ATLAS DBM

Purpose

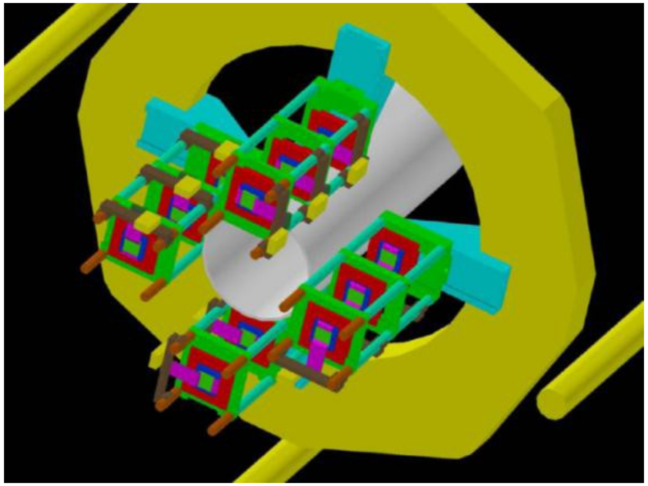
- Bunch-by-bunch luminosity monitor
  - pixelized and larger acceptance than BCM
  - aim < 1% per BC per LB



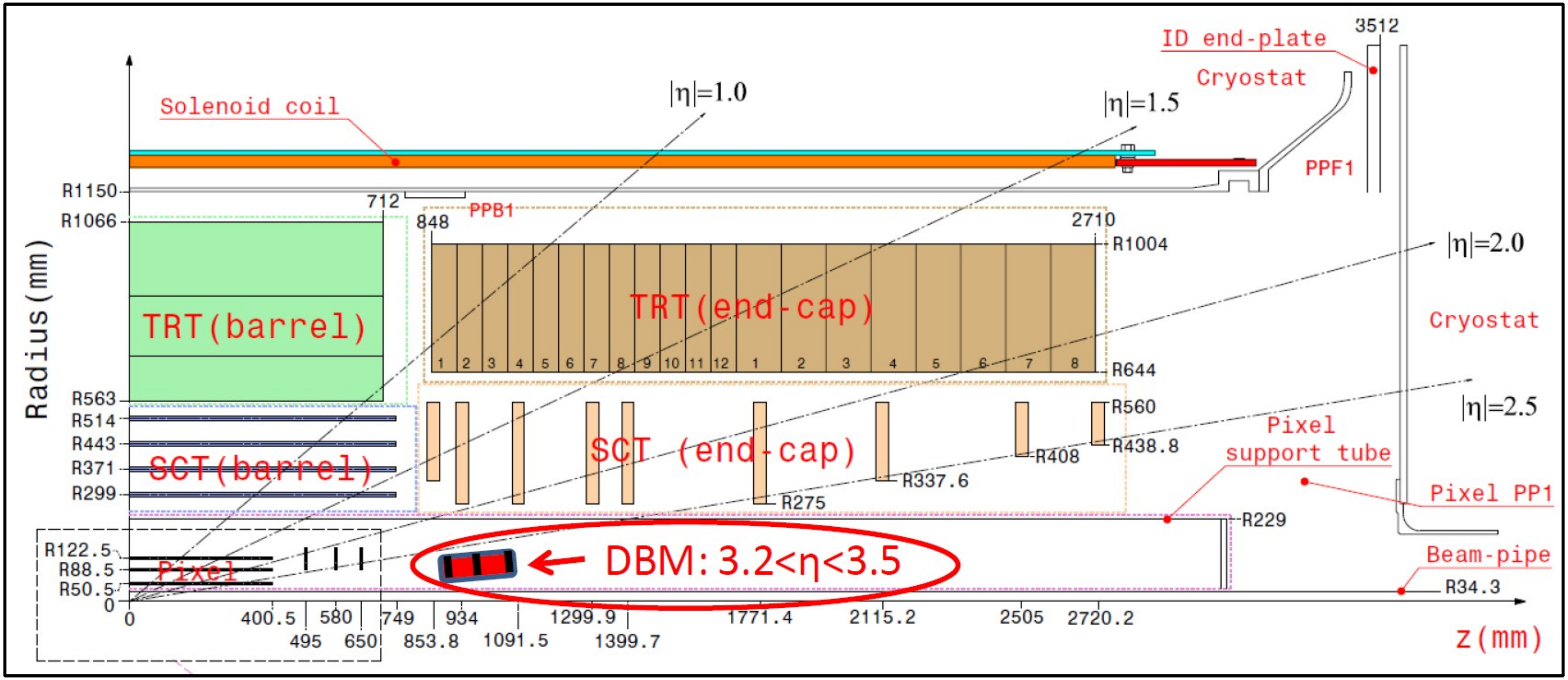
- Bunch-by-bunch beam spot monitor
  - need telescope structure for tracking
  - distinguish halo and collision events

Design

- 4 telescopes of 3 sensors per side
  -> 24 modules
- At $|\eta| \approx 3.3$
- Use pixel support structure
- Use IBL read-out chip

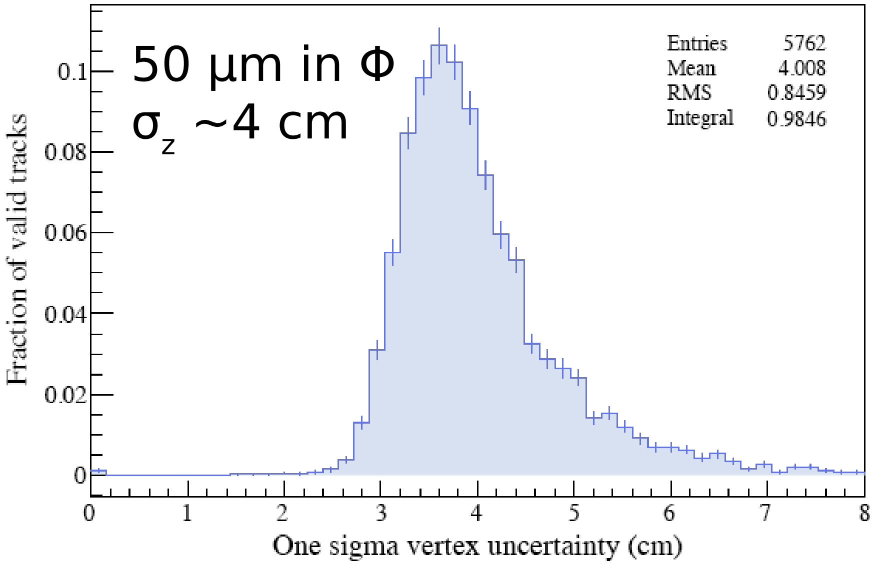


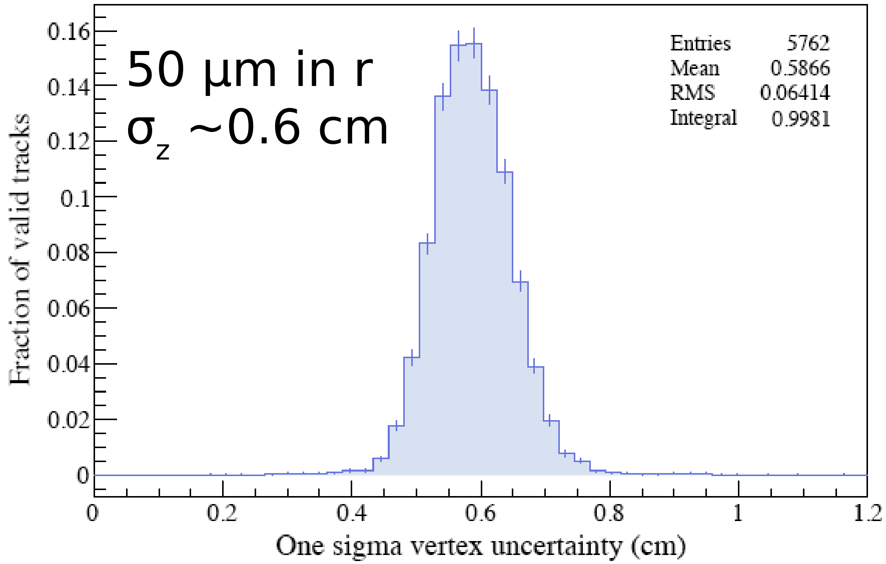
- Location of DBM



DBM Specs

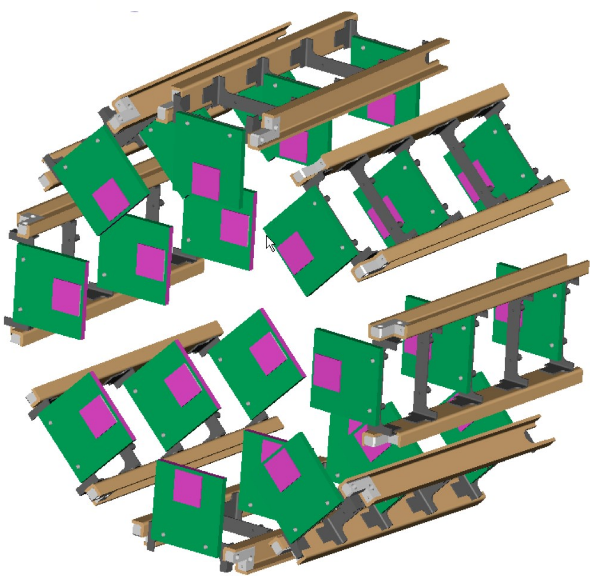
Property	Specification
Sensor size pixel size channels	21 mm x 18 mm 250 um x 50 um 336 x 80 = 26880
Sensor thickness	400 – 500 um
Min. CCD	200 um -> 7200 e-
Min. CCD after 2e15 cm^{-2}	100 um -> 3600 e-
Max operation voltage	1000 V
Read-out chip	FE-I4

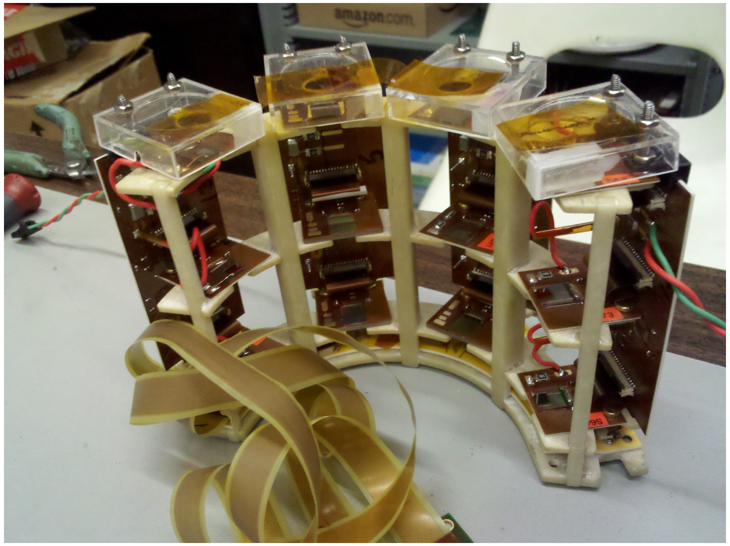




CMS Pixel Lumi Telescope (PLT)

- Dedicated, stand–alone luminosity monitor
- Eight 3-plane telescopes each end of CMS
- 1.6^0 pointing angle r = 4.8 cm, z = 175 cm
- Diamond pixel sensors pixel area: 3.9 mm x 3.9 mm
- Count 3-fold coincidences fast-or signals (40 MHz)
- Full pixel readout pixel address, pulse height (1 kHz)
- Stable 1% precision on bunch-by-bunch relative luminosity

