Characterisation of Detectors

EURIZON detector school

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2023/07/21

European network
for developing new horizons for RIs

A simple scintillator?

Radiation damage

Absorption at edges

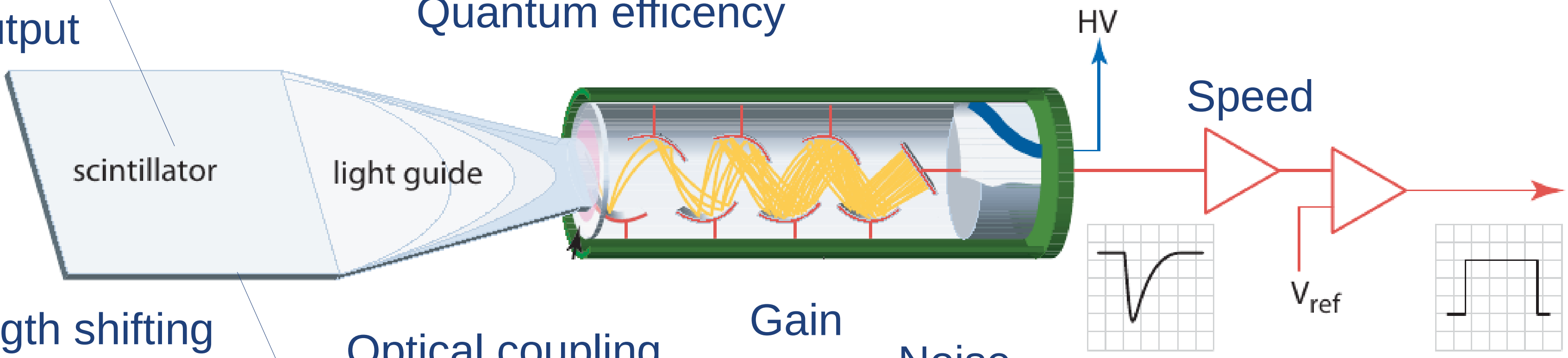
Spectral response

HV stability

Light output

Quantum efficency

Speed



Wavelength shifting

Optical coupling

Gain

Noise

Kolanoski, Wermes 2015

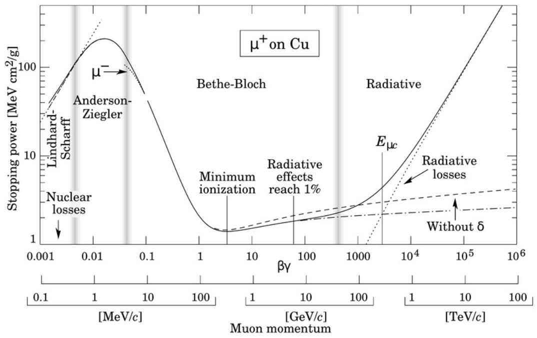
Afterpulsing

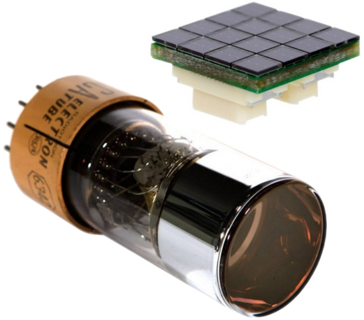
Energy resolution

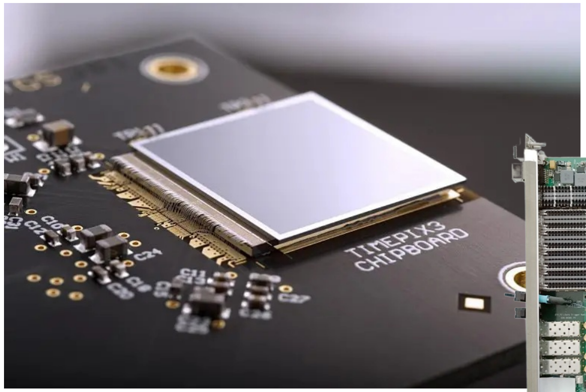
Magnetic field

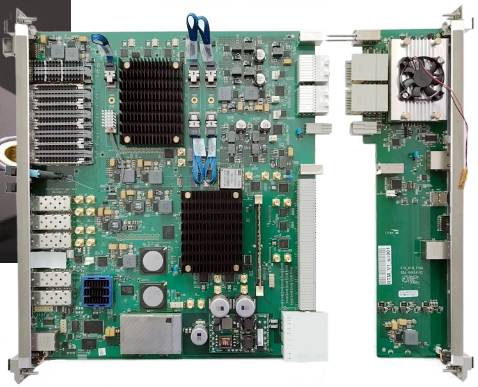
Longevity in air

Path of the signal

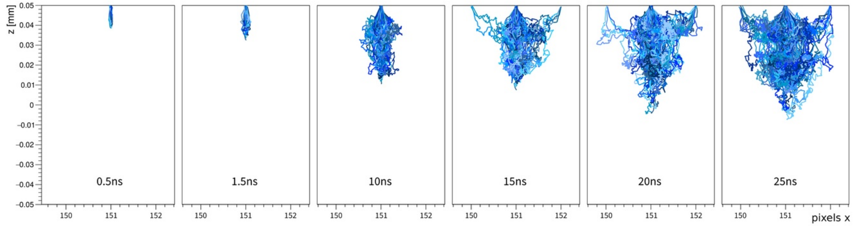


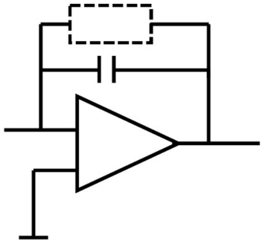






Energy Deposition → Signal generation → Conversion → Analogue signal processing → Digital signal processing → Data acquisition





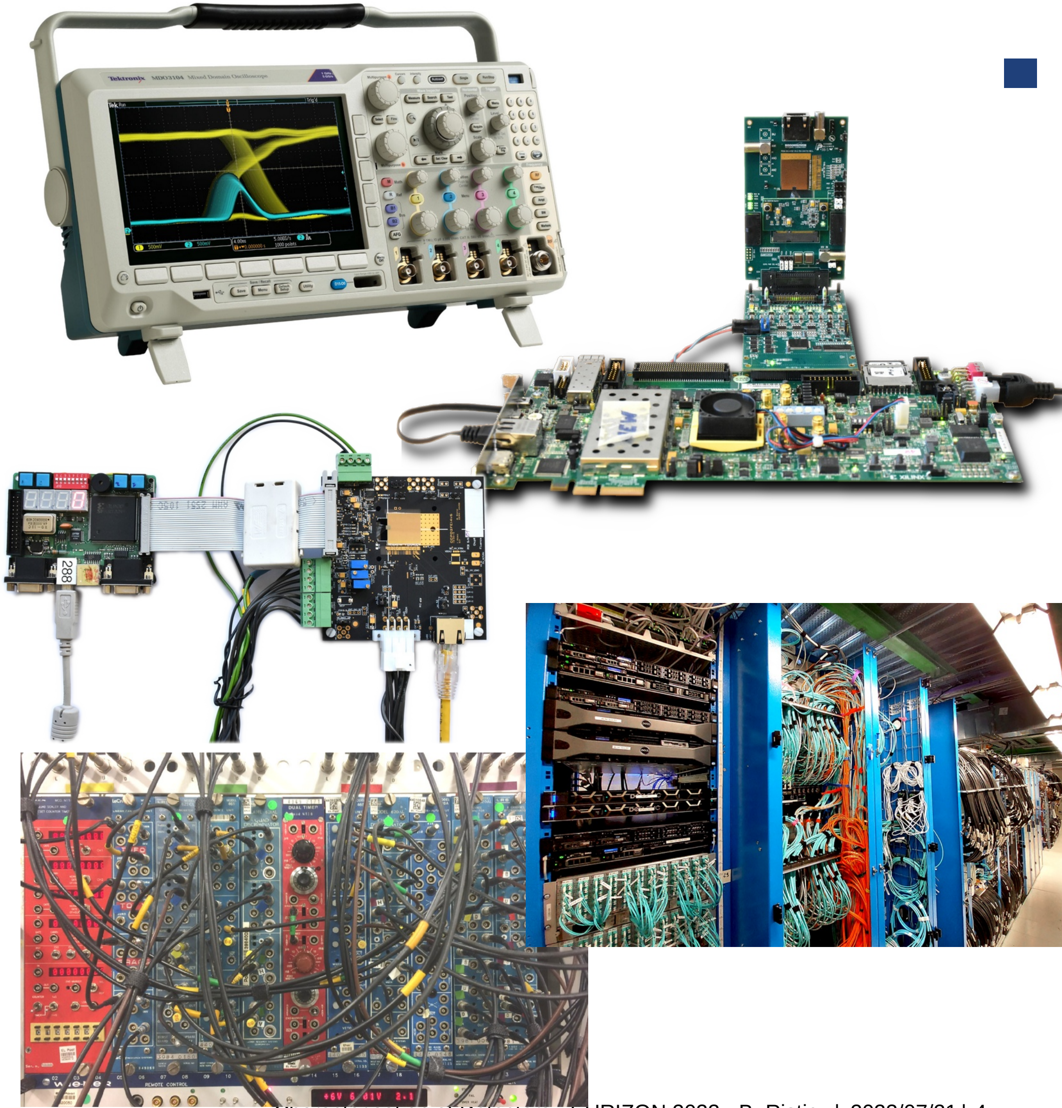
Read-out systems

- Specialised setup for each kind of detector
- Can be “as simple” as a NIM crate
- Most likely not as performant as final detector readout
- Often combination of ASIC + custom board

➔ Limits in capabilities

➔ Abstraction of information

➔ Has to be understood and calibrated well to interpret signals



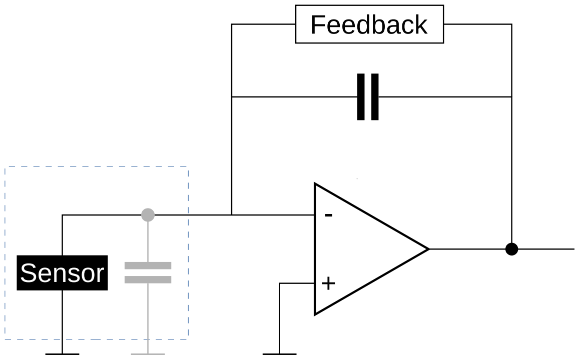
Analogue chain

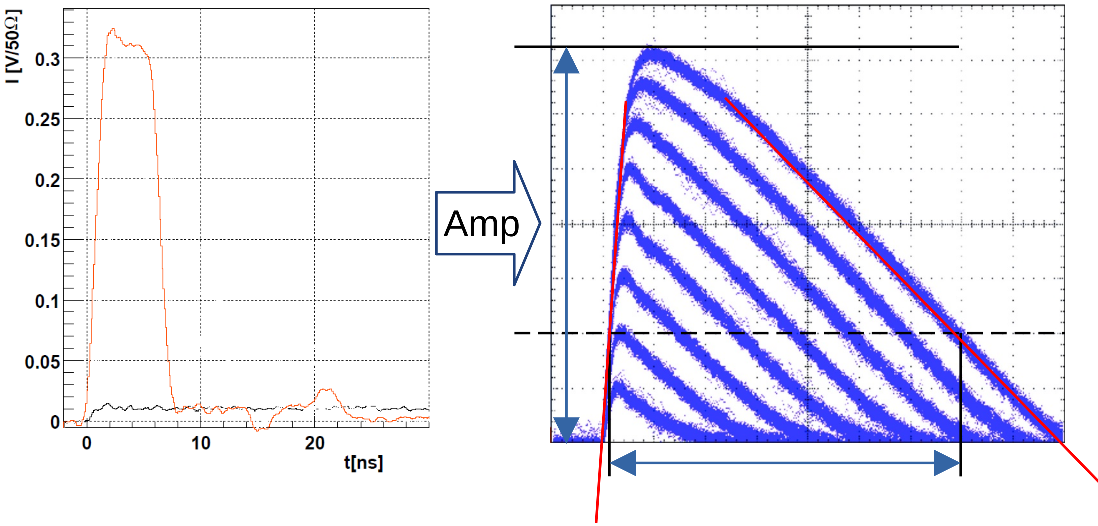
First step: Amplification

- Most sensitive part of signal processing
- Sensor signals are often small
  - ➔ Significant amplification at low noise
  - ➔ Current to voltage conversion
- Characteristics usually tunable
  - Gain, speed, power consumption

… and depending on external circuit
  - e.g. input capacity

- Digitisation by ADCs, TDCs, sample+hold,...
  - ➔ Usually discriminator needed





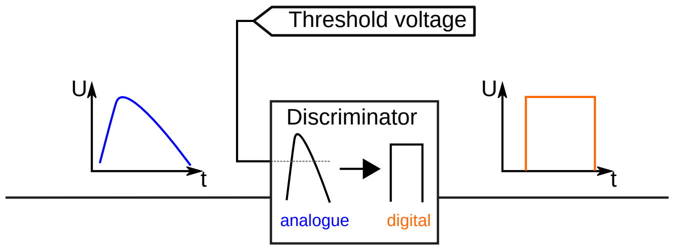
Analogue chain – Discriminators

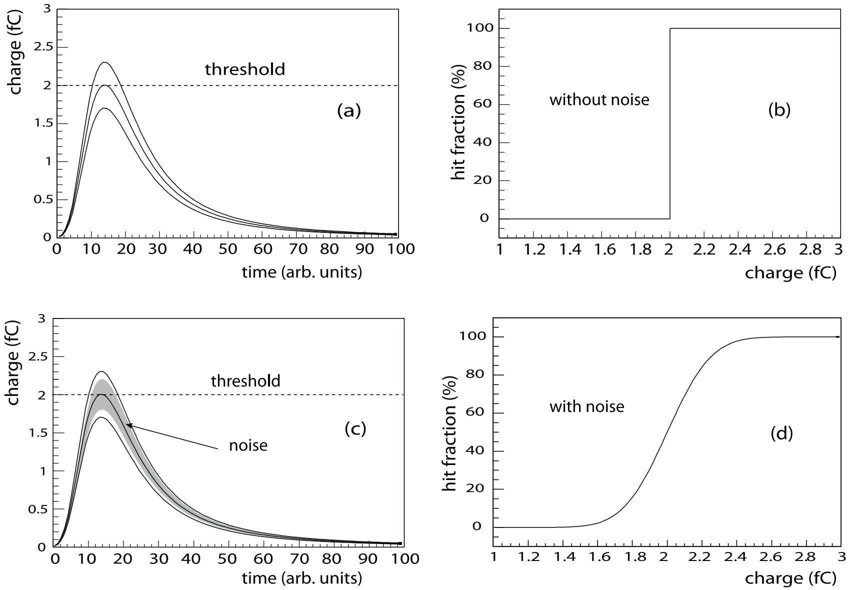
- Ideally step function: $P_{hit} = 0$ for $Q < Q_{thr}$, $P_{hit} = 1$ for $Q \geq Q_{thr}$
- Noise in electronic system (main contribution Gaussian)
  - Equivalent Noise Charge: width of distribution
- Step function smeared (folded with normal distribution)

$$P_{hit}(Q) = \Theta(Q - Q_{thr}) \otimes \exp\left(\frac{-Q^2}{2\sigma^2_{noise}}\right) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q_{thr} - Q}{\sqrt{2}\sigma_{noise}}\right)$$

