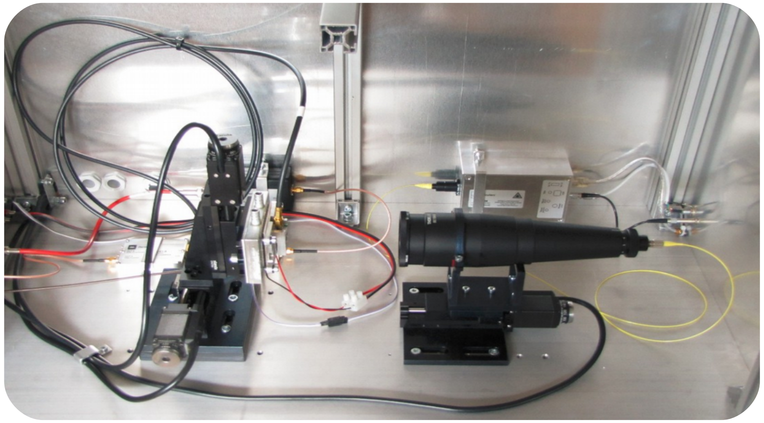
Confronting irradiation damage

From understanding to actions

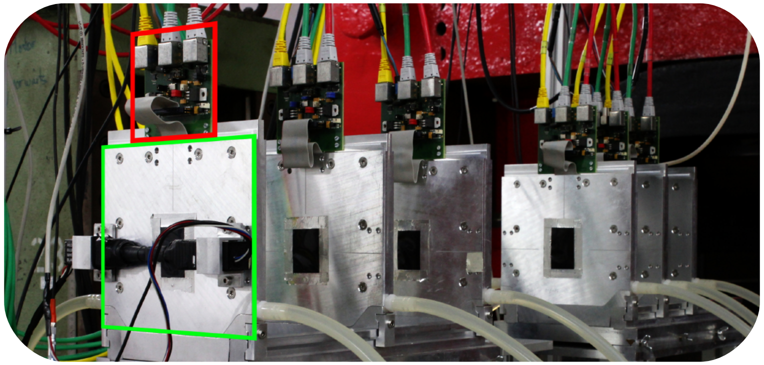
Hendrik Jansen

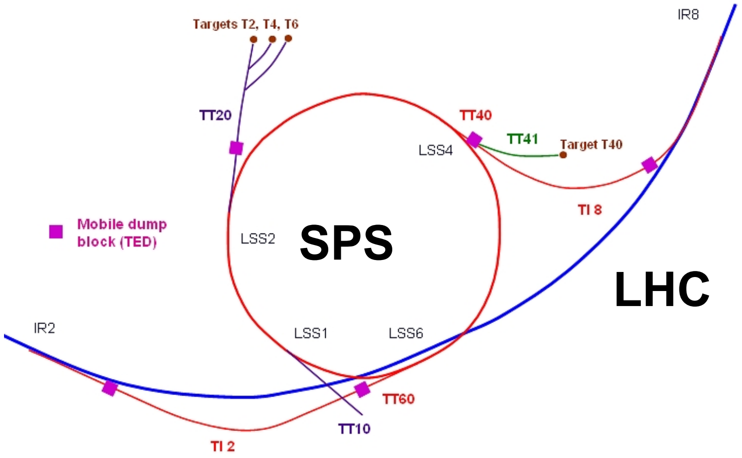
Outline

- HEP detector overview
  - what we have
  - why we need to do better
- Radiation damage in semiconductor sensors
- Characterisation techniques
- Clever ideas mitigating radiation damage



http://particulars.si/





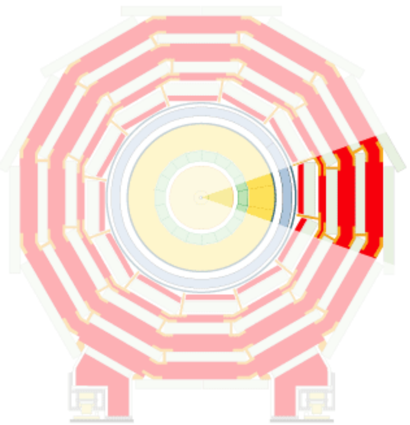
HEP detector: CMS overview

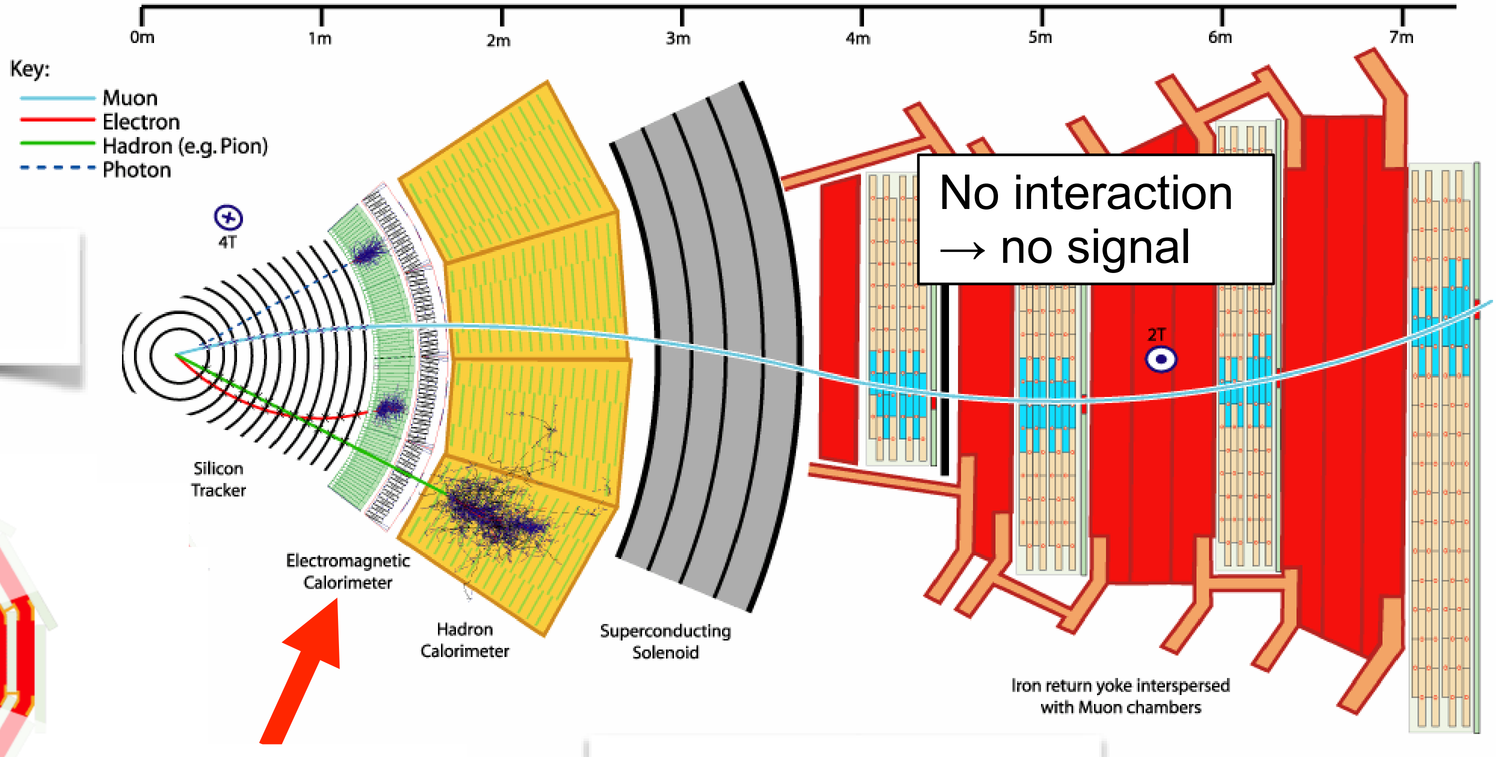
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

Calorimeter: Energy measurement of photons, electronics and hadrons through total absorption

Muon-Detectors: Identification and precise momentum measurement of muons outside of the magnet

Vertex: Innermost tracking detector





No interaction → no signal

picture: CMS@CERN

Good energy resolution up to highest energies

Radiation hard (hadron collider)

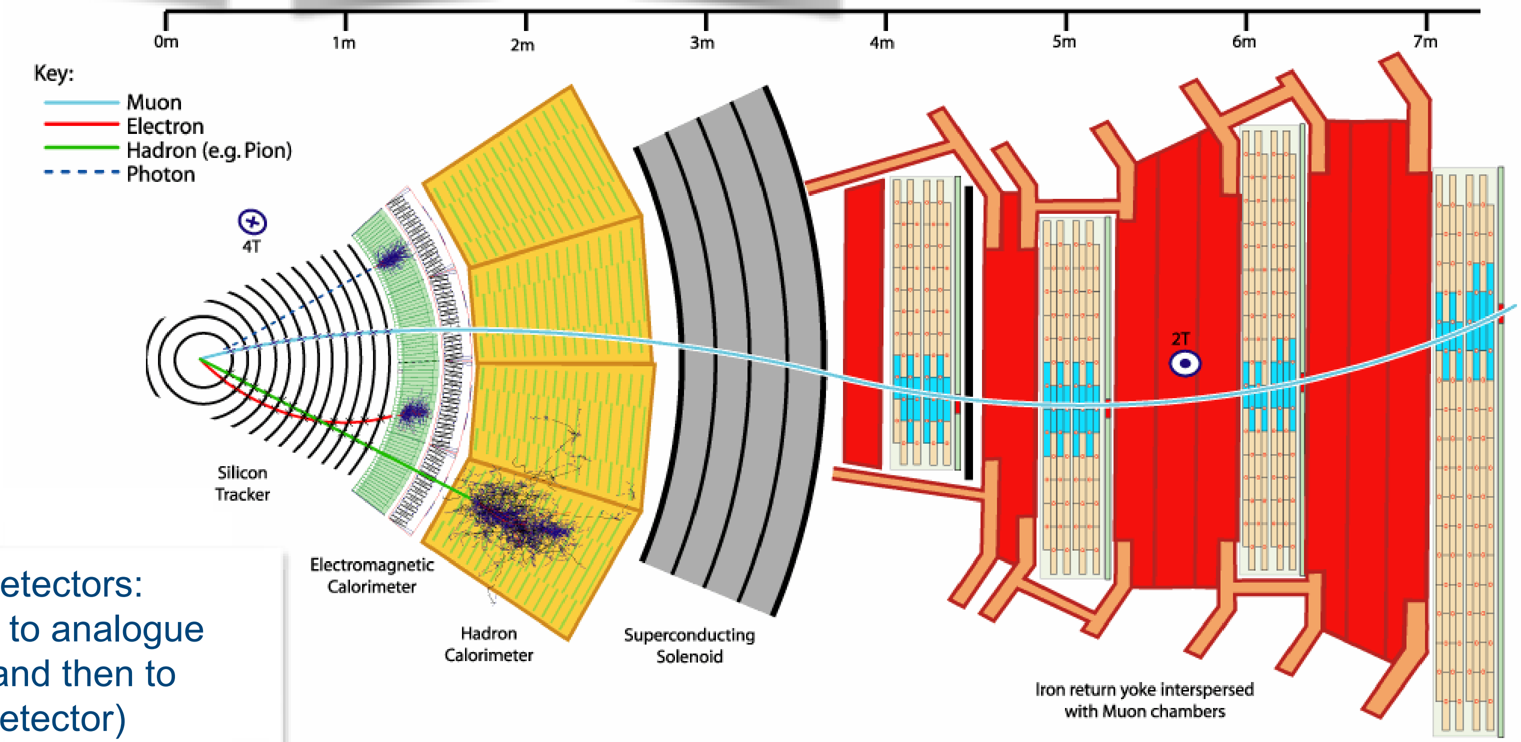
Slide from I. Gregor

HEP detector: signal types

Calorimeter: ionisation
→ charge measurement
→ electrical signal (analogue or digital)

Calorimeter: ionisation
→ light signals from crystals or scintillators converted into electrical signals (analogue or digital)

Muon-Detectors:
charge in gas detected by wires
→ electrical signal converted into digital signals



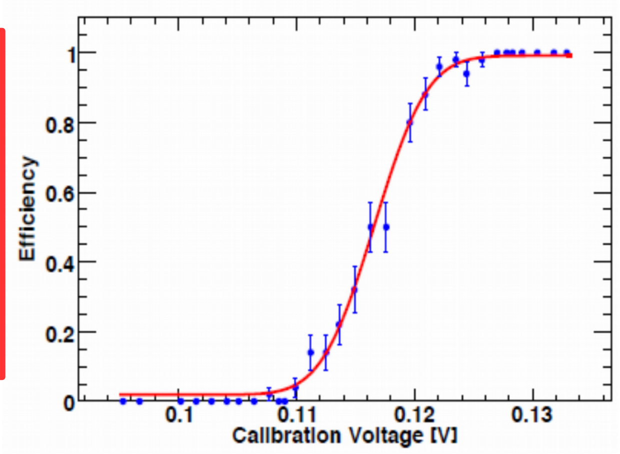
Tracker: silicon detectors:
charge converted to analogue (amplifier stage) and then to digital (on or off detector)

Tracker: gas detectors: charge converted to digital (on detector or off detector)

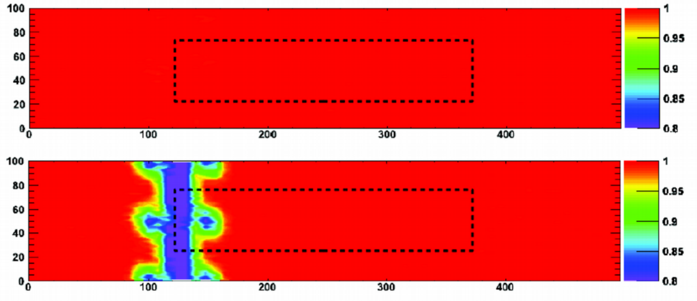
Slide from I. Gregor

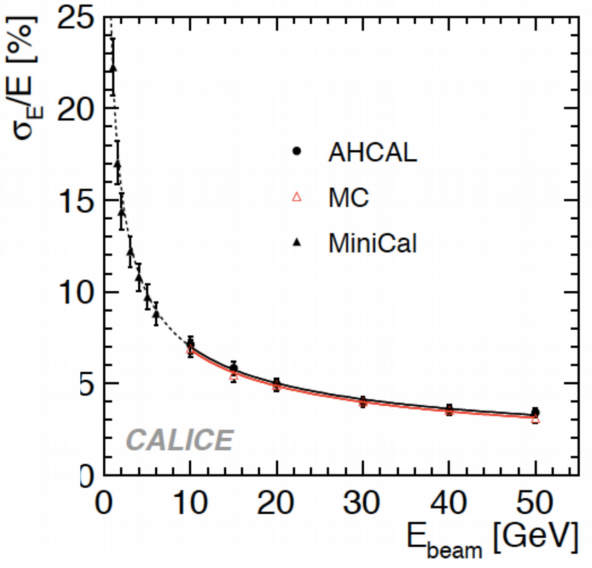
Important figures of merit

- Tracking detector (systems)
  - Signal-to-noise ratio (before/after irrad.)
  - Detector resolution
  - Efficiency a.f.o. various parameters
  - Charge collection efficiency (before/after irrad.)



- Calorimeter
  - Signal-to-noise ratio
  - Energy resolution
  - Single photon peak
  - Electron/hadron ratio



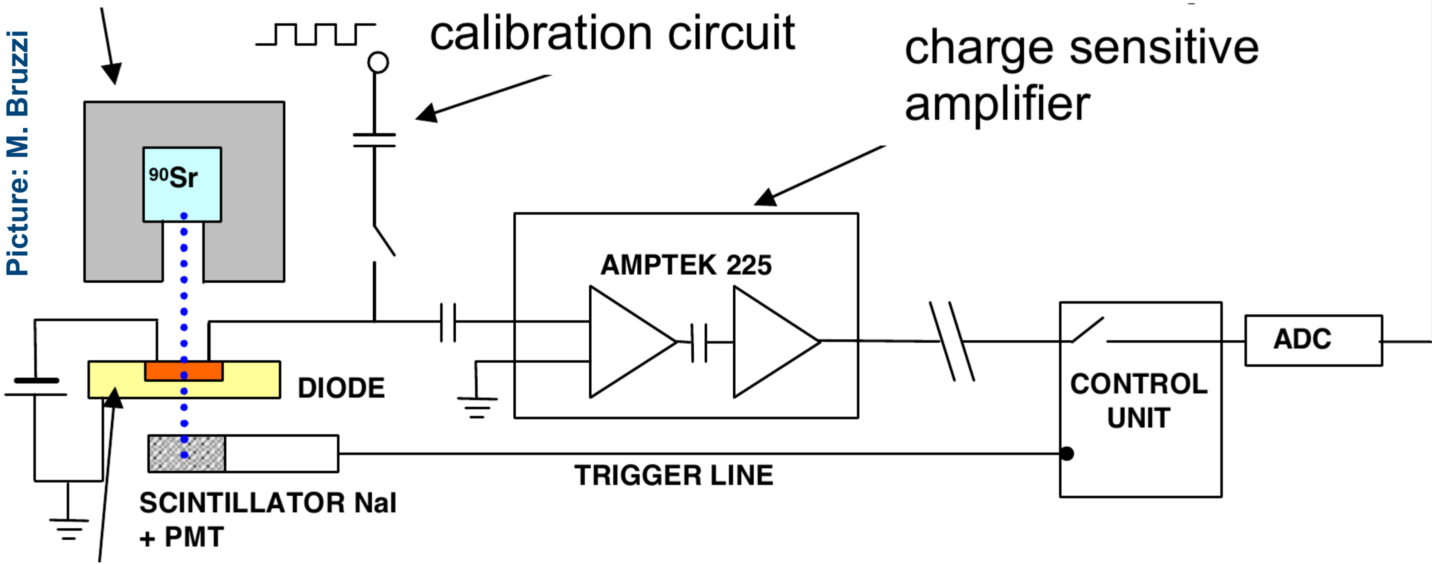


- Other (new) requirements:
  - Timing in tracking and calorimetry
  - Environmental challenges (cryogenic detectors)
  - Detectors in high-rate experiments

Slide from I. Gregor

Important tracker parameters (1)

- Charge collection (CC): collected charge in sensor volume
  - Important parameter affected by radiation damage and other effects
  - Charge induced by charged particle from radio-active source, laser, beam
  - Measurement of CC normalised to optimal value a.f.o. other parameter (charge collection efficiency CCE)
    - Bias voltage
    - Radiation level



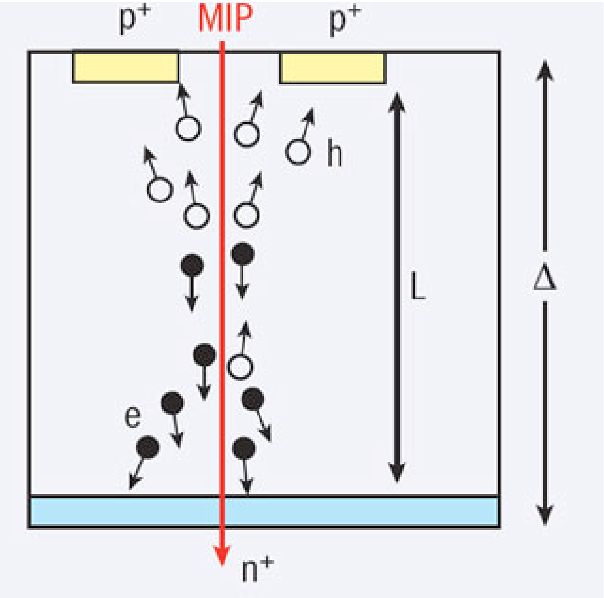
Sr90 source

calibration circuit

charge sensitive amplifier

Silicon sensor

Picture: M. Bruzzi



Picture: U. C. DaVia

Can be measured with bench top set-up in a laboratory

Slide from I. Gregor

Important tracker parameters (2)

- Signal-to-noise ration (SNR): signal amplitude over intrinsic noise of the detector
  - Parameter for analogue signal
  - Good understanding of electrical noise needed
    - Noise measurements
    - Noise simulations
  - Signal induced by source, laser, test beam
  - Optimal SNR > 20
  - SNR also important for efficiency vs. purity:

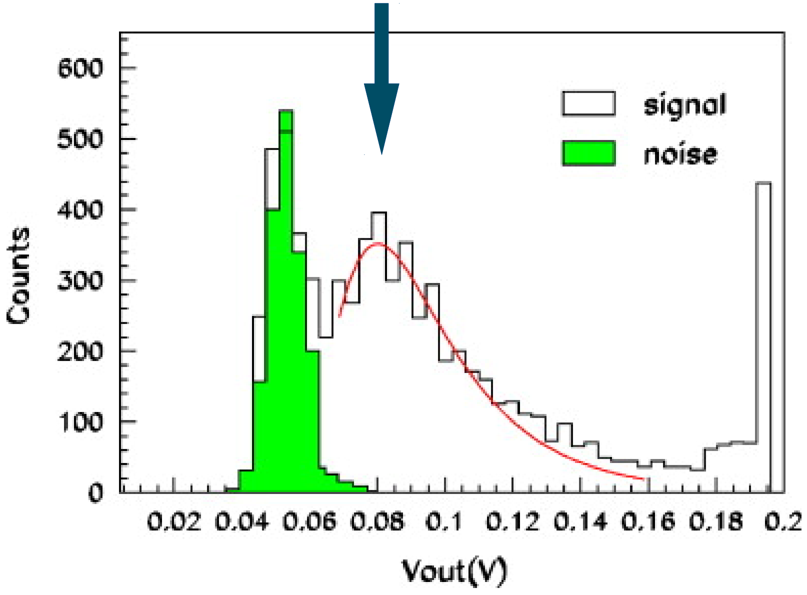
Can be measured with bench top set-up in a laboratory

Detection efficiency is probability to detect particle, typically 99.X% for one layer.

For 7 layers?

$$\epsilon = 0.99 \qquad \epsilon = 0.98$$
$$\epsilon^7 = 0.93 \qquad \epsilon^7 = 0.87$$

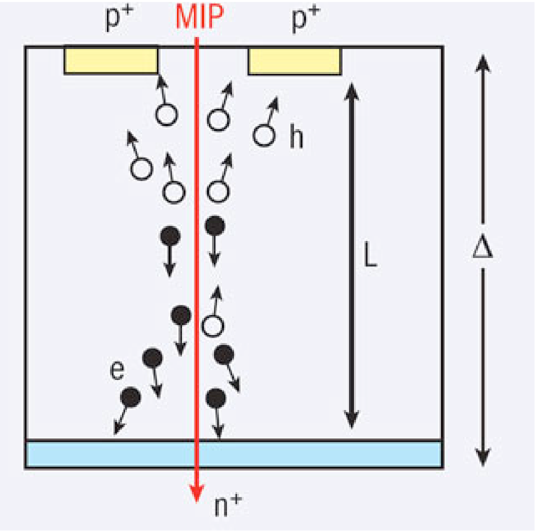
most probable peak!



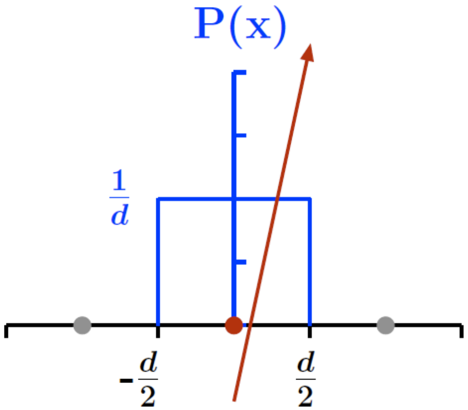
Slide from I. Gregor

Important tracker parameters (3)

- Spatial resolution of a tracking device
- Depending on detector geometry and charge collection
  - Pitch, i.e. distance b/w channels
  - Charge sharing b/w channels
- Simple case:
  - Traversing particle creates signal below one entity
  - All charge is collected on this entity (strip/pixel)
  - Assume flat distribution over sensor for many particle passages:
    → Unity probability distribution



Picture: U. C. DaVia



$$P(x) = \frac{1}{d} \qquad \Rightarrow \int_{-d/2}^{d/2} P(x)\,dx = 1$$

The reconstructed point is always the middle of the strip:

$$\langle x \rangle = \int_{-d/2}^{d/2} x\,P(x)\,dx = 0$$

Slide from I. Gregor

Important tracker parameters (4)

- Calculate the resolution (standard deviation)

$$\sigma_x^2 = \langle (x - \langle x \rangle)^2 \rangle = \int_{-d/2}^{d/2} x^2 \, P(x) \, dx = \frac{d^2}{12}$$

- Resulting in general term for BINARY resolution:

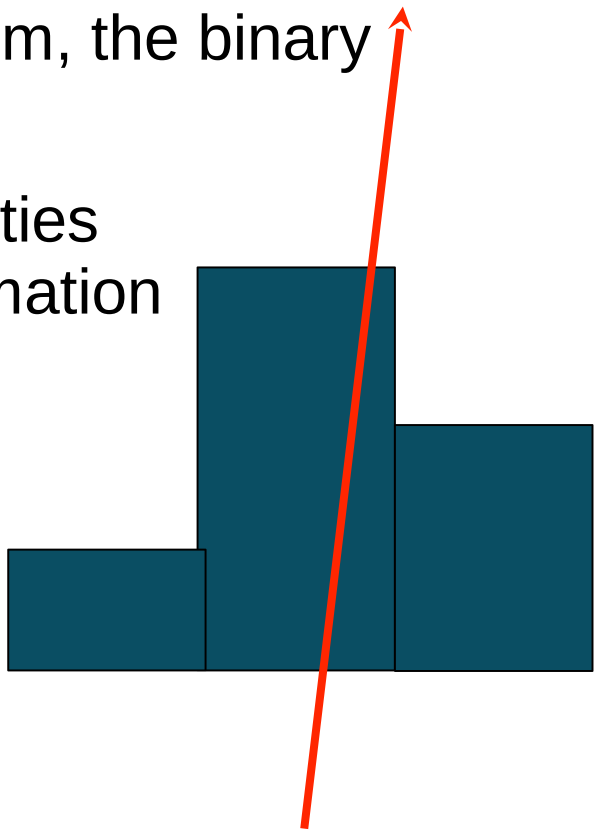
$$\sigma = \frac{d}{\sqrt{12}}$$

very important !