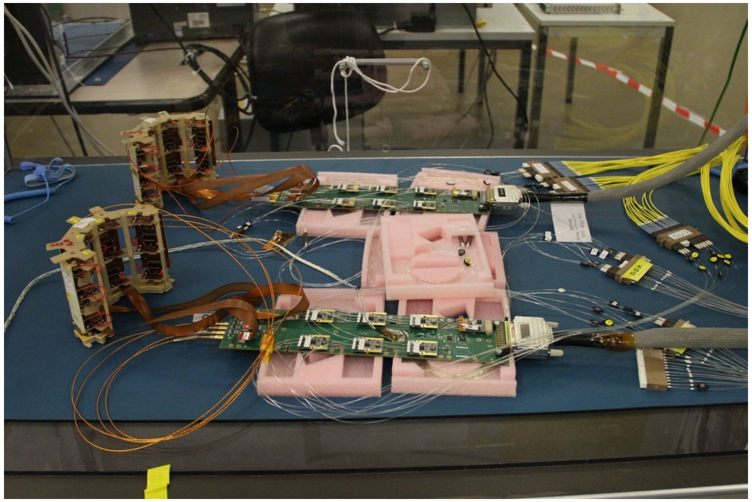




Courtesy
S. Schnetzer

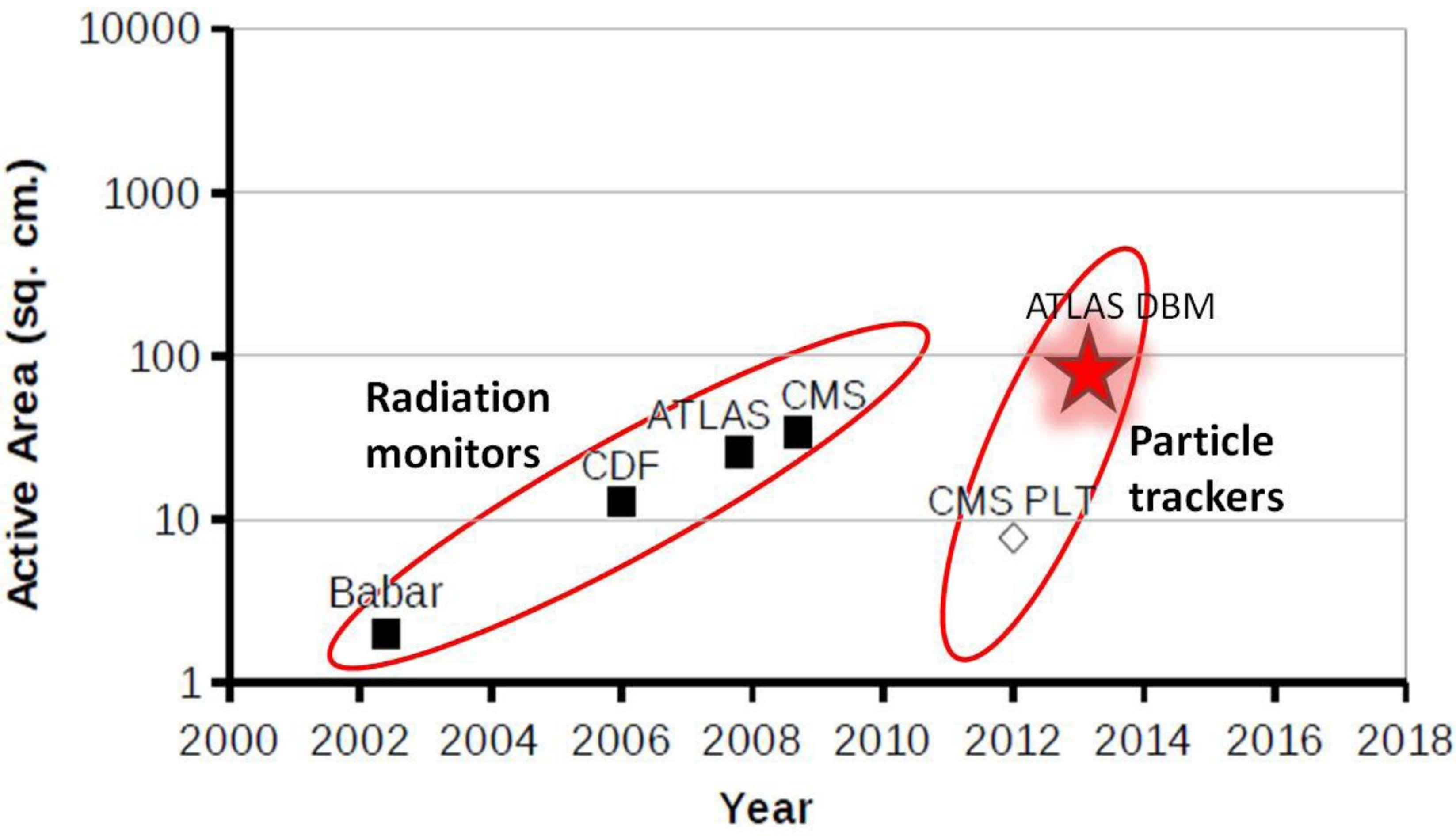
PLT Status

- Two full cassettes (each 4 telescopes) under continuous, stable operation at CERN
- Full system set up
- Near flawless operation
- Both studies in Oct test-beam
- Installation of 2 cassettes during winter shut-down behind HF, z = 15 m



All planes for full PLT produced

CVD Diamond in HEP



R&D efforts

Cryogenic BLM in Triplet Magnets

- Place BLMs as close to the beam as possible
  → Better separation of collision debris and halo/losses
  → 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 using liquid He cooling
  → Measure temperature dependence of diamond properties

Details of Measuring Set-up

- The Transient-Current Technique (TCT) with α particles:

→ measure the transient current

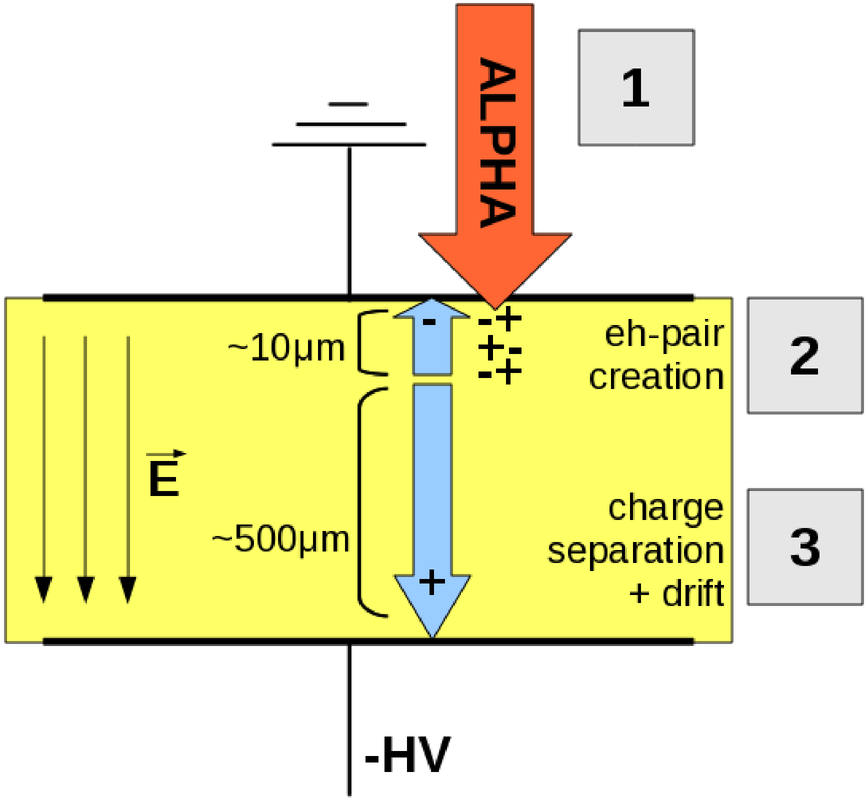
1) α particles impinge on top side
2) Create eh-pairs close to electrode
3) Electric field separates charges
4) Drifting charges induce current

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

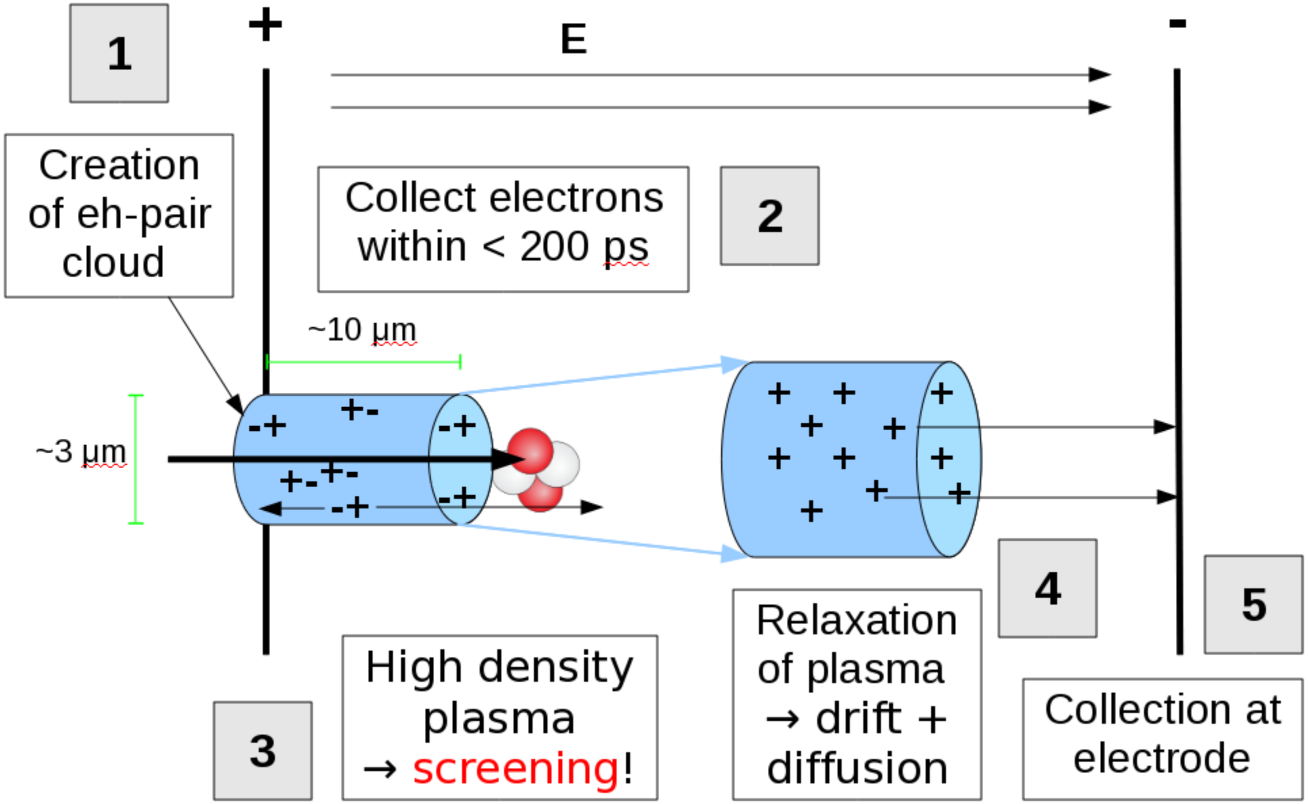
→ Use ultra-fast 2 GHz, 40 dB, 200 ps rise time current amplifier