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty} \exp\left(-\tau^2\right) d\tau = 1 - \mathrm{erf}(x)$$

- True threshold defined as 50% efficiency
- Steepness of curve indicator for amount of el. noise
- Calibration circuit / tunable source to find threshold





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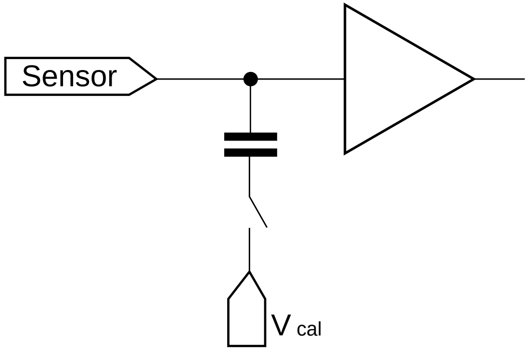
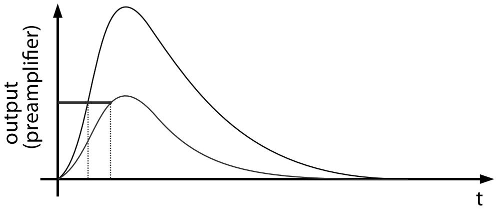
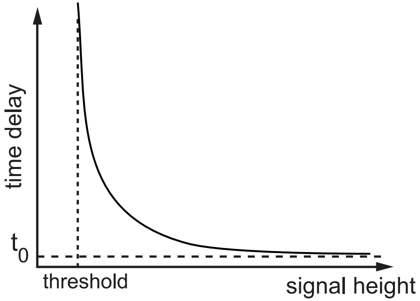
Read-out electronics – calibration

Test pulse injection

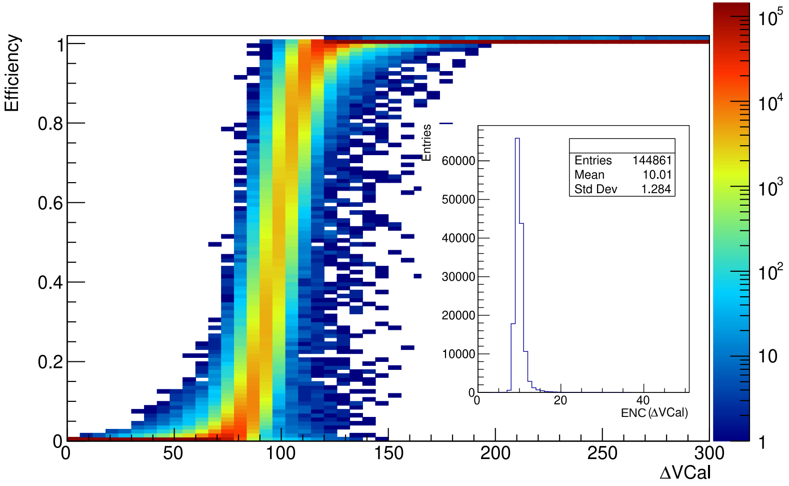
- Simulation of signals from particles
- Defined signal amplitude (and shape)
- Tuning and calibration of the analogue chain
- Calibration necessary
  - ➔ Photon source (→ later)

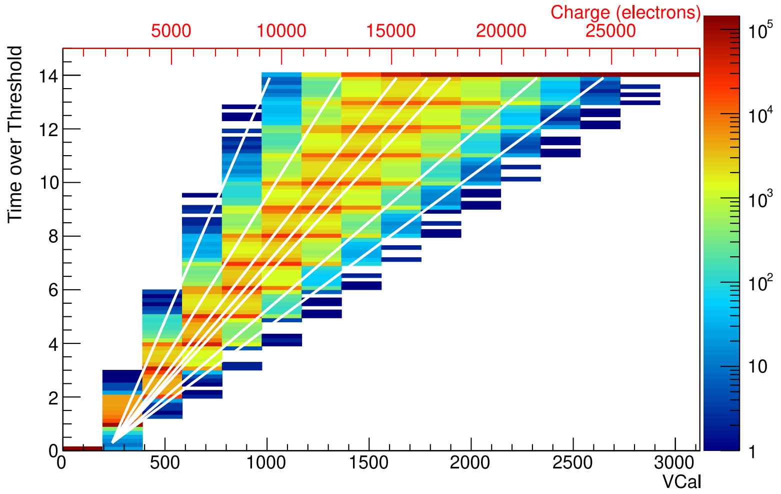






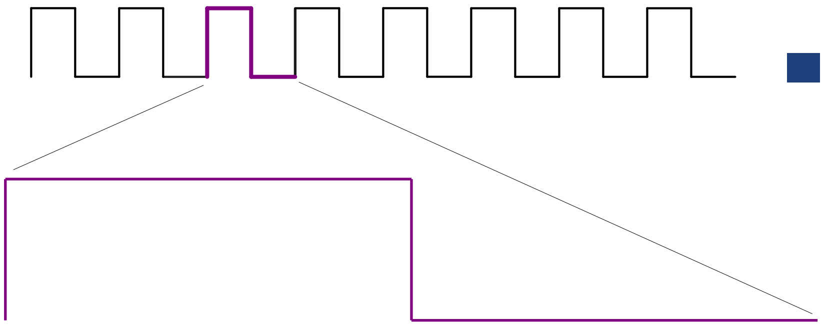
Kolanoski, Wermes 2015





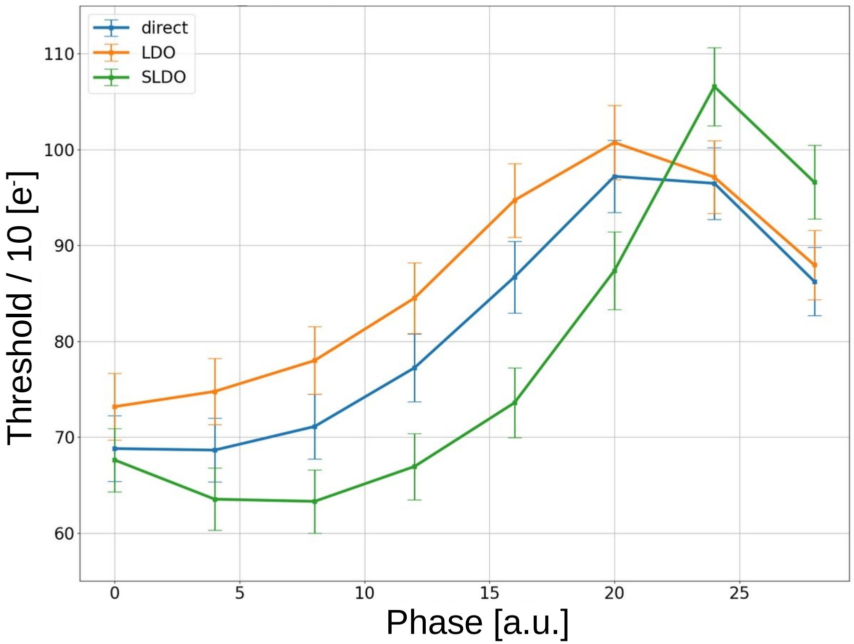
![ETH zürich]

Example from CMS



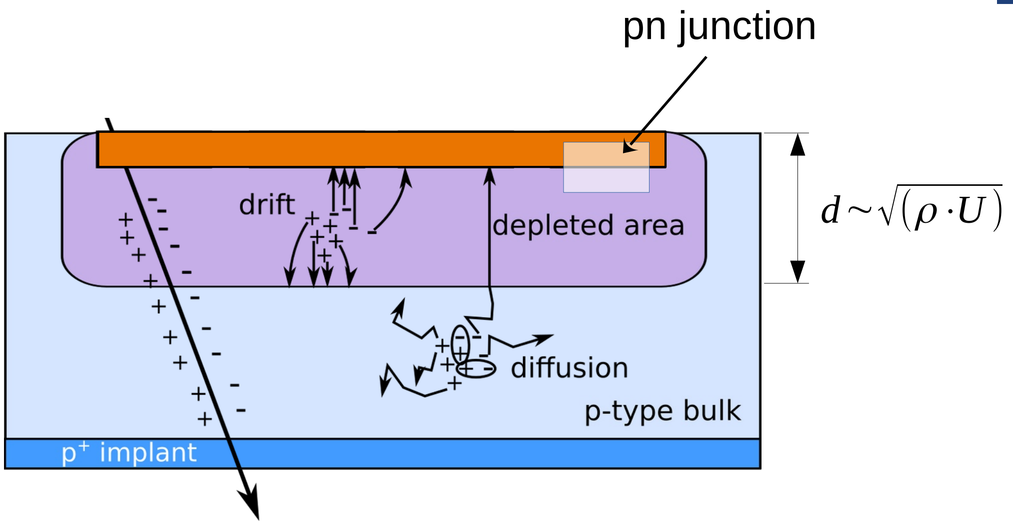
Threshold oscillations

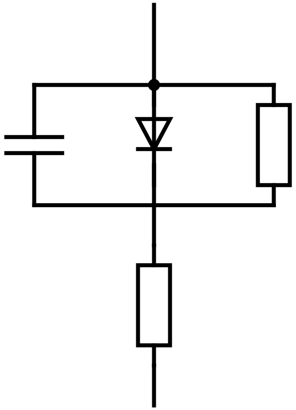
- Digital pixel read-out chip
  - Clocks present → varying power consumption
- Injection pulses are send with fixed phase to clock
- Realised that threshold varies up to 300e$^-$
  - Depends on phase of injection
  - Typical thresholds: 1000 – 3000e$^-$

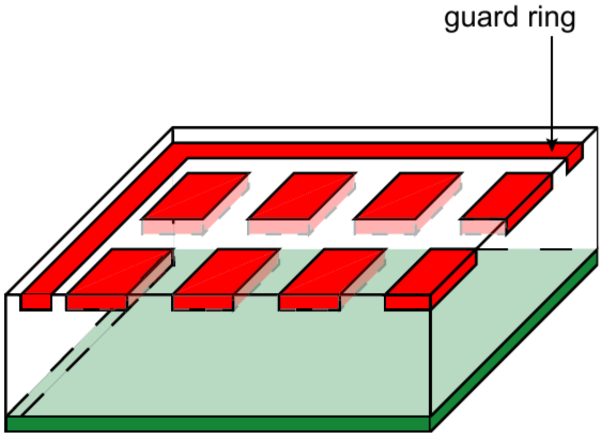


Pixel detectors

- Array of diodes
  - PN junction oriented through bulk
  - Operation in reverse-bias mode
- Ionising particles create electron-hole pairs
  - Collection by drift in depleted area
  - Otherwise diffusion
- Output signal: current pulse
  - Parasitic capacitance/resistance
  - Leakage current



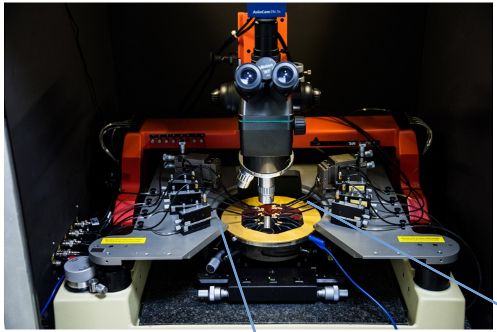


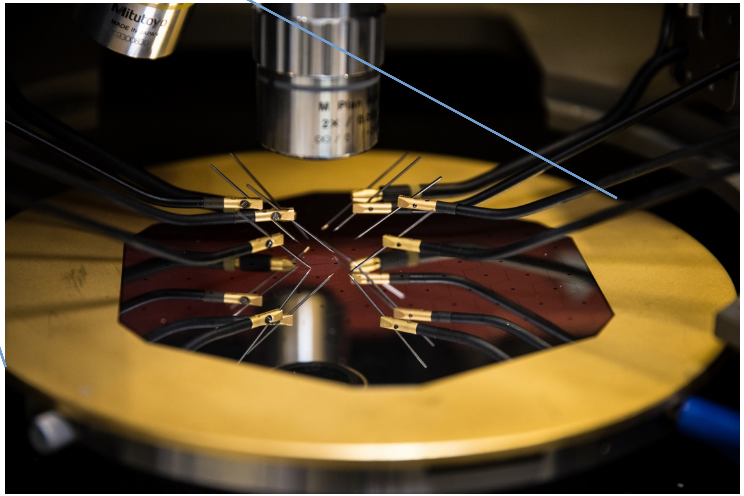


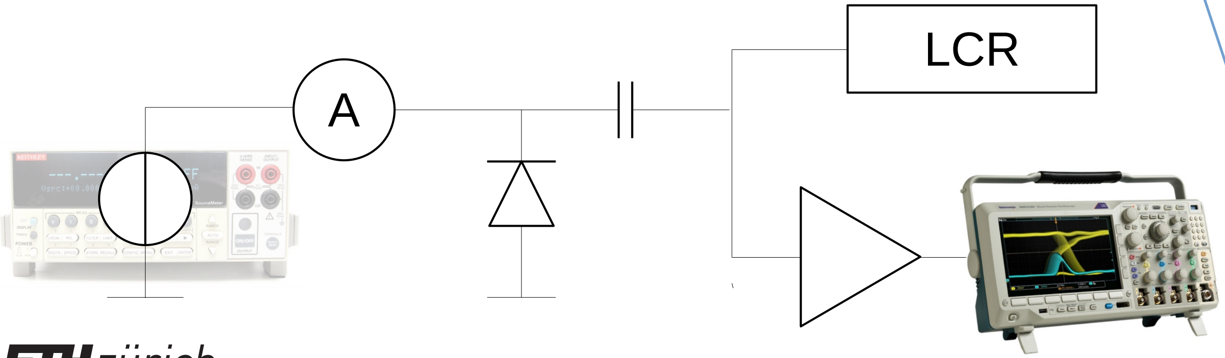
Pixel detectors – test setup

Similar to chip testing in industry

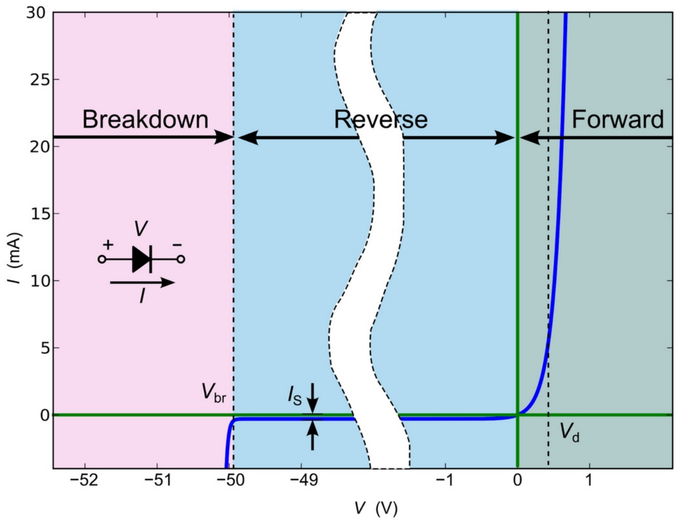
- Probe station with micromanipulators
- Direct sensor testing
  - No direct contact to pixel
- (High voltage) power supply
- pA current meter
- LCR meter
- Fast amplifiers + Scope