- For a silicon strip detector with pitch = 80 um, the binary resolution is ~23 um

- In case of charge sharing b/w read-out entities
→ Resolution improved by additional information of adjacent channels

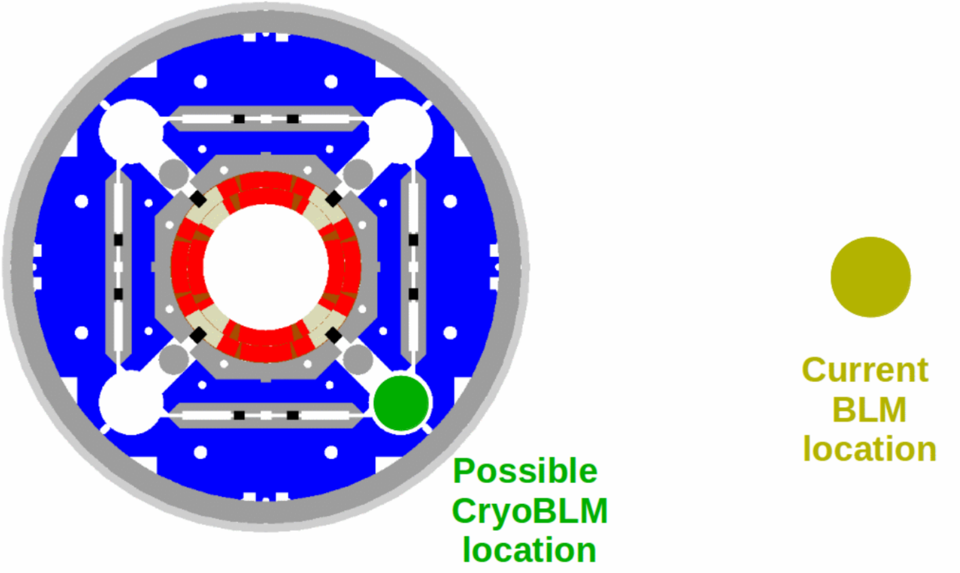
Needs to be measured in beam. More sophisticated algorithms for large angle tracks



Slide from I. Gregor

A new Beam Loss Monitor for LHC

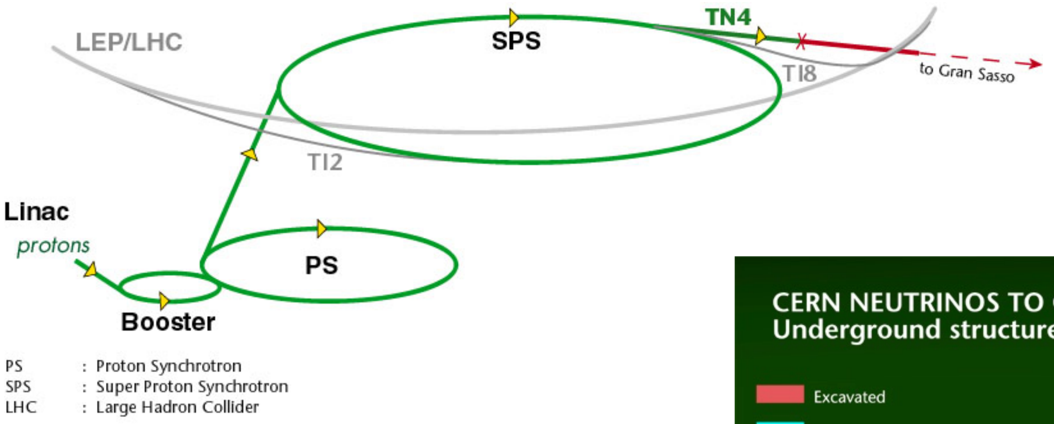
Goal:
Measure beam loss as precise as possible
→ Put detectors INSIDE the magnet
→ Need to operate detectors @ 1.8 K



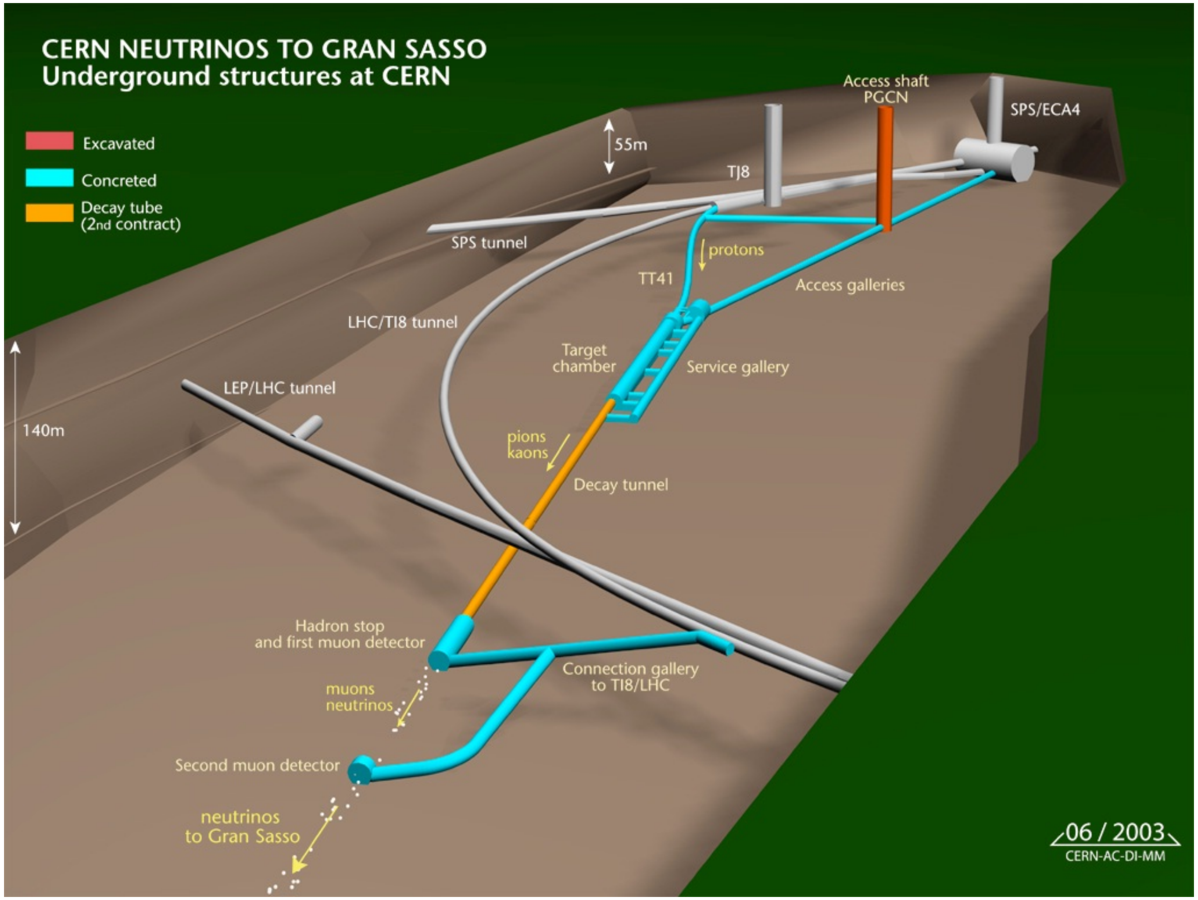
Questions:
– Which sensors work at 1.8 K?
– Do they behave differently?
– Radiation damage different?

CERN-THESIS-2013-232

More HEP: CNGS



Send neutrinos to Gran Sasso:
Protons on target → kaons/pions
→ Muons → Neutrinos



Measurement:
Proton intensity profile +
muon intensity profile
→ Correlate
→ Time-of-flight
→ Cross-check clock system
→ Travel neutrinos too fast ?!

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  - **why we need to do better**
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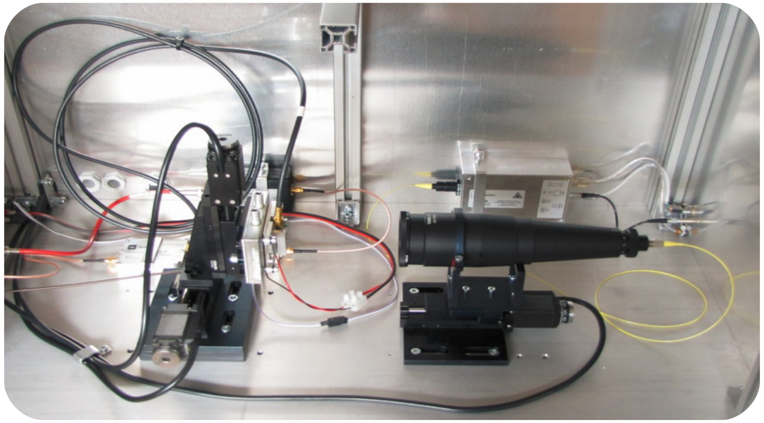
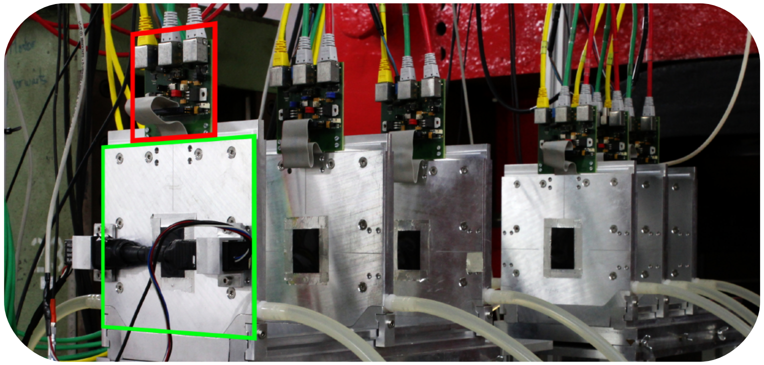
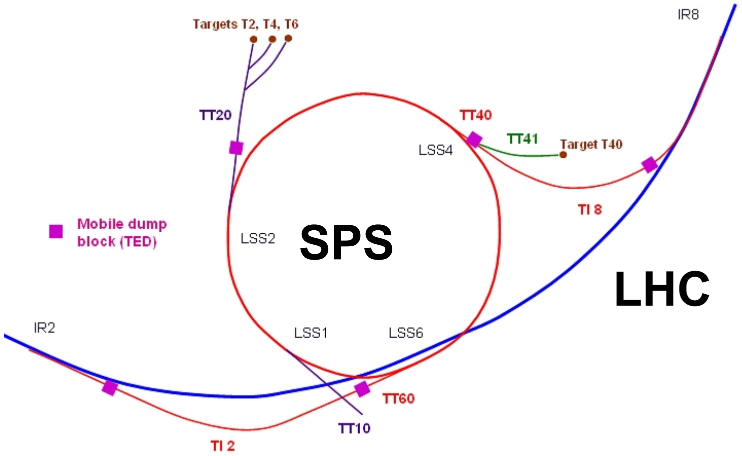
- Characterisation techniques
- Clever ideas mitigating radiation damage







Why is more R&D needed?

- We have all these nice detectors, why not use them?
  → Requirements change
- From LHC to HL-HLC:
  → higher luminosity
  → more interactions per bunch crossing
  → more radiation damage
  → ...
- At ILC:
  → Low material budget for high resolution tracking
  → Power pulsing (bunch trains)
  → …

→ need sophisticated R&D programs!

R&D answers ...

General:

- How much charge does my detector collect?
- Does my sensor work at 2 K? In space?
- Can I use my detector for a precise timing at high flux?
- What is the spatial resolution of my detector?

Fluence related:

- How (well) does my detector operate after high fluence?
- How does my sensor change with fluence? Why?
- Which material should I choose for my tracker upgrade?

… using different techniques

- Probe station for CV, IV + LCR meter
- Laser-/Source-based set-up + fast amplifier
- Cryogenic/temp-controlled set-up + ampere meter
- Test beam with beam telescope for tracking
- Irradiation campaign + test beam
- Cryogenic set-up + test beam
- ...

→ Will introduce an incomplete list of techniques later.

Let’s have a look at radiation damage first.

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  - why we need to do better
- **Radiation damage in semiconductor sensors**
- Characterisation techniques
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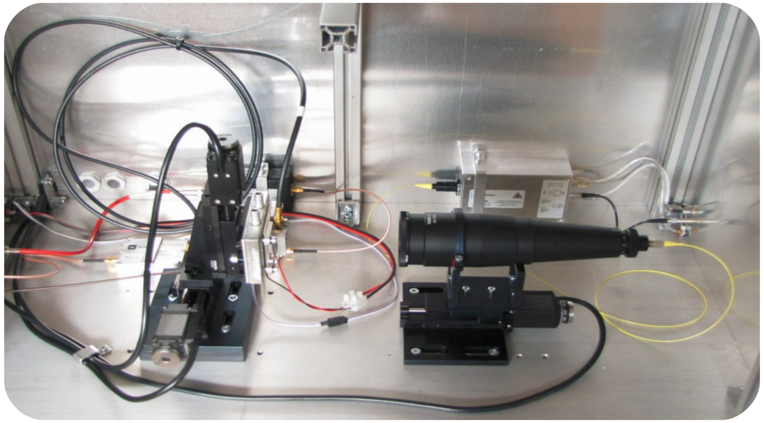
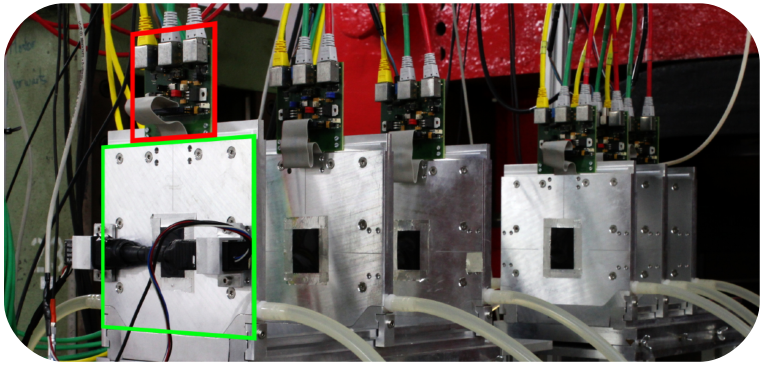
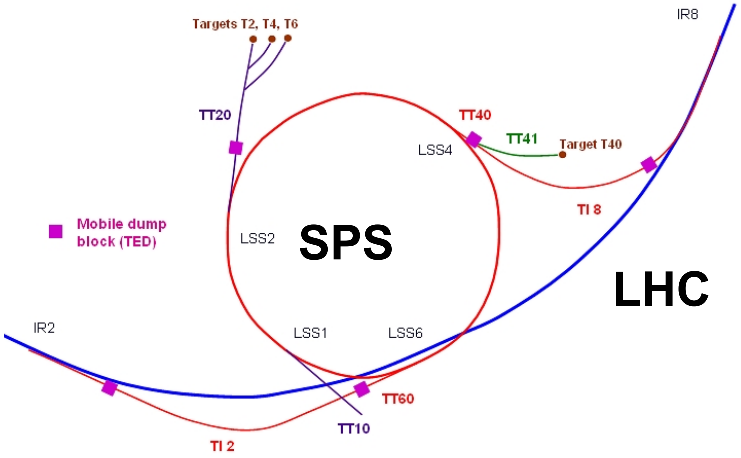
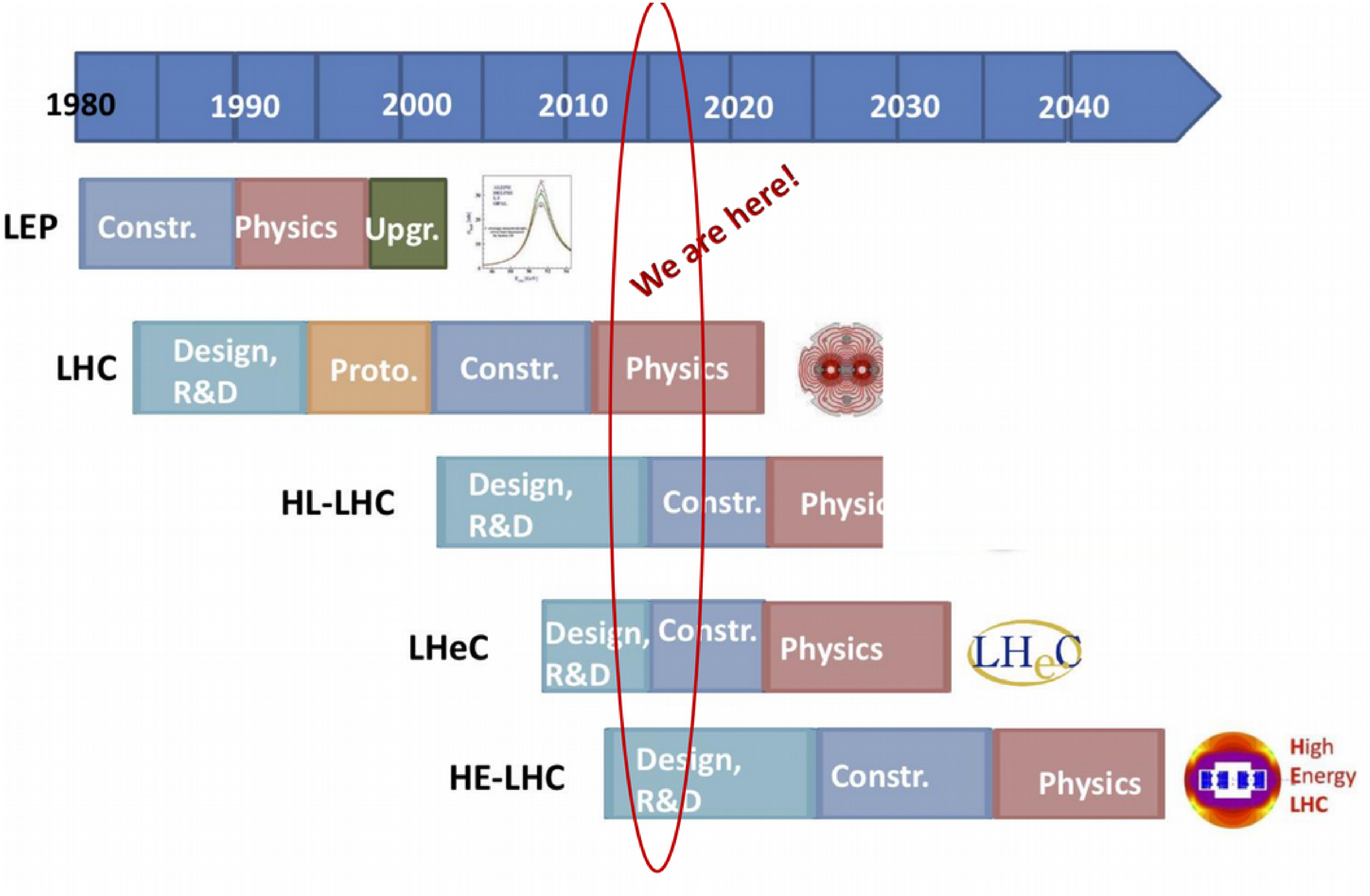






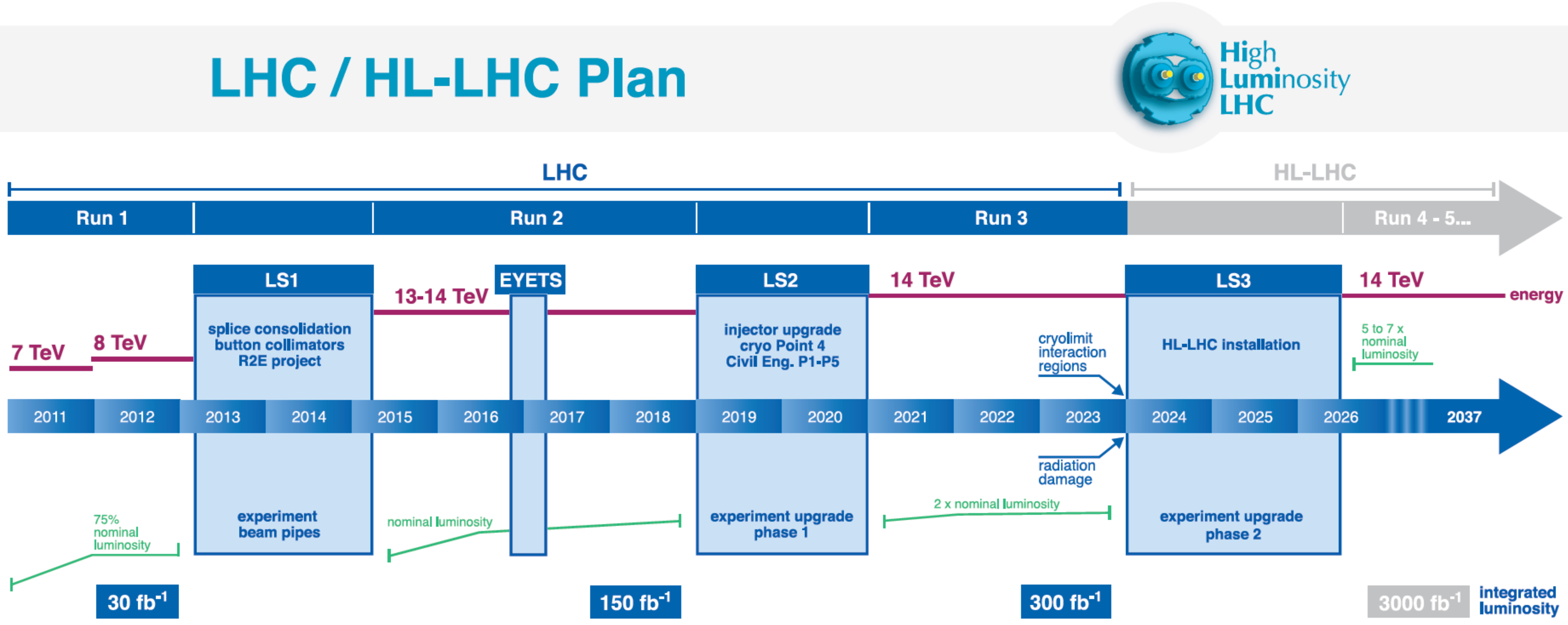
Past, present, future

- What fluences (and hence damage) shall we expect?



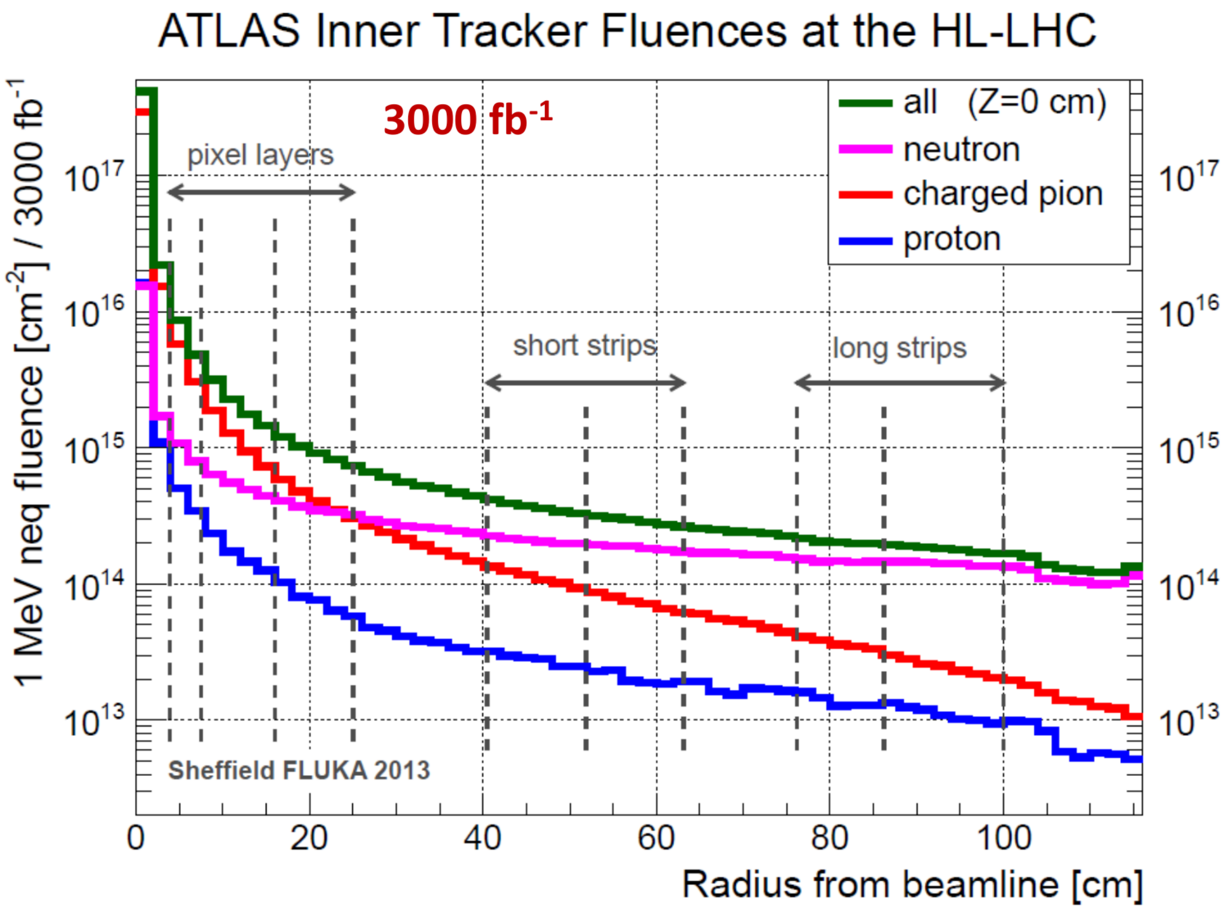
HL-LHC roadmap

- 300 fb-1 in 10 years of operation (end 2023)
- 3000 fb-1 expected for HL-LHC
  → for 10 y operation: yearly rad. damage of run I-III
- R&D takes time, better start now to be ready for installation in ~2024/25