→ Use broad-band 3 GHz scope

→ Use RF components



TCT and the Plasma Effect



From Ramo-Theorem:

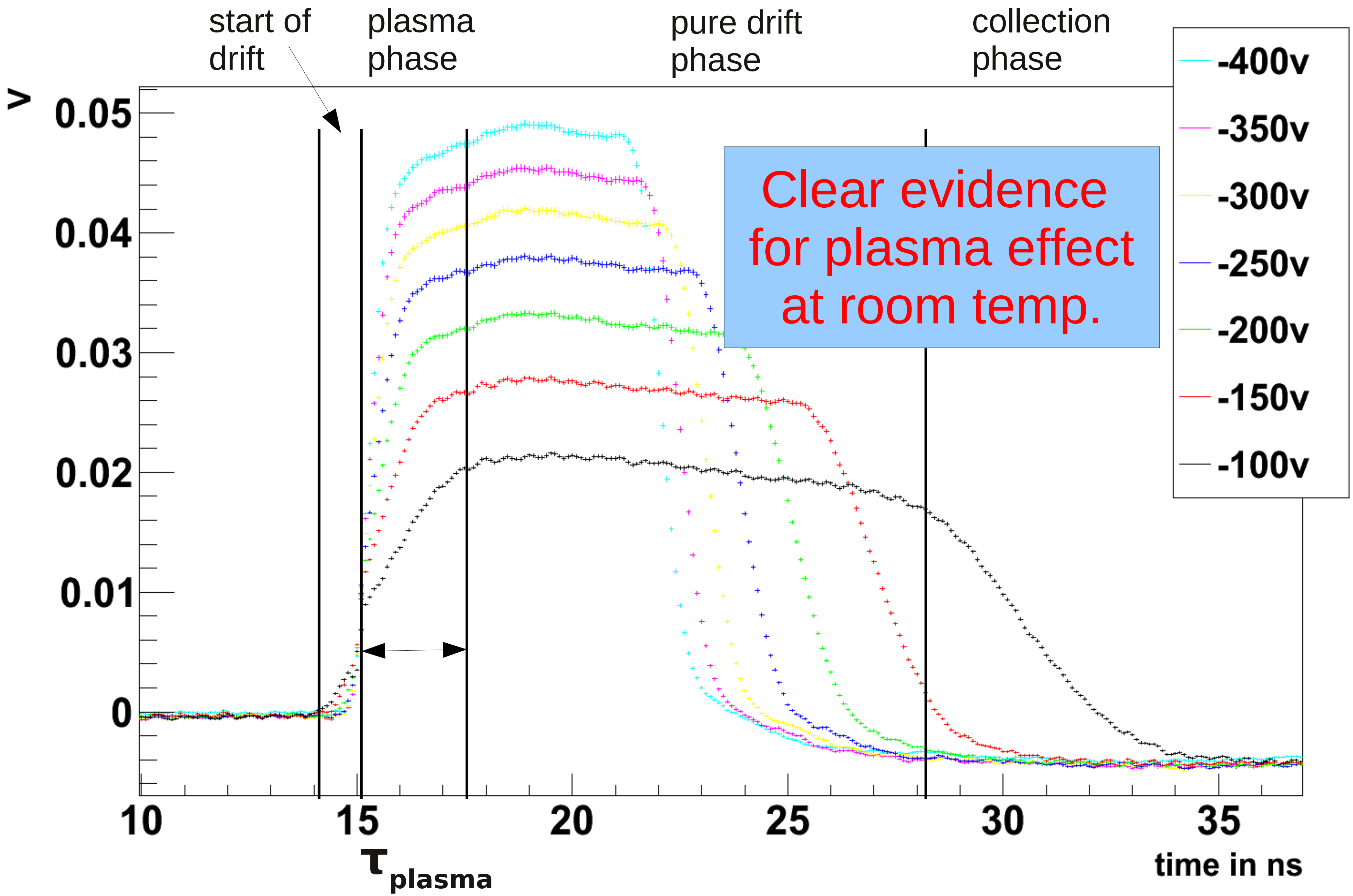
$$i(t) = \sum_k i_k(t) = \sum_k e\, E_w\, v_k(t) = \frac{e}{d} \sum_k v_k(t - t_k^{start});$$

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

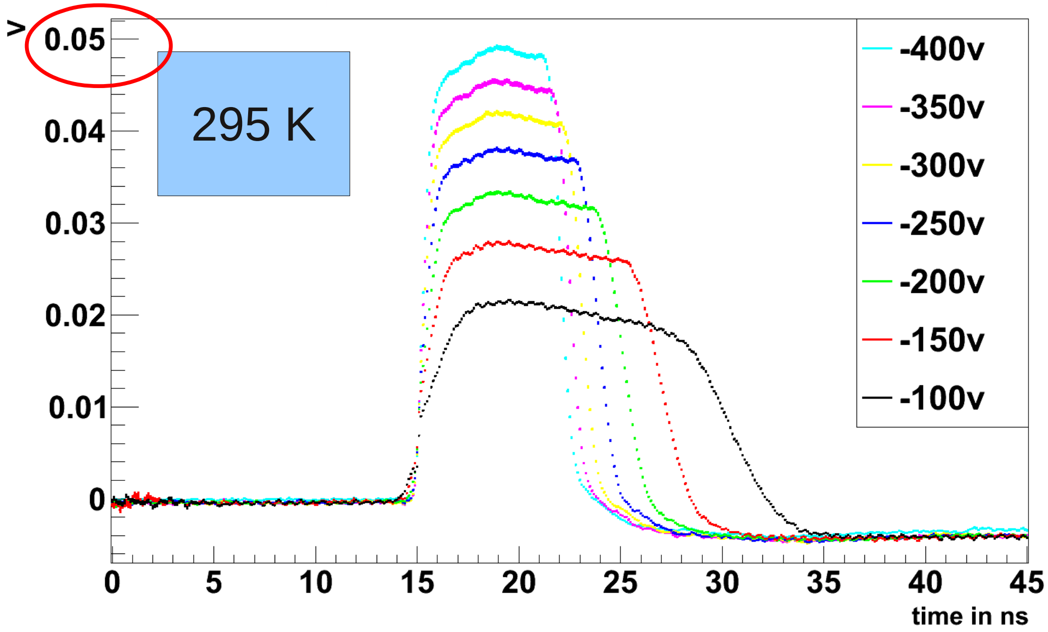
- **FACTS:**
  - → αs produce high density charge cloud
  - → Outer charges screen inner ones
    - → E-Field decreases inside the plasma
  - → Increased E-Field decreases lifetime of plasma

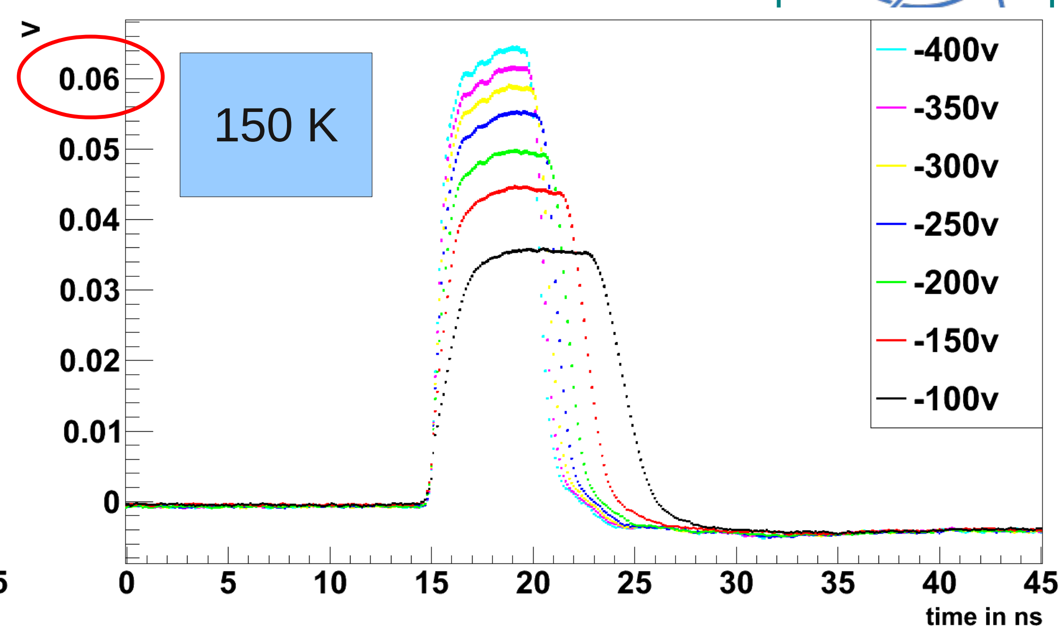
$$\rho_{cloud} \approx \frac{3 \cdot 10^5\, pairs}{(3\,\mu m)^2 \pi\, 10\,\mu m} \approx 10^{15}\, cm^{-3}$$