Pixel detectors – IV / CV curves



Leakage current measurement

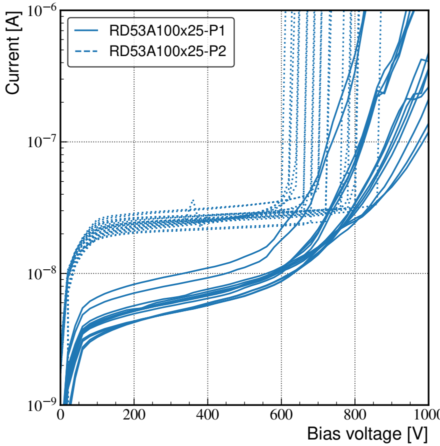
- Small current in reverse biasing mode
- U_{max} = breakdown voltage
  - Exponential increase of current
- Has to be absorbed by amplifiers
- Shape of curve shows parasitic effects
- Current in bulk is temperature dependent
  - Handle to disentangle effects

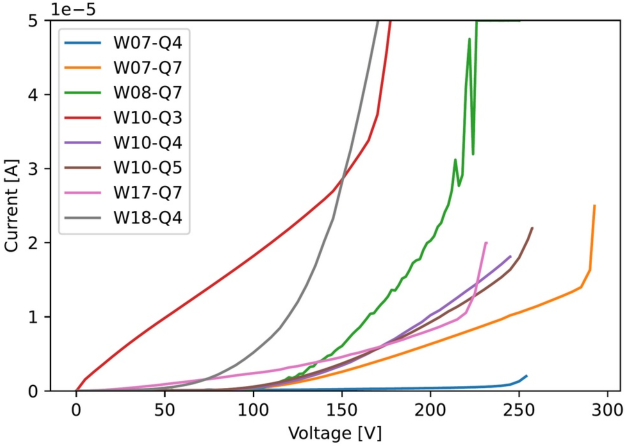
$$I_{\mathrm{DZ}} = \frac{e}{\tau_g} A d \cdot n_i$$

$$n_i \propto T^{3/2} \exp(-E_G/2kT)$$

$$d \propto \sqrt{V_{ext}}$$

$$U_{\max} = -\frac{\varepsilon_0 \varepsilon_r}{2e} \left(N_A^{-1} + N_D^{-1}\right) E_{\max}^2$$





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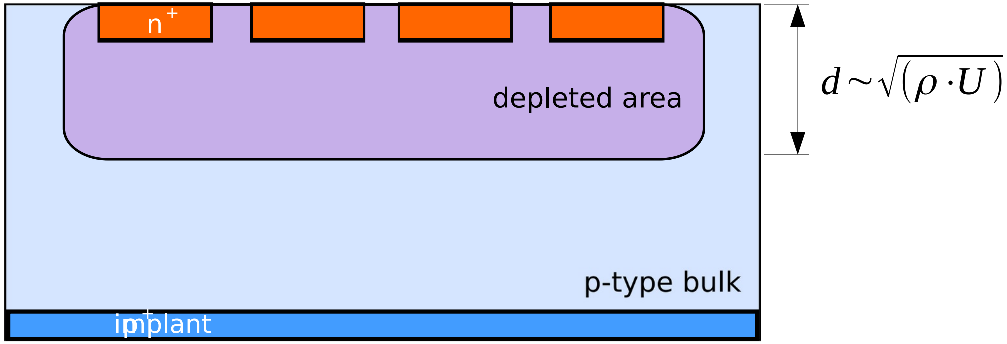
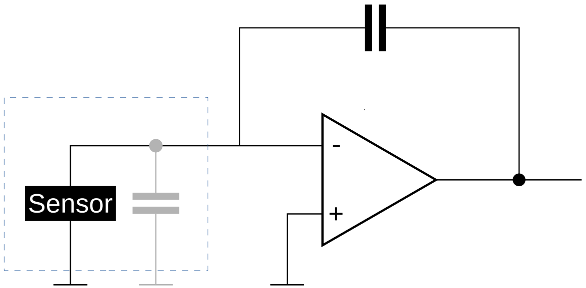
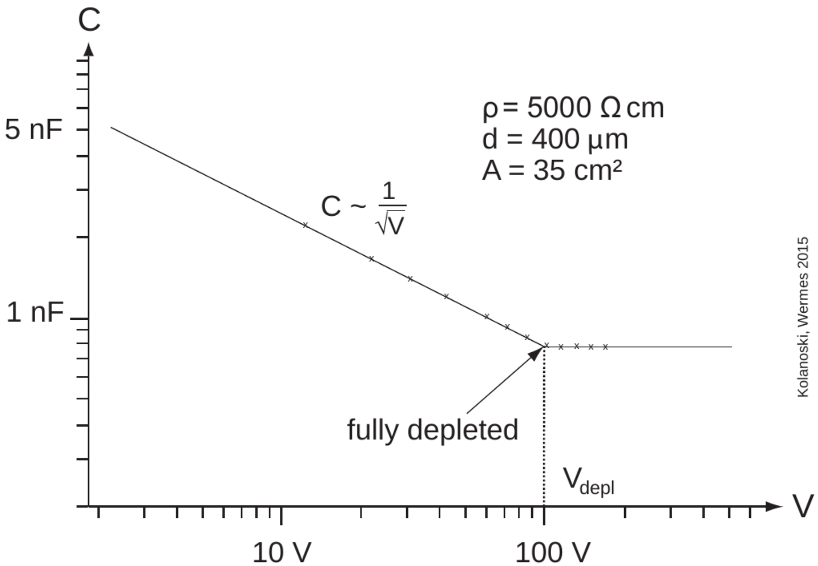


Capacitance vs. voltage

- Diode acts like capacitor
- Capacity grows with depletion depth
- C(U) measurement → depletion voltage
  - Assumption: depl. zone capacitance dominant
- Approximate input capacitance to amplifier

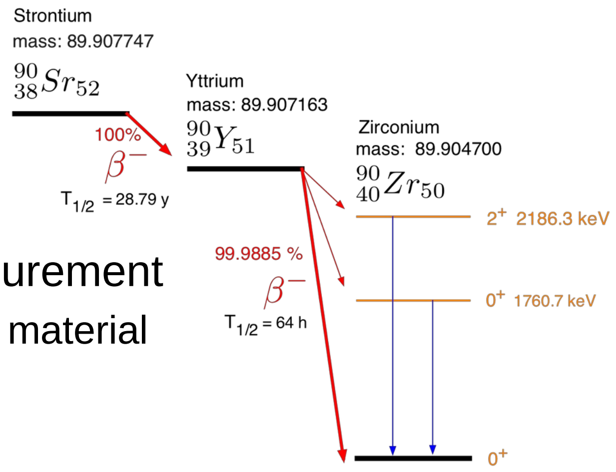
$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad d \propto \sqrt{V_{ext}}$$

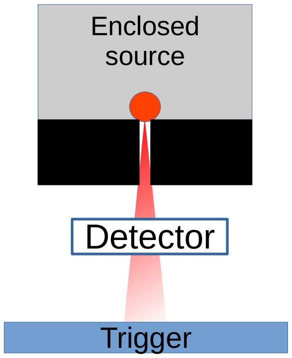


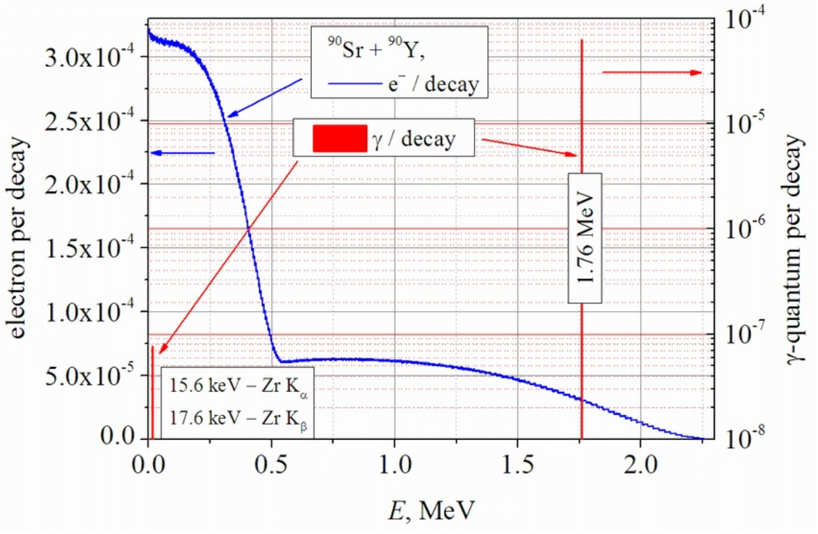


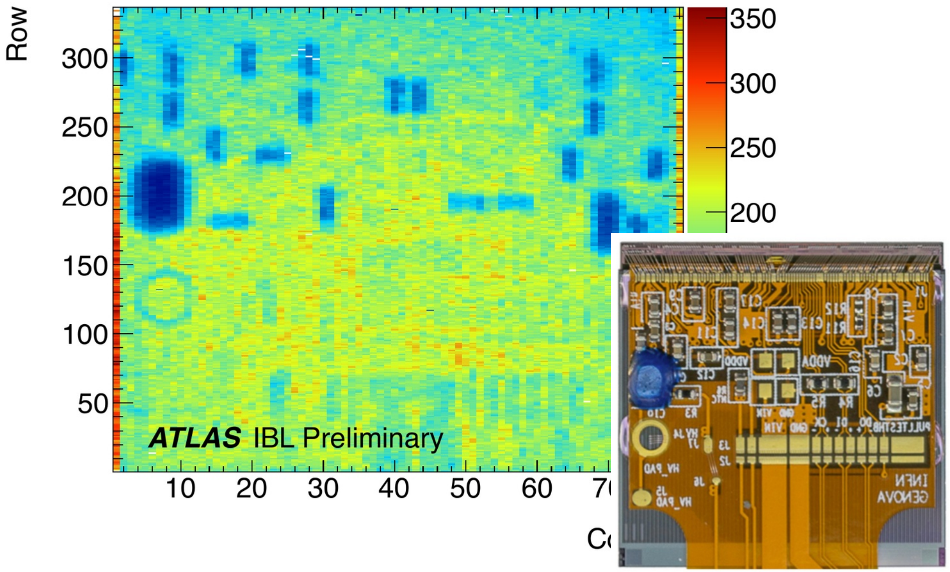
Source measurements

- Used for calibration and detection efficiency measurement
  - Beta source: broad spectrum, deep penetration into material
    - Emulates MIPs: Yt-51 max energy of beta particle:



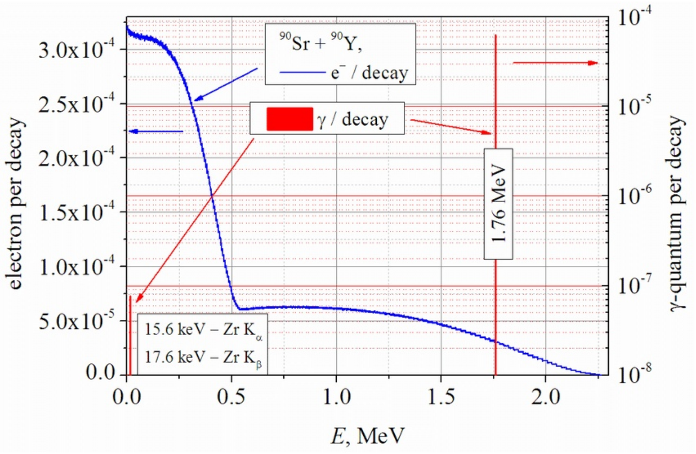


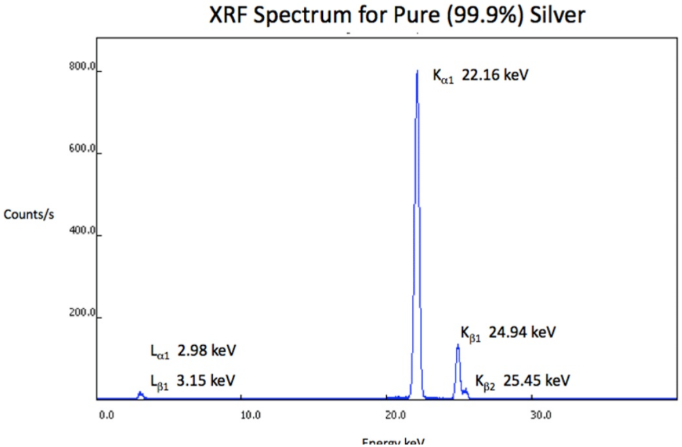


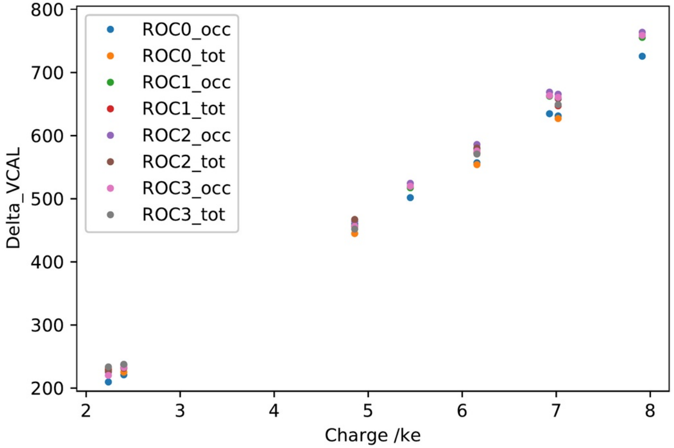


Source measurements – charge calibration

- Used for calibration and detection efficiency measurement
  - Gamma source: narrow spectrum, point-like interaction
  - X-ray tube: broad spectrum, can be narrowed down by fluorescence