Fluence

- Most damage for detectors close to the IP: usually vertex/pixel detector



I. Dawson, et al., Sheffield University,
ATLAS upgrade radiation background simulation

Fluence

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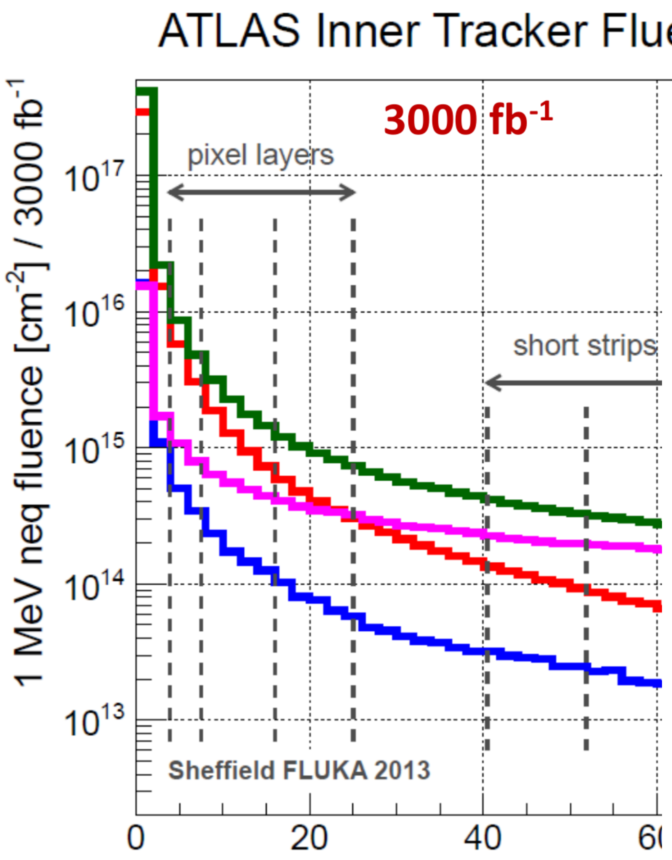
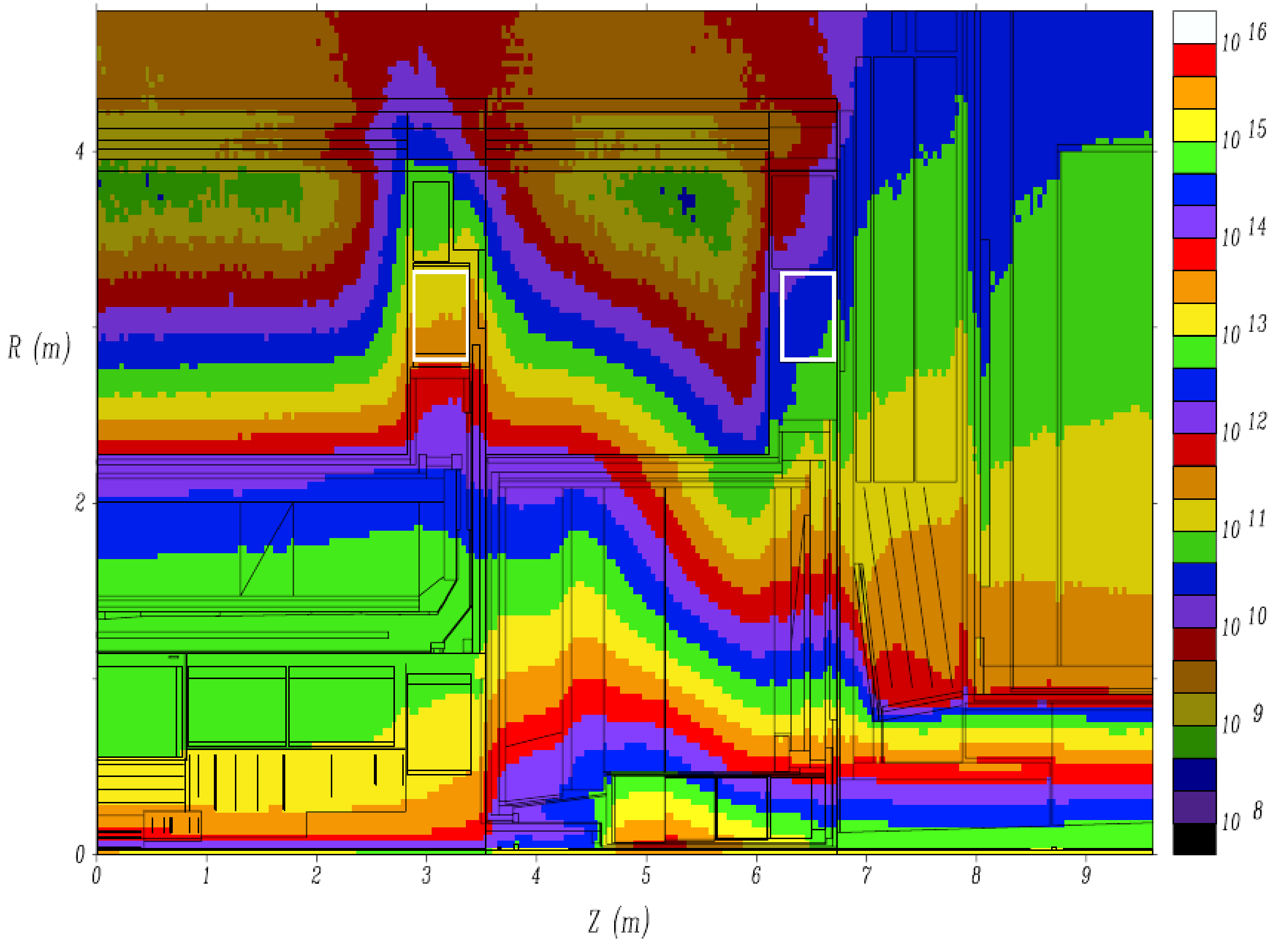
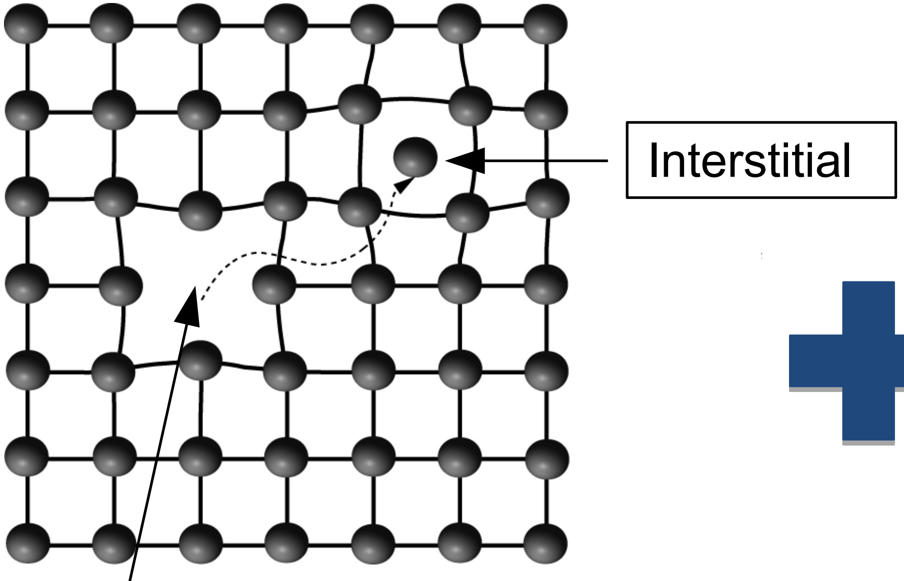

ATLAS Inner Tracker Fluences at the HL-LHC

2008 JINST 3 P10005

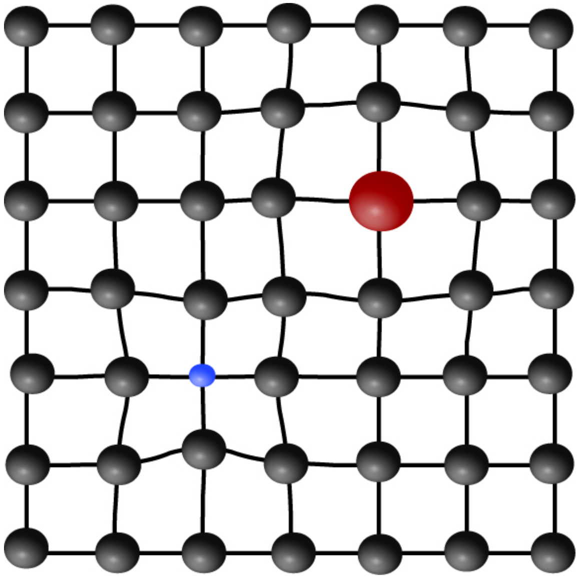


Radiation damage

- Radiation induced



- Material impurities



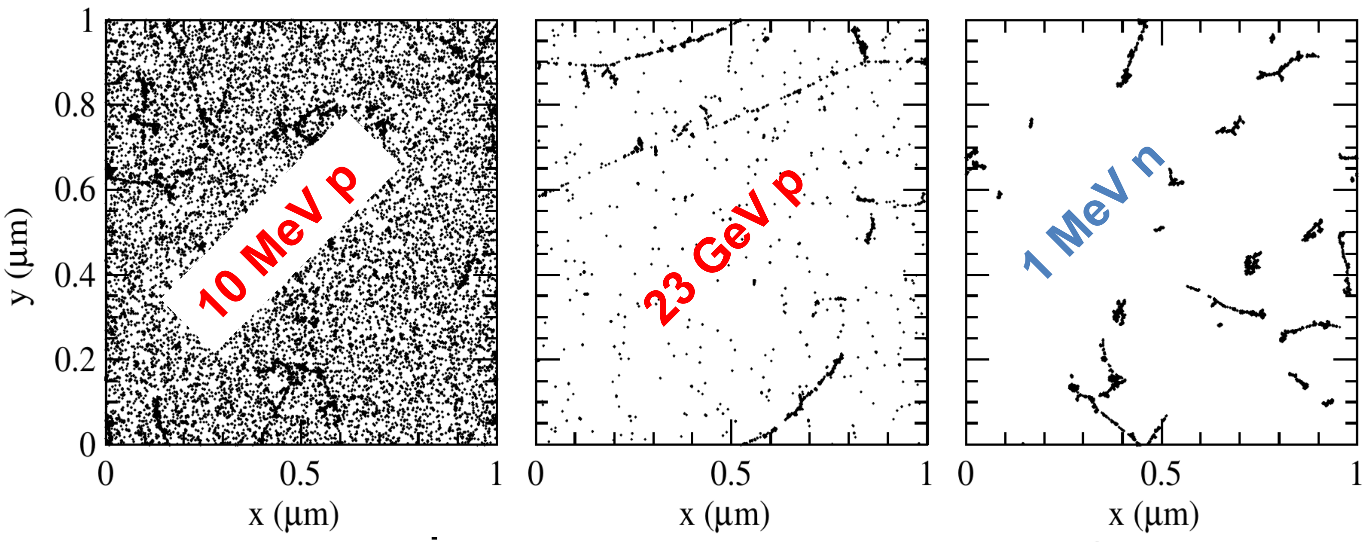
Bulk damage (NIEL):
- crystal damage created by neutrons, pions, protons, electrons
→ Irradiation + migration creates complex defects: V2, VO, …

Surface damage (IEL):
- at oxide-Si-interface

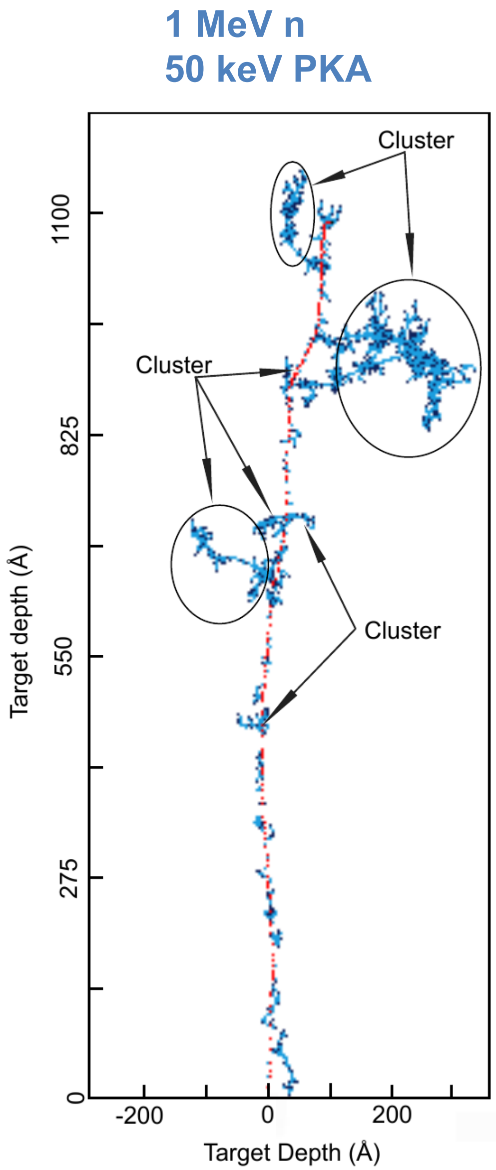
Thesis A. Junkes, UHH

Creation and impact of bulk defects

- Depends on particle charge, mass, energy



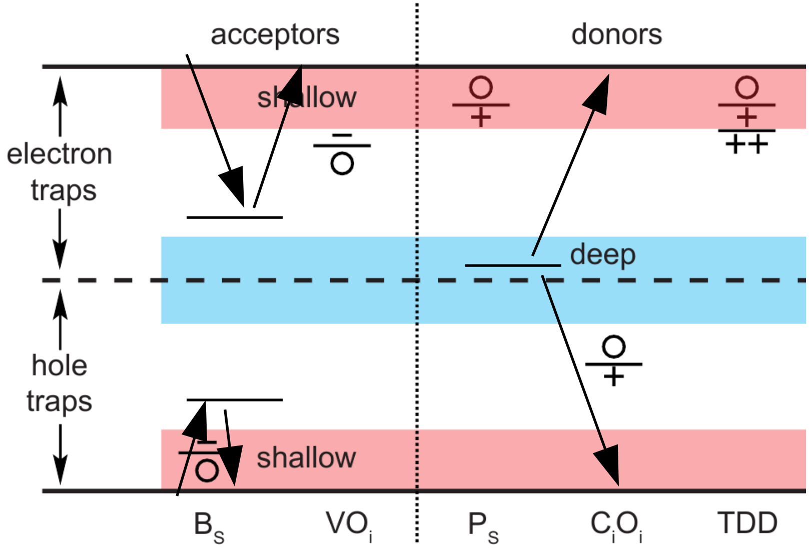
Mika Huhtinen, NIMA 491 (2002) 194



enable trapping, generation, recombination

$$\tau_{trapping} = \frac{1}{\sigma v_{th} N}$$

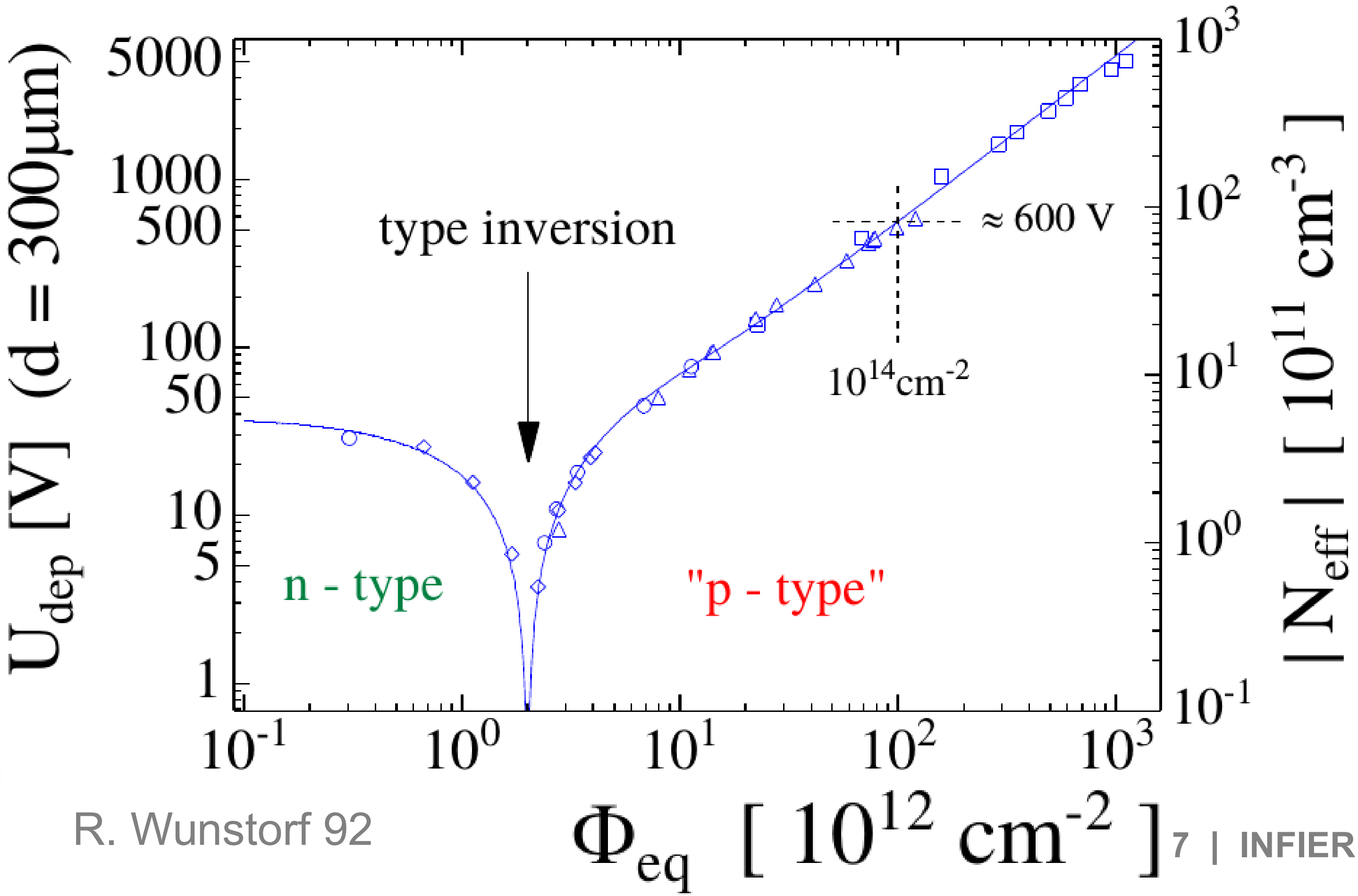
$$\tau_{detrap} = \frac{1}{\sigma v_{th} N} * \exp\left(E_a / k_B T\right)$$



Read more in:
Thesis A. Junkes, UHH

Macroscopic effects

- Change of depletion voltage (and possible type inversion)



R. Wunstorf 92

Macroscopic effects

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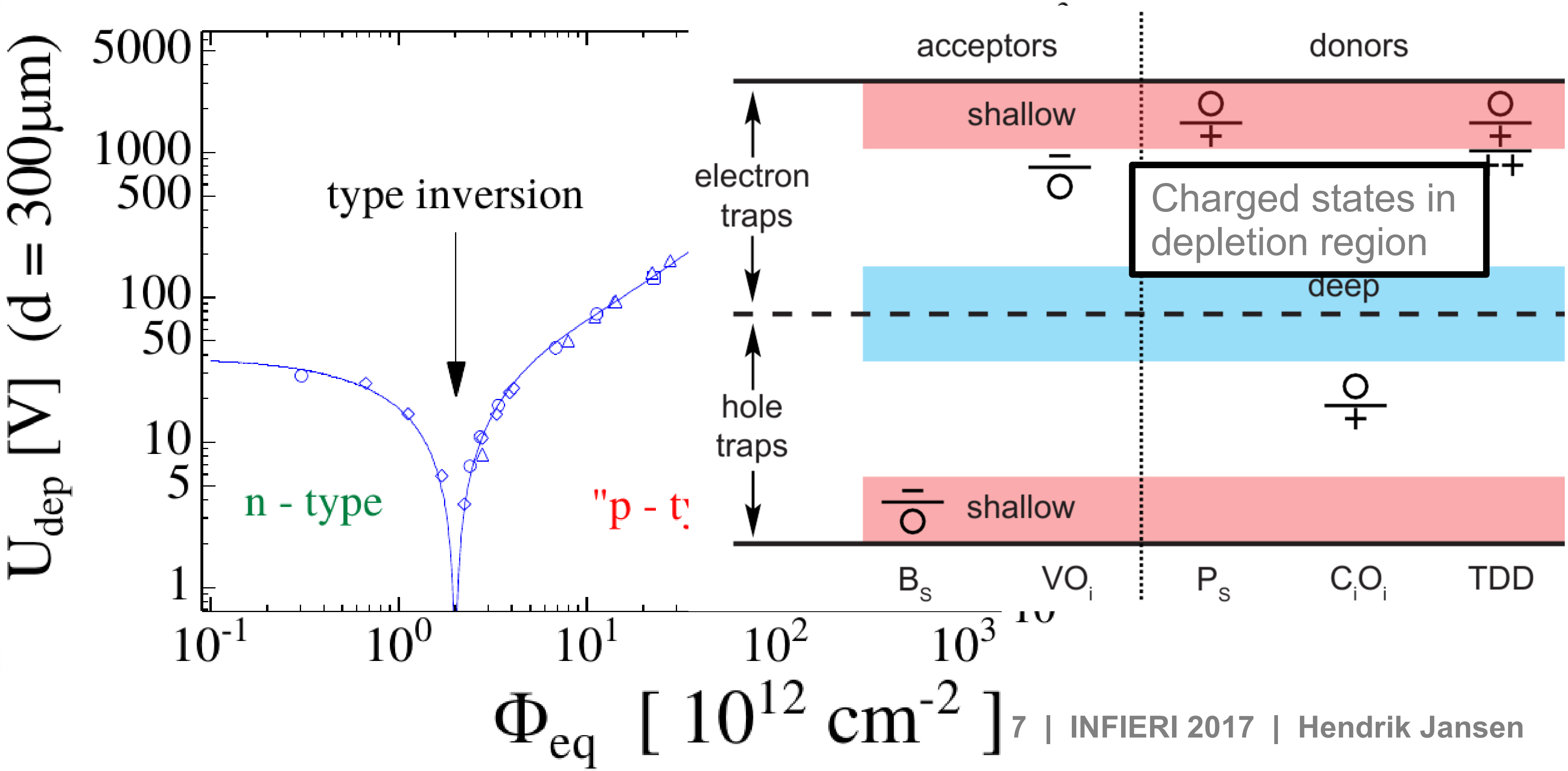
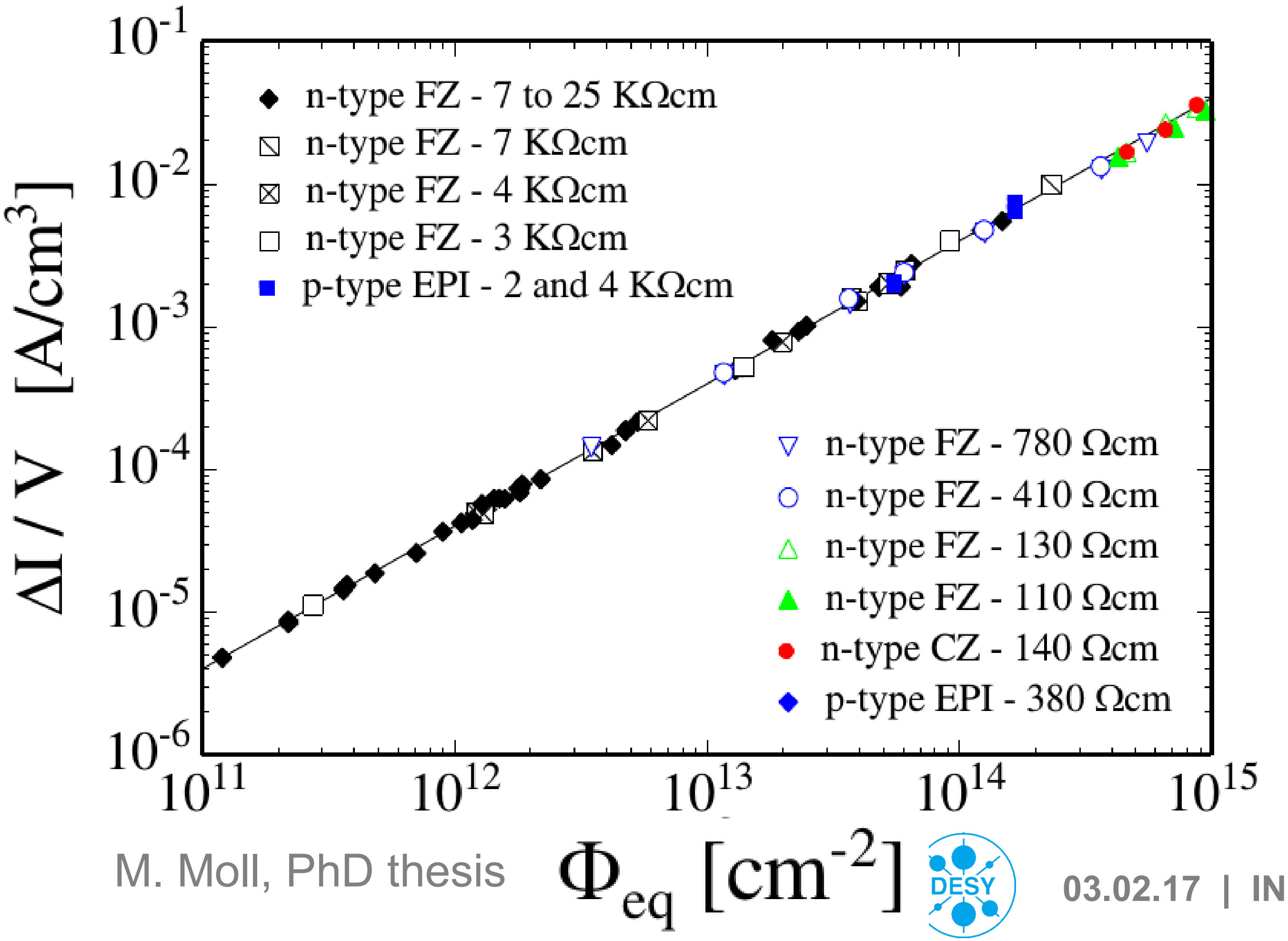


Charged states in depletion region

Macroscopic effects

- Change of depletion voltage (and possible type inversion)
- Increase in leakage current