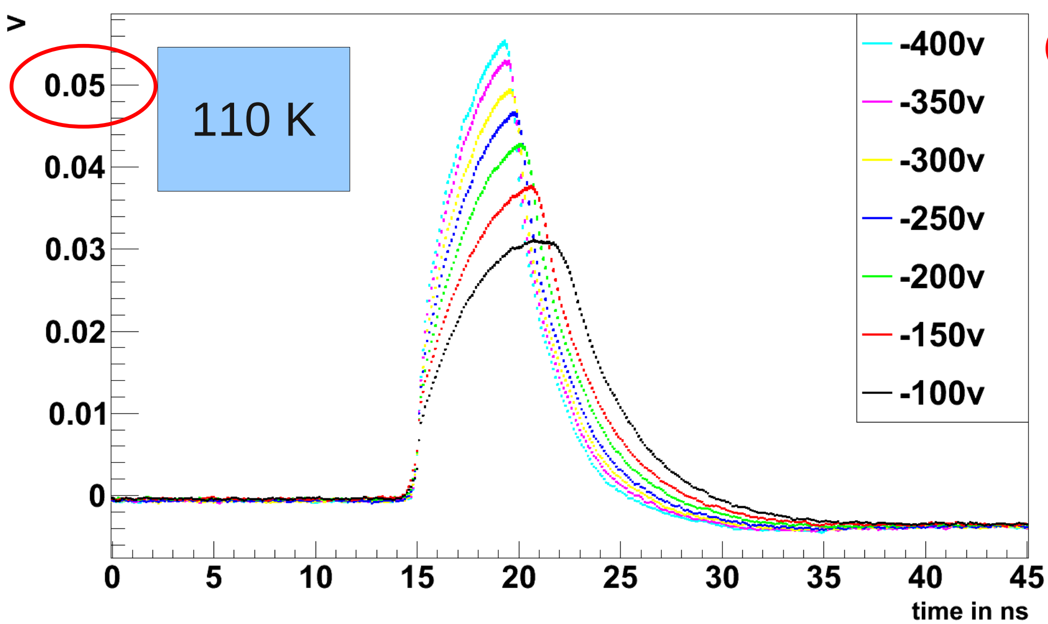
Plasma Effect at 295 K

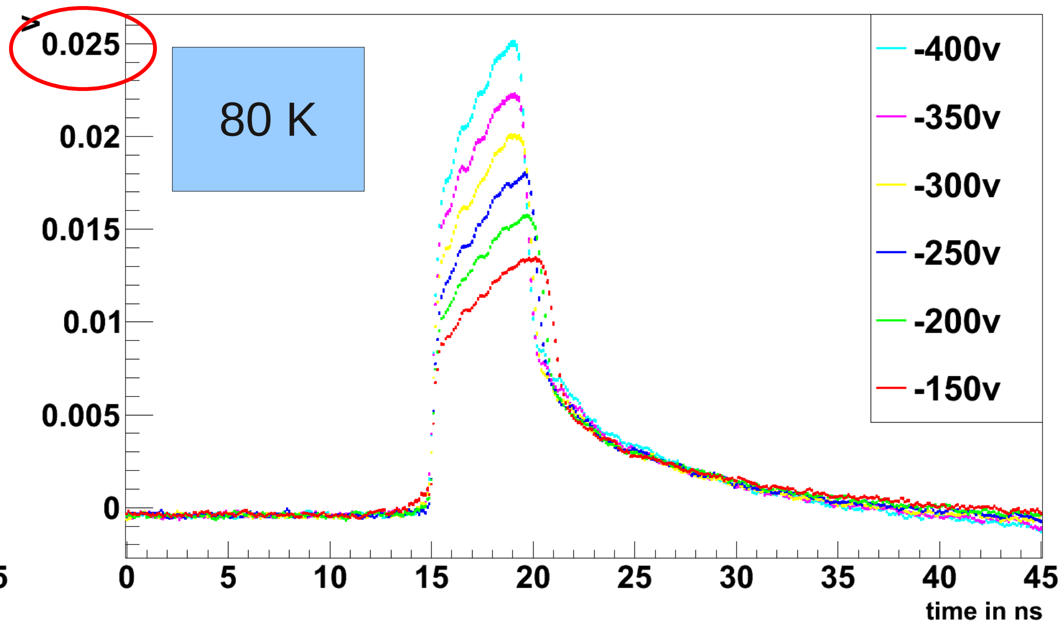


TCT Hole Pulses

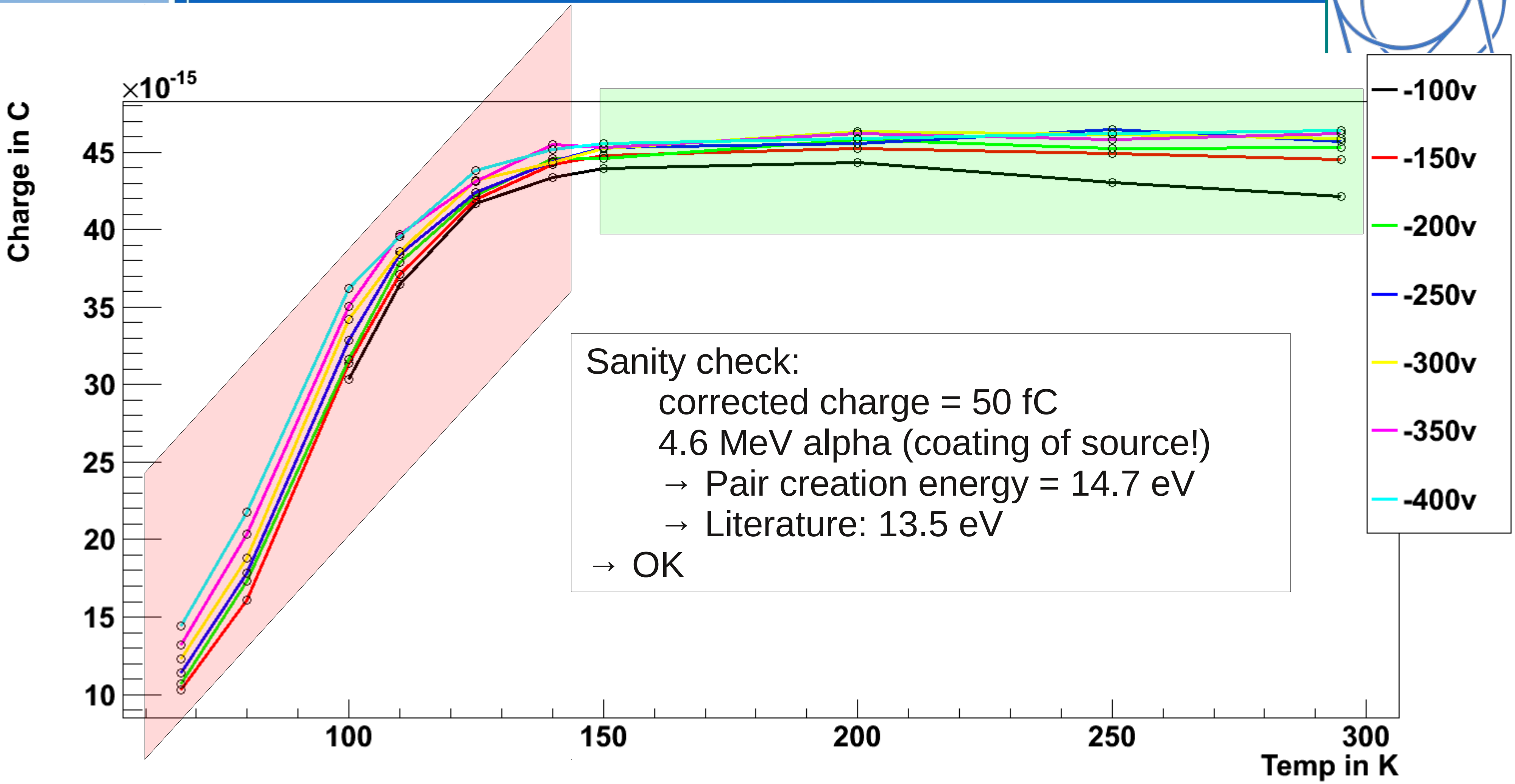






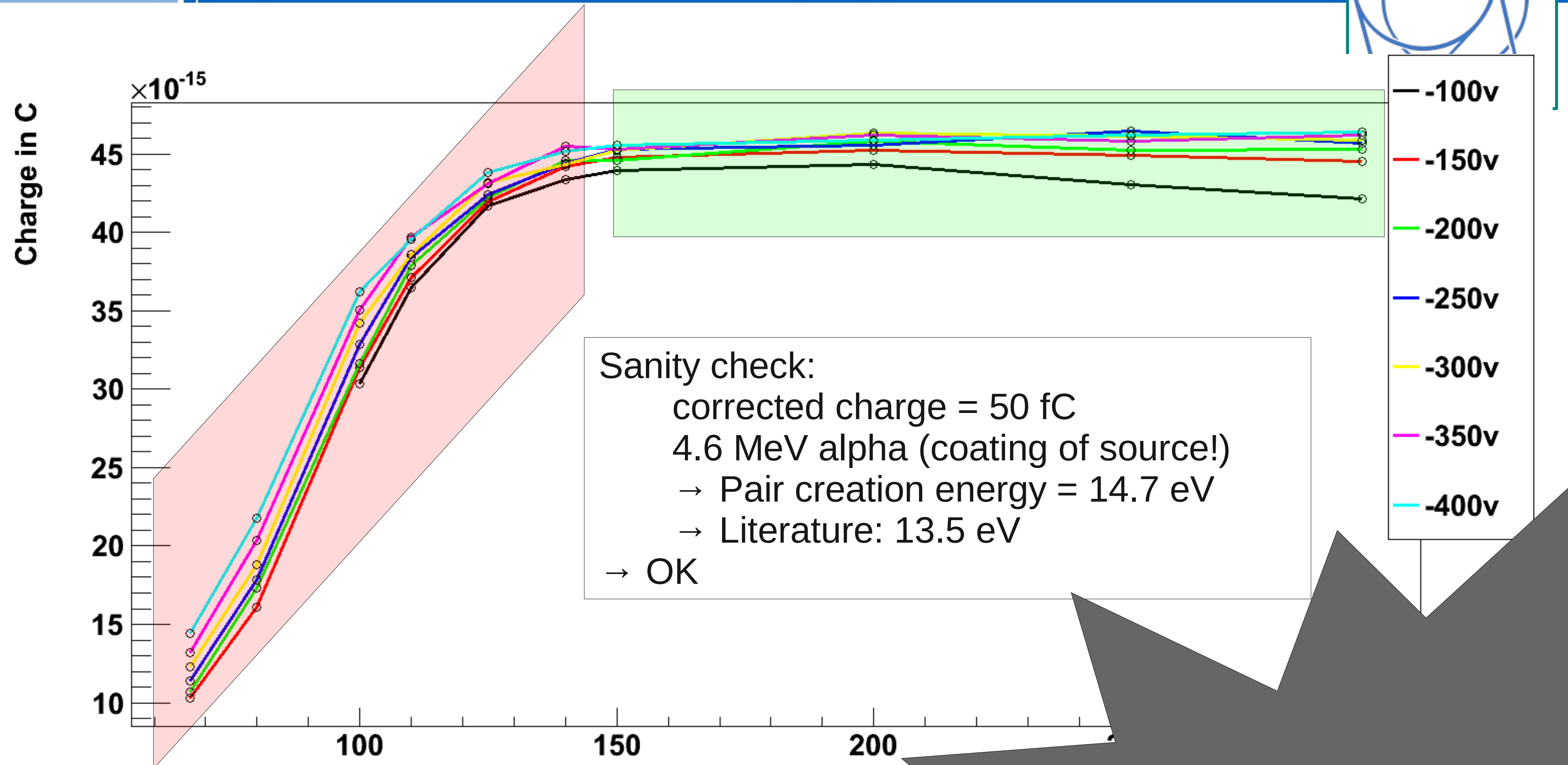


Integrated Charge



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

Integrated Charge

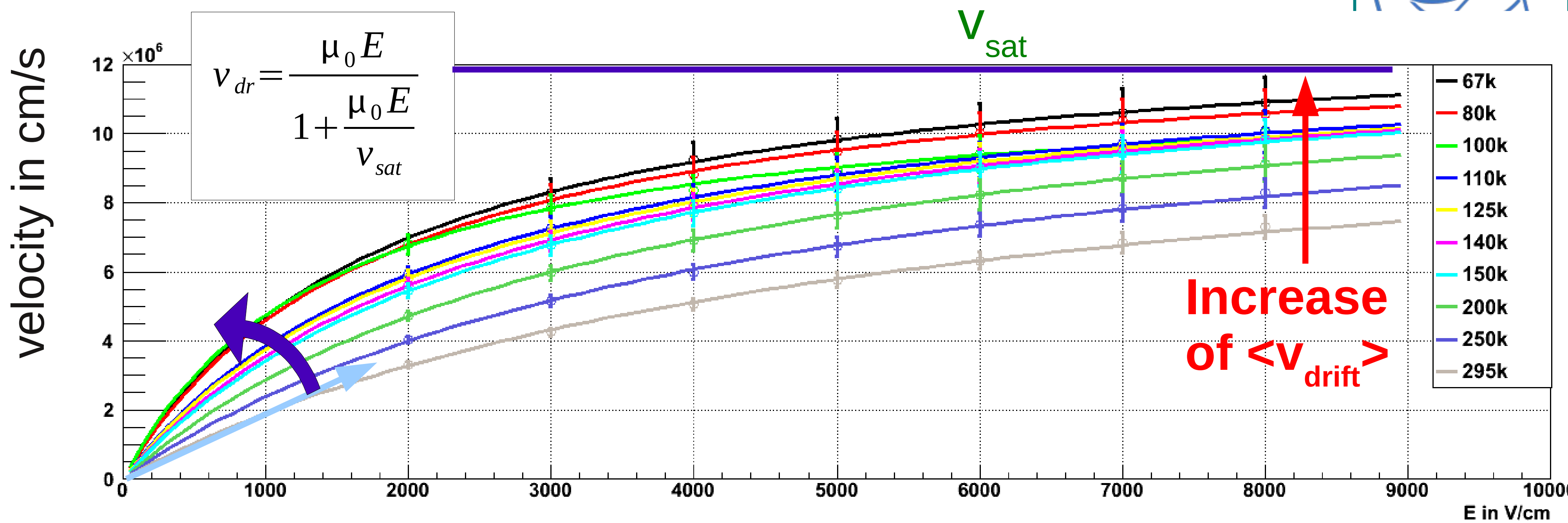


Sanity check:
corrected charge = 50 fC
4.6 MeV alpha (coating of source!)
→ Pair creation energy = 14.7 eV
→ Literature: 13.5 eV
→ OK