Source measurements – charge calibration

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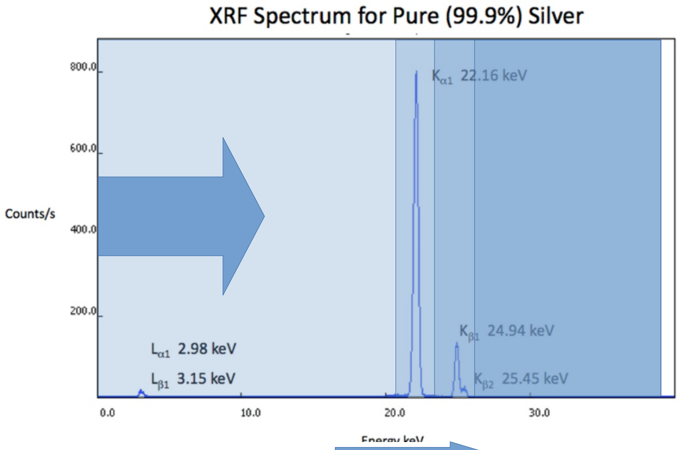
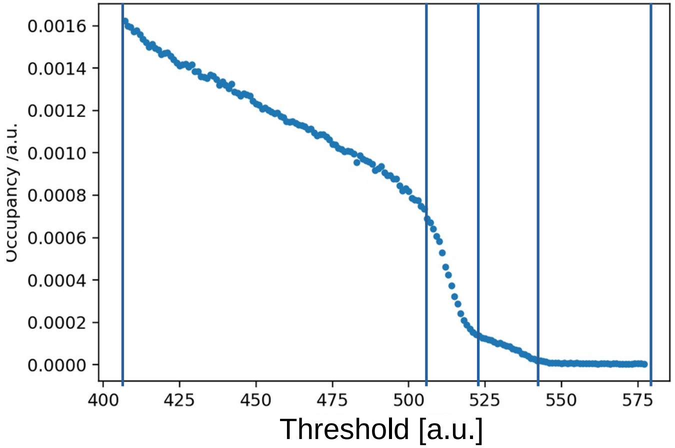
  - Gamma source: narrow spectrum, point-like interaction
  - X-ray tube: broad spectrum, can be narrowed down by fluorescence

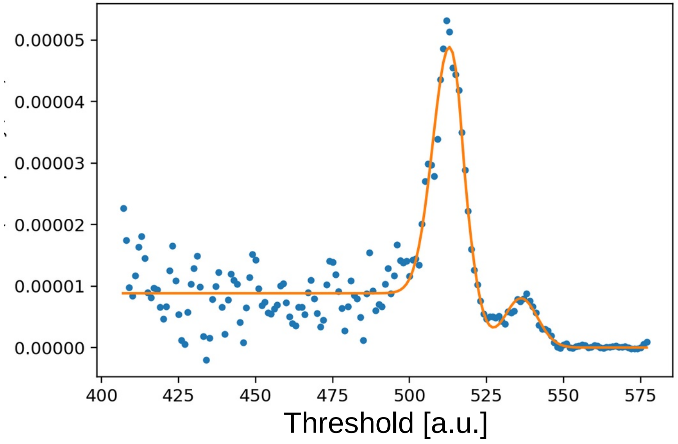
➔ Record signal amplitude and identify characteristic peaks

- Alternative if tunable discriminator accessible
  - ➔ Record integral of amplitude distribution

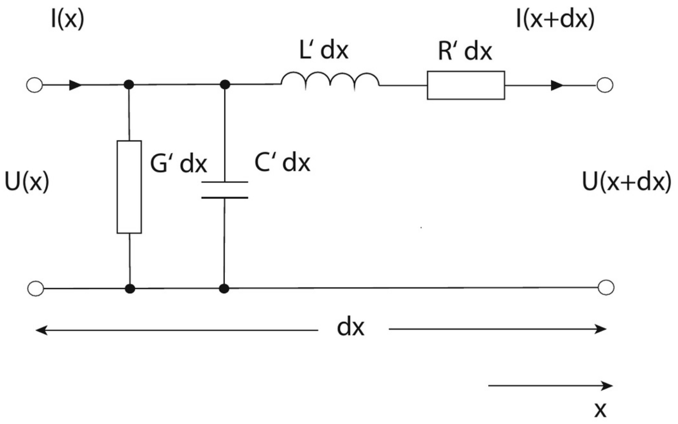




$$\frac{\partial}{\partial Q}$$



Signal transmission



- Cables: wave-guides with dampening and impedance
- Infinite chain of RLC elements

$$U(x,t) = U_0\, e^{i\omega t\, -\, \gamma x}$$

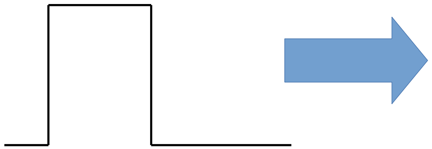
$$\gamma = \pm\sqrt{(R' + i\omega L')(G' + i\omega C')} = \pm(\alpha + i\beta)$$

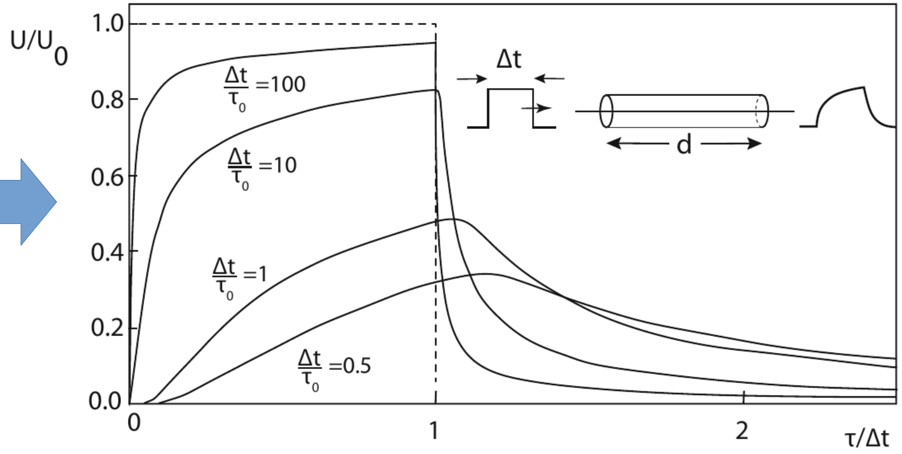
$$c_{ph} = \frac{1}{\sqrt{L'C'}} = \frac{1}{\sqrt{\epsilon\epsilon_0\mu\mu_0}}$$

➔ Delays and dampening

➔ Distortion of signal

➔ Reflections





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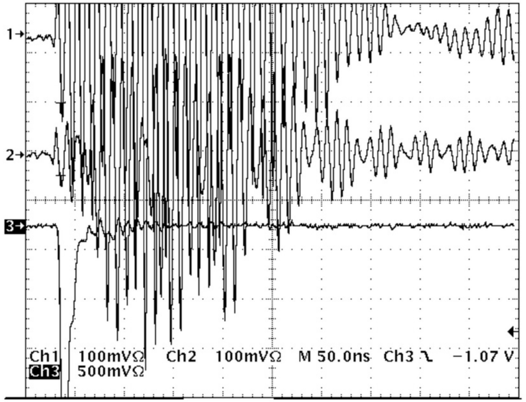
Noise

Often one of the main challenges when designing a setup / board

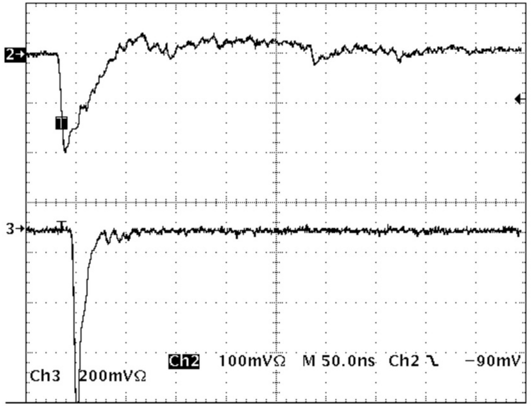
- Figure of merit: Signal to Noise ratio → aim for O(10)
- Most vulnerable node: input to pre-amplifiers

Pickup noise

- Each cable, PCB trace and pin is an antenna
  - Shorten, remove and shield
  - Differential signalling



Few cm
to few mm



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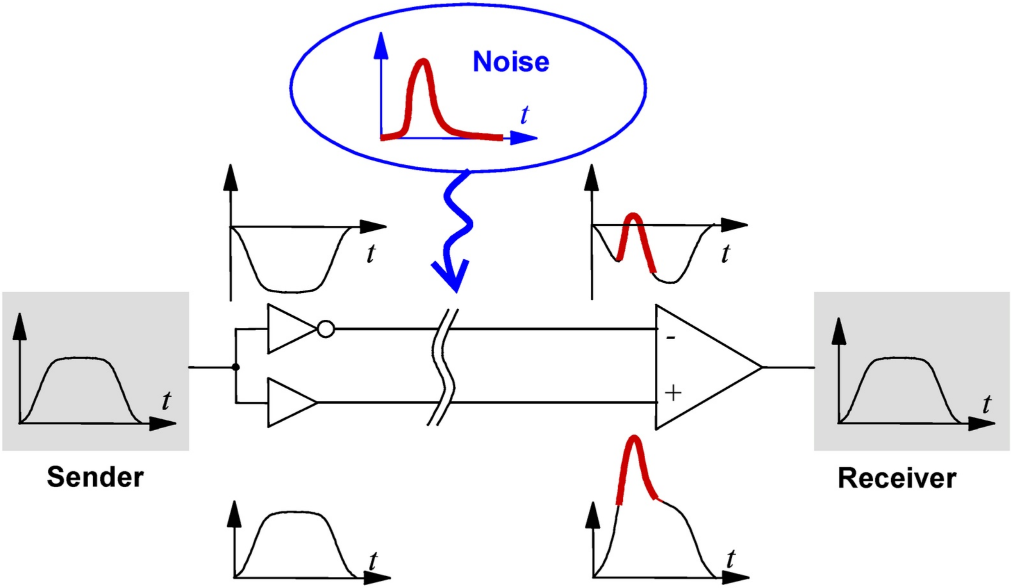

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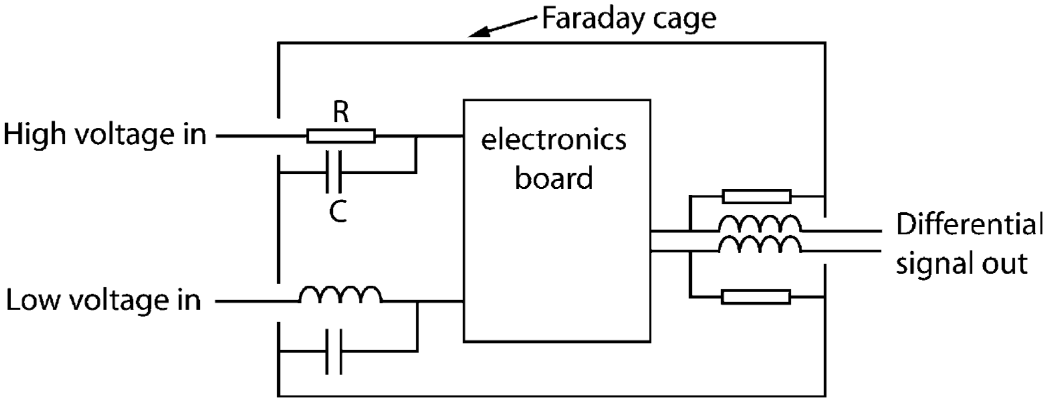
  - Filters and ferrite rings if possible



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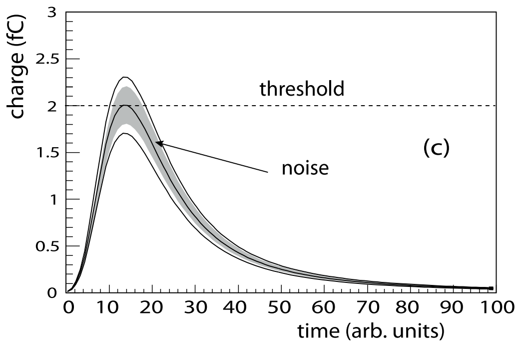
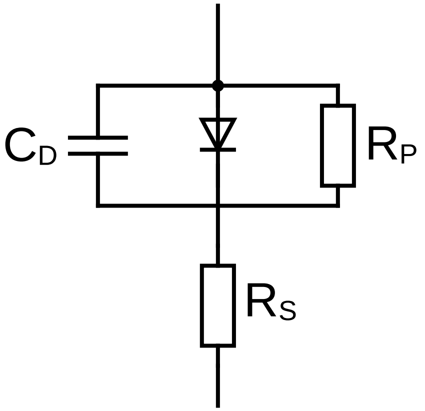
Electronic / thermal noise

- Electronic Noise Charge $\propto \sqrt{TR_S} \cdot C_D$
  - ➔ See “Discriminators”

Further effects

- Shot noise, radioactivity, light leaks,...





Testbeam measurements

Test of components under realistic conditions

- Particle beam with defined properties (composition, energy, rate…)
  - Usually secondary beam particles
- Dedicated beam instrumentation
- Environment close to experiment

but…

- Usually short periods of time
- Beam halls inherently (el.) noisy
- Shared beam lines
- Often not at home institute

➔ Thorough preparation vital

Testbeam measurements

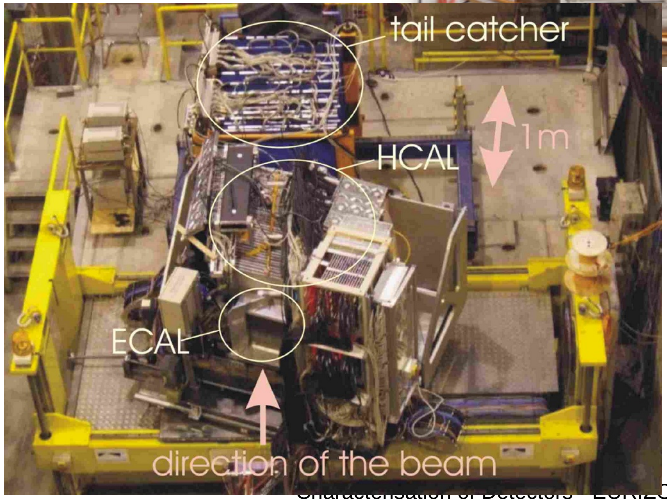
Exploration of configuration space of detectors

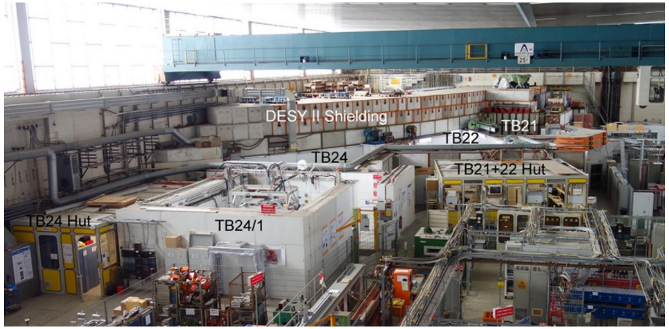
- Detection, particle identification, tracking... performance

  … vs. powering / tuning / temperature of DUT

  … vs. beam energy / composition

  … vs. position on detector
- Angular scans
  - Many sensors are tilted in final detector
- Simulation of operation in magnetic field
- Beam lines available all over the world with various energies and intensities
  - Next ones: Bonn and Hamburg