M. Moll, PhD thesis

Macroscopic effects

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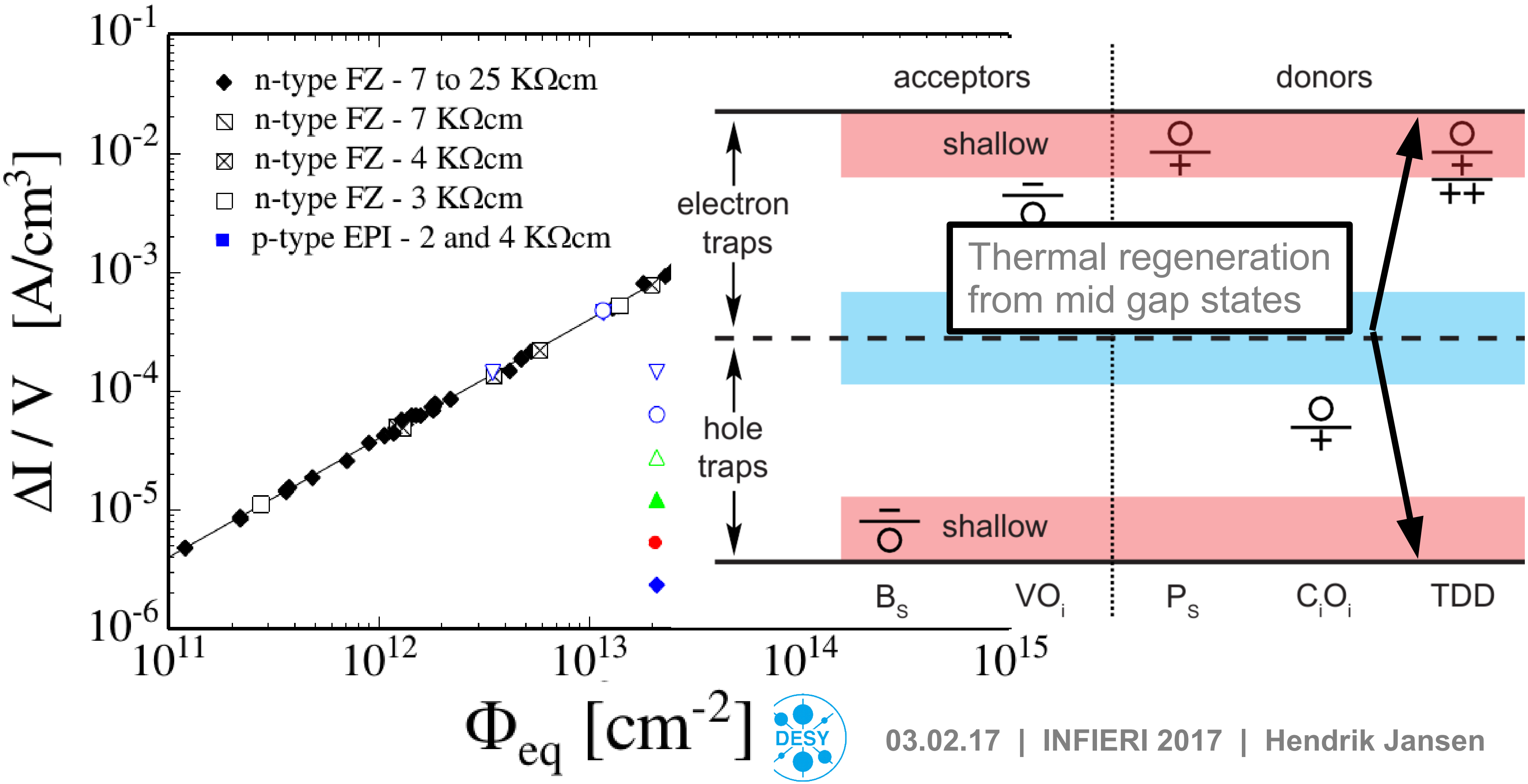
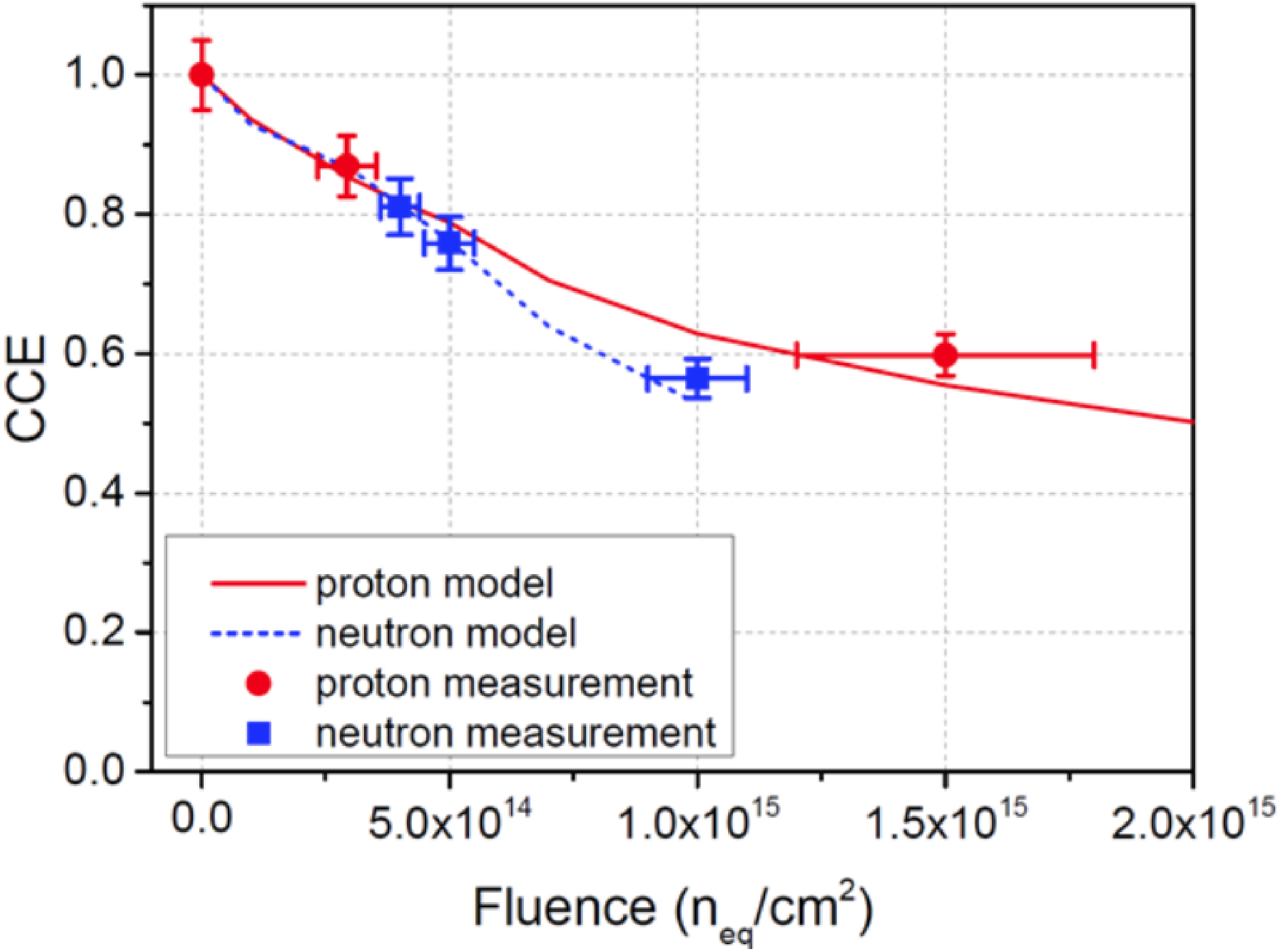


Thermal regeneration from mid gap states

Macroscopic effects

- Change of depletion voltage (and possible type inversion)
- Increase in leakage current
- Decrease in charge collection efficiency



CMS Tracker JINST 9 (2014)12

Macroscopic effects

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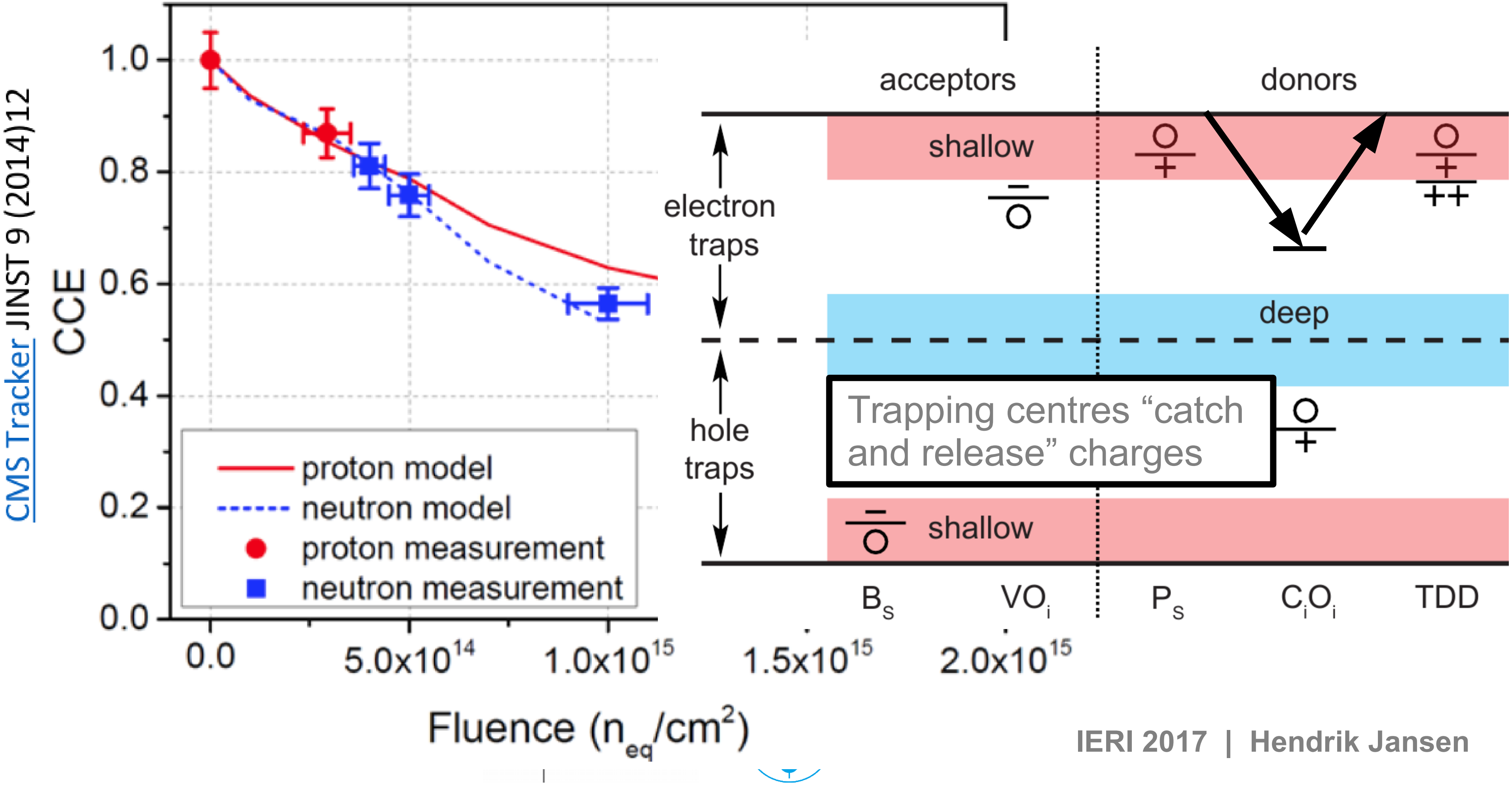
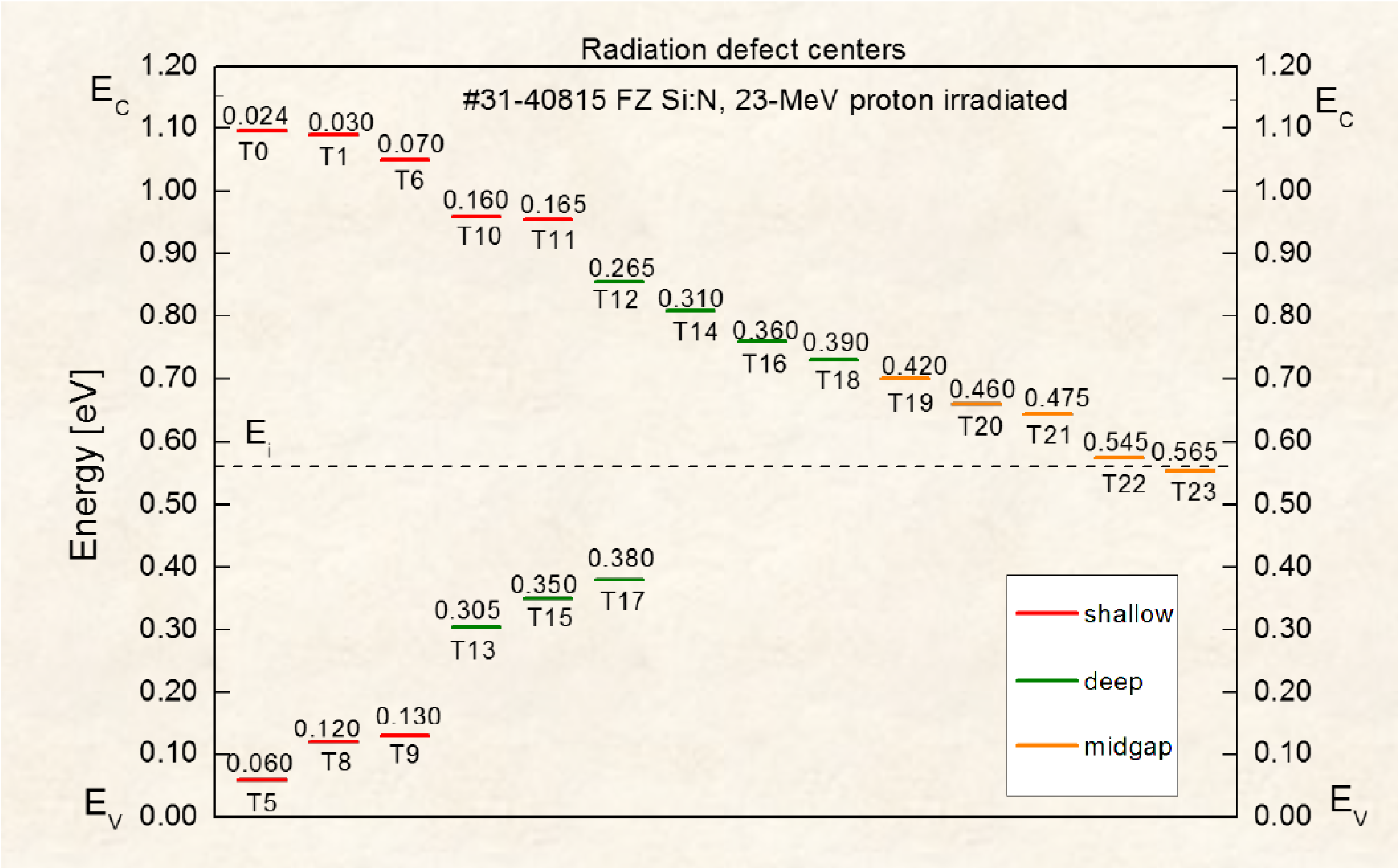


CMS Tracker JINST 9 (2014)12

Trapping centres “catch and release” charges

Cumbersome work ….

- Identification of ~20 defects in silicon

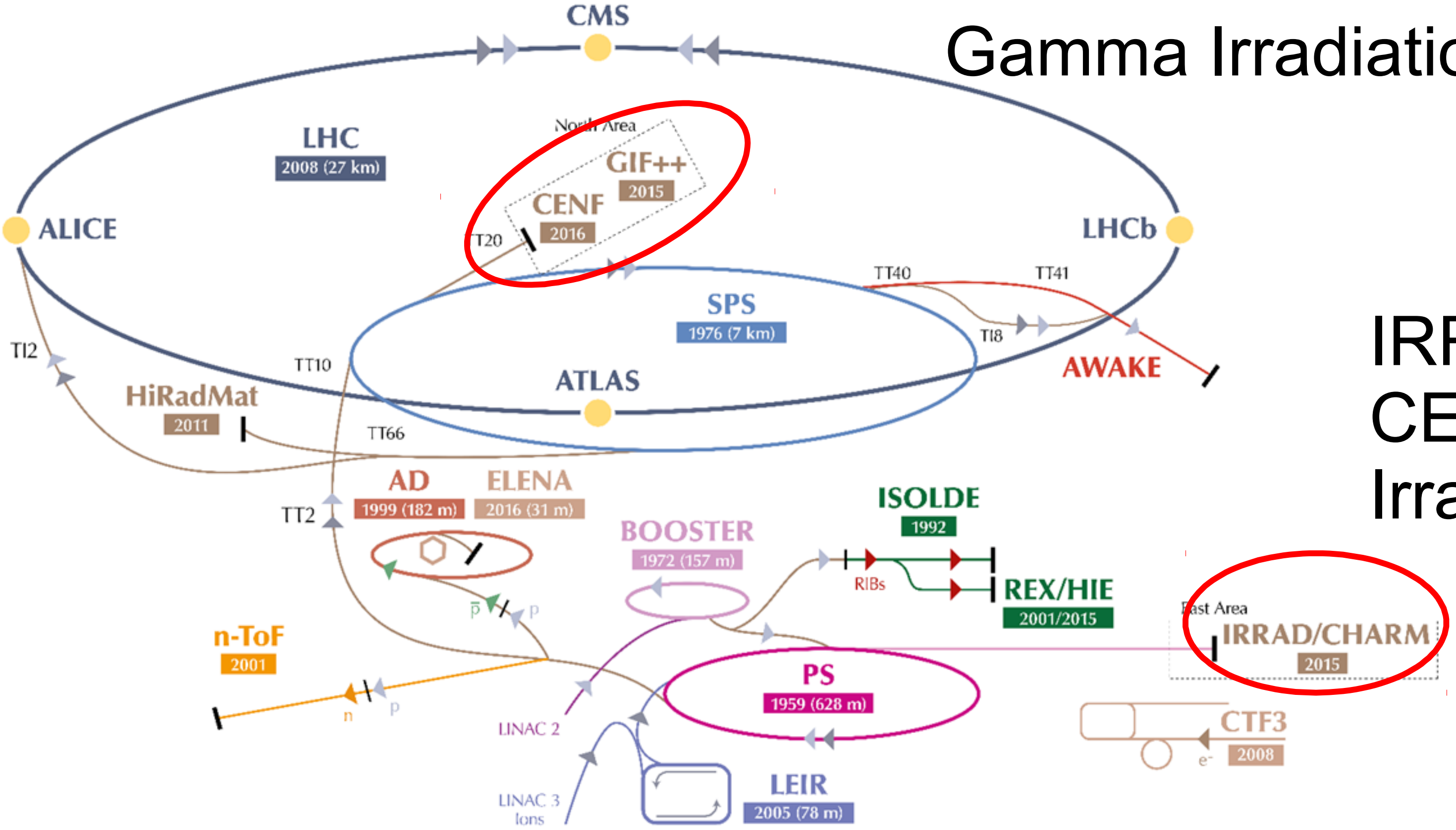


We’ll see later about the techniques ….

P. Kaminski et al., 29th RD50

Keeping ahead of damage

- Dedicated irradiation facilities to simulate expected flux
- Damage depends on particle type and energy
  → many facilities



GIF:
Gamma Irradiation Facility

IRRAD:
CERN Proton
Irradiation Facility

Material from B. Gkotse, BTTB5

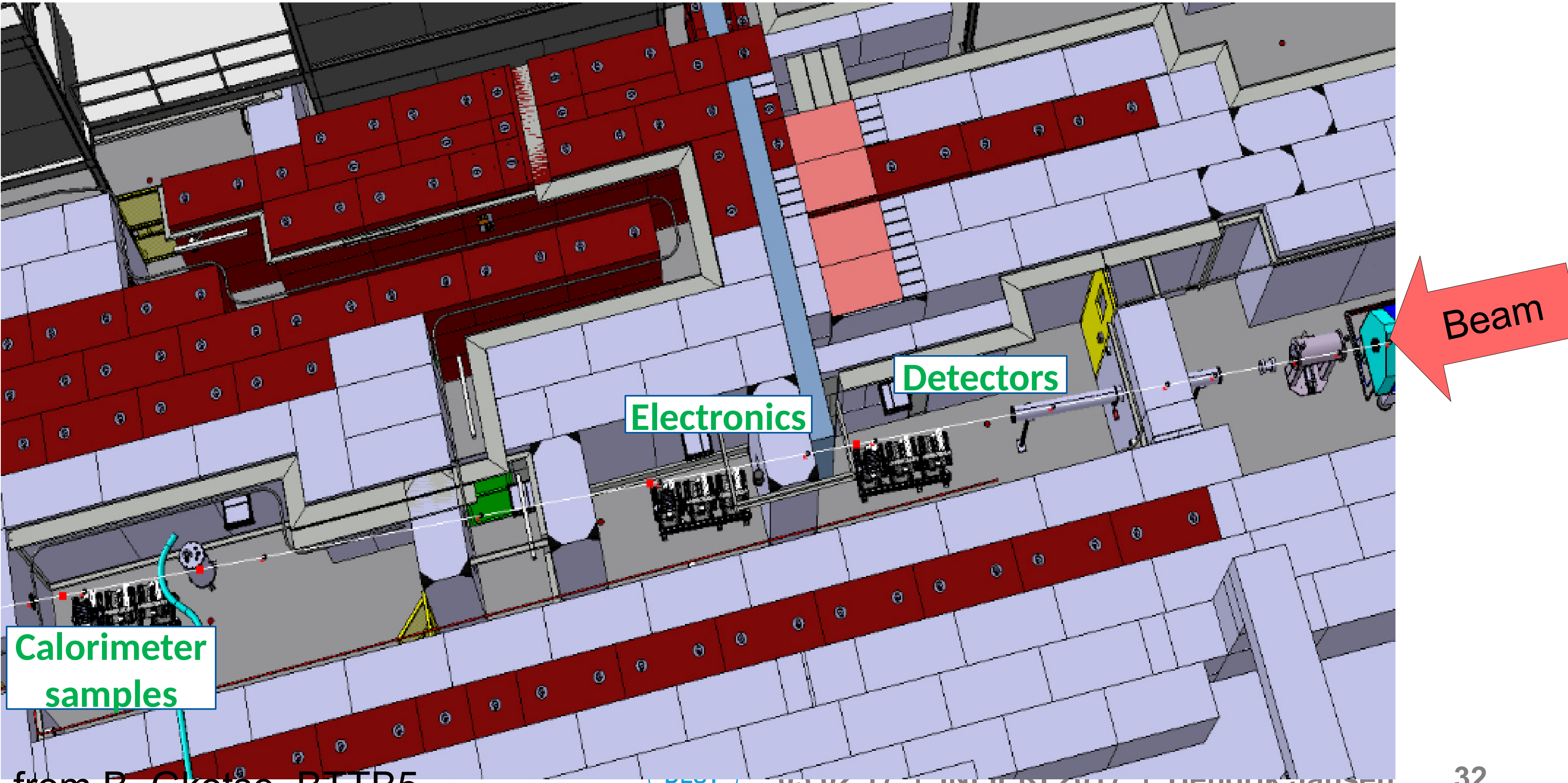
GIF

- E_γ = 0.66 MeV; max. dose-rate 2.5 Gy/h @ glass contact

Material from B. Gkotse, BTTB5

IRRAD

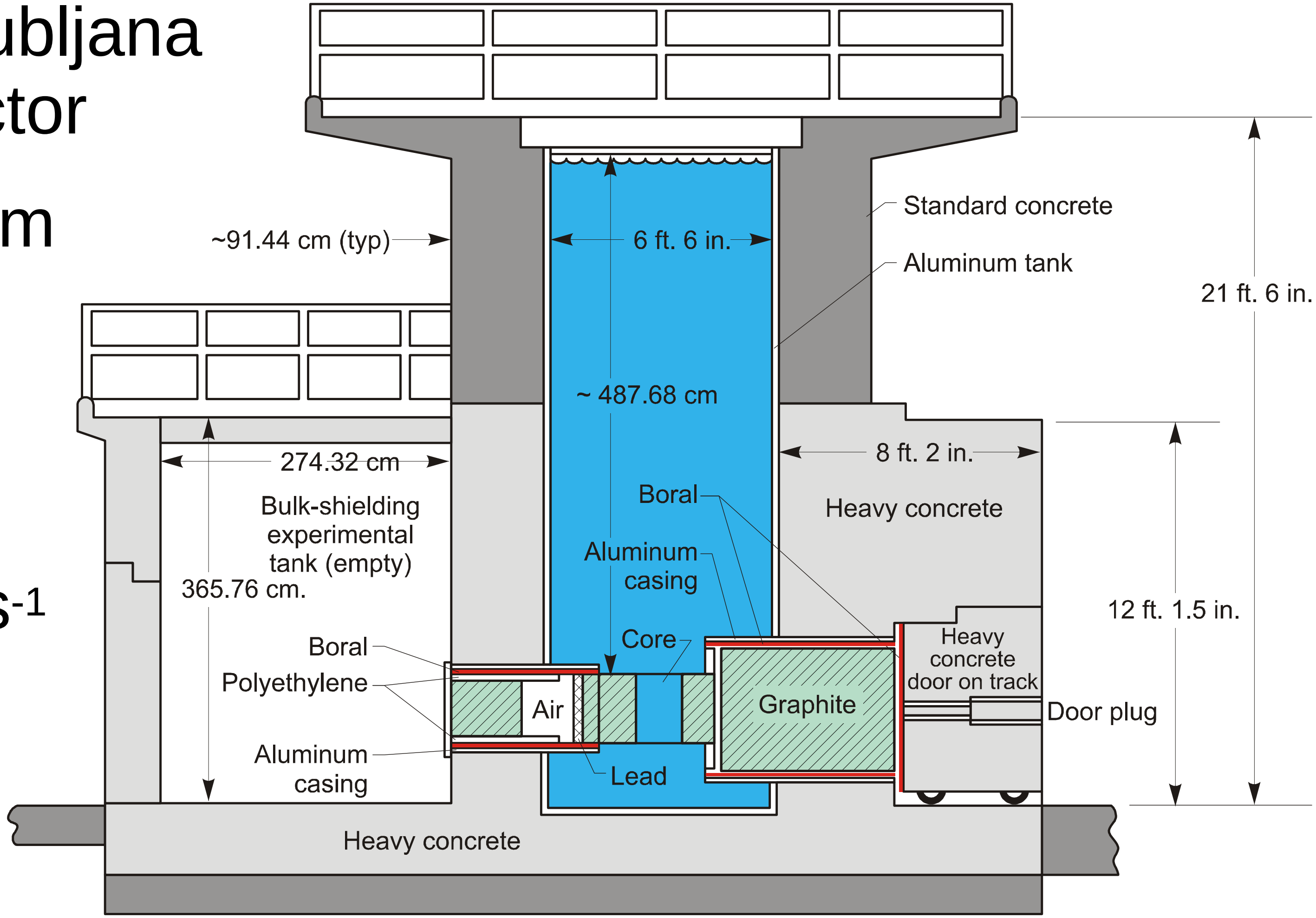
- Component testing of HEP experiments
- Proton beam of 24 GeV/c, 12 x 12 mm^2
- Fluence: 1e16 p/cm^2 in 14 days



Material from B. Gkotse, BTTB5

Other irradiation facilities

- Neutron damage is also important
- Neutron irrad. possible at reactors, e.g. Ljubljana JSI TRIGA Reactor
- 250 kW maximum
- Fast & thermal neutrons
- Flux: up to 4e12 cm^{-1}s^{-1}



Material from B. Gkotse, BTTB5

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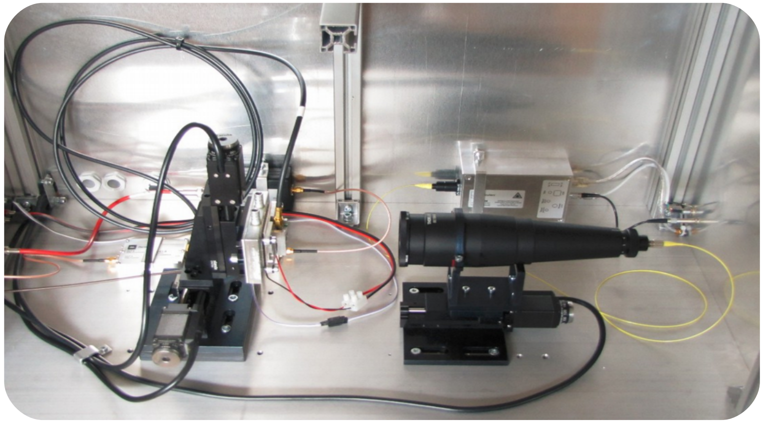
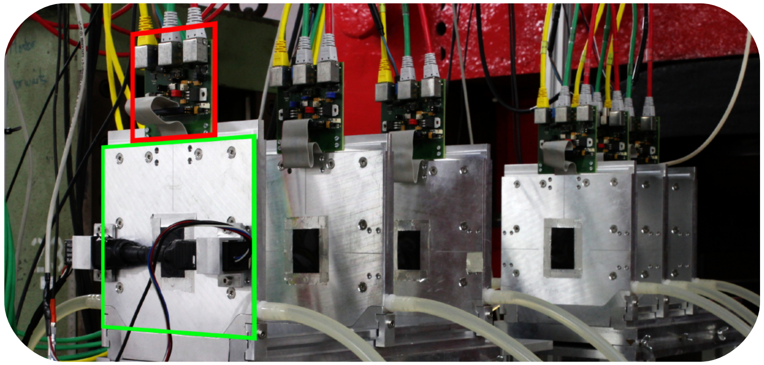
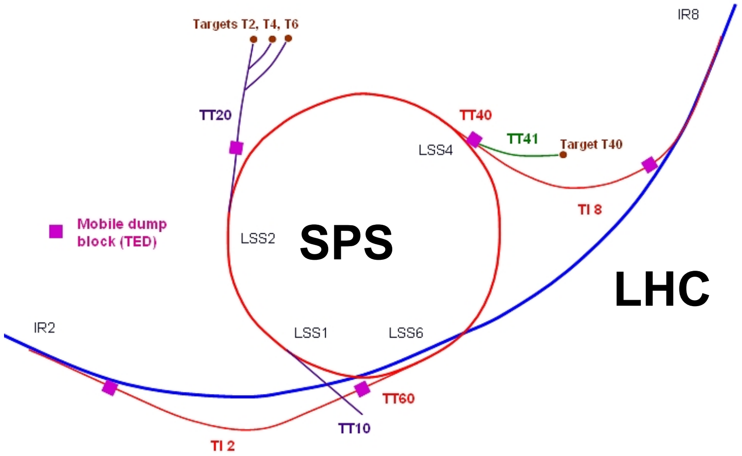
  - why we need to do better
- Radiation damage in semiconductor sensors
- **Characterisation techniques**
  - **lab-based**
  - with beams
- Clever ideas confronting radiation damage