Breaking News: Measured αs at 4.7 K last week

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

Hole Mobility and Velocity



Fits yield:

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

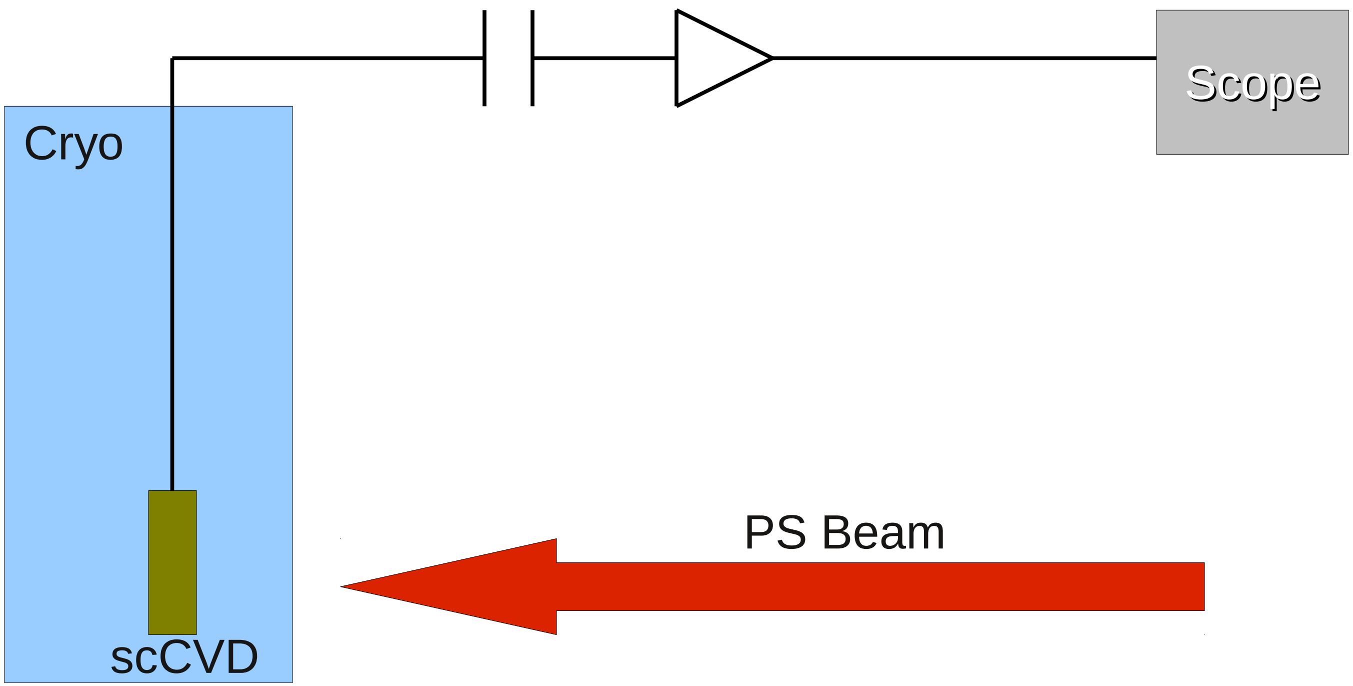
$$v_{sat}^{295\,K} = 11.8 \cdot 10^6 \pm 0.8 \cdot 10^6\, cm/s \qquad v_{sat}^{67\,K} = 13.4 \cdot 10^6 \pm 1.4 \cdot 10^6\, cm/s$$

- Mobility μ_h and avg. drift velocity <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

Beam tests

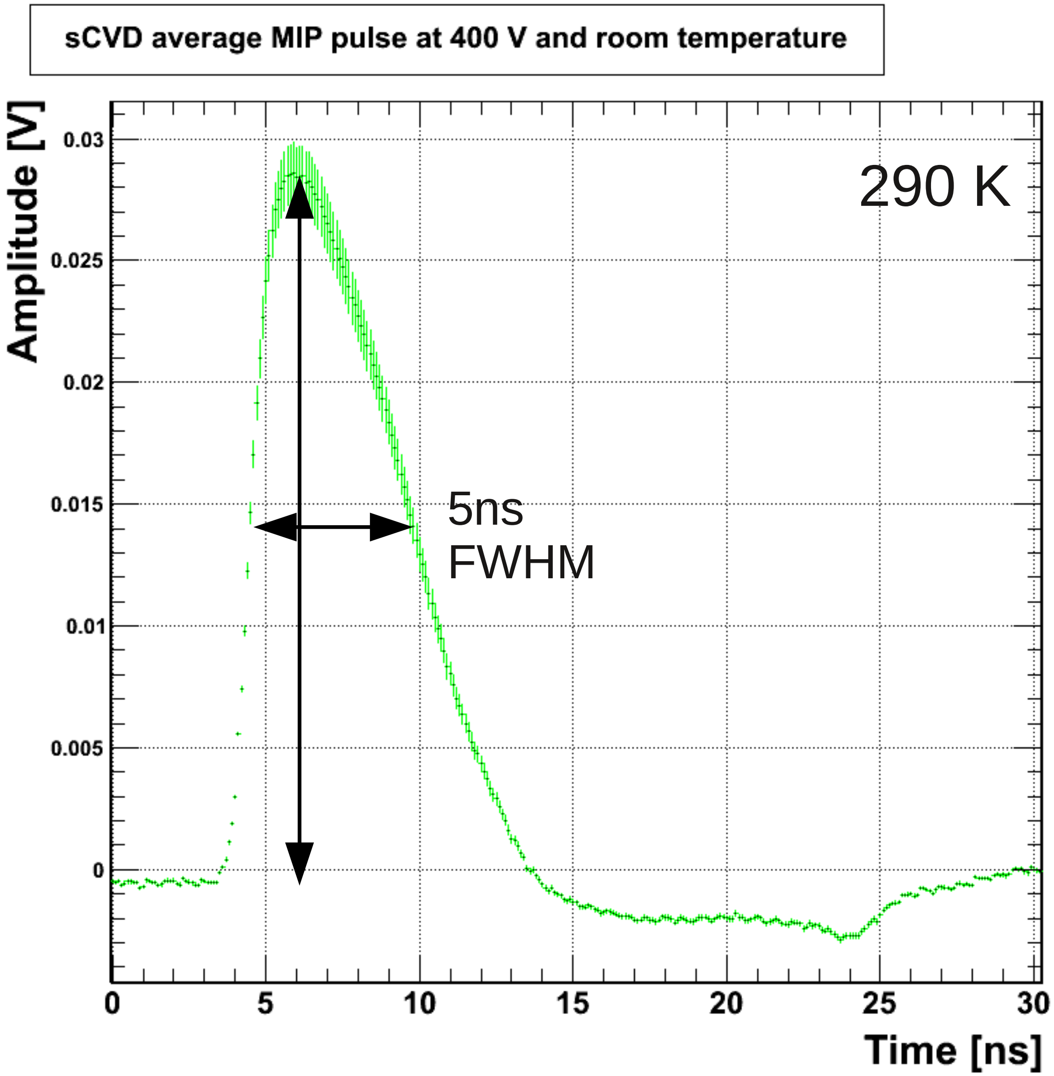
Set-up

- PS Beam on Cryostat (24 GeV protons)
- Diamond cooled down to LiHe temperature
- AC-coupled to 2GHz pre-amplifier