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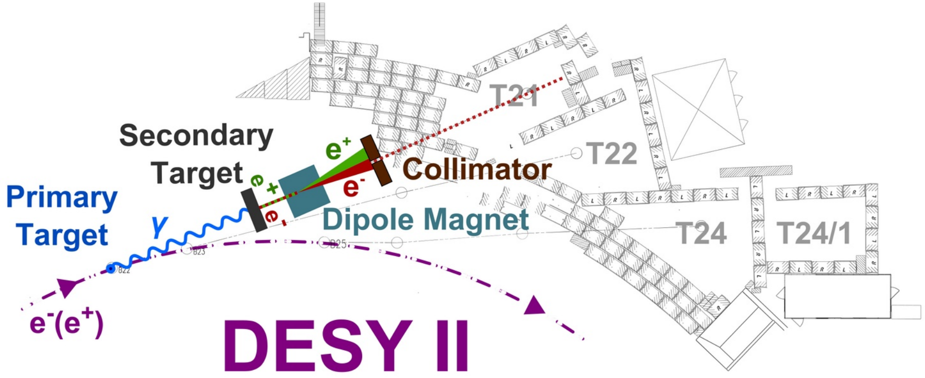
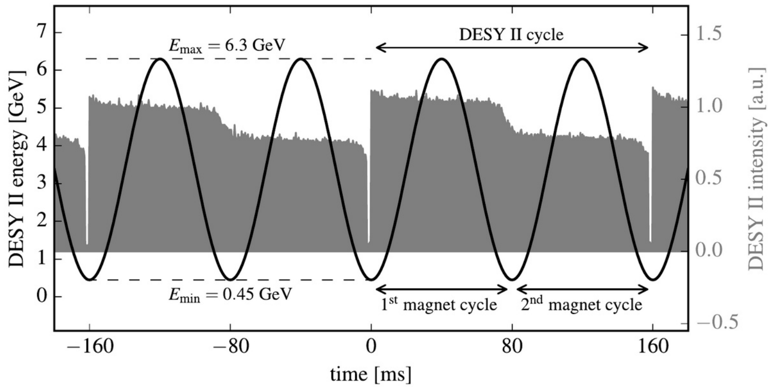
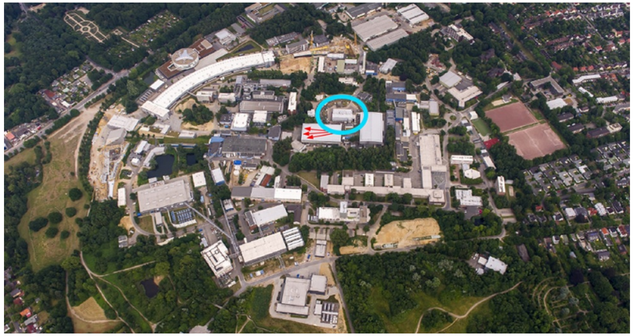
Beam generation

DESY

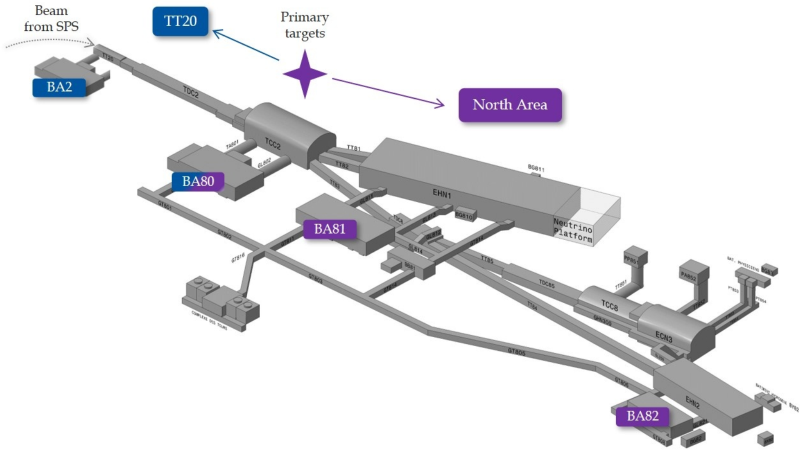
- Up to 7 GeV primary electron beam from DESY II
- Beam extraction via double conversion
  - Bremsstrahlung via fibre target in beam orbit
  - Pair production on secondary target (often copper)
- Pure e^+ or e^- beam with tunable energy up to 6 GeV
  - Filtering by dipole magnet
- “Continuous” extraction with duty cycle depending on requested beam energy
- Usually only one user per beam line





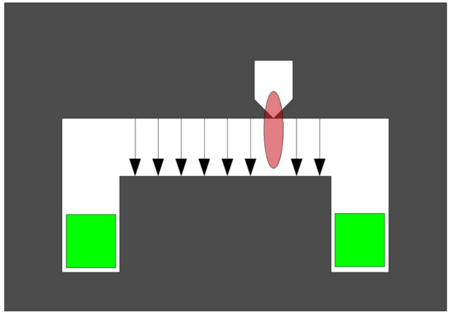


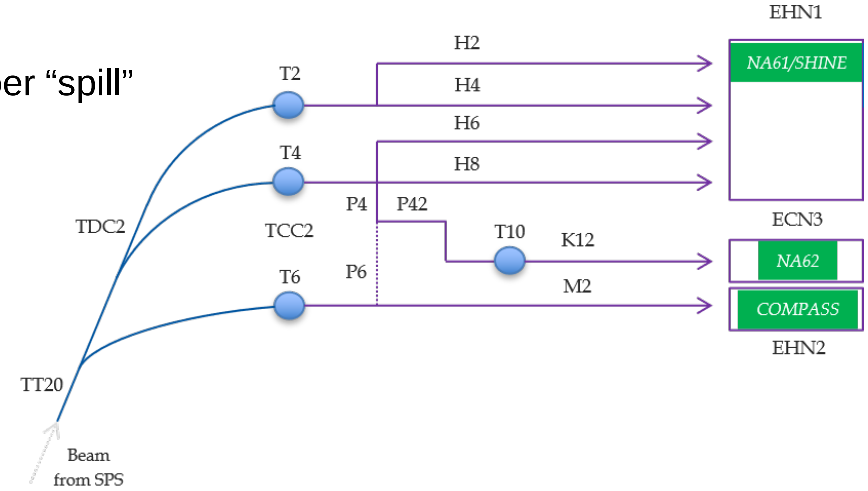
Beam generation

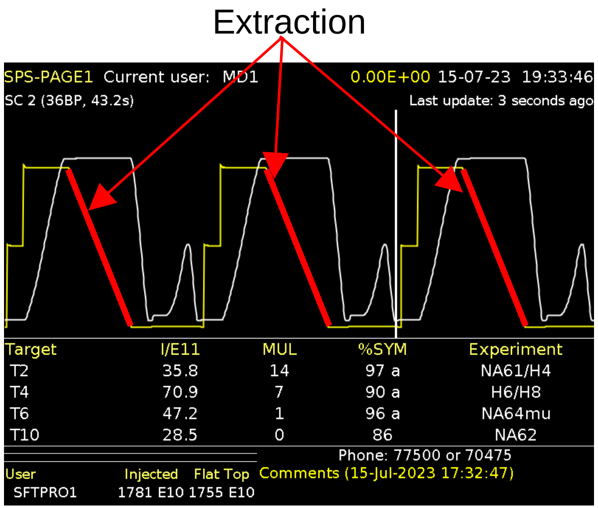


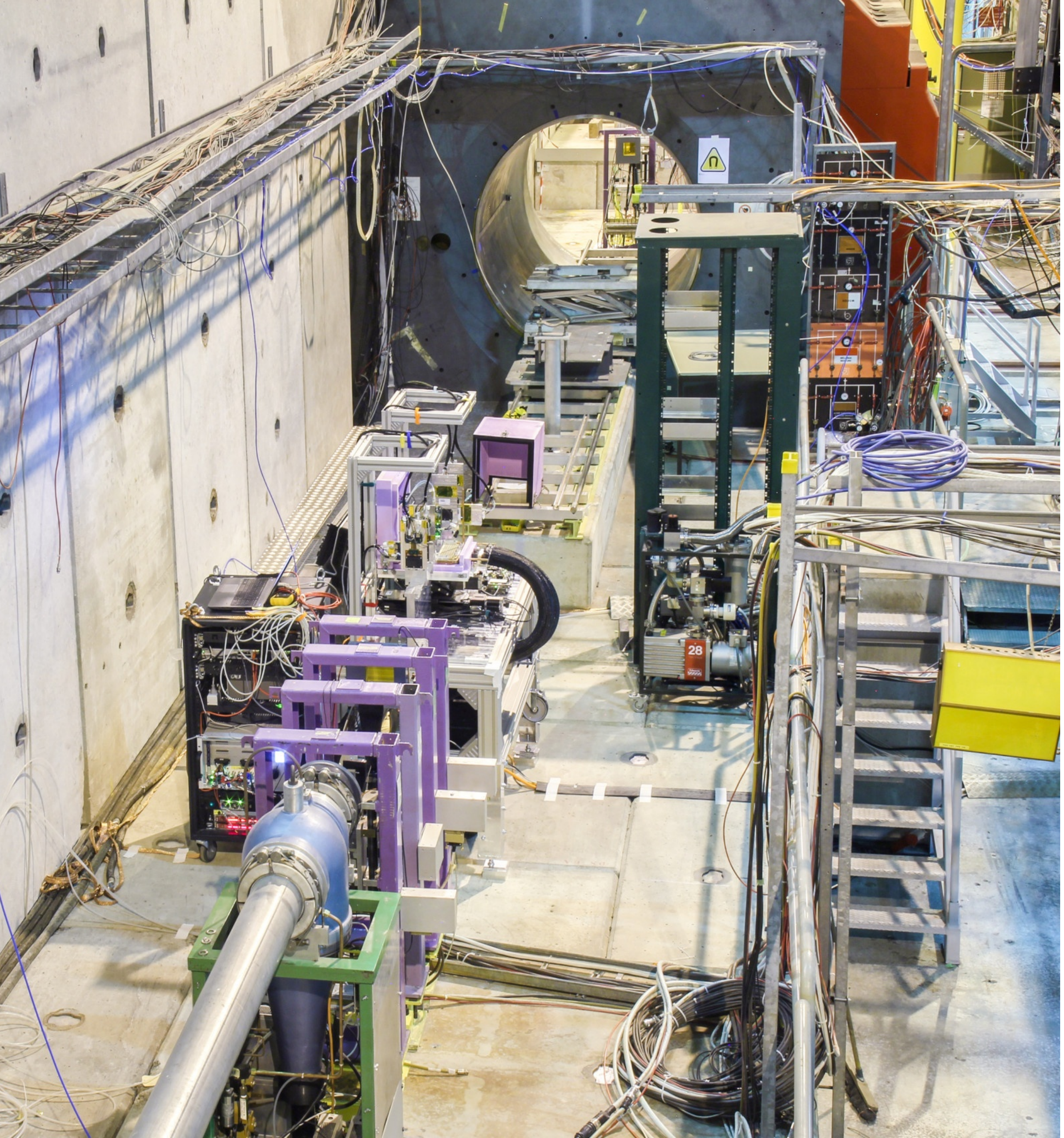
SPS North Area

- 400 GeV p primary beam
- Slow extraction due to septum magnet
  - ~5s extraction up to three times a minute
- Secondary generation through selectable target
- Mixed beam of K, π, $e^{+/-}$, p or $e^{+/-}$-beam with tunable purity
  - 10 – 400 GeV
- Up to few million particles per "spill"









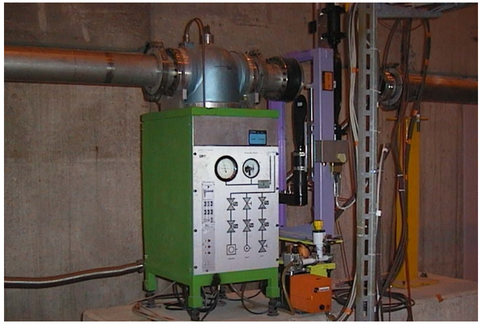
Example: SPS H8 beam line at CERN

- Usually 180 Gev/c pions
- Slow extraction over 4.8 s
- Up to three extractions per minute
- Up to $O(10^6)$ particles per spill

Instrumentation

- Particle identification via Threshold Cherenkov detectors
- Delay Wire Chambers
- Scintillators
- Magnets for beam forming/positioning

Particle identification

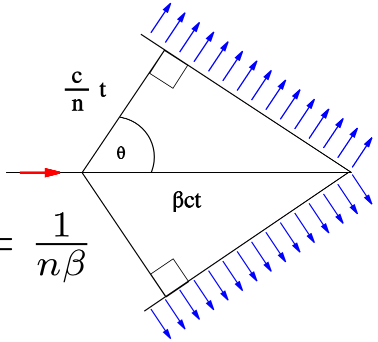


Threshold Cherenkov counter and CEDARs

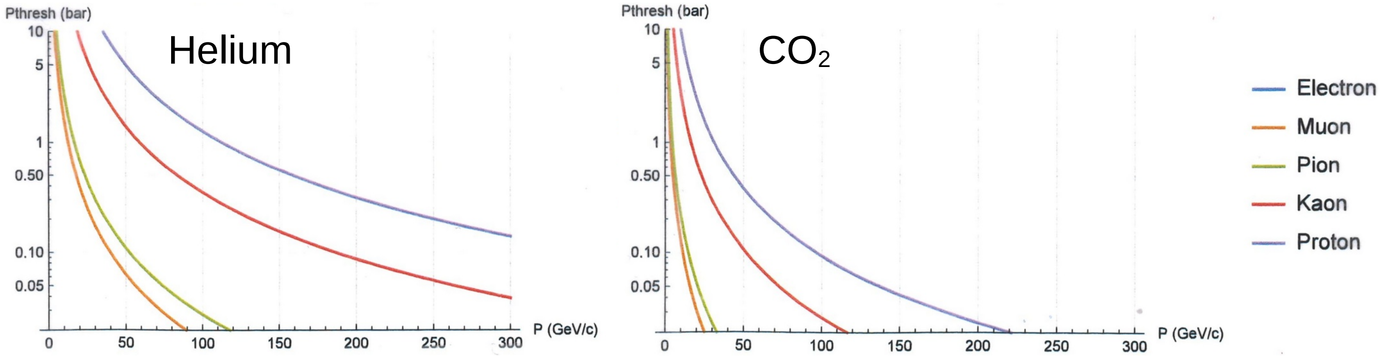
- Cherenkov light: particle speed > speed of light in medium
  - Momenta of particles in beam line similar (Δp = 1..10%)
  - Gaseous detector: refractive index changes with gas type and pressure