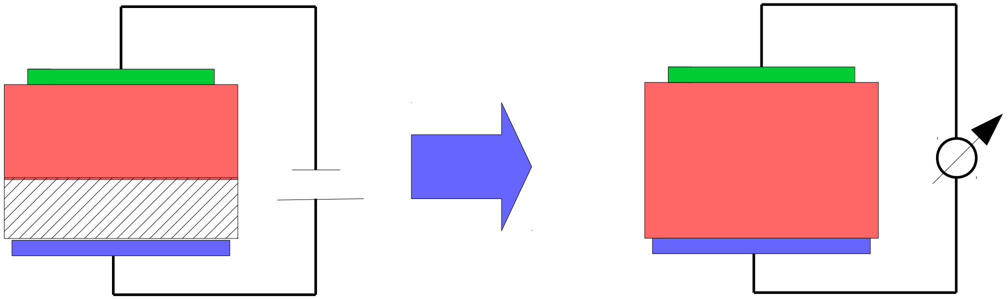


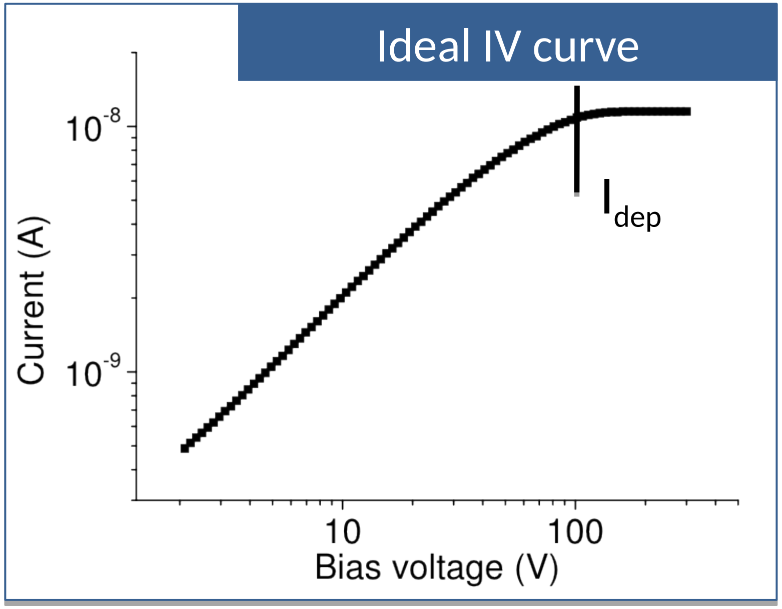
Basic sensor tests

CV and IV measurements

- Use a probe station
- IV (back → front) shows current characteristic:

  reverse current, depletion current/voltage, breakdown, …





Courtesy A. Junkes

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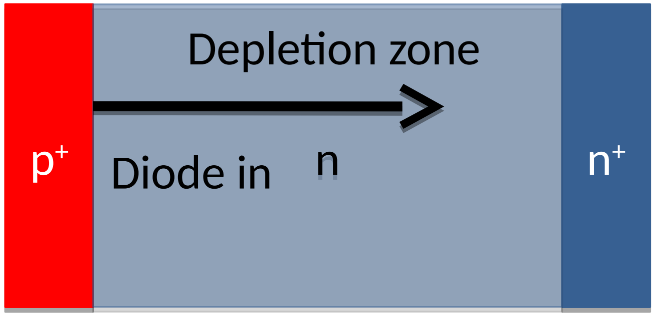
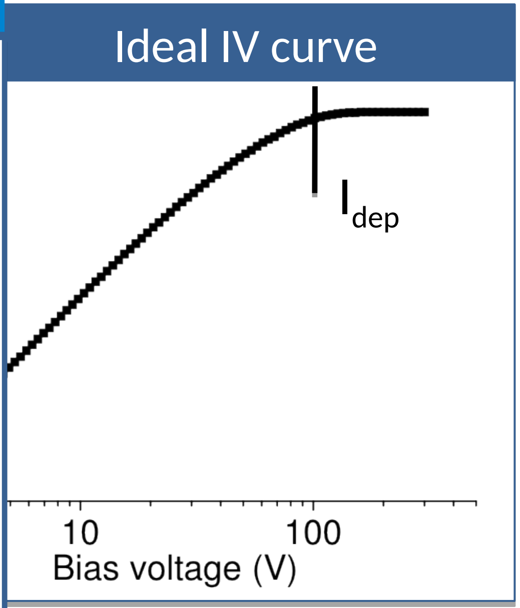
  reverse current, depletion current/voltage, breakdown, …

Basic pn-junction properties



reverse-bias reveals
- I_{dep}
- V_{dep} ($\propto N_{eff}$)
- C_{end} (detector thickness)

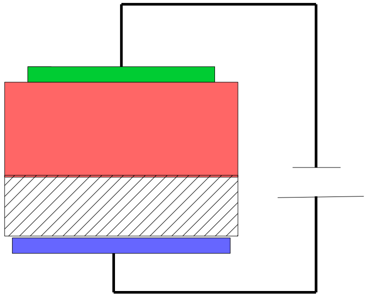
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

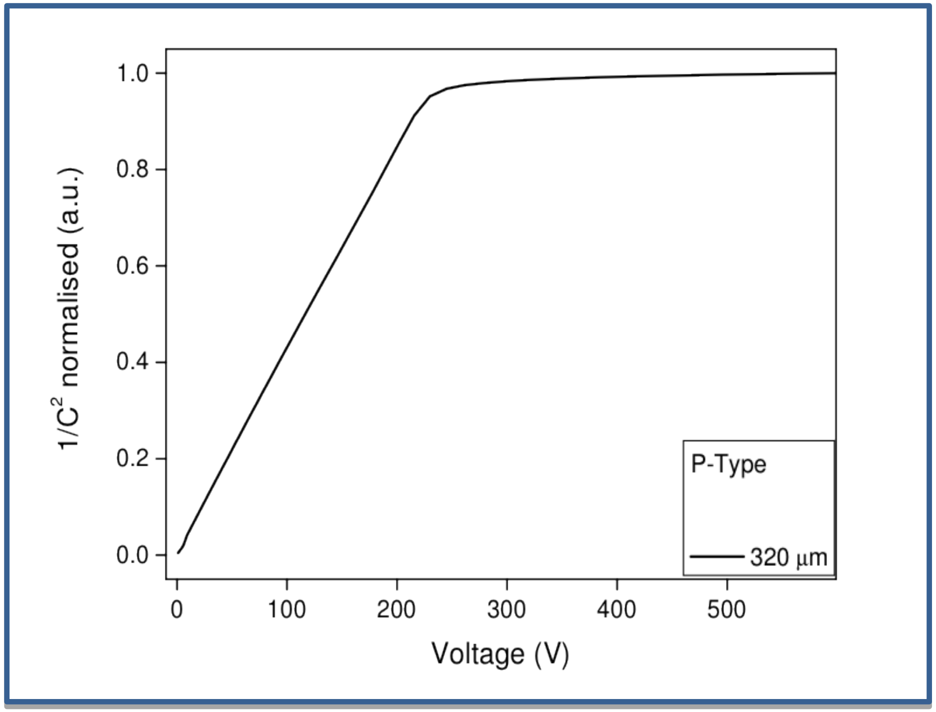


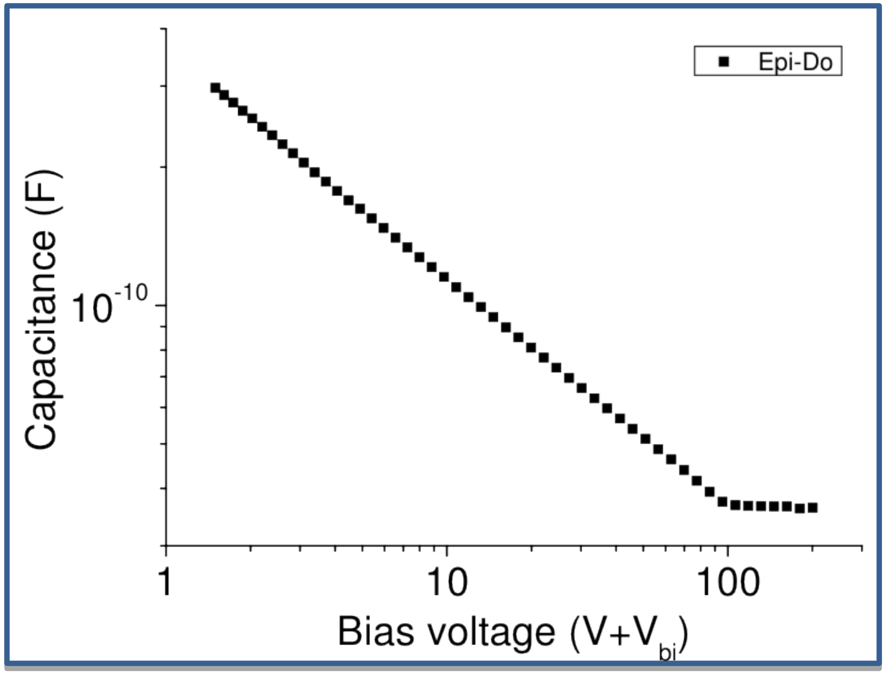
Courtesy A. Junkes

CV and IV measurements

- Use a probe station
- IV (back → front) shows current characteristics
- C vs V or 1/C^2 vs 1/V reveals full depletion voltage and detector capacitance



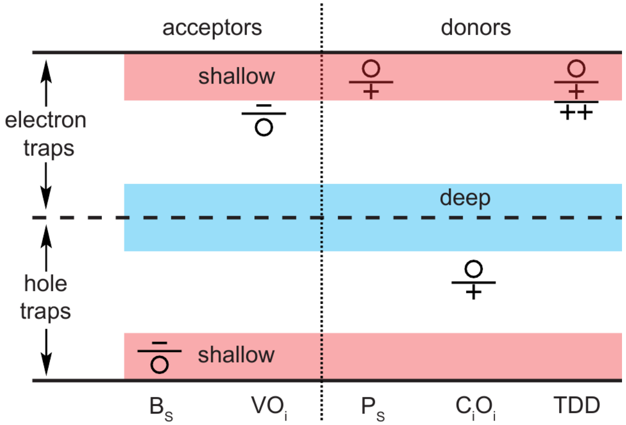




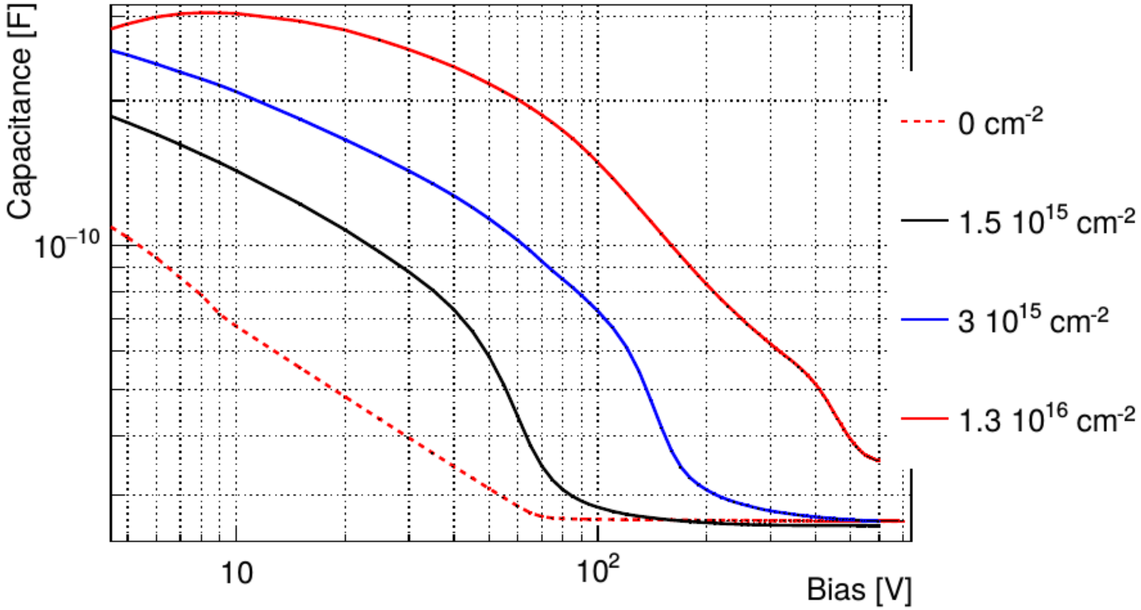
Courtesy A. Junkes

CV and IV measurements

- What happens with irradiation?

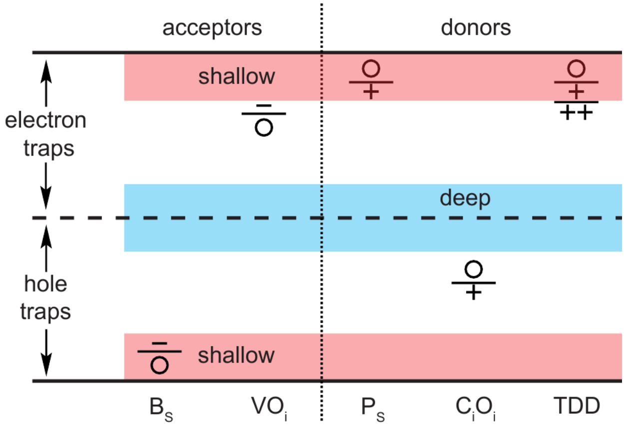


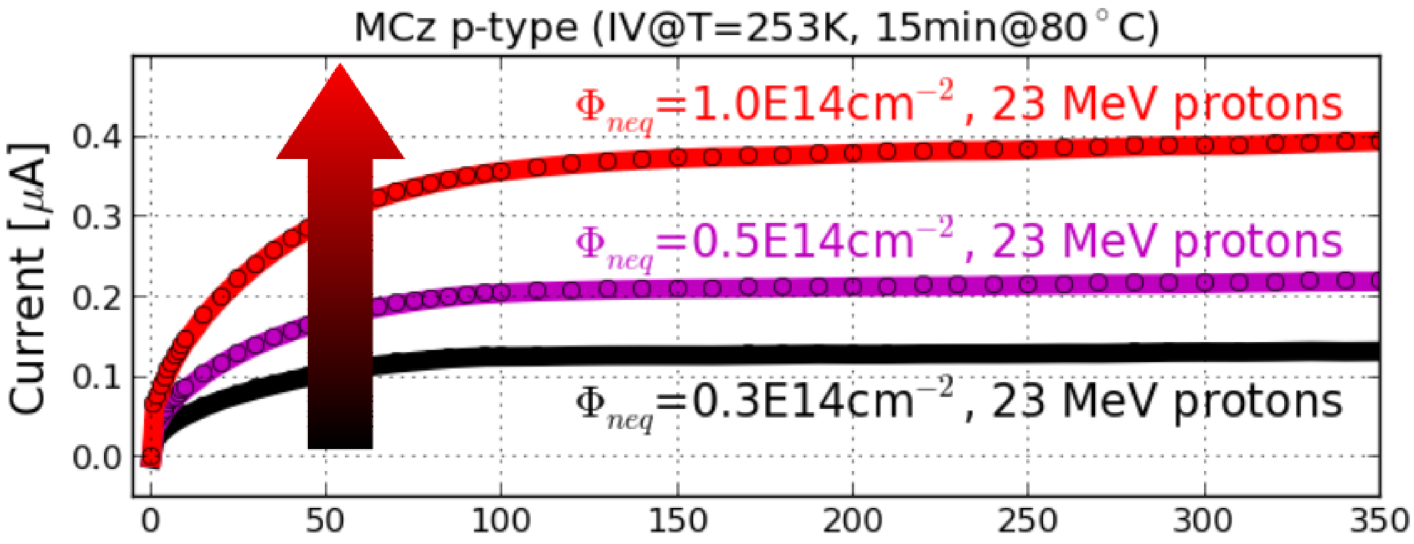
Matteo Centis, Thesis UHH



CV and IV measurements

- What happens with irradiation?

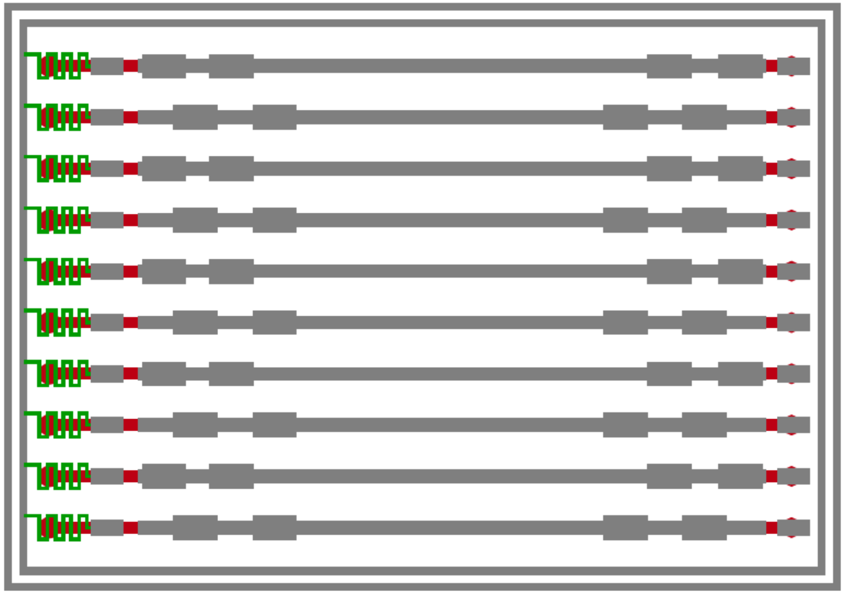


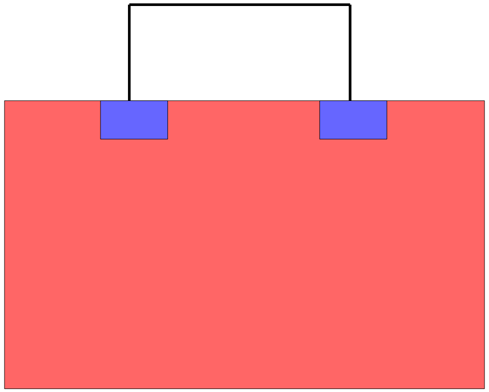


Elena Dolegani, 29th RD50

CV and IV measurements

- Use a probe station
- IV (back → front) show current characteristic
- C vs V or $1/C^2$ vs 1/V reveals full depletion voltage
- IV (bias-ring → strip): poly-silicon resistor
- IV, CV (strip → strip): inter-strip resistance/capacitance



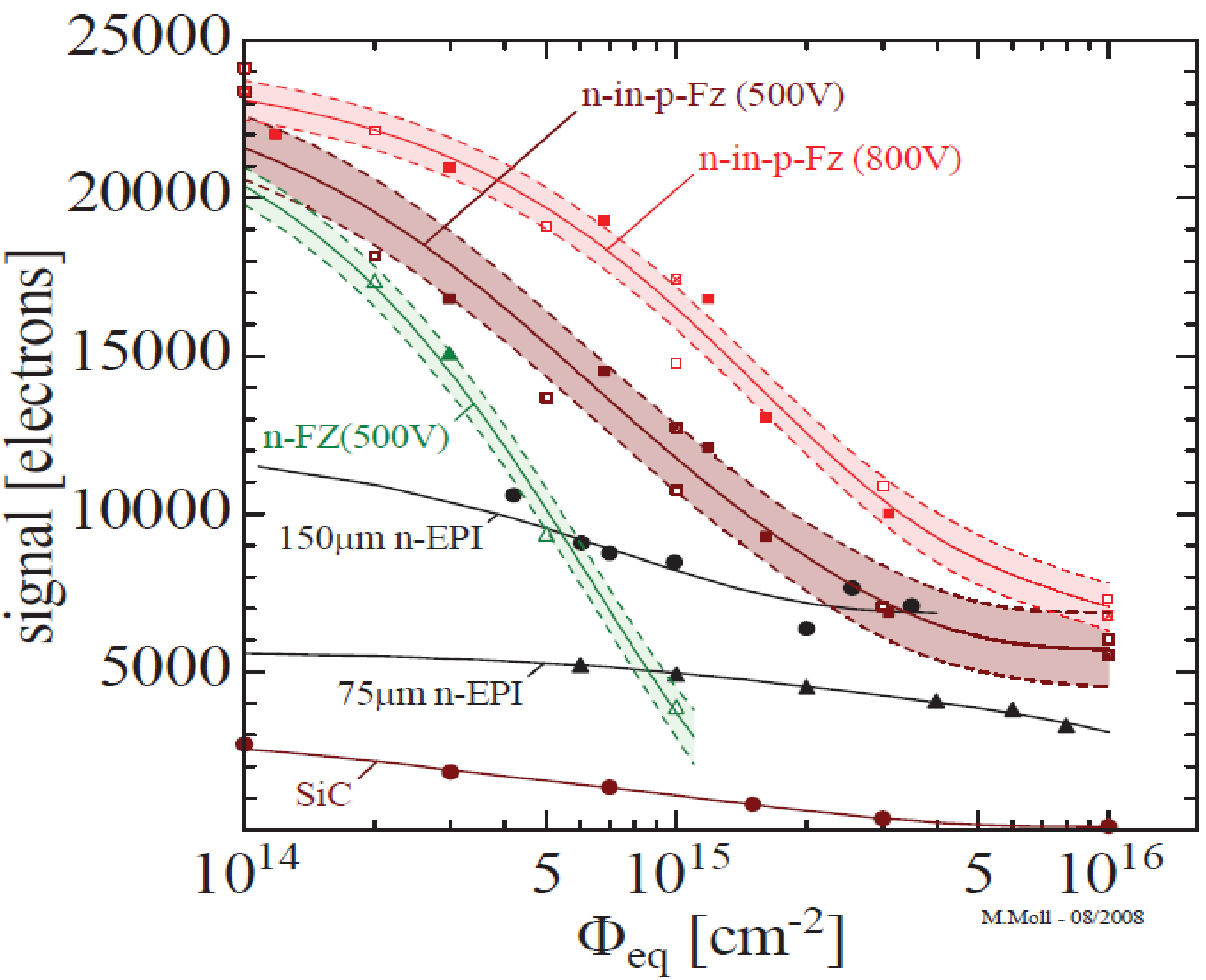


TSC measurements

Why material studies?

- Signal degradation depends on

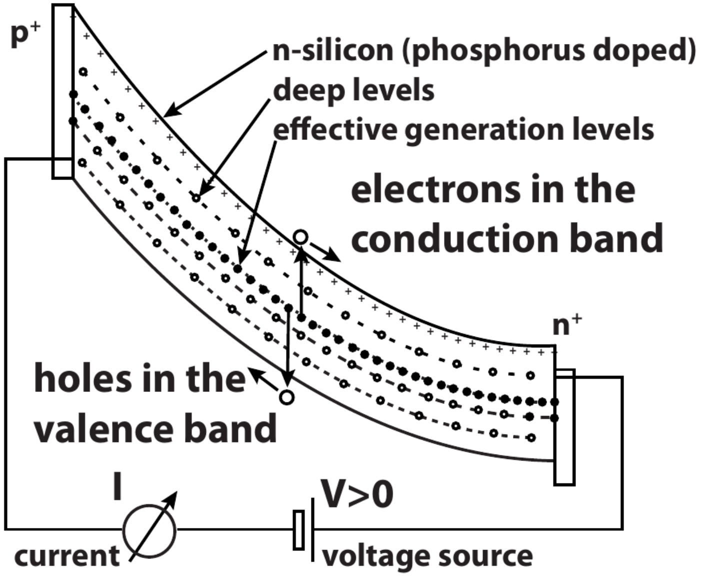
  - thickness
  - operation voltage
  - fluence
  - material



Thermally stimulated current technique

- Principle:
  1) Cooling
  2) Filling of traps (once per cycle)
  3) Heating + recording current
  4) Data analysis

1



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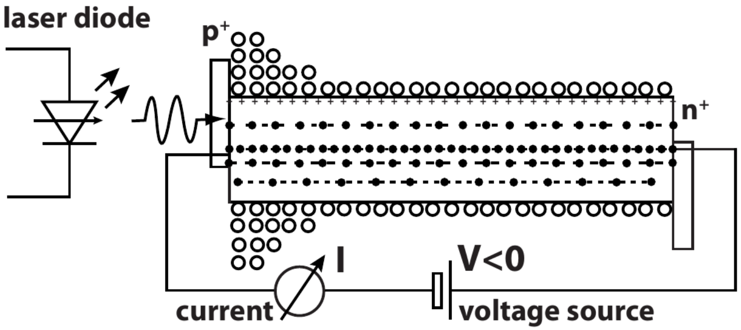
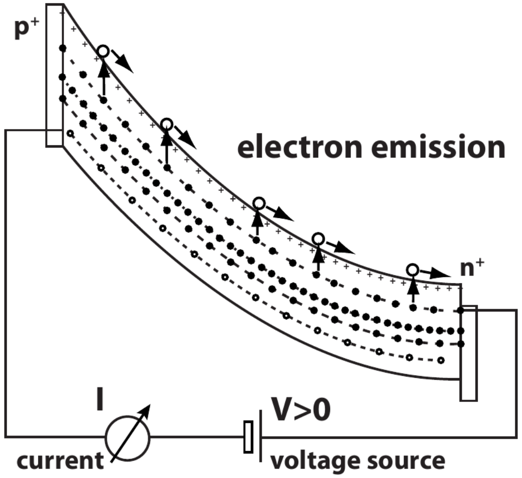
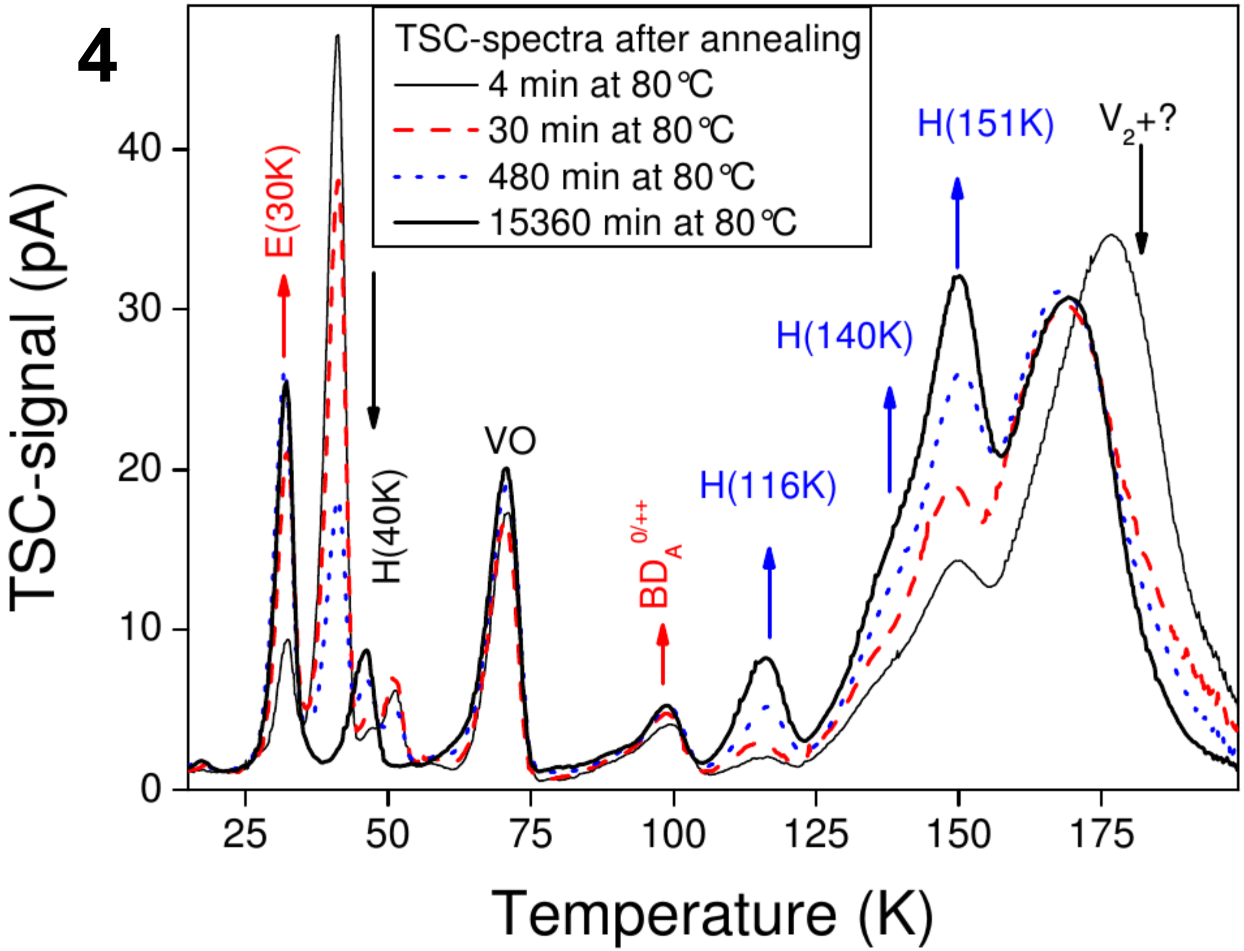