Courtesy
C. Kurfuerst

TCT signals with PS protons



Courtesy
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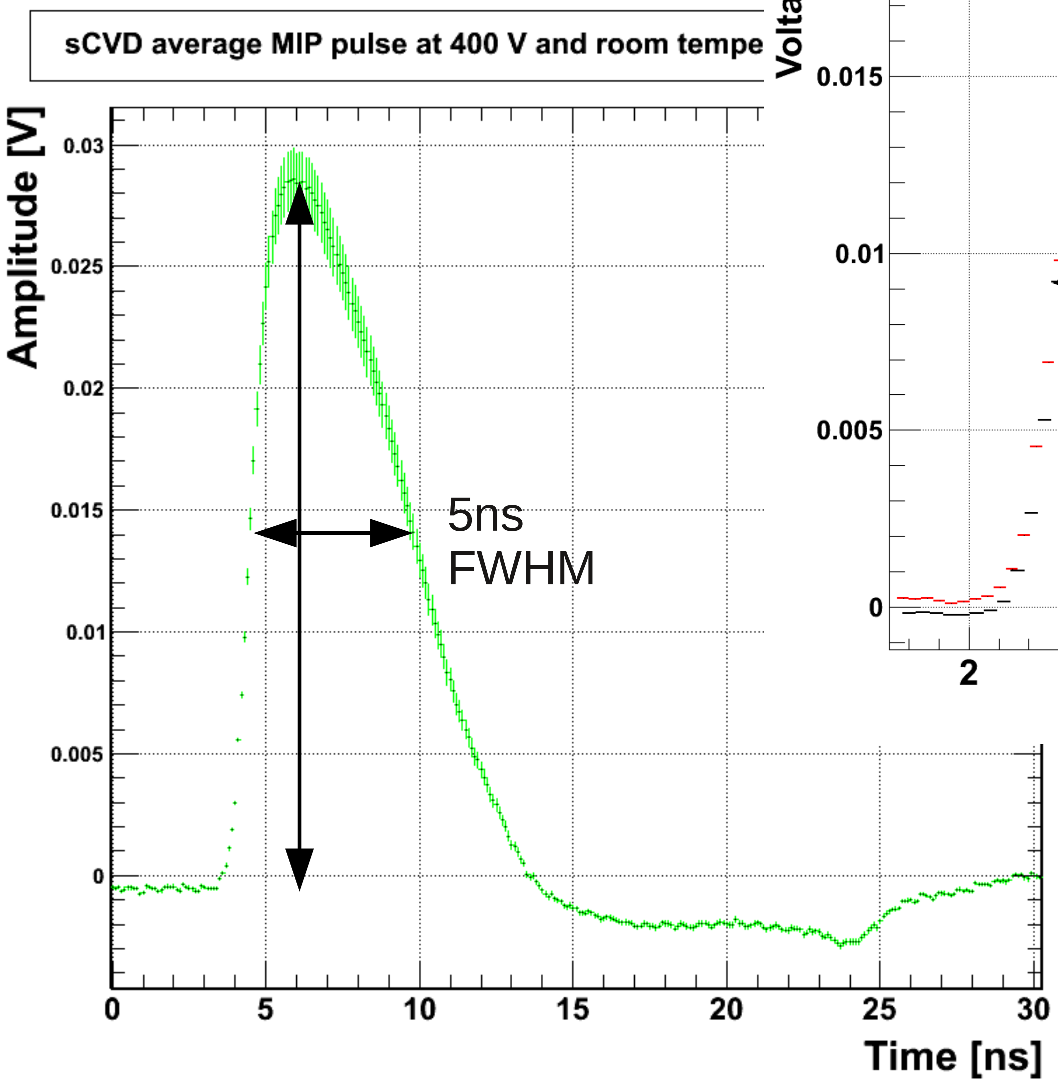
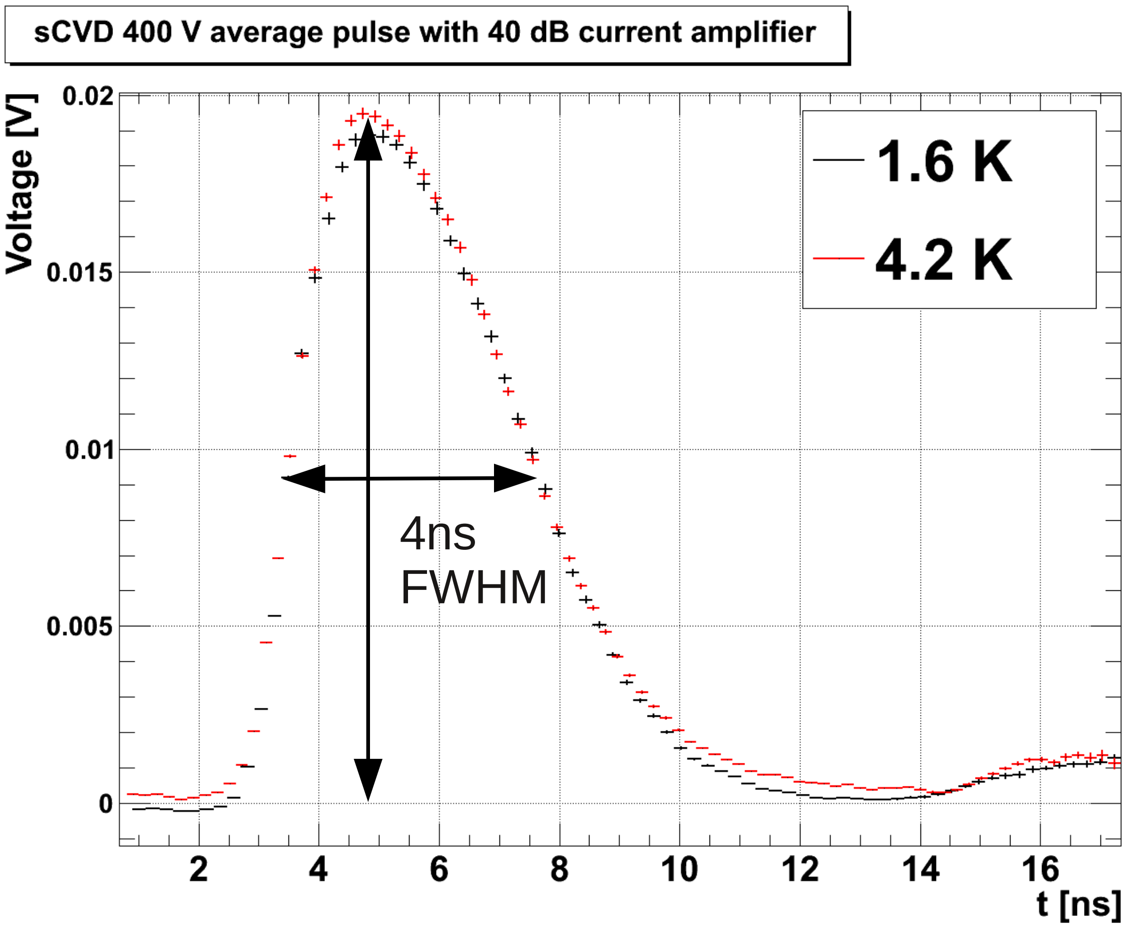
TCT signals with PS protons



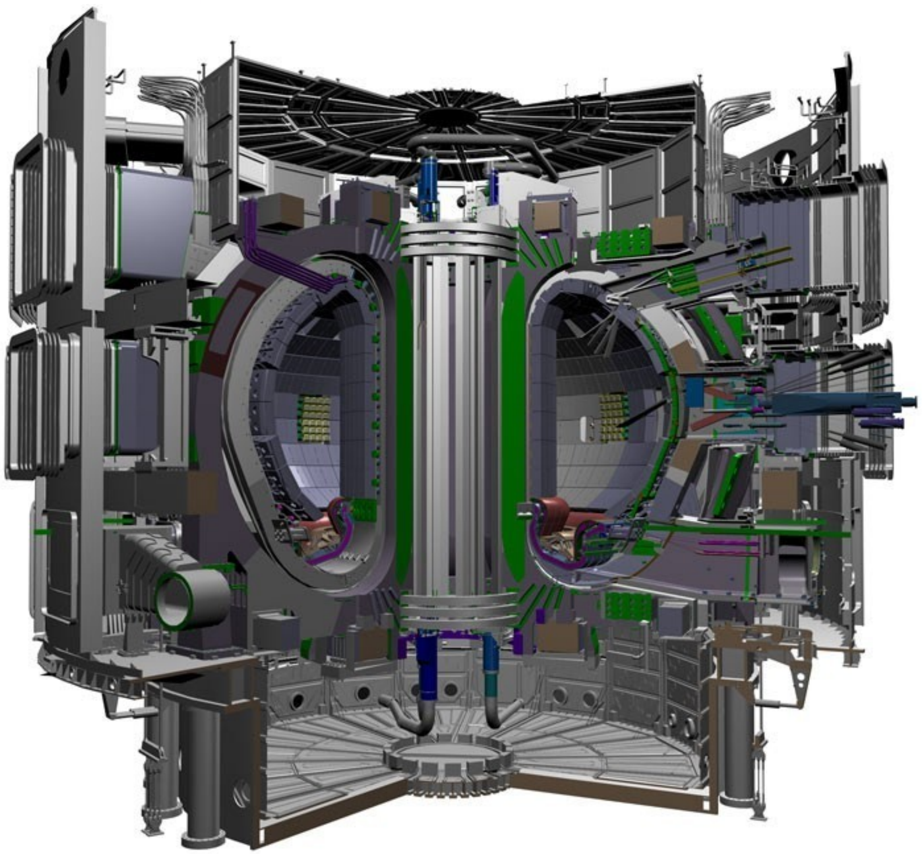


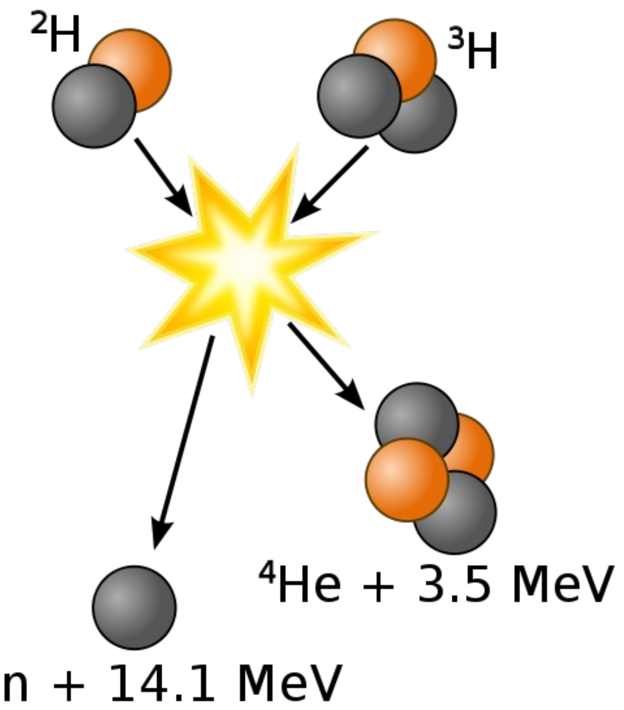
Pulses shorter and smaller at LiHe temperature

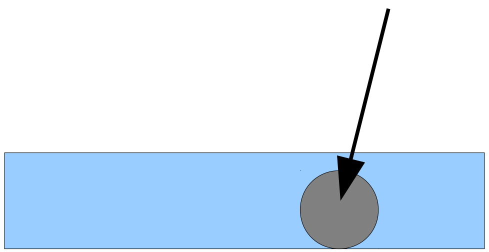
Neutron measurements

Neutron Flux at ITER

- Measure 14 MeV neutron flux







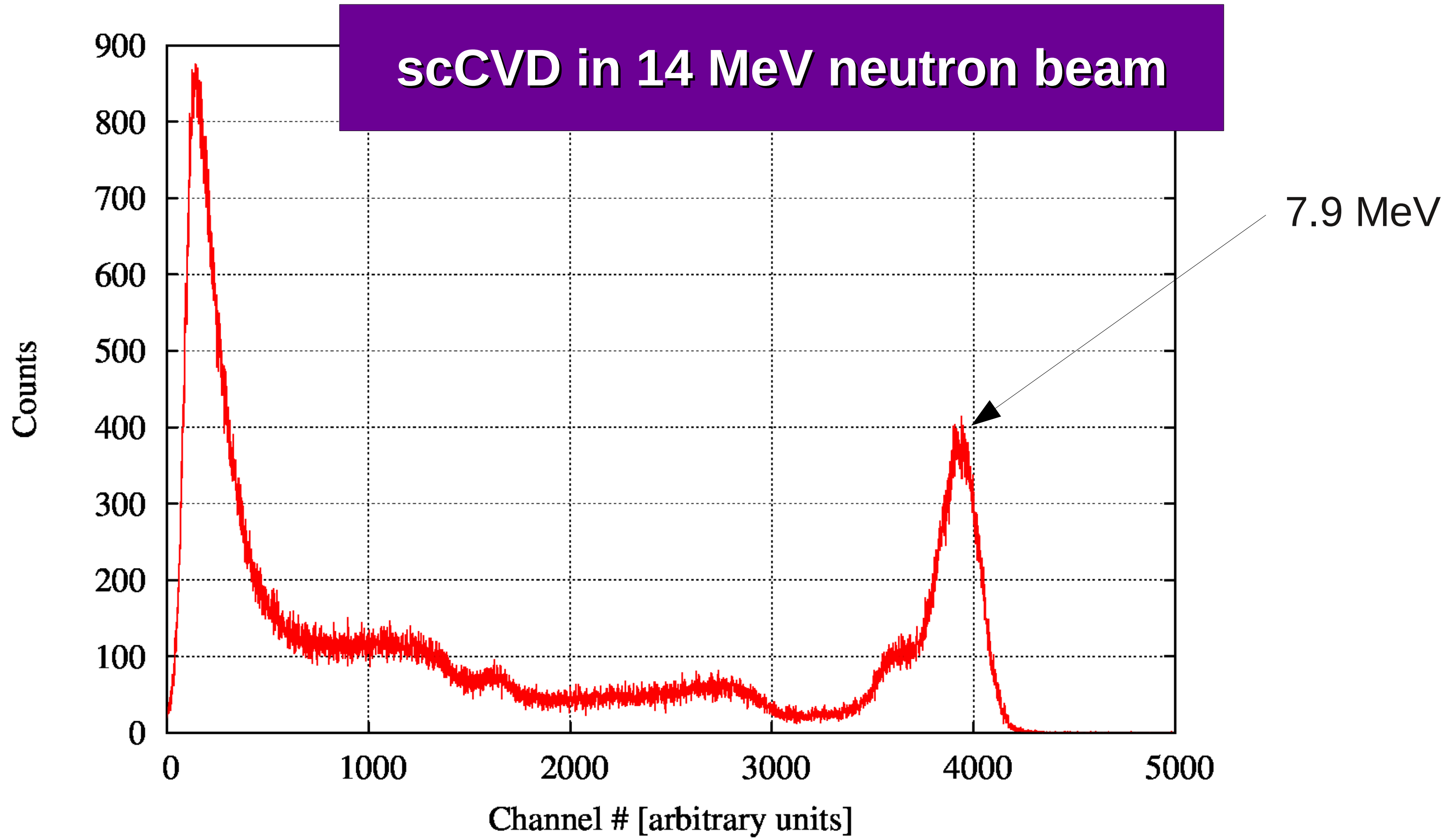
$(n,\alpha)^9Be$: $C + n \rightarrow {}^9Be + \alpha$

$E_{max} = 7.915$ MeV

α absorption in diamond

Neutron Flux at ITER

- Neutron Beam measurements



-> measure neutron flux online
and give feed-back to ITER machine

$$\Phi = \frac{Counts}{\varepsilon\,\eta\,Y(E,\sigma)}$$

Courtesy
C. Weiss

Diamond ...