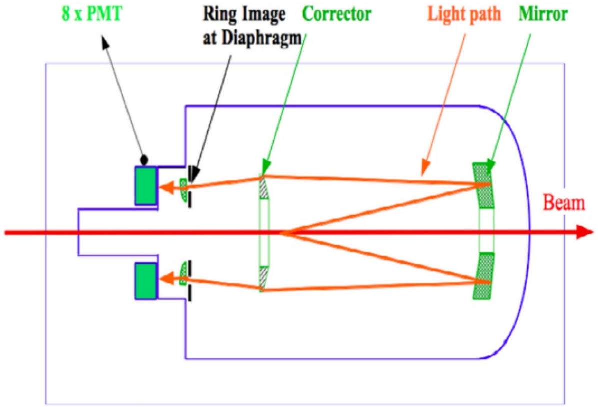
➔ Particle types only detected for certain detector configuration

➔ Discriminate via gas type and pressure



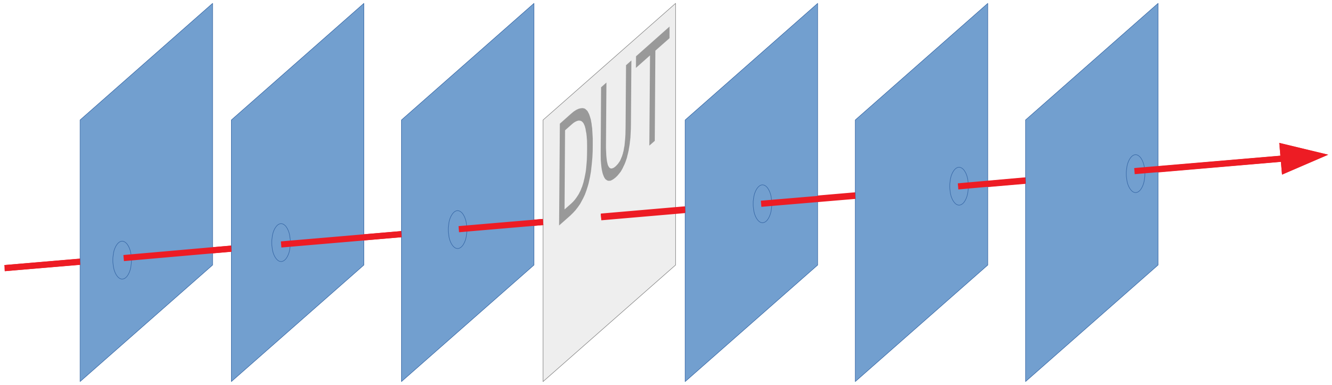
$$\cos\theta = \frac{1}{n\beta}$$

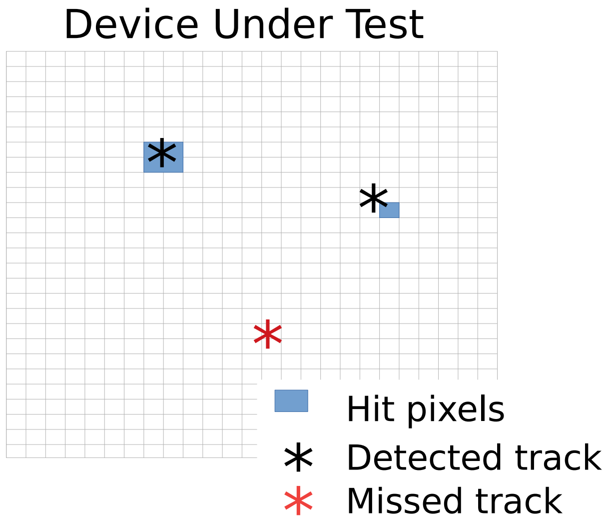




Particle tracking

- Spatially resolved response of device under test (DUT)
- Tracking of particles by beam telescopes
  - Multiple position sensitive planes (often pixel or strip detectors)
- Extrapolation of track to DUT and observation of response





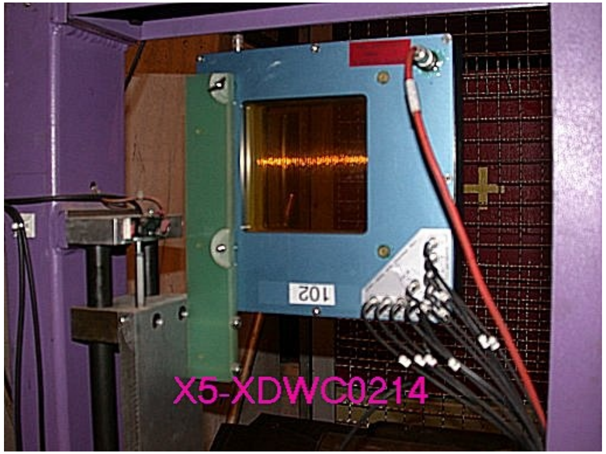
Particle tracking

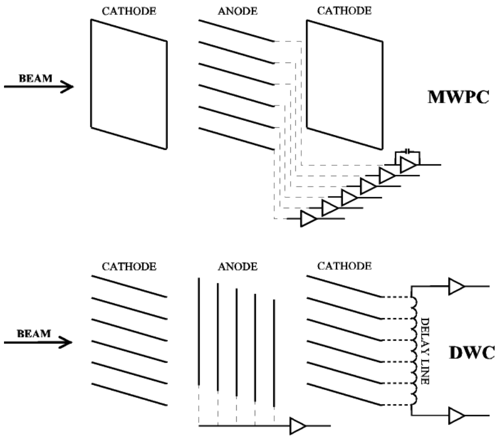
Delay wire chambers

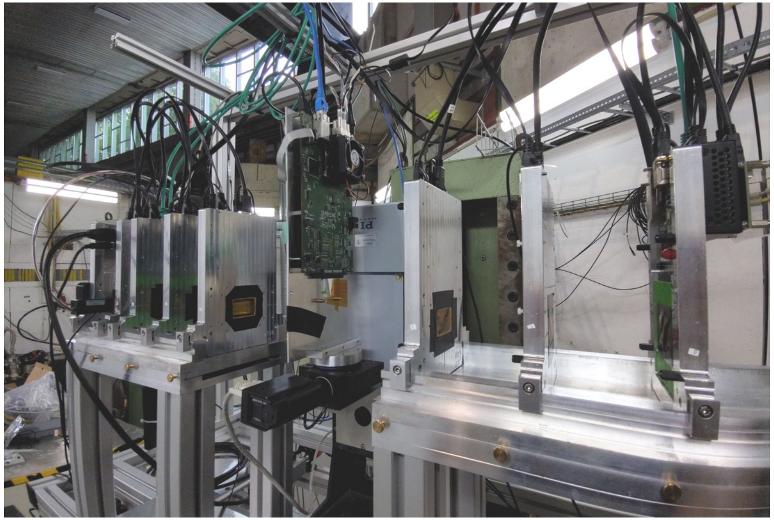
- Very lightweight, sensitive area of 10x10 cm²
  covering full beam spot
- Resolution around 200 µm
- Rate limited to about 10 kHz

Silicon tracking detectors

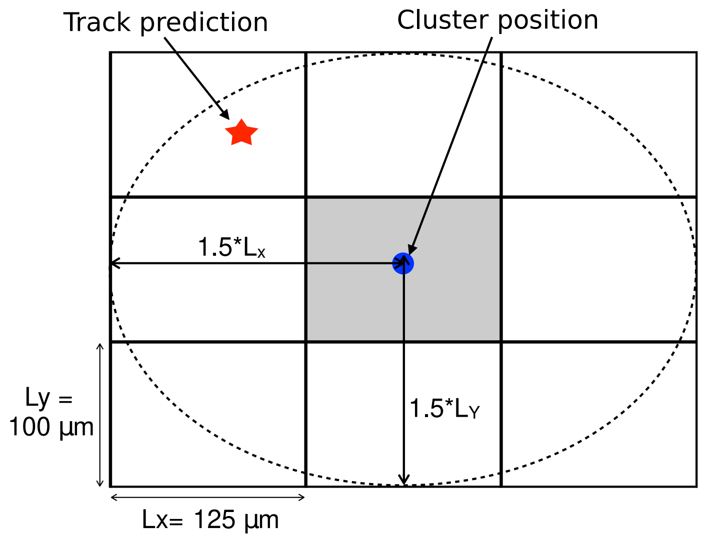
- Lightweight, sensitive area of up to 2x2 cm²
- Resolution < 10 µm
- Rates up to several MHz possible



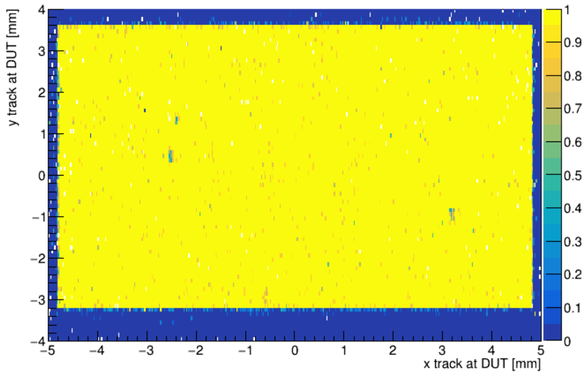


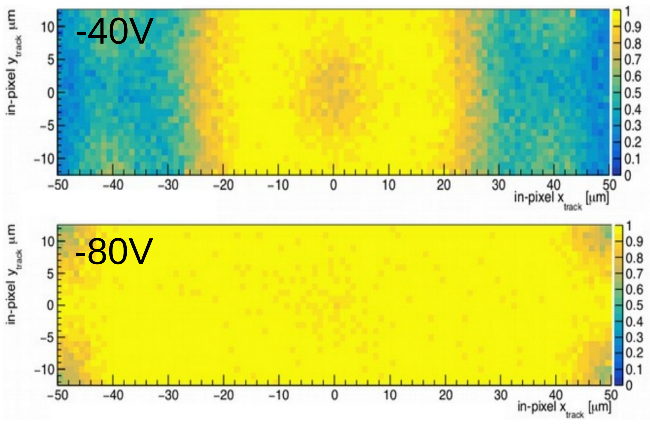


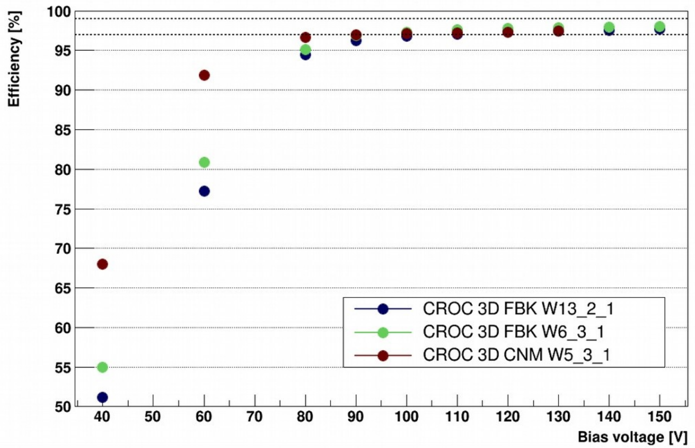
Efficiency measurement



- Efficiency defined as fraction of detected tracks through pixel $\epsilon = \frac{N_{matched}}{N_{reconstructed}}$
  - PDG recommendation for uncertainty Clopper-Pearson confidence interval of 1σ
- Telescope resolution != ∞
  - ➔ Matching radius around hit position
- Statistical uncertainty: we are aiming for ‰ accuracy
  - ➔ Large data set needed
- Global efficiency vs. in-cell/in-pixel efficency
- Efficiency vs. sensor bias / threshold / incidence angle

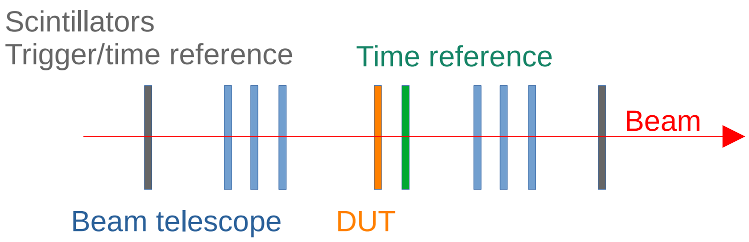


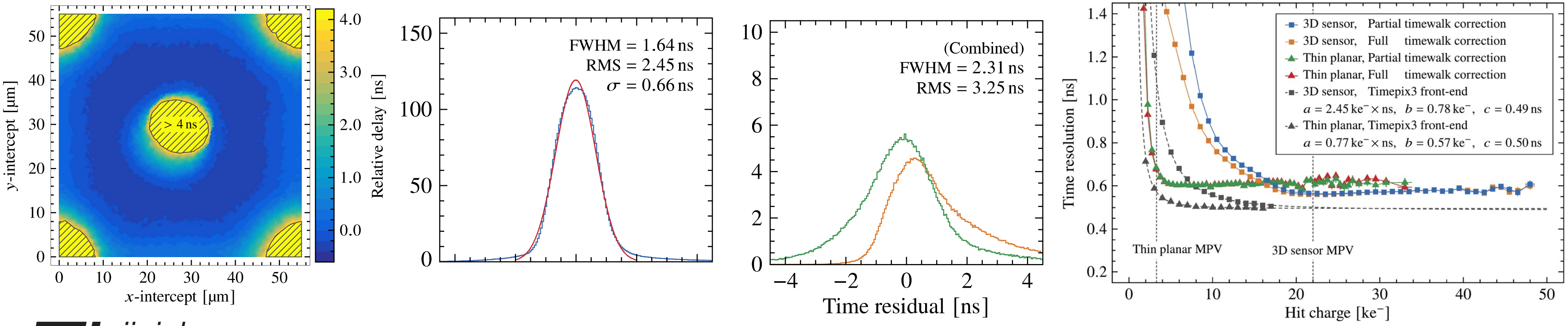




Timing

- Combination of precise tracking and time of arrival (TOA) information
  - Usually dedicated detectors for timing: Scintillators, MRPC
  - ➔ Additional sources of uncertainty
  - ➔ $\sigma^2 = \sigma^2_{\mathrm{signal}} + \sigma^2_{\mathrm{analog}} + \sigma^2_{\mathrm{digital}} + \sigma^2_{\mathrm{timeref}}$
- Corrections for position, deposited charge, TOA necessary
  - Asynchronous beam, time walk