3



The analysis



→ Energy from rising edge
→ N_t from area
→ σ from fit to peak

Defect spectroscopy:
Calculate concentration, energy, and cross-section from TSC-signal:
- shallow traps towards low T
- deep traps towards high T

Annealing at 80 C:
- Simulate shut-down time in short period.
- what happens electrically

Annealing at 200 C:
- Affects also the crystal structure itself: Migration of silicon atoms from e.g. interstitials to vacancies
- Defect identification

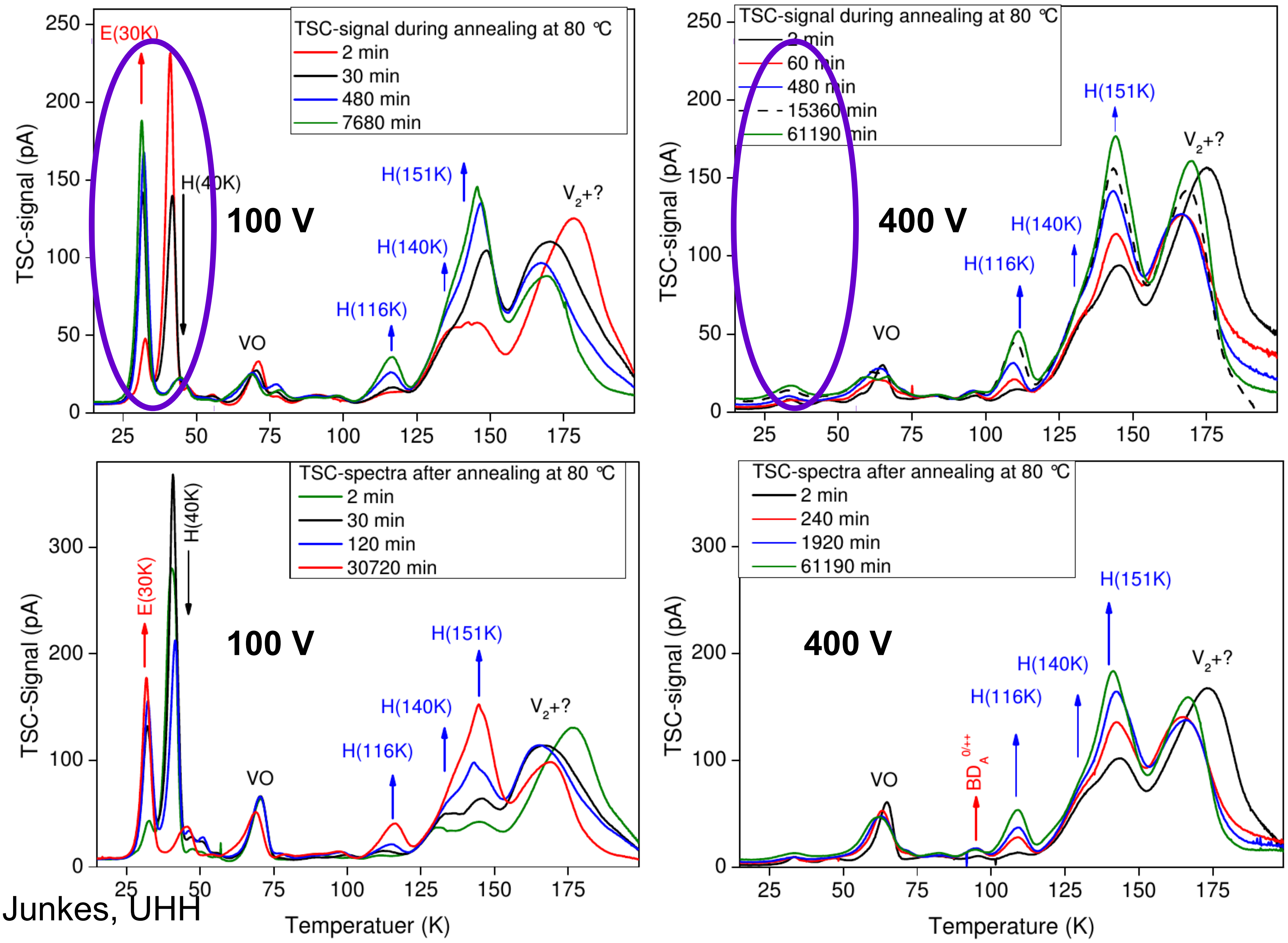
Thesis A. Junkes, UHH

Comparison

@ 1e15 n

Epi-standard

Epi-oxygen enriched

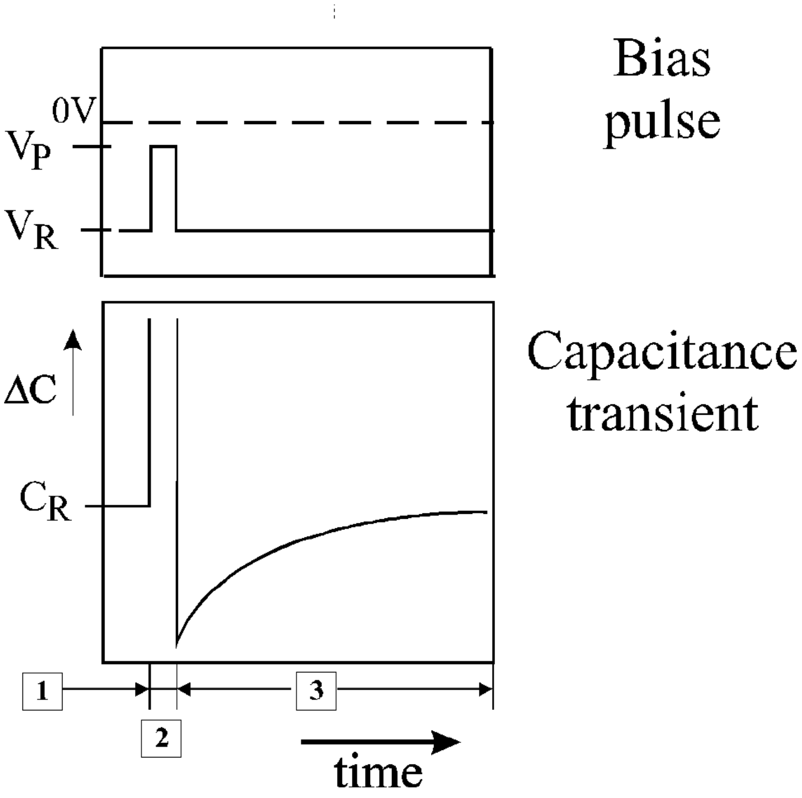


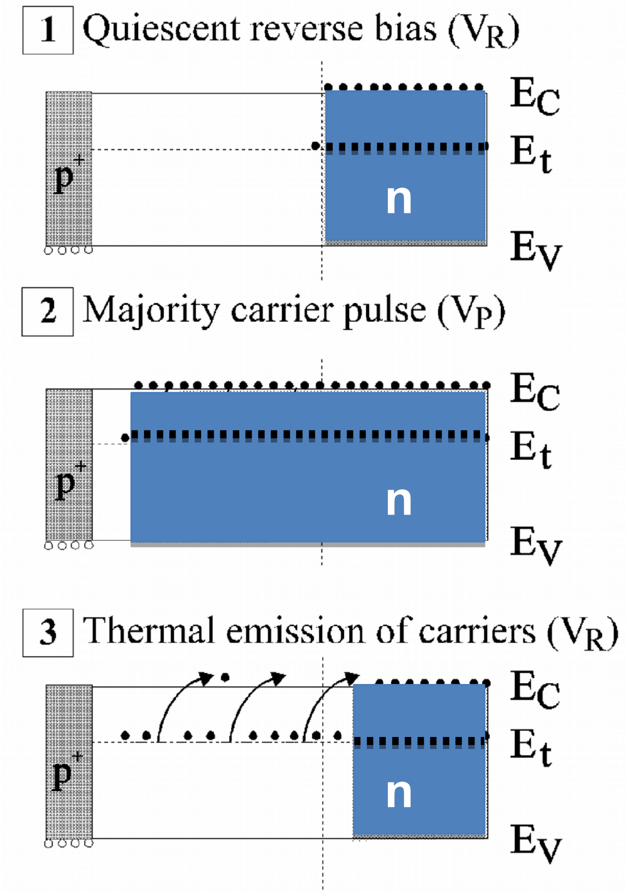
Thesis A. Junkes, UHH

DLTS measurements

Deep Level Transient Spectroscopy

- Principle:
  1. Diode under reverse-bias
  2. Filling of traps with charge carriers at various T
  3. Emission from filled traps → change of capacitance

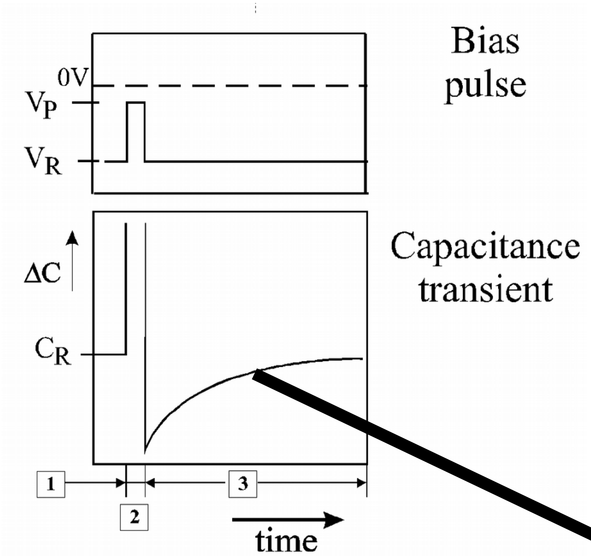


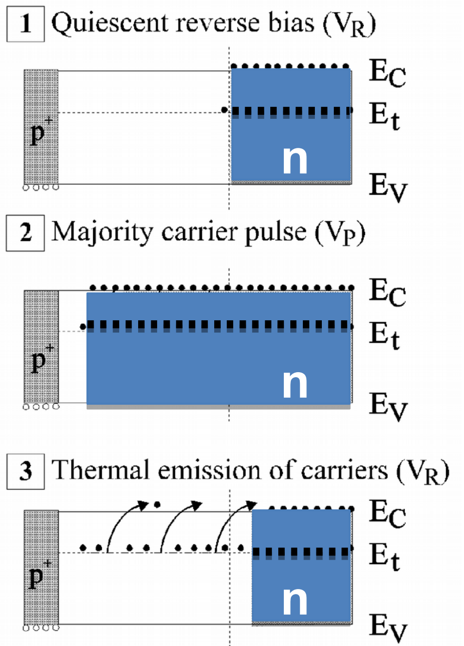


Thesis M. Moll, UHH

Deep Level Transient Spectroscopy

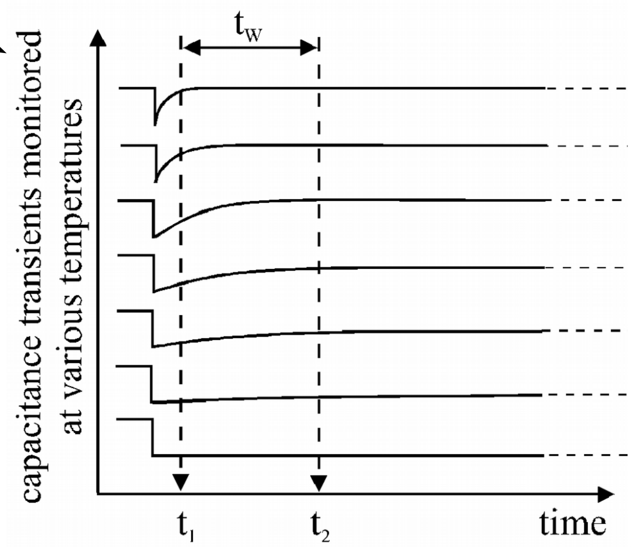
- Principle:





- Multi-shot technique
  → Traps filled for each T!
  - Capacitance transient recorded a.f.o. t, T
  - Transient follows: $\Delta C(t,T) = \Delta C_0 \exp(-e_n(T)\cdot t)$
  - Emission time constant from shape
  - Concentration:

$$N_t \approx 2N_D \frac{\Delta C}{C_0}$$



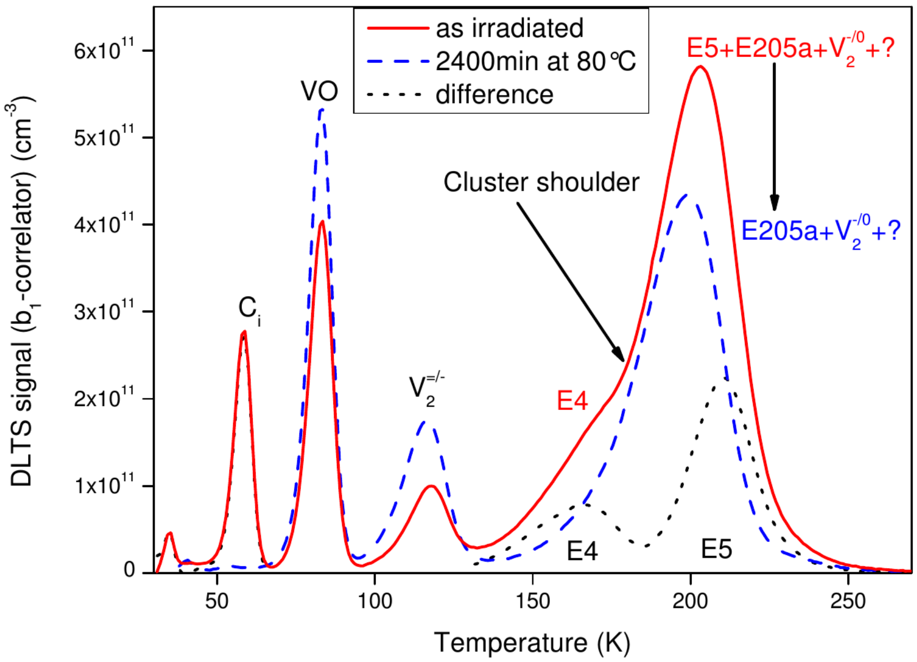
$$\tau_{trapping} = \frac{1}{\sigma v_{th} N}$$

$$\tau_{detrap} = \frac{1}{\sigma v_{th} N} * \exp\left(E_a / k_B T\right)$$

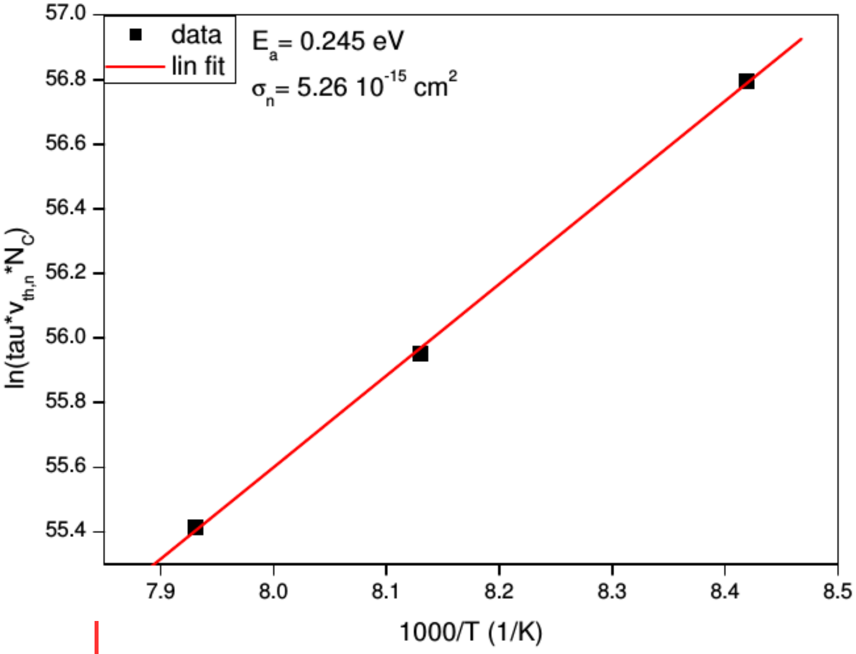
M. Moll, PhD thesis 1999, Uni HH

Analysis

- From ΔC vs T:



From transient:



Thesis A. Junkes, UHH

$$e_{n,p} = \sigma_{n,p} v_{th,n,p} N_{C,V} \exp\left(-\frac{\Delta E_a}{k_B T}\right)$$

from fit

from literature

from measurement

$$v_{th,n,p} = \sqrt{\frac{3k_B T}{m^*_{n,p}}}$$

$$\frac{e}{v N_C} \equiv \frac{1}{\tau v N_C} = \sigma \exp(-E_a/kT)$$

$$\tau v N_C = \frac{1}{\sigma \exp(-E_a/kT)}$$

$$\ln(\ldots) = -\ln(\sigma) + \frac{E_a}{kT}$$

Intermediate summary

- Understanding microscopic details helps understand macroscopic measurements:

  – IV after irradiation
    → more current → more mid-gap traps
  – CV after irradiation
    → Different V_{dep} → N_{eff} has changed
  – Compare TSC and DLTS spectra before/after irradiation
    → Identify new defects:
      - Energy level
      - Density a.f.o fluence
      - Cross section

Current measurements

The Transient-Current Technique

- Measuring drifting charges:

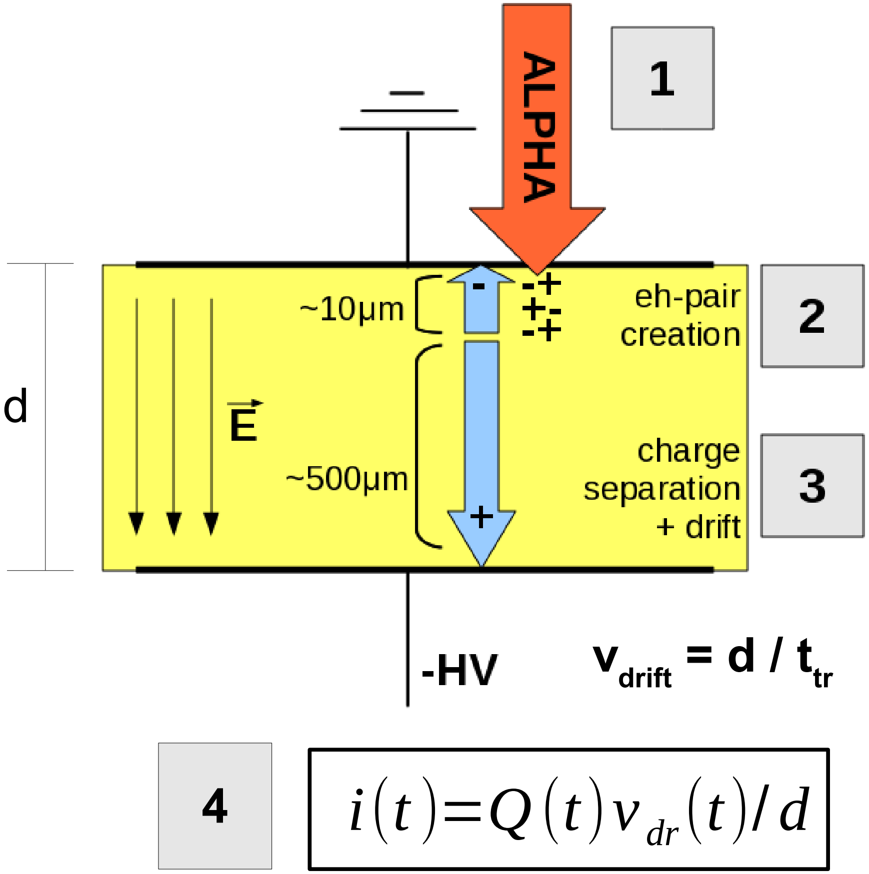
  1) α particles impinge on top side
  2) Create eh-pairs close to electrode
  3) Electric field separates charges
  4) Drifting charges induce current