- ... is in use as radiation monitors for ATLAS, CMS, LHC.
- ... is very promising candidate for future detectors.

- ... is radiation-hard, fast, low noise, high sensibility range.
- ... doesn't need cooling.

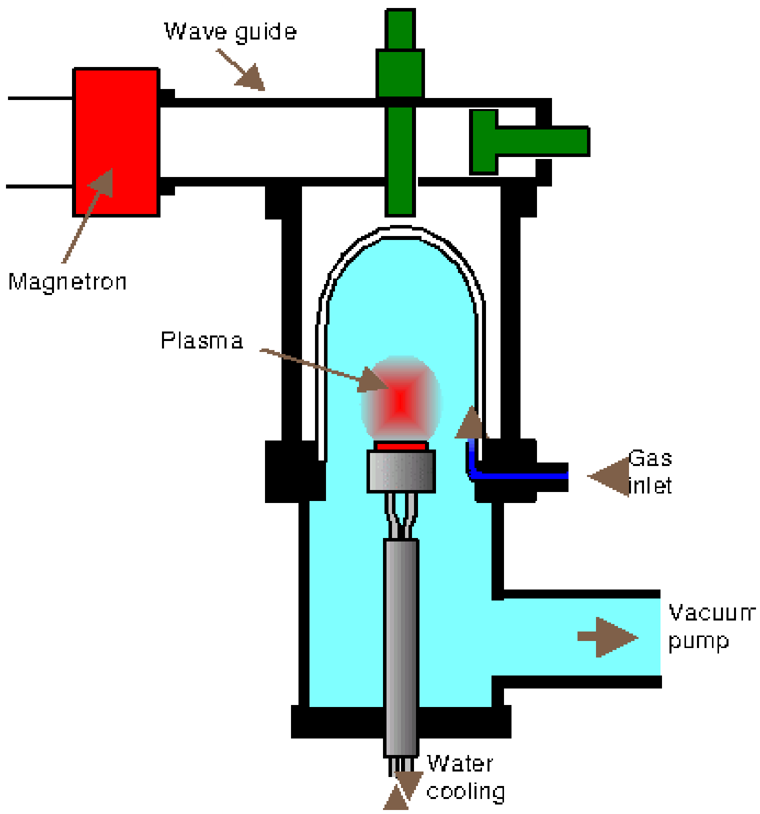
- ... needs more research:
  impurities composition energy levels of traps
  high/low T features contacts edge effects etc

- ... brings researchers together: CERN RD42, GSI Carat.
  Diamond communities are growing!