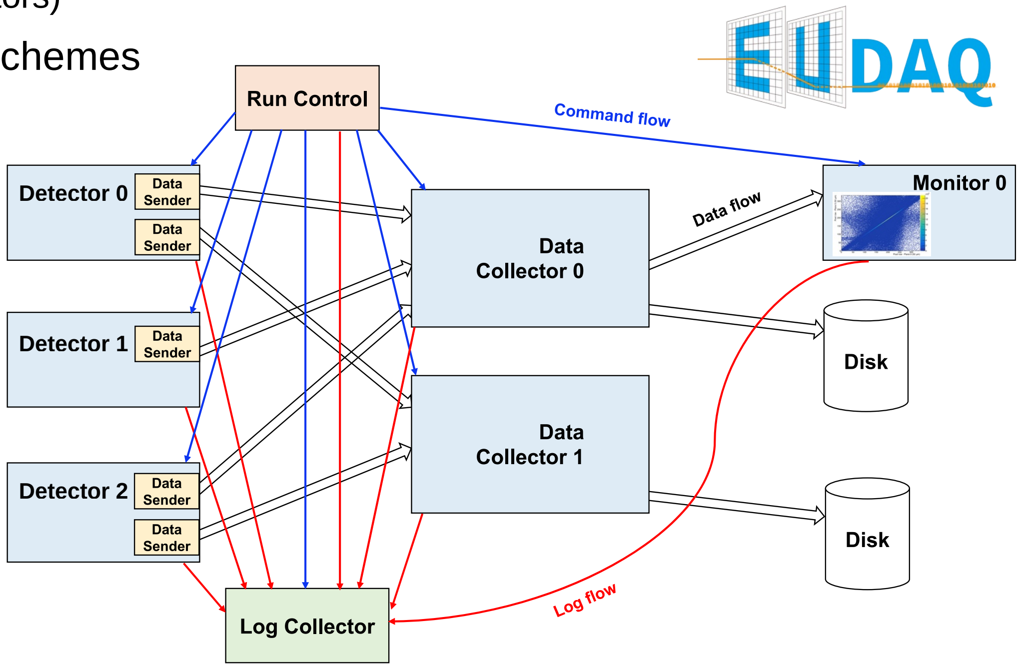


Data taking with heterogeneous systems

- Typical system
  - Reference detector: beam line instrumentation (Particle ID, energy measurement, tracker (telescope))
  - Devices under test
  - Trigger devices (can be reference detector, often scintillators)
- Various detector technologies with different readout schemes
  - Triggered with varying integration windows
  - Shutter based
  - Data driven

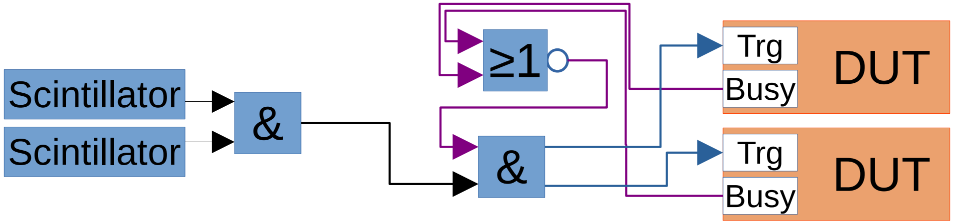
➔ Triggers and data streams have to be synchronised

➔ Common (high-level) data taking and triggering system

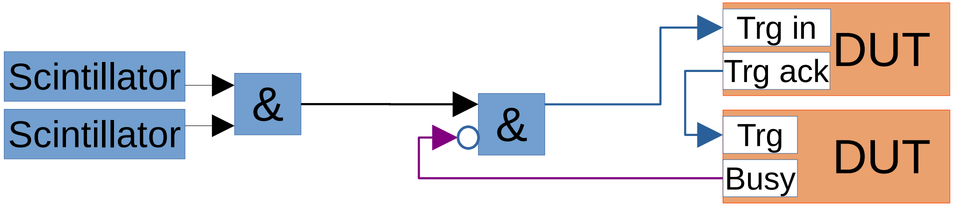


Trigger synchronisation schemes

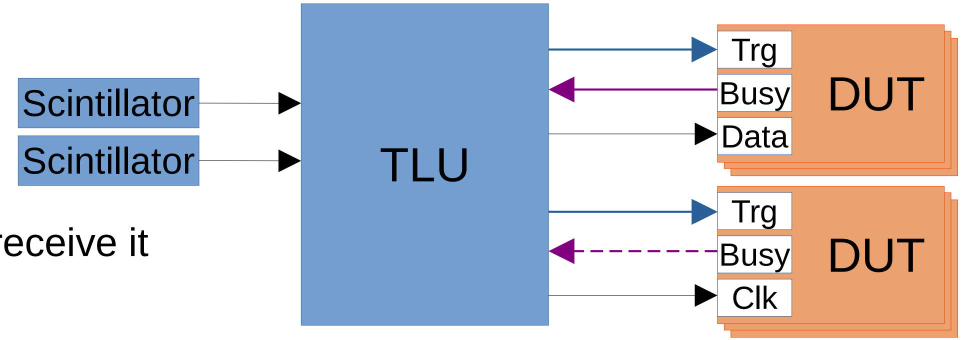
- Trigger / Busy scheme
  - Each DUT can veto trigger with busy
  - Rate determined by slowest device
  - Not robust



- Trigger / Acknowledge scheme
  - DUT has no busy or misses triggers
  - Use DUT as trigger filter
  - Delays can become significant

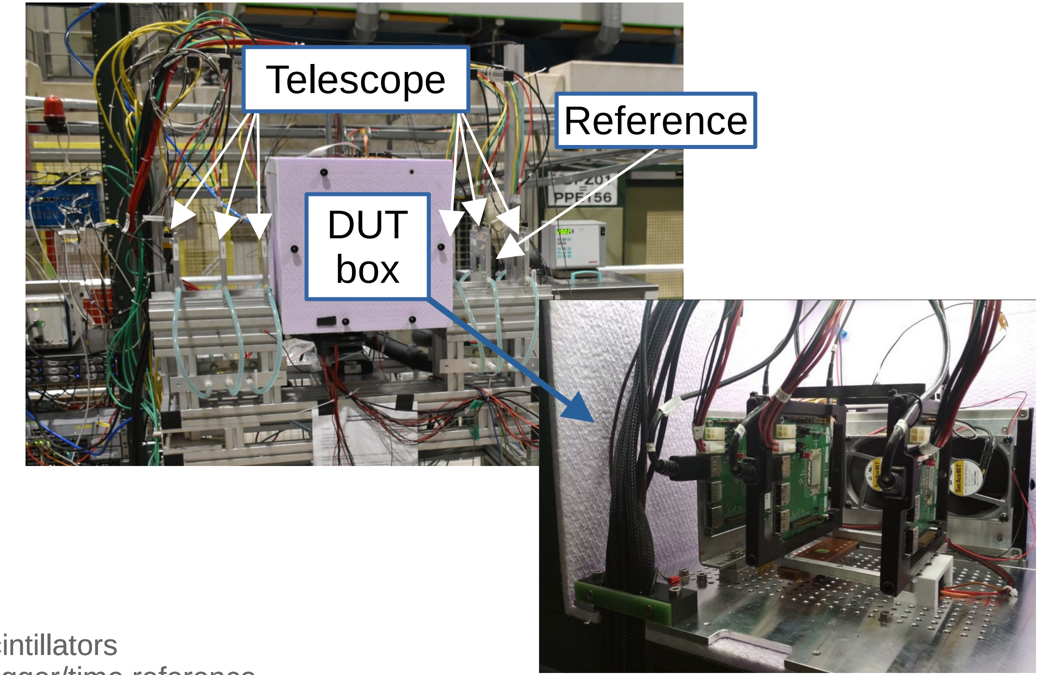


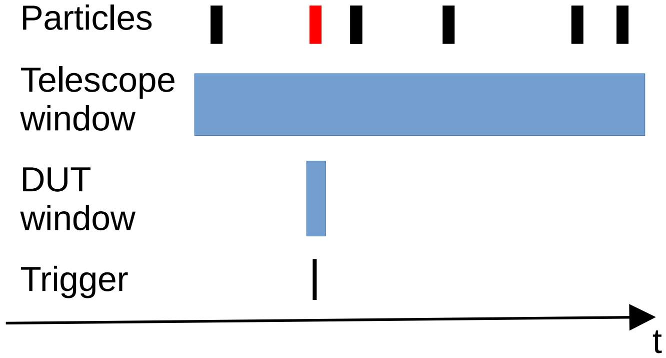
- Trigger / Busy scheme with data
  - Trigger ID or time stamp is sent to DUTs
- Synchronous mode
  - No busy needed
  - DUTs receive clock & generate timestamp/ID or receive it from TLU
  - Trigger-less (data driven) operation possible

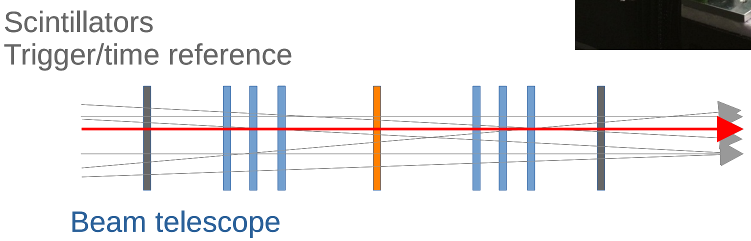


Example – EUDET telescopes and ATLAS/CMS pixel devices

- MIMOSA26 based beam telescope
  - ➔ Integration time: 115 µs (shutter based)
  - ➔ Multiple tracks with no time stamping
- ATLAS/CMS pixel detector: trigger based
  - Window 25 … 400 ns long → fraction of tracks visible
- Trigger via scintillators or additional pixel detector
  - ➔ Only tracks with hits on reference plane accepted
  - ➔ Time stamping of tracks







Artificial / rapid aging

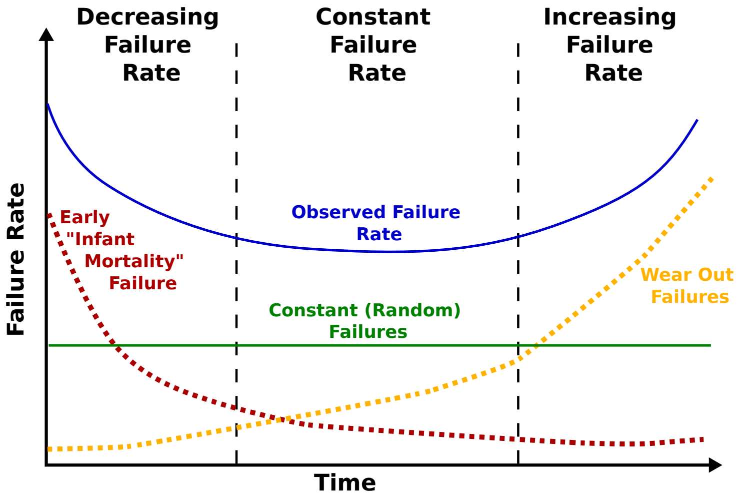
- Detectors must last for years without access
- Harsh conditions: radiation, heat/cold, magnetic field

➔ Lots of redundancy and hardening

➔ Testing must identify weak points visible after years

➔ Rapid ageing

- Irradiation to end of life doses and fluences



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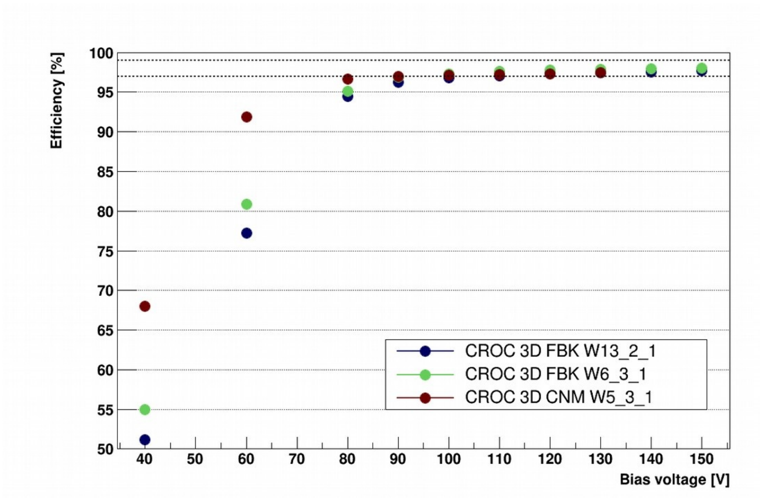
  - Ionising radiation → electronics, chemical bonds
  - Non-ionising radiation → crystal lattices



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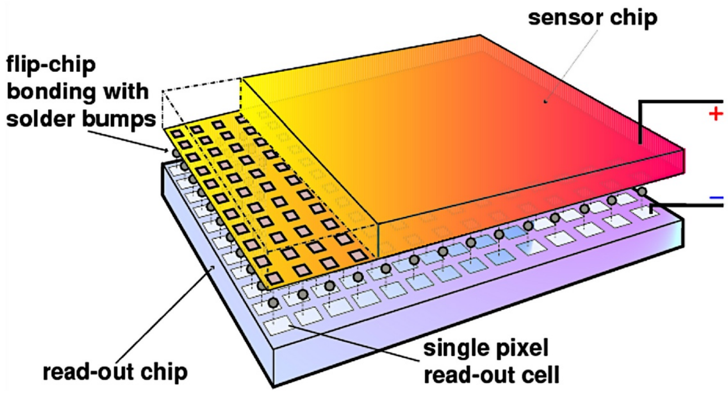
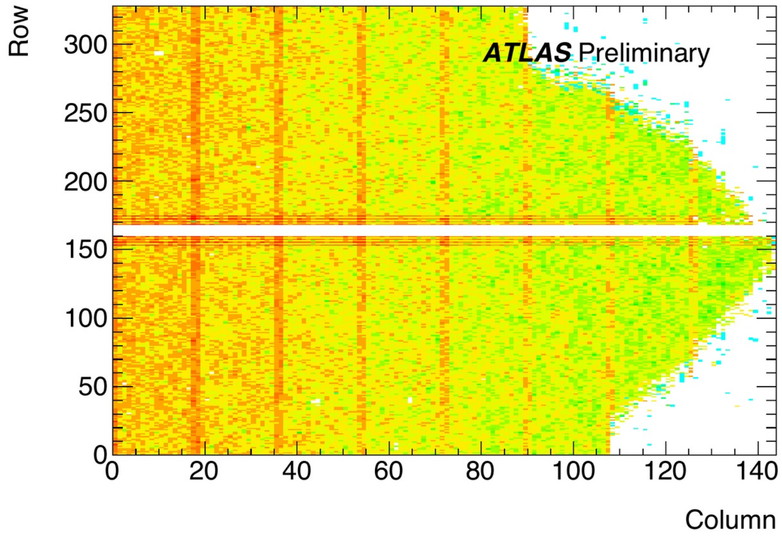
➔ Testing must identify weak points visible after years