  → measure the transient current

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

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

  → record signal with oscilloscope

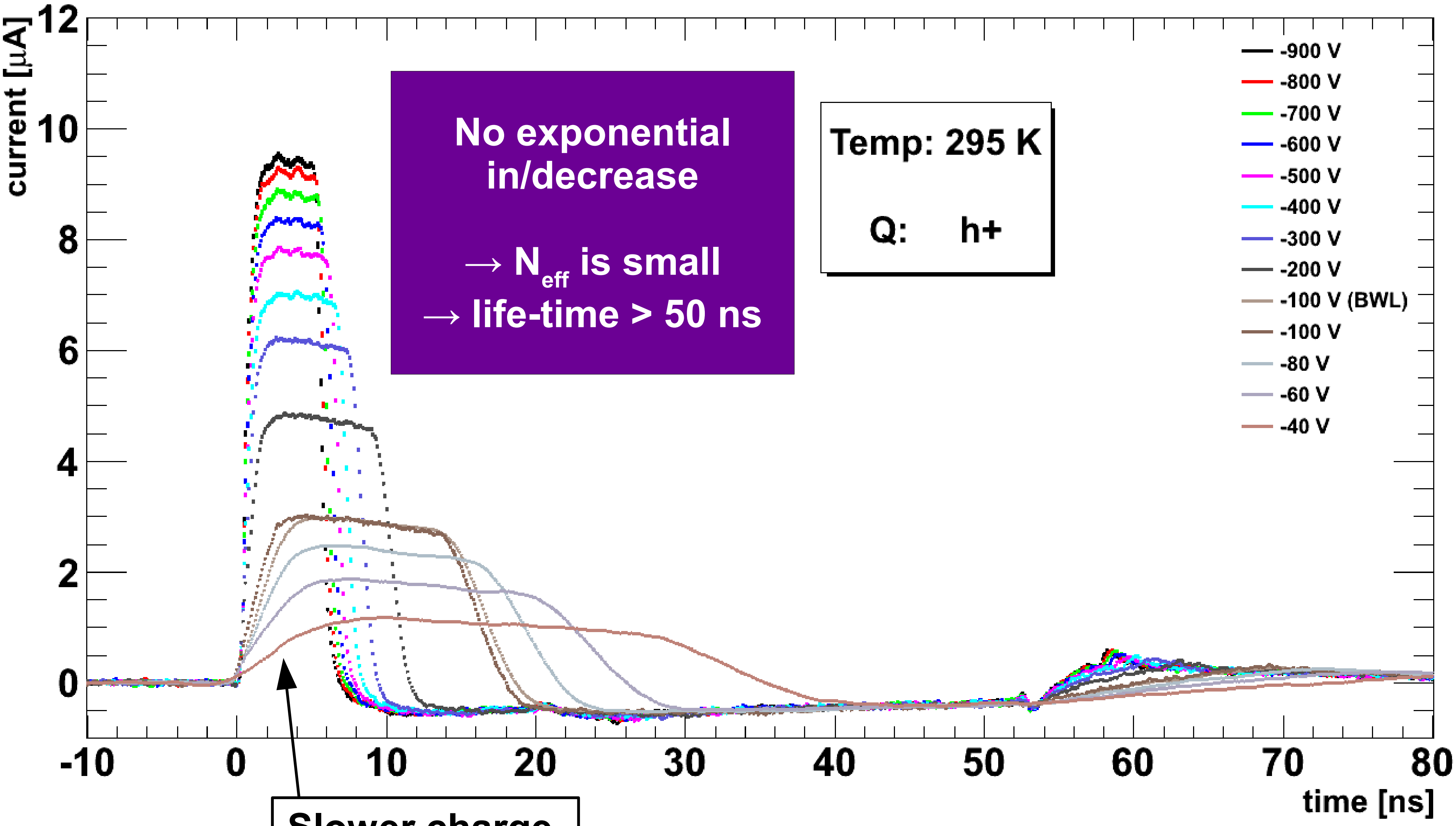


$$v_{drift} = d / t_{tr}$$

$$i(t)=Q(t)v_{dr}(t)/d$$

e.g. in diamond

TCT Pulses at RT: Holes

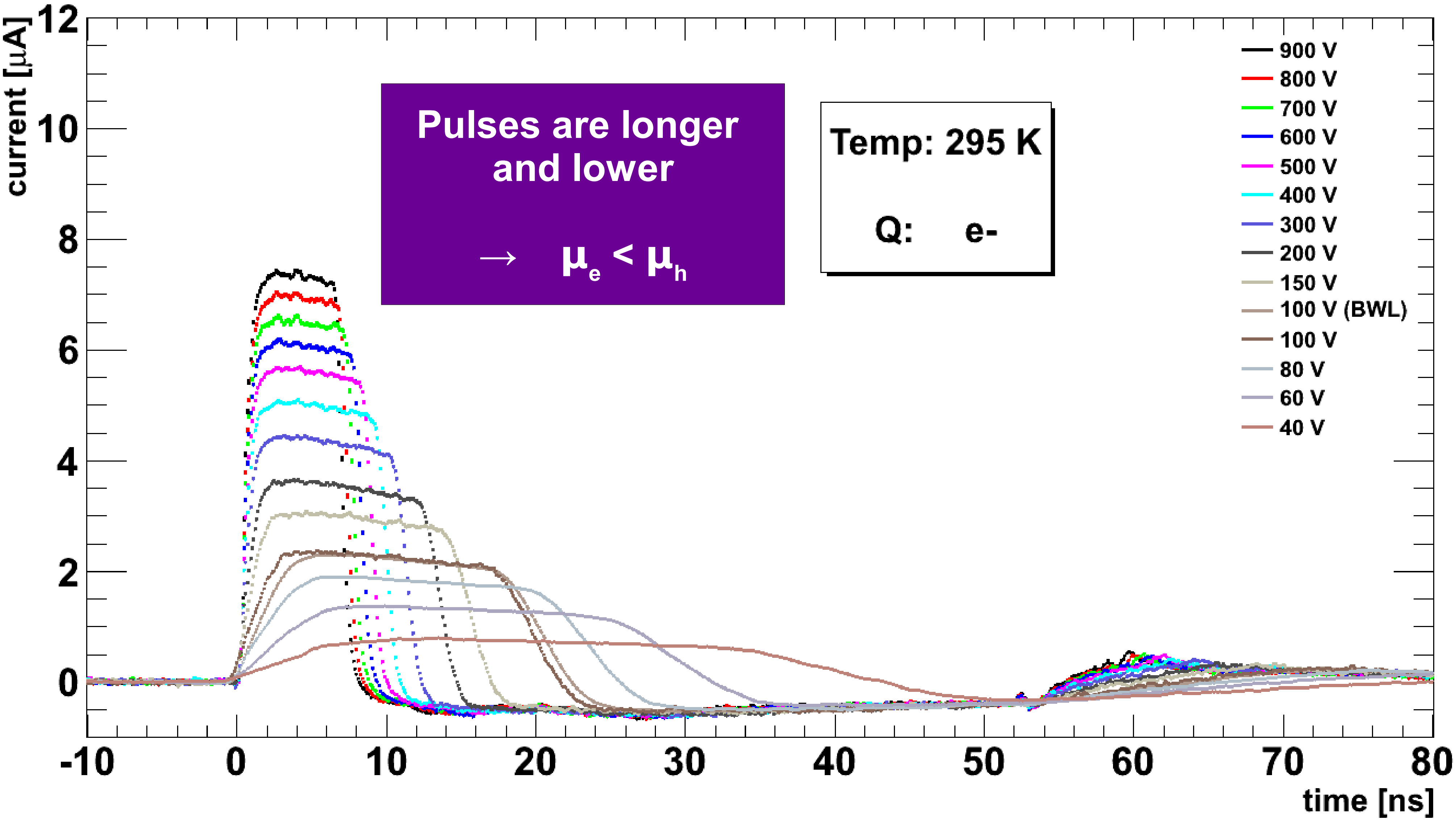


No exponential in/decrease

→ N_{eff} is small
→ life-time > 50 ns

Slower charge release

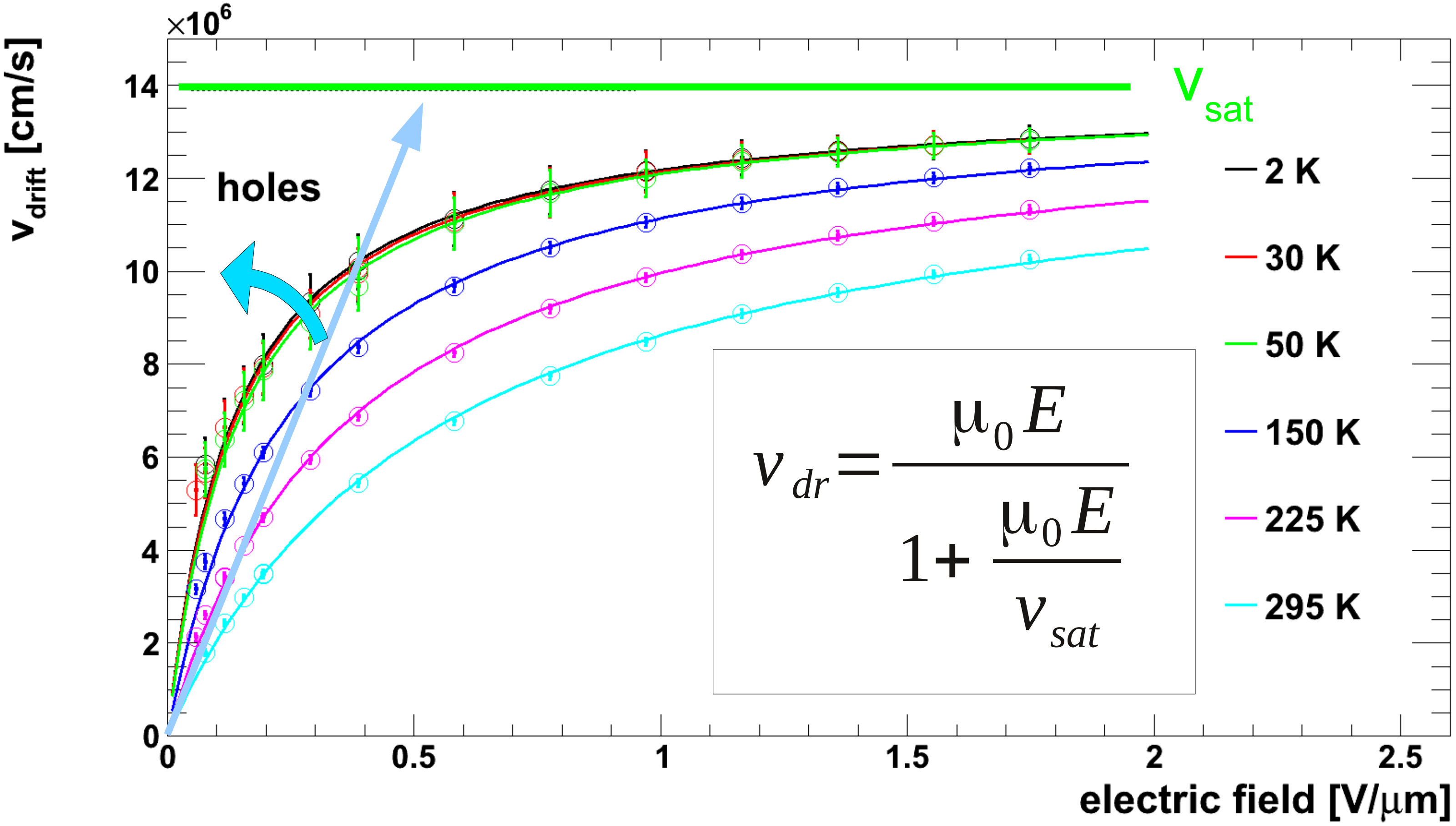
TCT Pulses at RT: Electrons



Pulses are longer and lower

→ $\mu_e < \mu_h$

Hole Drift Velocity

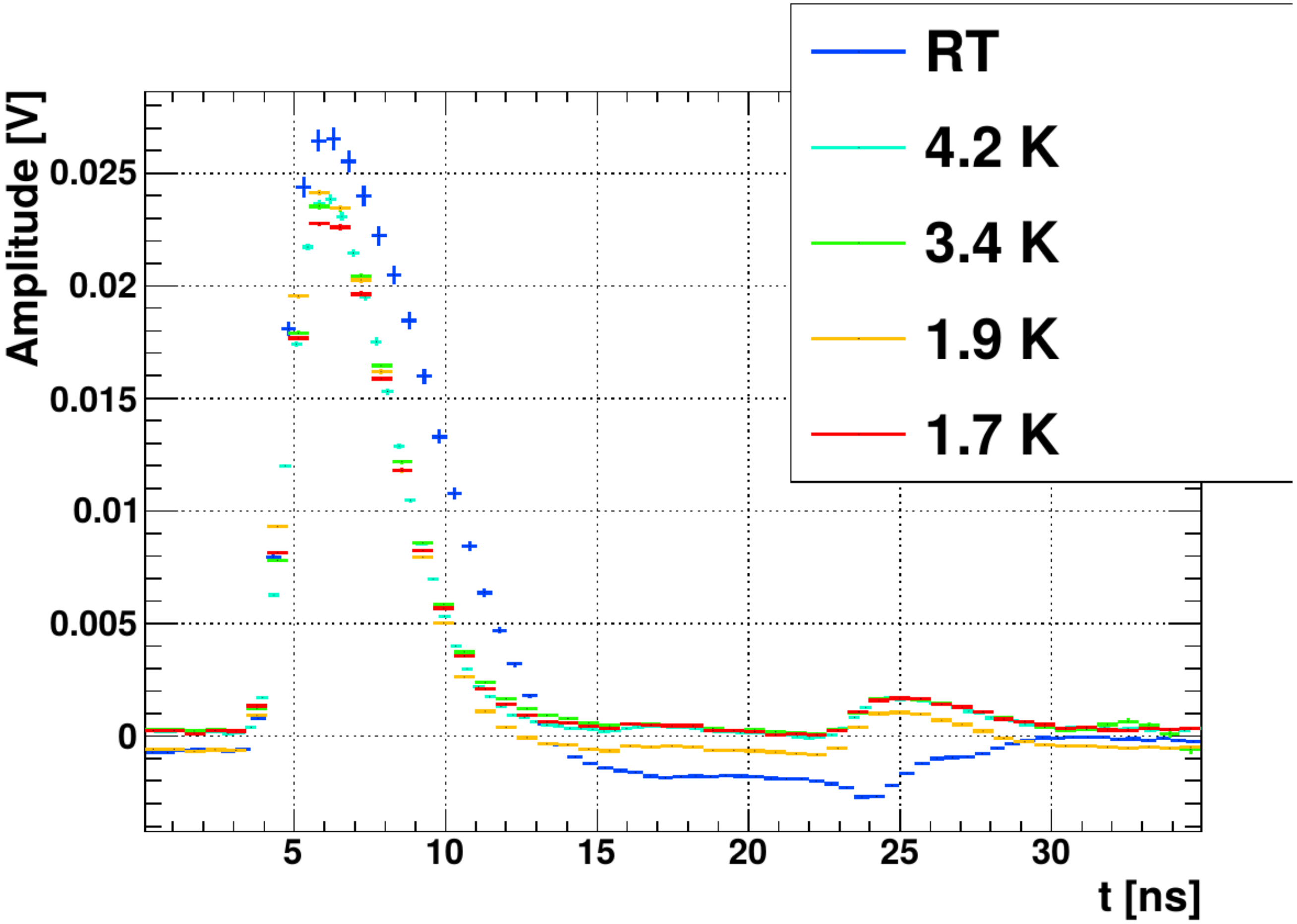


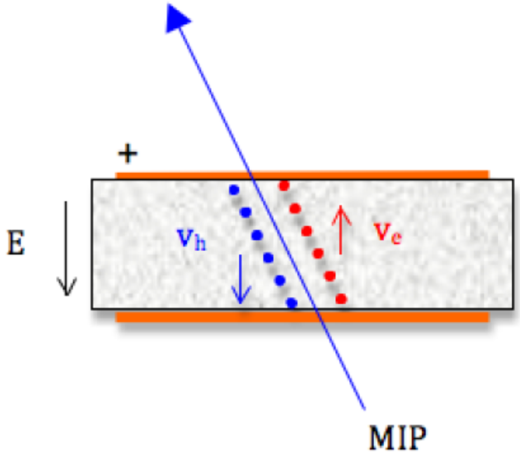
$$v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_{sat}}}$$

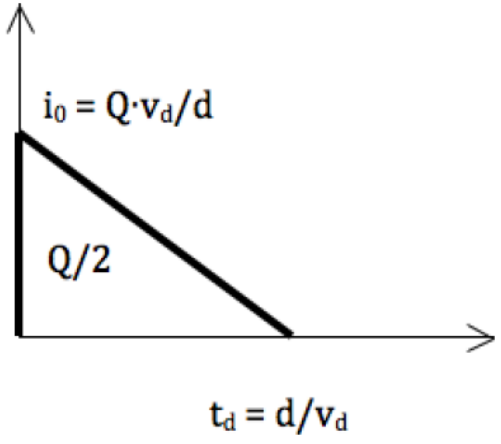
- μ_h increases with decreasing T down to 2 K
- v_{sat} ~ constant with temperature: 14e6 cm/s

TCT pulses from MIPs in silicon

- Current pulses for different temps:





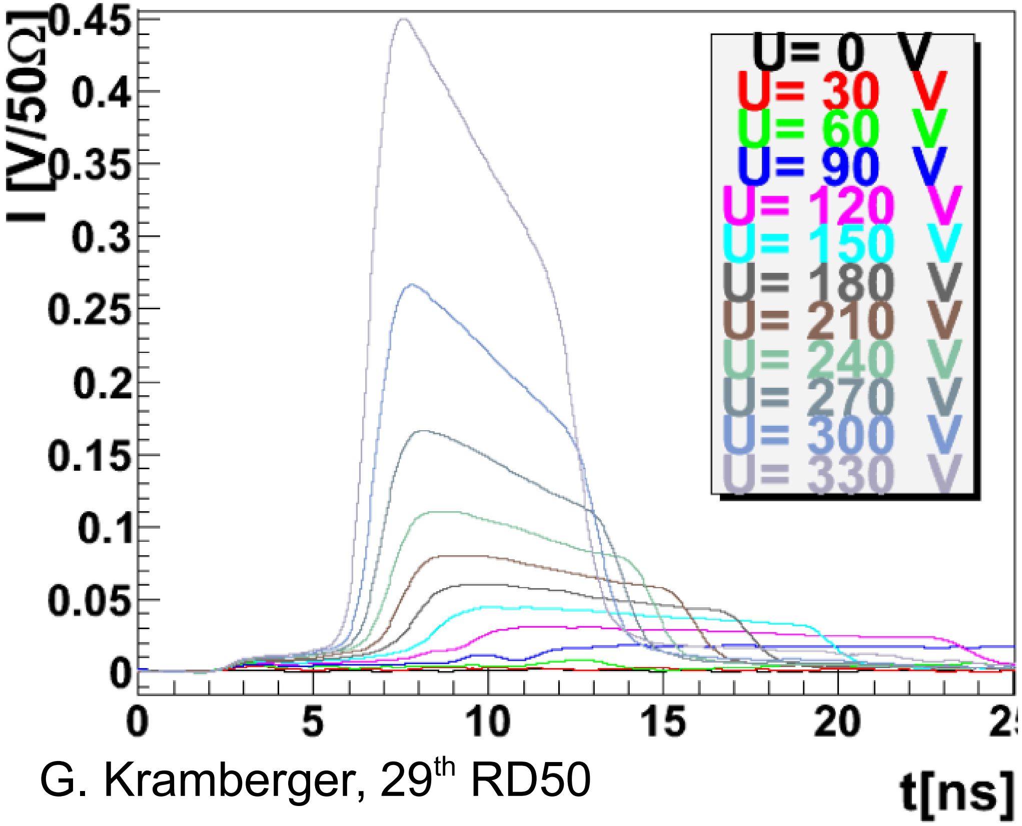


C. Kurfuerst
CERN-THESIS-2013-232

TCT and irradiation

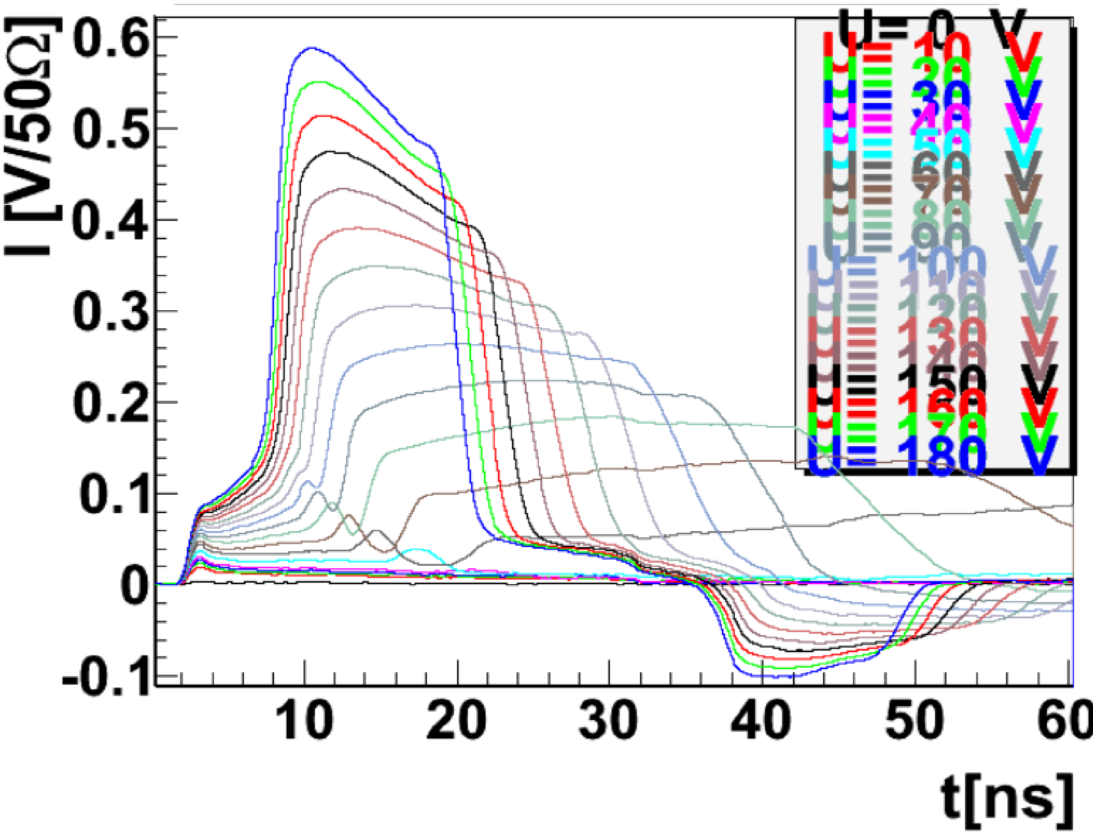
- Very sensitive to changes during drift:
  - Number of charges (trapping, amplification)
  - Velocity of charges (electric field, mobility)

un-irradiated



G. Kramberger, 29th RD50

irradiated



Intermediate summery

- TCT measures the current induced by drifting charges
- With irradiation, the shape of the signal changes:

  - N_{eff} → slope during drift
  - Traps → decrease of current during drift
  - …

→ “See” effects that influence the drift of charge carriers

(does not mean you understand the microscopic details)

edge-TCT measurements

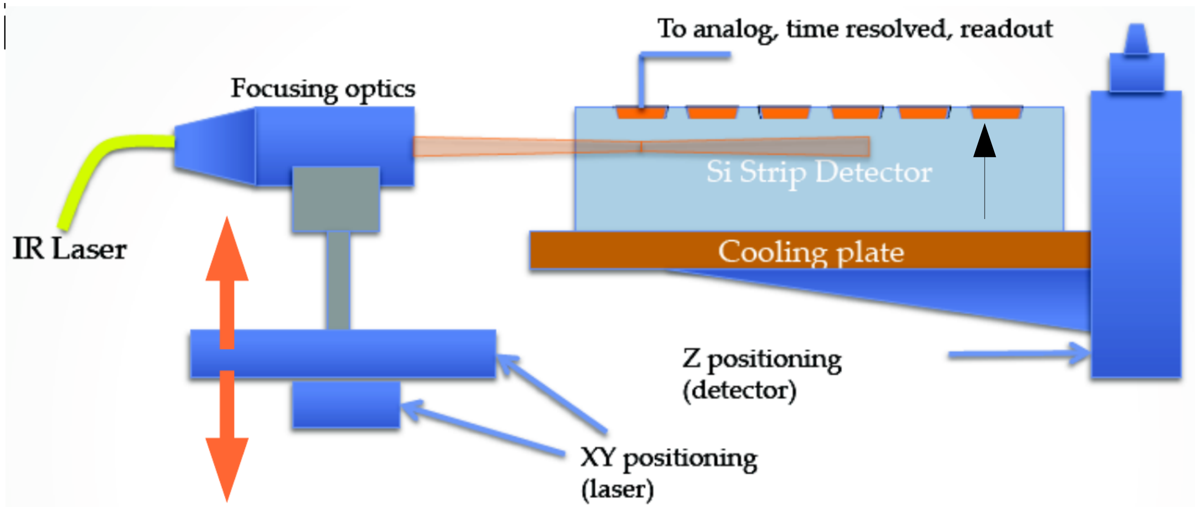
Edge-TCT

- Shoot with laser from the side
- Charge carriers created at selected depth with respect to strips
- Sensor properties can be studied as a function of depth
- Spatial resolution given by laser width (vertical). Measurements averaged over strip width.

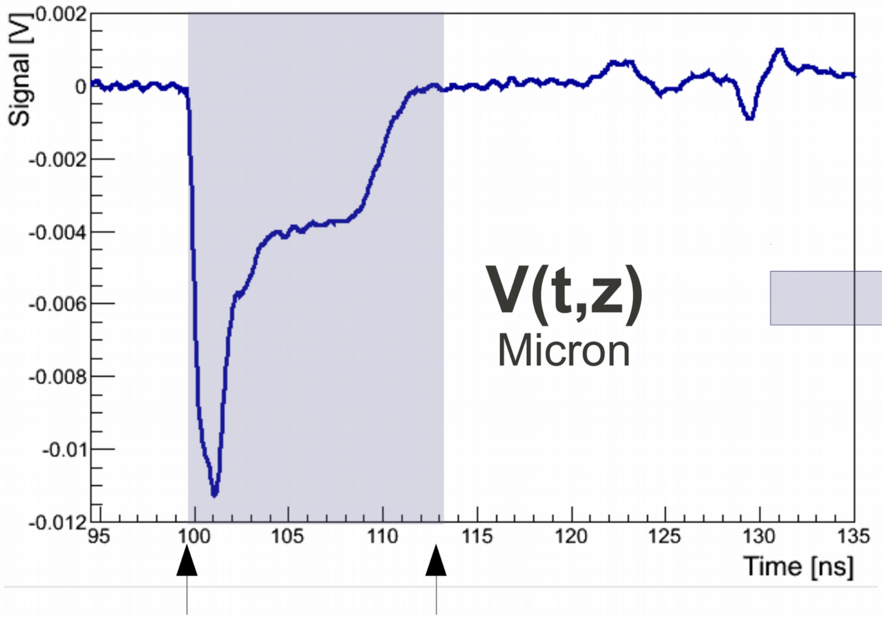
- Measure current a.f.o. ti

  → Charge profile

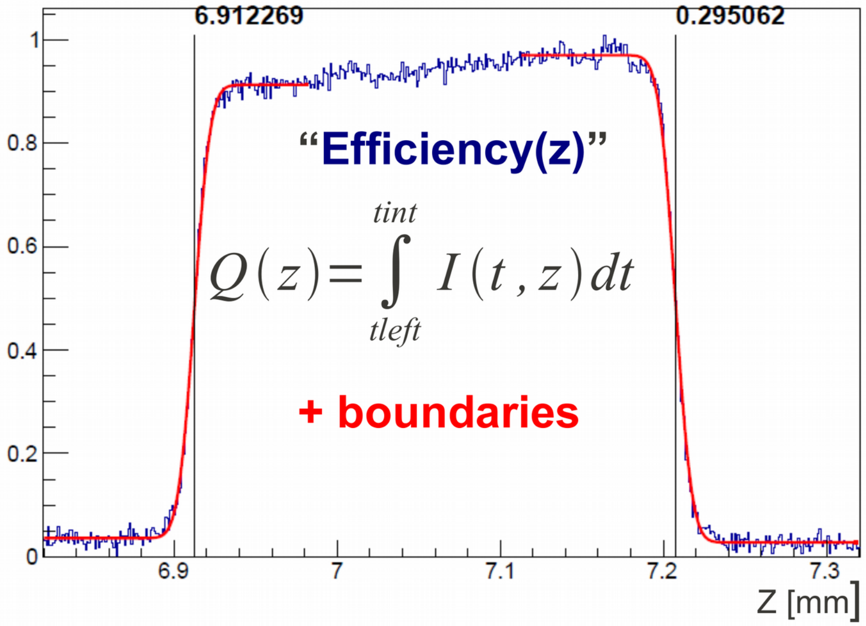
  → Velocity profile
  → **Calculate E(z)**



Procedure



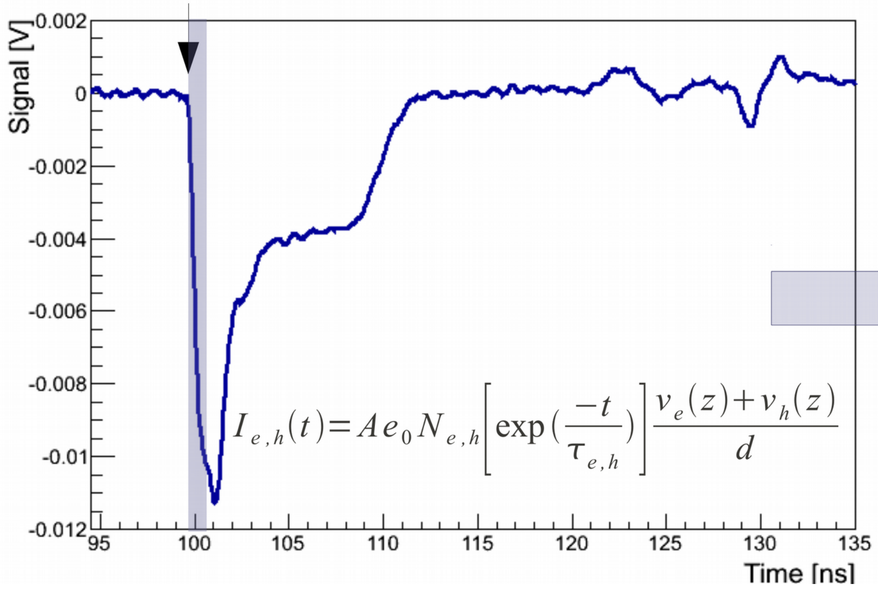
tleft **tint**



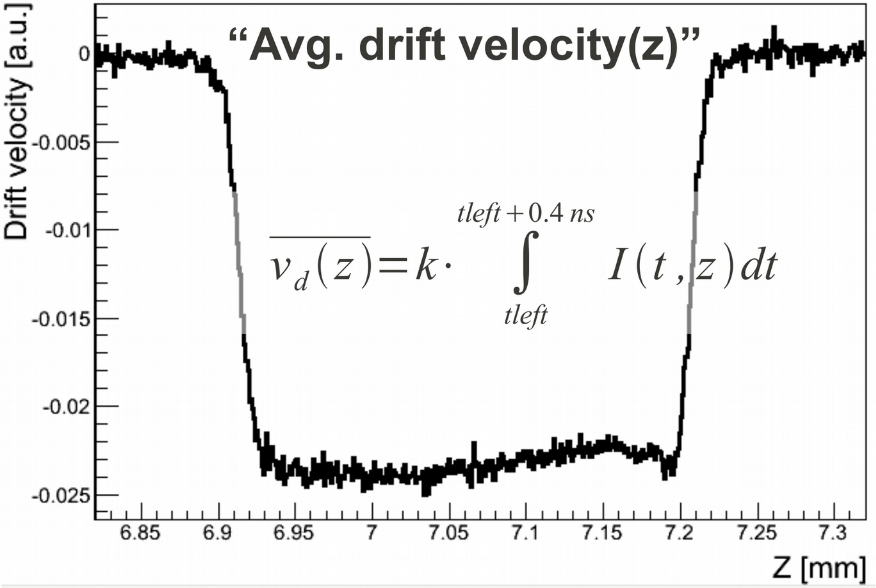
"Efficiency(z)"

$$Q(z)=\int_{tleft}^{tint} I(t,z)\,dt$$

+ boundaries



$$I_{e,h}(t)=Ae_0N_{e,h}\left[\exp\left(\frac{-t}{\tau_{e,h}}\right)\right]\frac{v_e(z)+v_h(z)}{d}$$