Back-up

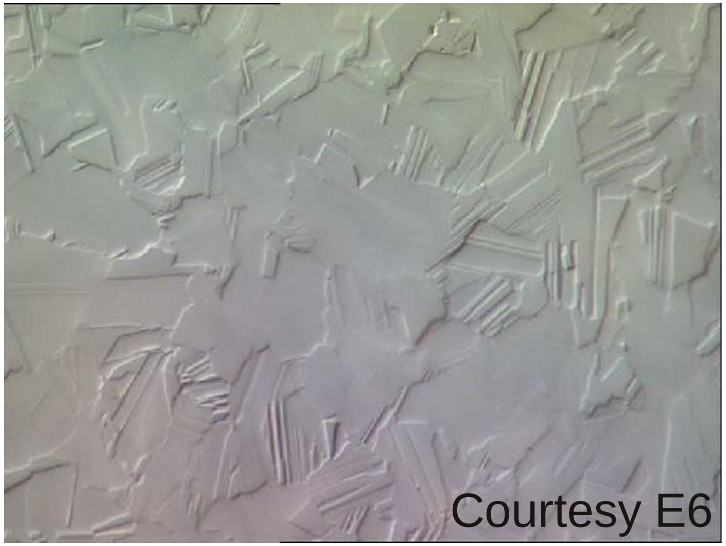
Production of CVD diamonds

- Microwave growth reactor

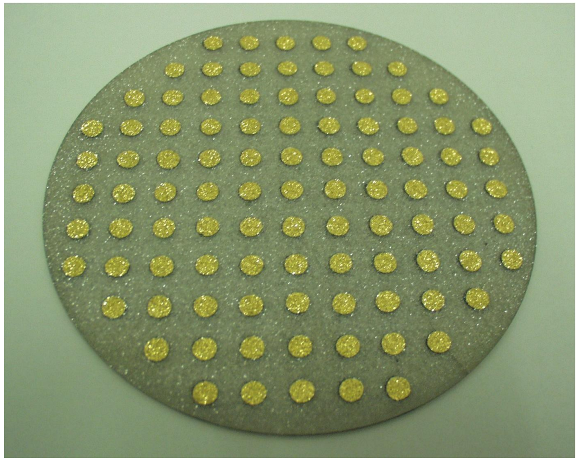


- Diamond synthesis from plasma
- Material copies substrate

- Surface image of pCVD

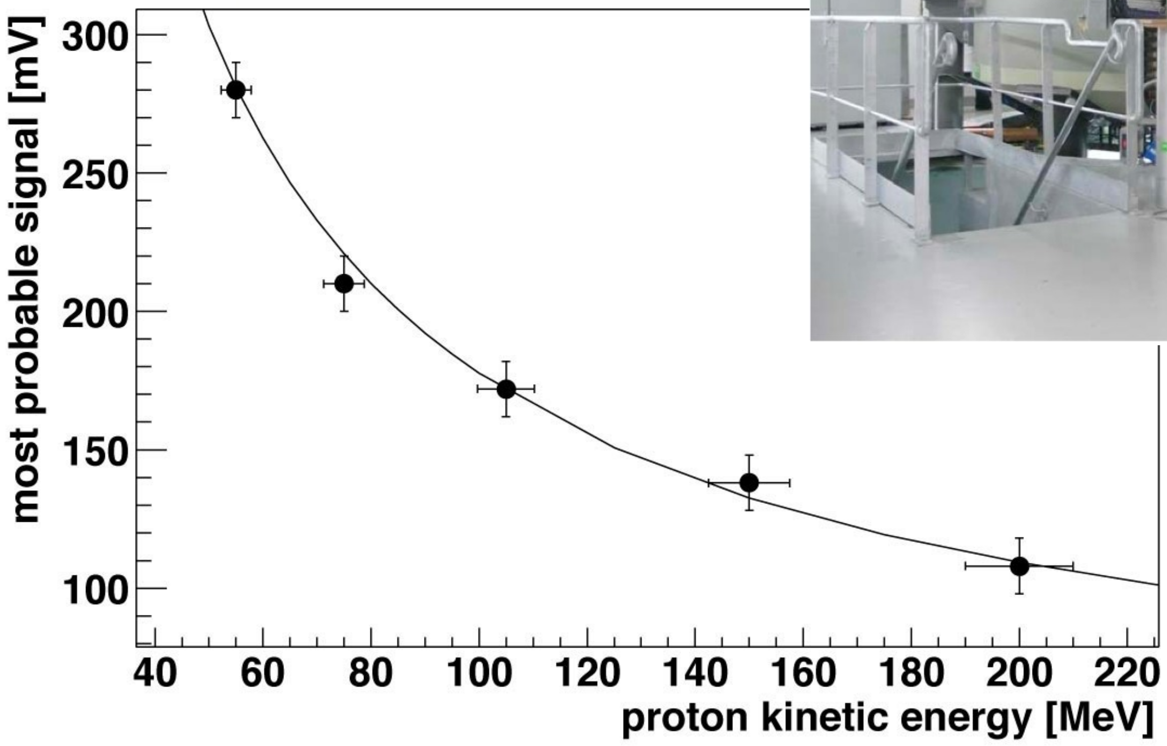


- pCVD diamond wafer



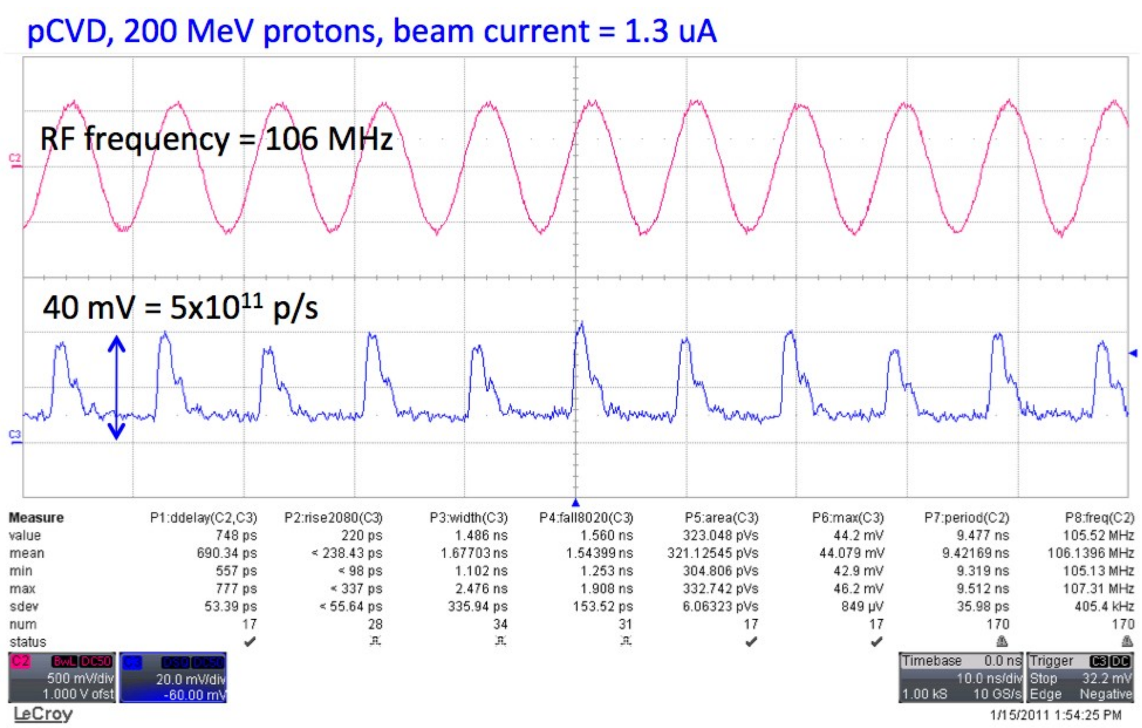
Dots are on 1 cm grid

- Distribution of measured total signal charge



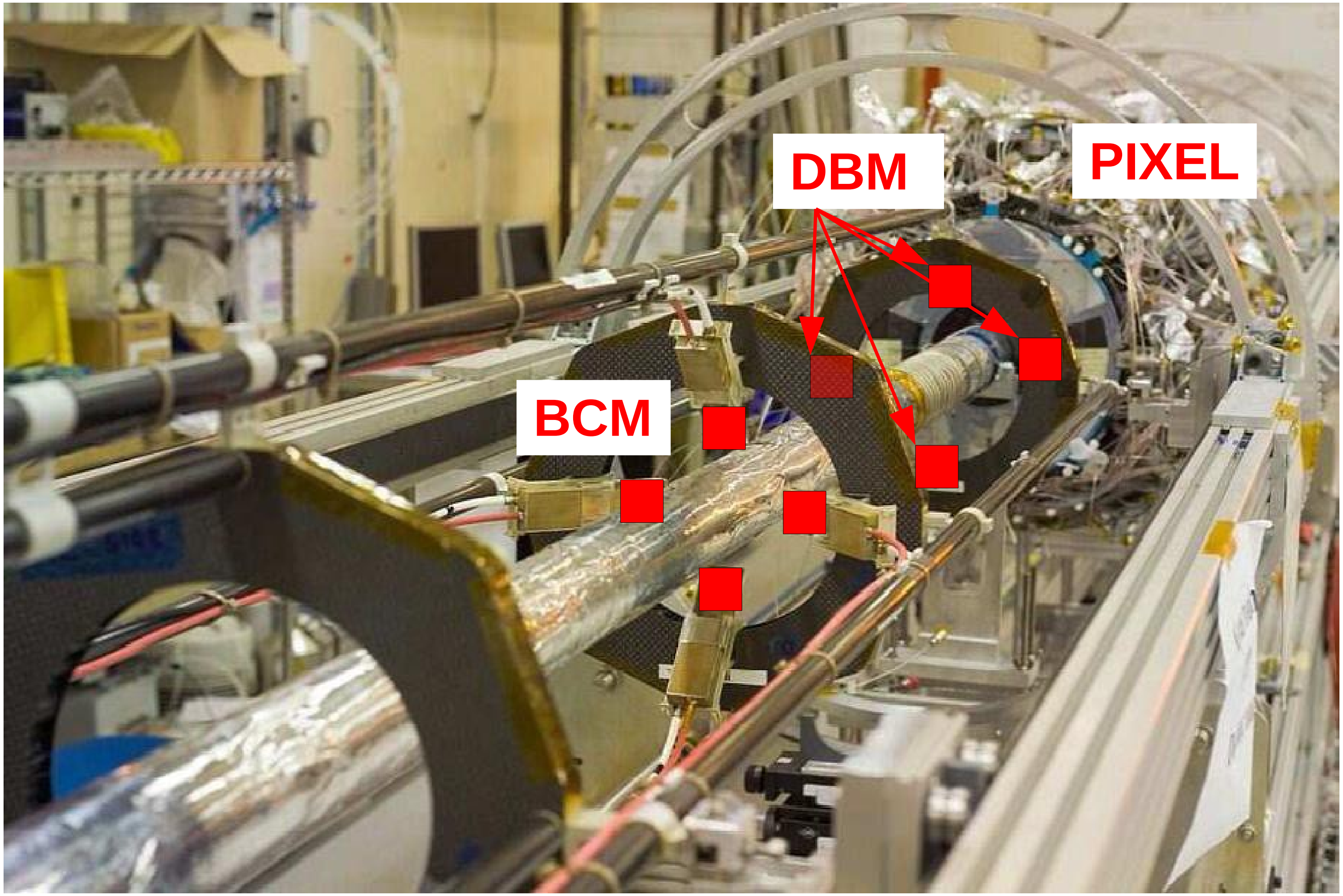
IBA Cyclotron

Signal range

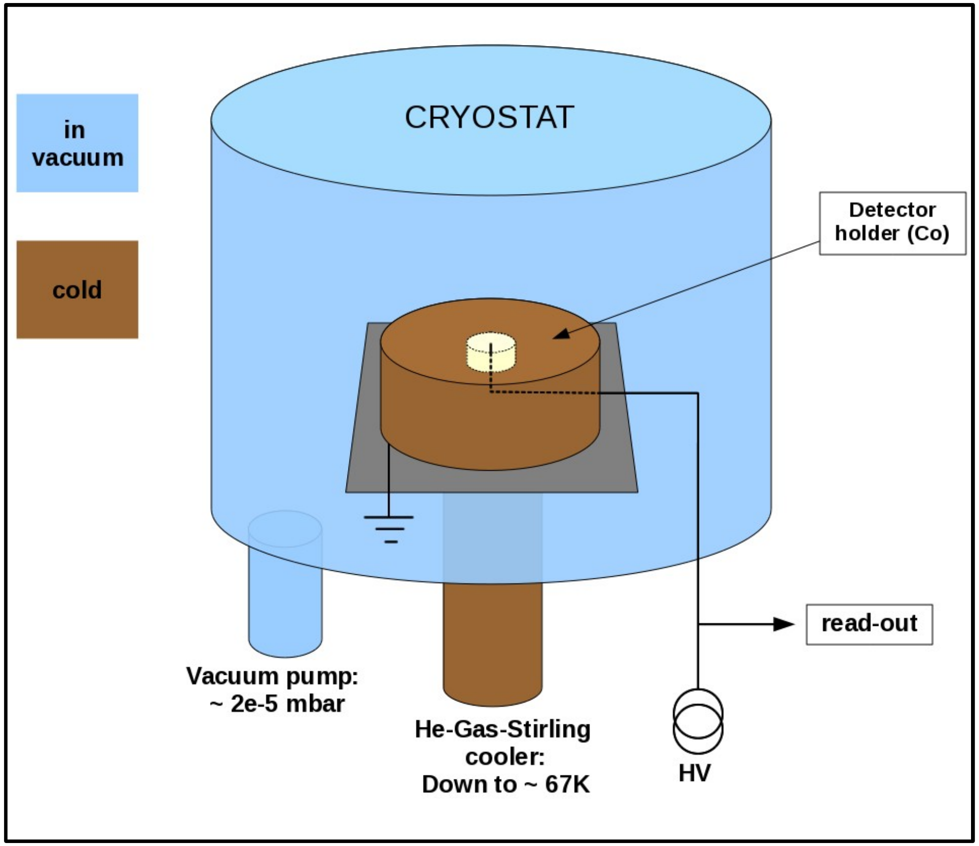


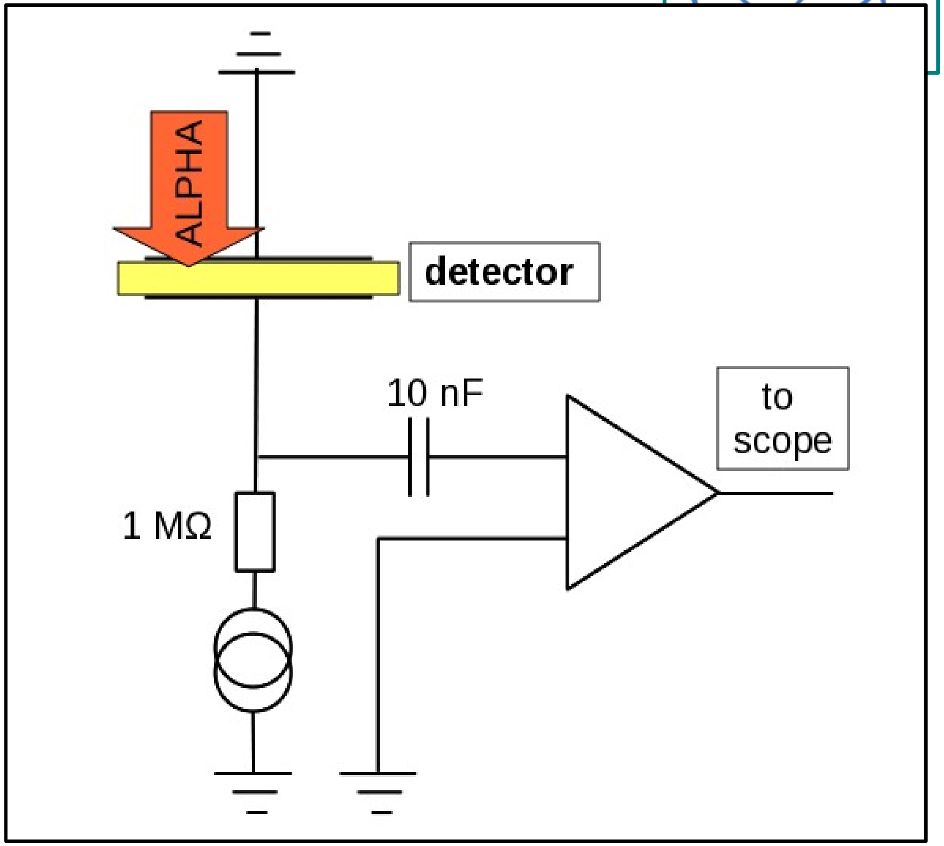
Measure	P1:ddelay(C2,C3)	P2:rise2080(C3)	P3:width(C3)	P4:fall8020(C3)	P5:area(C3)	P6:max(C3)	P7:period(C2)	P8:freq(C2)
value	748 ps	220 ps	1.486 ns	1.560 ns	323.048 pVs	44.2 mV	9.477 ns	105.52 MHz
mean	690.34 ps	< 238.43 ps	1.67703 ns	1.54399 ns	321.12545 pVs	44.079 mV	9.42169 ns	106.1396 MHz
min	557 ps	< 98 ps	1.102 ns	1.253 ns	304.806 pVs	42.9 mV	9.319 ns	105.13 MHz
max	777 ps	< 337 ps	2.476 ns	1.908 ns	332.742 pVs	46.2 mV	9.512 ns	107.31 MHz
sdev	53.39 ps	< 55.64 ps	335.94 ps	153.52 ps	6.06323 pVs	849 µV	35.98 ps	405.4 kHz
num	17	28	34	31	17	17	170	170
status								

ATLAS DBM

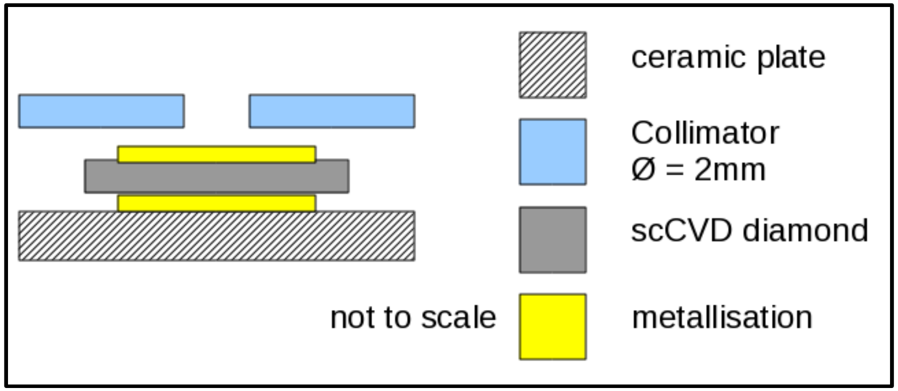


Details of Measuring Set-up





- **SETTINGS:**
  - → TCT in vacuum
  - → Temp: 4.5 K - 300 K, bias ≤ 1000 V
  - → Read-out from HV-side
  - → Use collimator (avoid edge-effects)



Reaction Yield:

$$Y(E_n) = (1 - e^{-n\sigma_t(E_n)})\frac{\sigma_\alpha(E_n)}{\sigma_t(E_n)}$$

$$Y(E_n) = \frac{C(E_n)}{\varepsilon(E_n)\Phi(E_n)}$$