➔ Rapid ageing

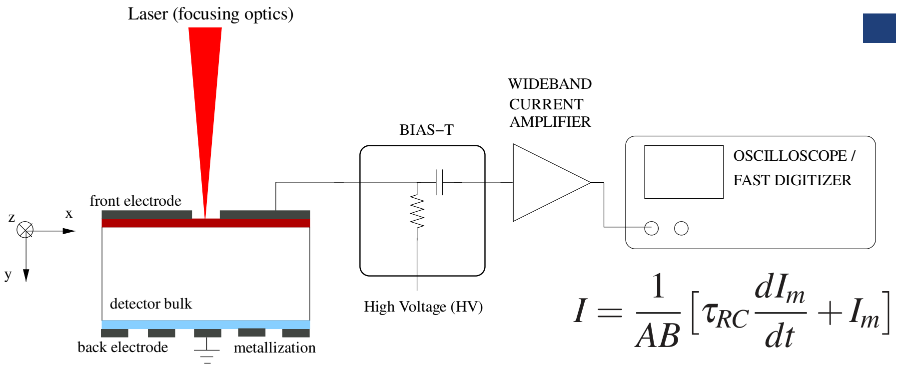
- Irradiation to end of life doses and fluences
  - Ionising radiation → electronics, chemical bonds
  - Non-ionising radiation → crystal lattices
- Power cycling and emergency shutdowns
- Thermal cycling and extreme conditions
  - Beam pipe bake-out
  - Failure of cooling system





Further techniques and info

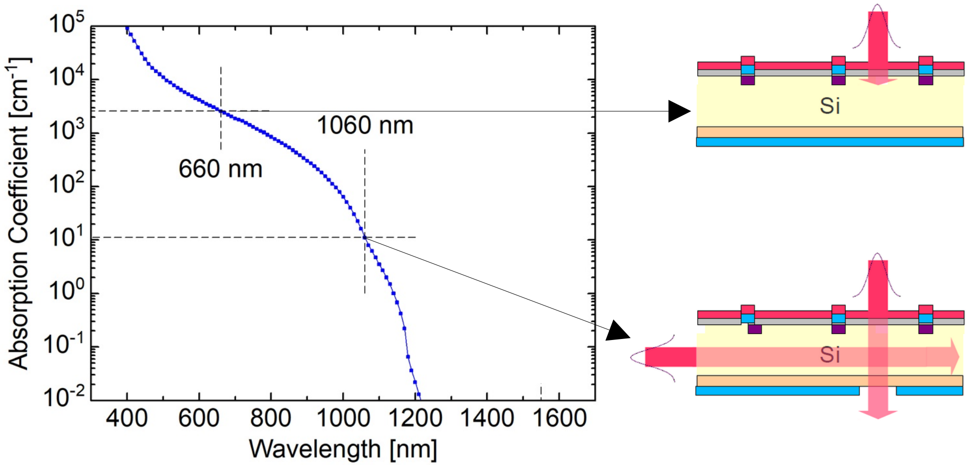
Pixel detectors – TCT measurements



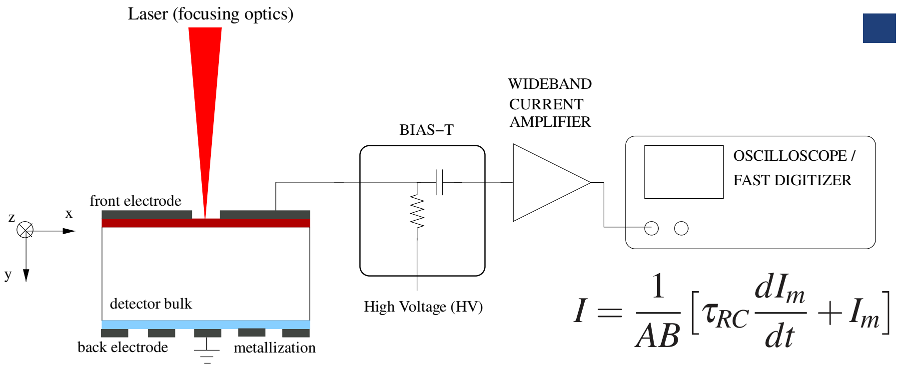
Observation of movement of charge carriers

$$I_{e,h}(t) \propto N_{e,h} \exp\left(\frac{-t}{\tau}\right) \mu_{e,h} E$$

- Study of E-field, charge mobility, ionisation, signal formation….
- Charge injection via particles or Lasers
- Wavelength defines penetration depth
  - NIR: deep penetration, MIP-like signal
  - Red: shallow penetration (5-10µm)
    ➔ study electrons and holes individually



Pixel detectors – TCT measurements



$$I = \frac{1}{AB}\left[\tau_{RC}\frac{dI_m}{dt} + I_m\right]$$

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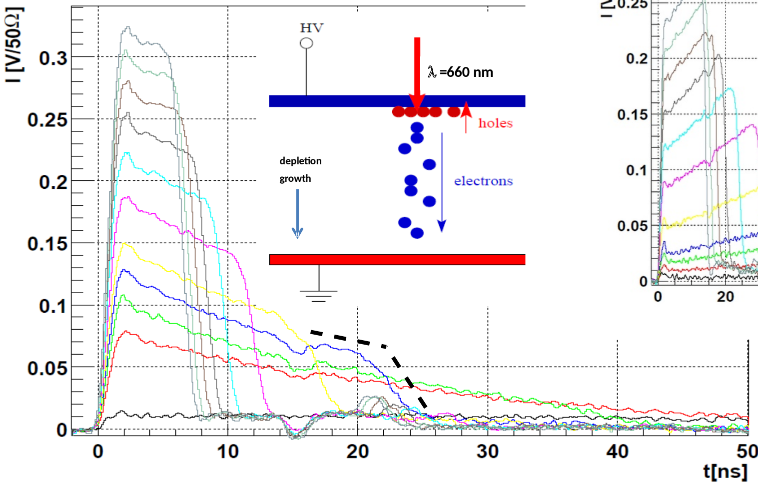
- Charge injection via particles or Lasers
- Wavelength defines penetration depth
  - NIR: deep penetration, MIP-like signal
  - Red: shallow penetration (5-10µm)
    ➔ study electrons and holes individually

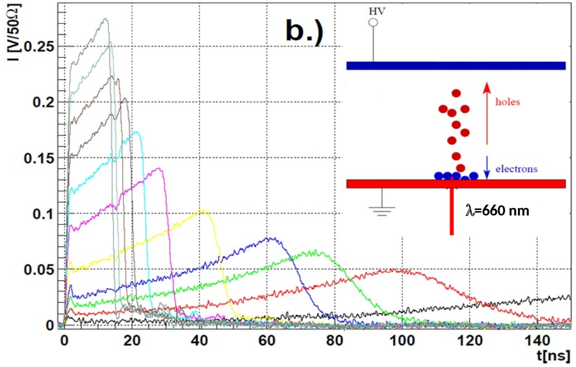
Inferred properties

- Induced charge: $Q = \int_0^{t_{\mathrm{int}}} I_{e,h}(t)$
- Full depletion voltage ~ 30V (presence of knee)
- Mobility of charge carriers: $\mu_{e,h} \propto (V \cdot t_{\mathrm{drift}})^{-1}$
- Sign and the concentration of space charge

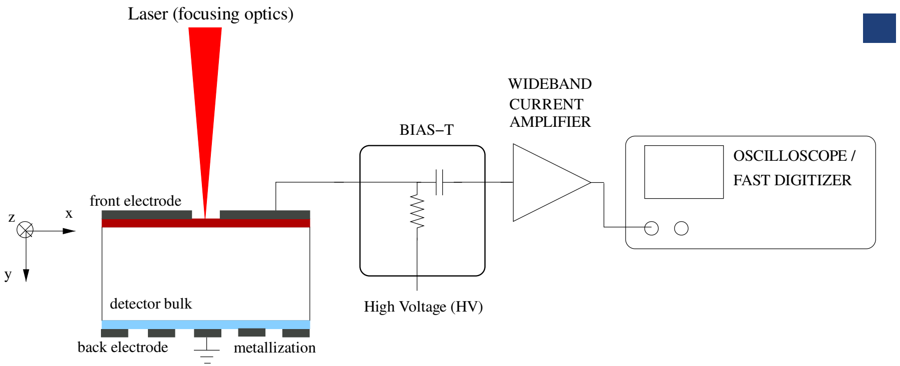
Movement of electrons



Movement of holes



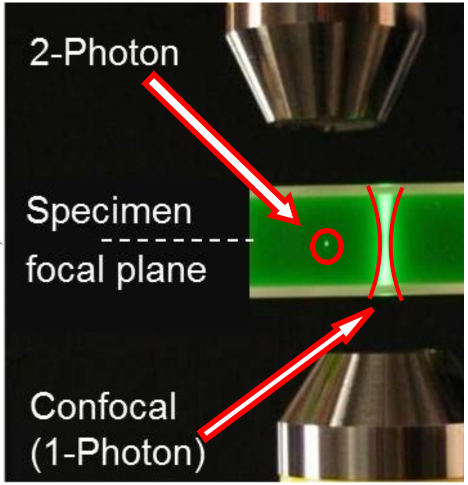
Pixel detectors – TCT measurements



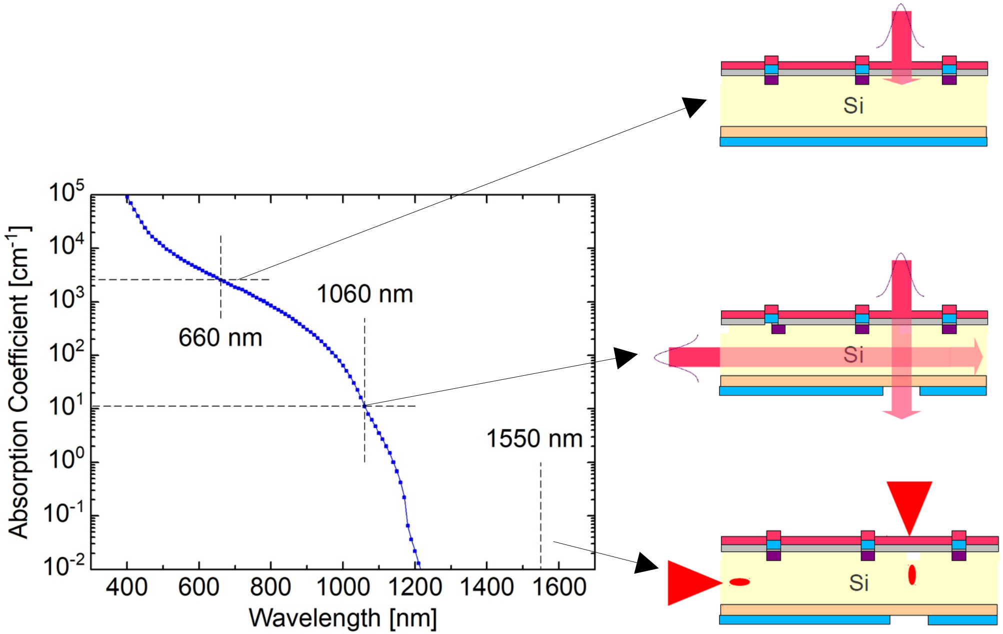
Observation of movement of charge carriers

- Charge injection via particles or <u>Lasers</u>
- Wavelength defines penetration depth
  - FIR: silicon mostly transparent

➔ Two-photon absorption
  - Very focussed beam → “point-like” charge deposition
  - High resolution: < 2 x 2 x 20 µm³



Yanez, Uni of Central Florida



Spatial resolution

- Resolution derived from residuals: $r(x) = x_{\mathrm{hit}} - x_{\mathrm{track}}$
- Tricky part: disentangle tracking from intrinsic resolution

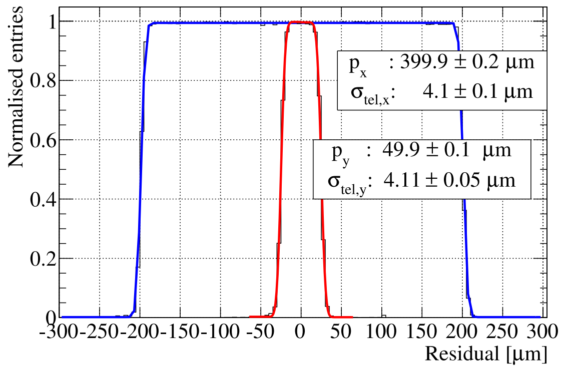
$$\sigma^2_{\mathrm{residual}} = \sigma^2_{\mathrm{intrinsic}} + \sigma^2_{\mathrm{track}}$$

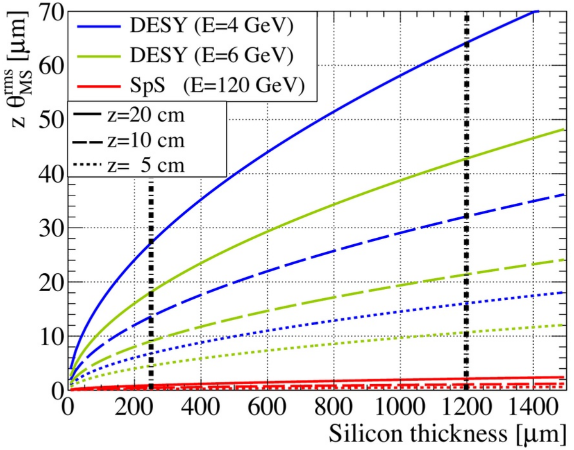
  - Material and beam energy: multiple scattering

$$\theta^{\mathrm{rms}}_{\mathrm{MS}} = \frac{13.6\,\mathrm{MeV}}{\beta c p}\, z_{\mathrm{ch}} \sqrt{\frac{t}{X_0}} \left[1 + 0.038 \ln \frac{t}{X_0}\right]$$

  - Geometry of telescope
  - Hit reconstruction from clusters
- Extract parameters by fit of “smeared box”

$$f(x) = \mathrm{rect}_d\left(\frac{p}{2}\right) * \mathcal{N}\left(\mu, \Sigma^2\right)$$





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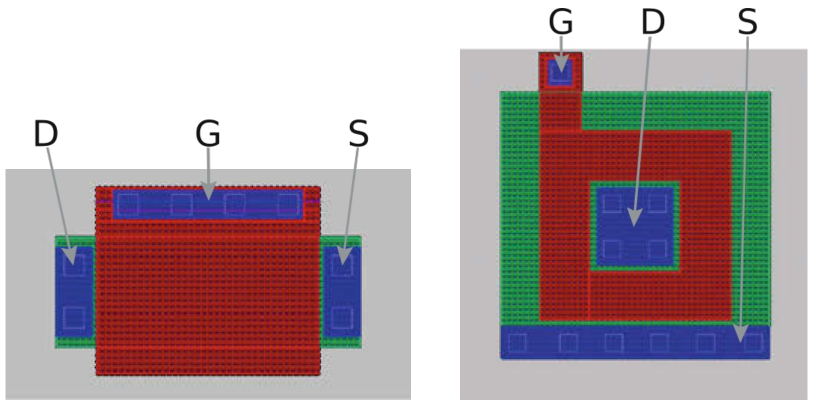
Radiation damage

Total Ionising Dose effects – Surface damage

- Creates e-h pairs in Si-SiO² interfaces
  - Parasitic conductive channels
  - Working points of transistors shifted
  - Single event upsets (SEU)



Non-Ionising Energy Loss (NIEL)

- Displacement of lattice atoms
  - Effecive doping concentration
  - Increased leakage current
  - Charge Trapping