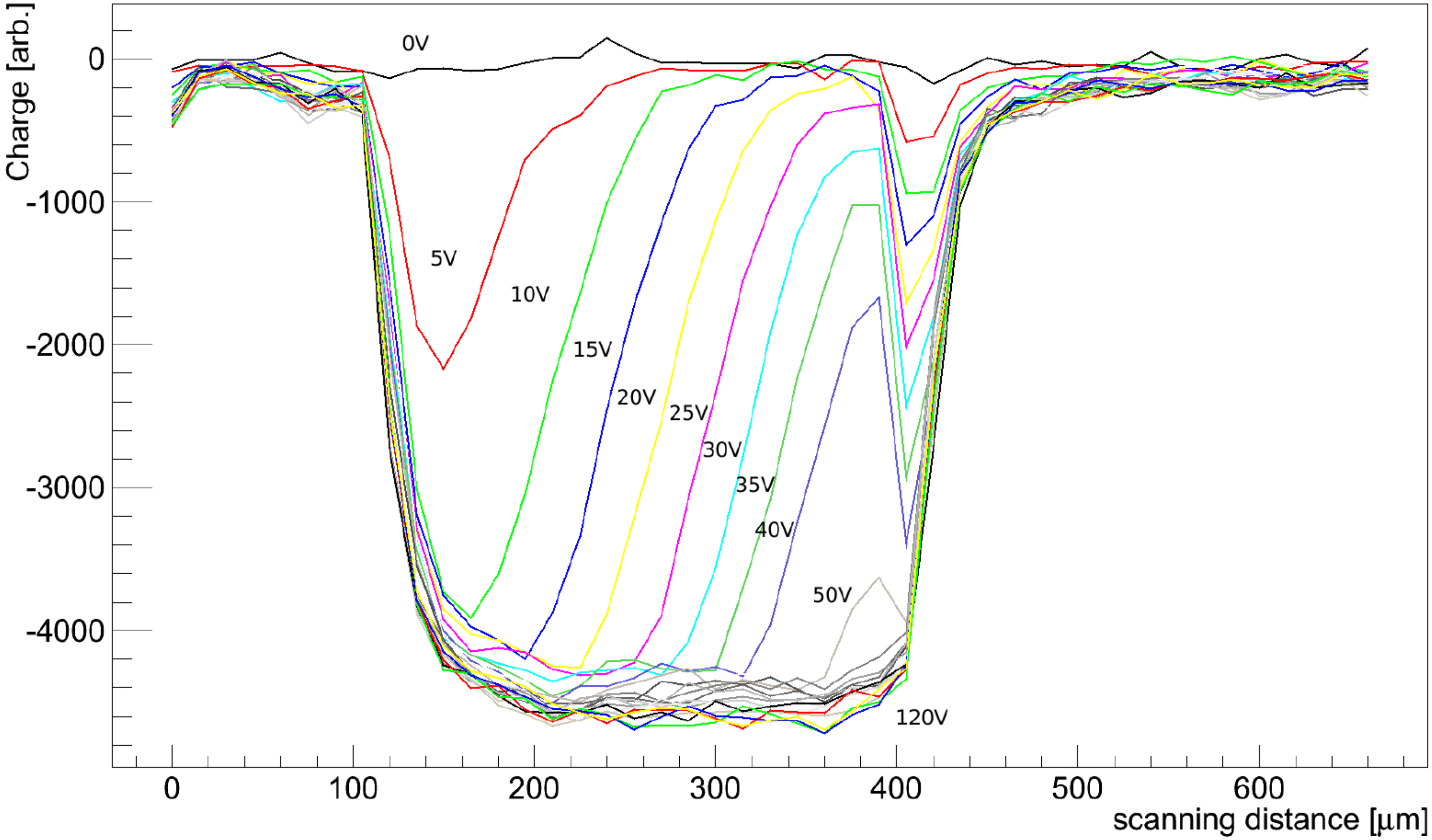
"Avg. drift velocity(z)"

$$\overline{v_d(z)}=k\cdot\int_{tleft}^{tleft+0.4\,ns} I(t,z)\,dt$$

Slide from M. F. Garcia

Results

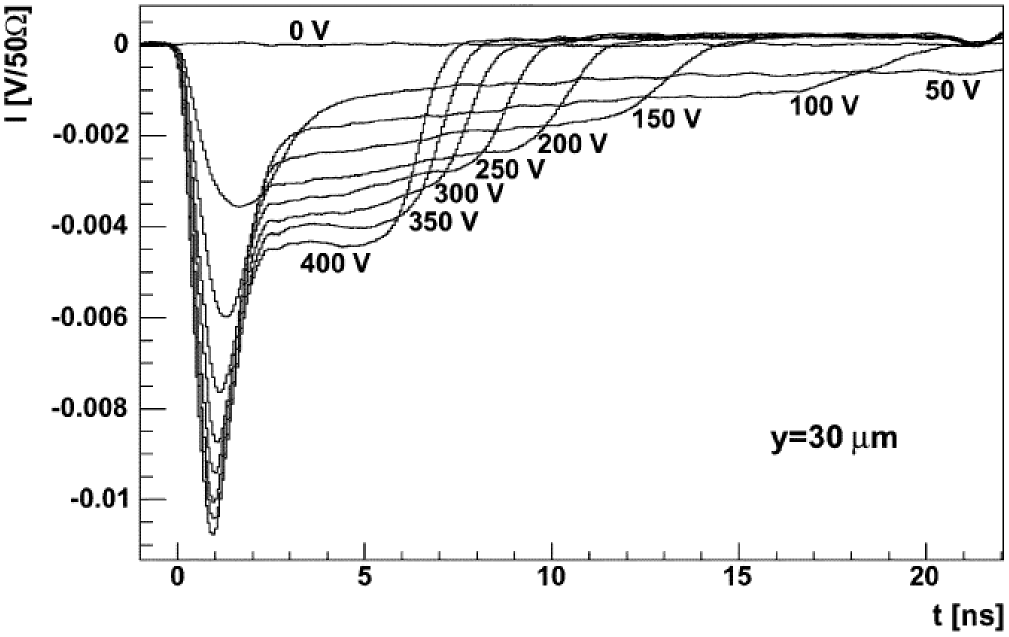
- Integrate current → charge

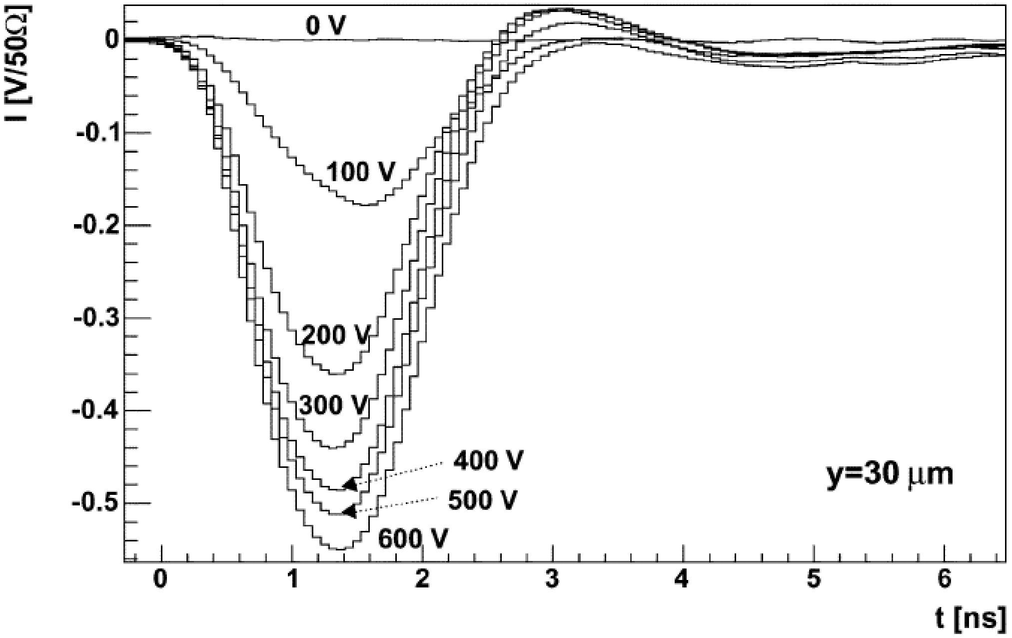


M. Haranko, former DESY summer student

Results for transient

- Comparison for
  un-irradiated sensor   with irradiated sensor

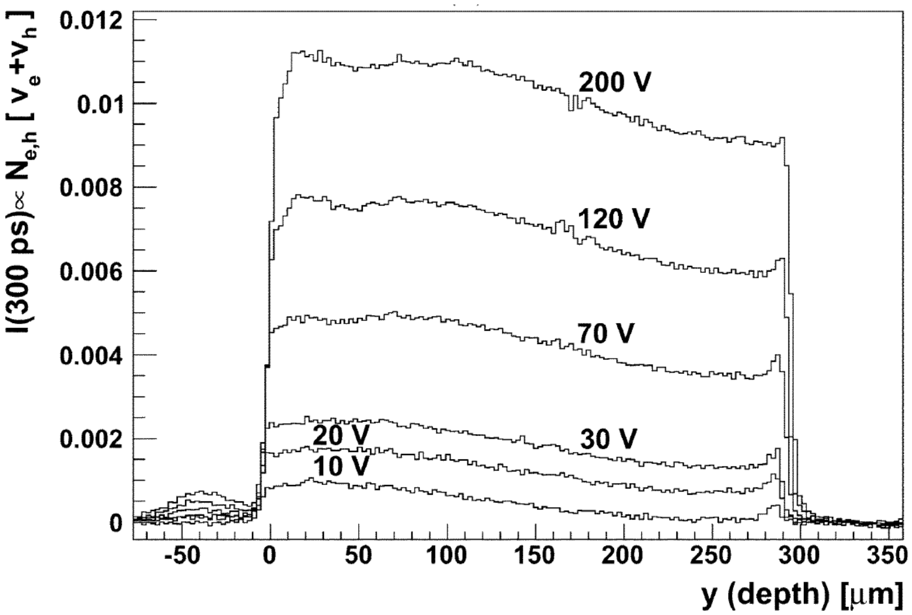


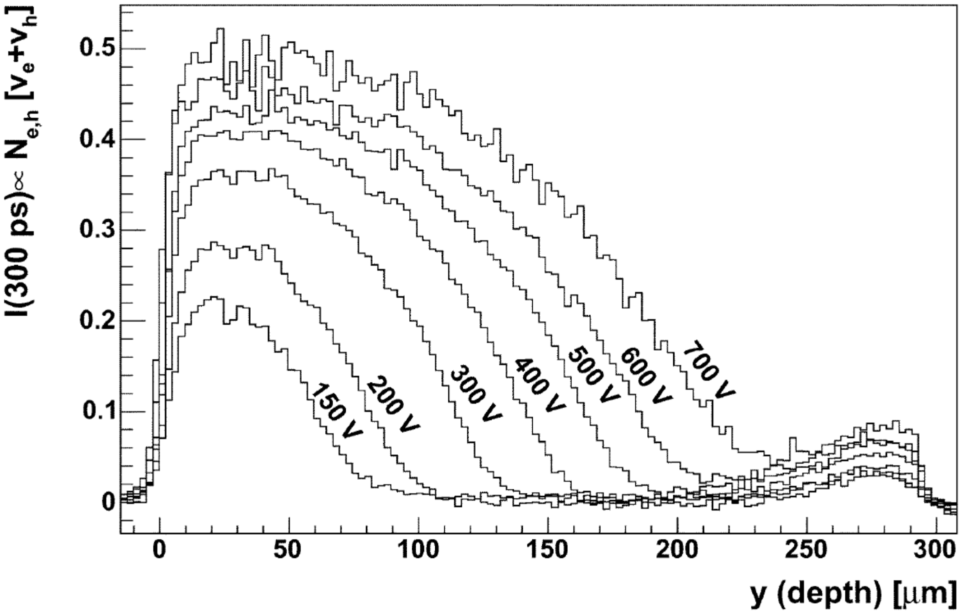


IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 4, AUGUST 2010

Results for electric field

- Comparison for
  unirradiated sensor with irradiated sensor





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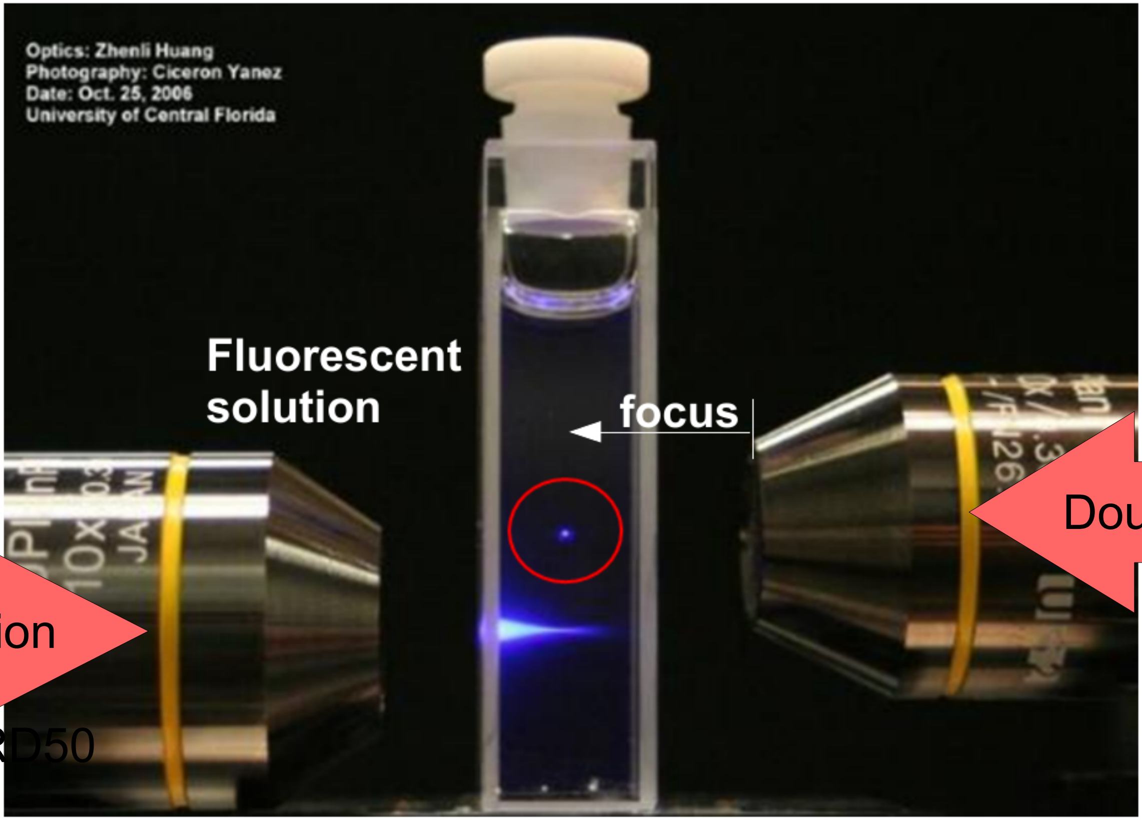
DPA-TCT technique

-

improving edge TCT

Double Photon Absorption Technique

- Laser TCT: create charge along entire path
- DPA-TCT: well defined volume of carrier generation
  - exploits non-linear effect of absorption at high intensity
  - single photon energy is SMALLER then band-gap
    → happens only at/near the focus



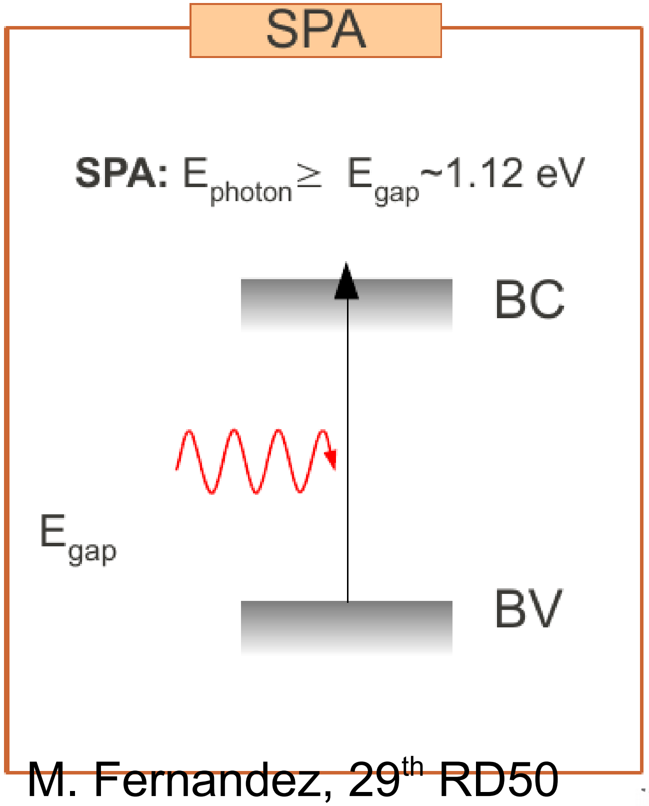
Double Photon Absorption

Single Photon Absorption

M. Fernandez, 29th RD50

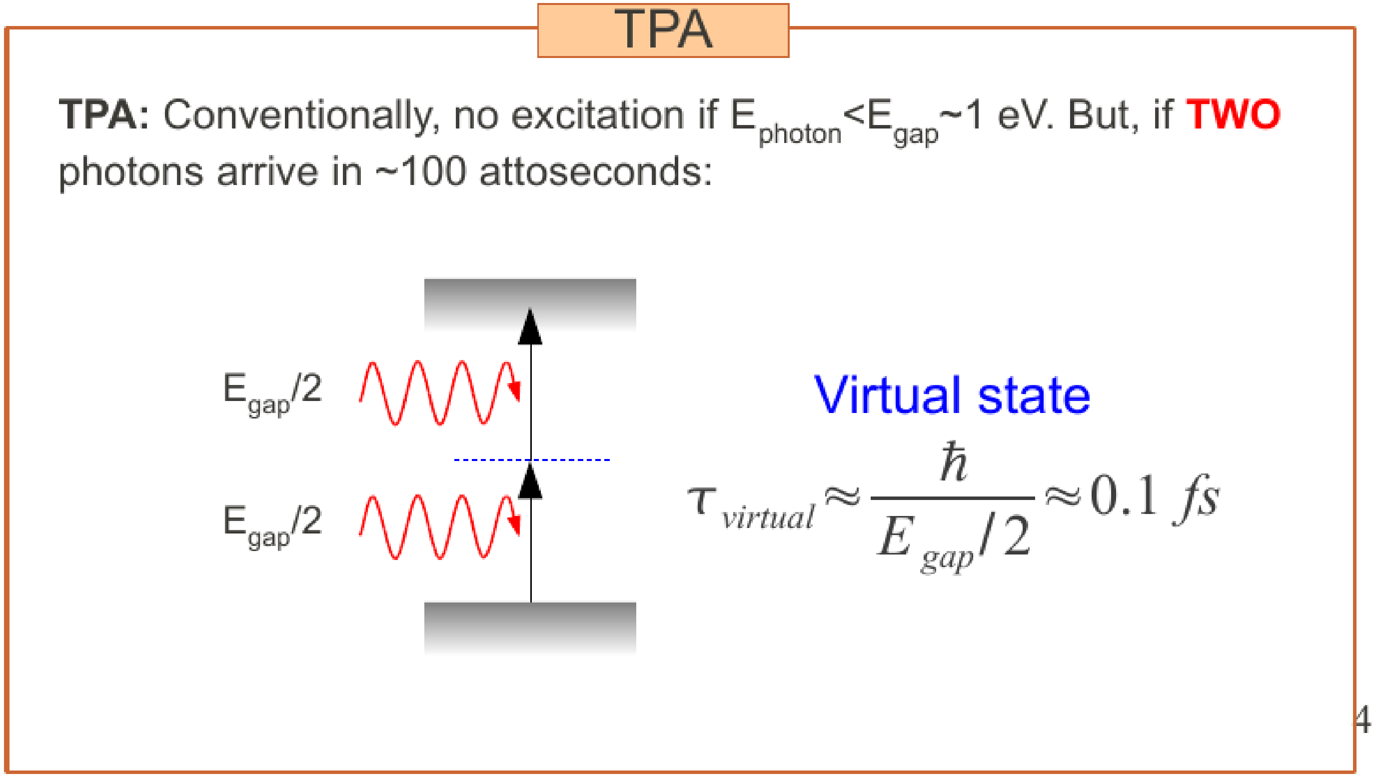
Double Photon Absorption Technique

- Laser TCT: create charge along entire path
- DPA-TCT: well defined volume of carrier generation
  - exploits non-linear effect of absorption at high intensity
  - single photon energy is SMALLER then band-gap
    → happens only at/near the focus



SPA

SPA: $E_{photon} \geq E_{gap} \sim 1.12$ eV



TPA

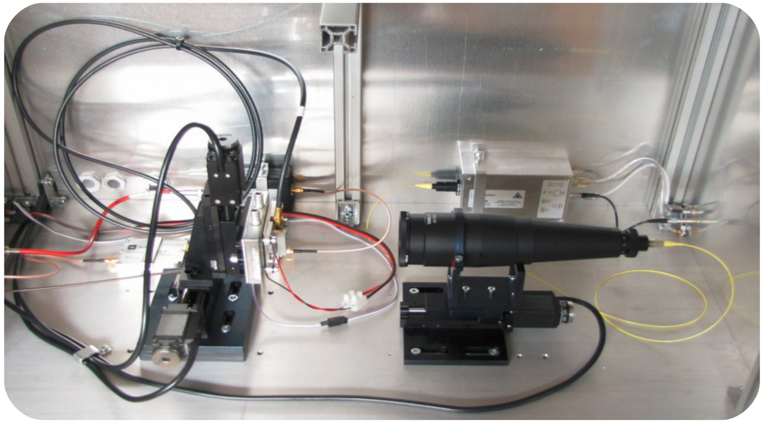
TPA: Conventionally, no excitation if $E_{photon} < E_{gap} \sim 1$ eV. But, if **TWO** photons arrive in ~100 attoseconds:

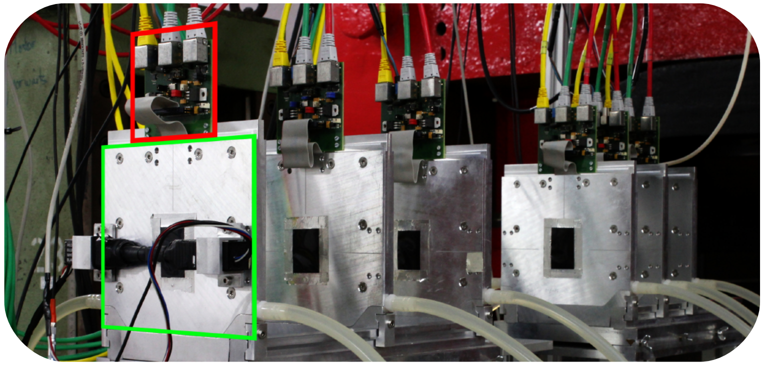
$$\tau_{virtual} \approx \frac{\hbar}{E_{gap}/2} \approx 0.1\ fs$$

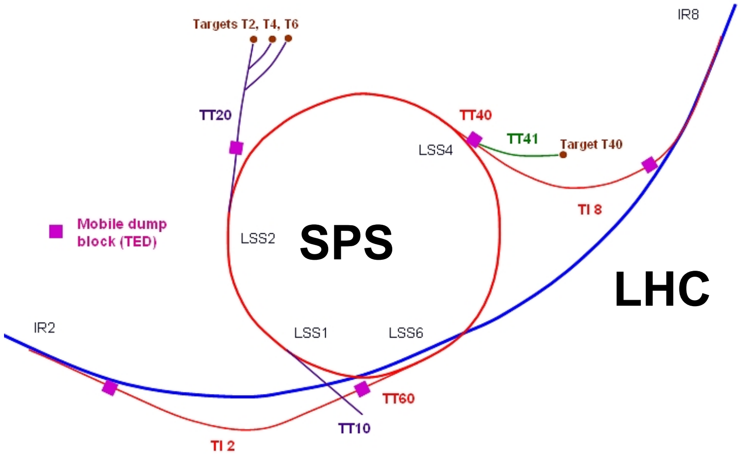
M. Fernandez, 29th RD50

Outline

- HEP detector overview
  - what we have and
  - why we need to do better
- Radiation damage in semiconductor sensors
- **Characterisation techniques**
  - lab-based
  - **with beams**
- Clever ideas confronting radiation damage







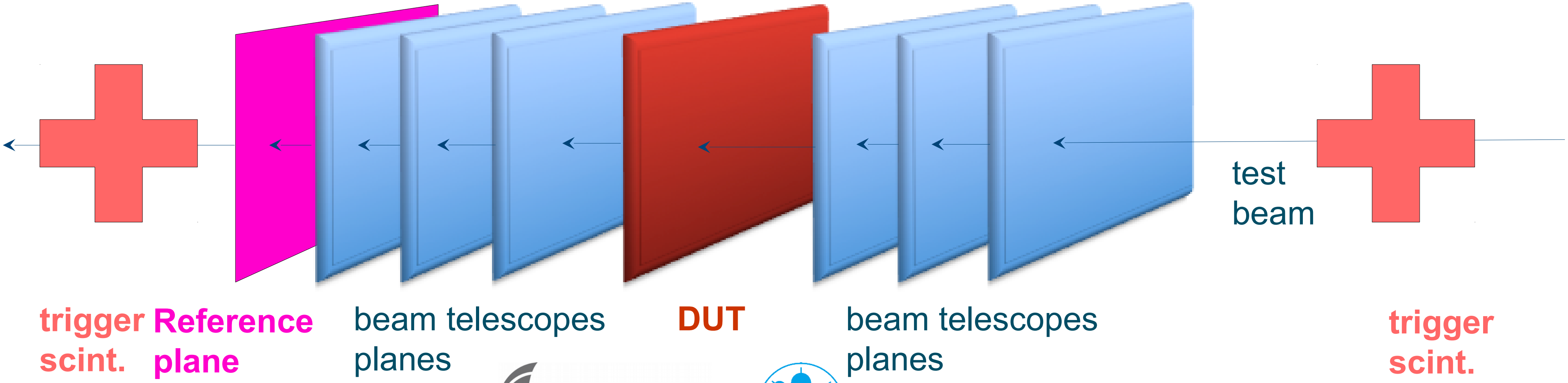
Beam telescopes and test beams

Test beam studies

- How to study a tracking device in a test beam?
- Need reference frame for precise tracking of beam particles

  → Usually use tracking up + downstream the Device Under Test
  → Reference system at least the same resolution compared to the DUT

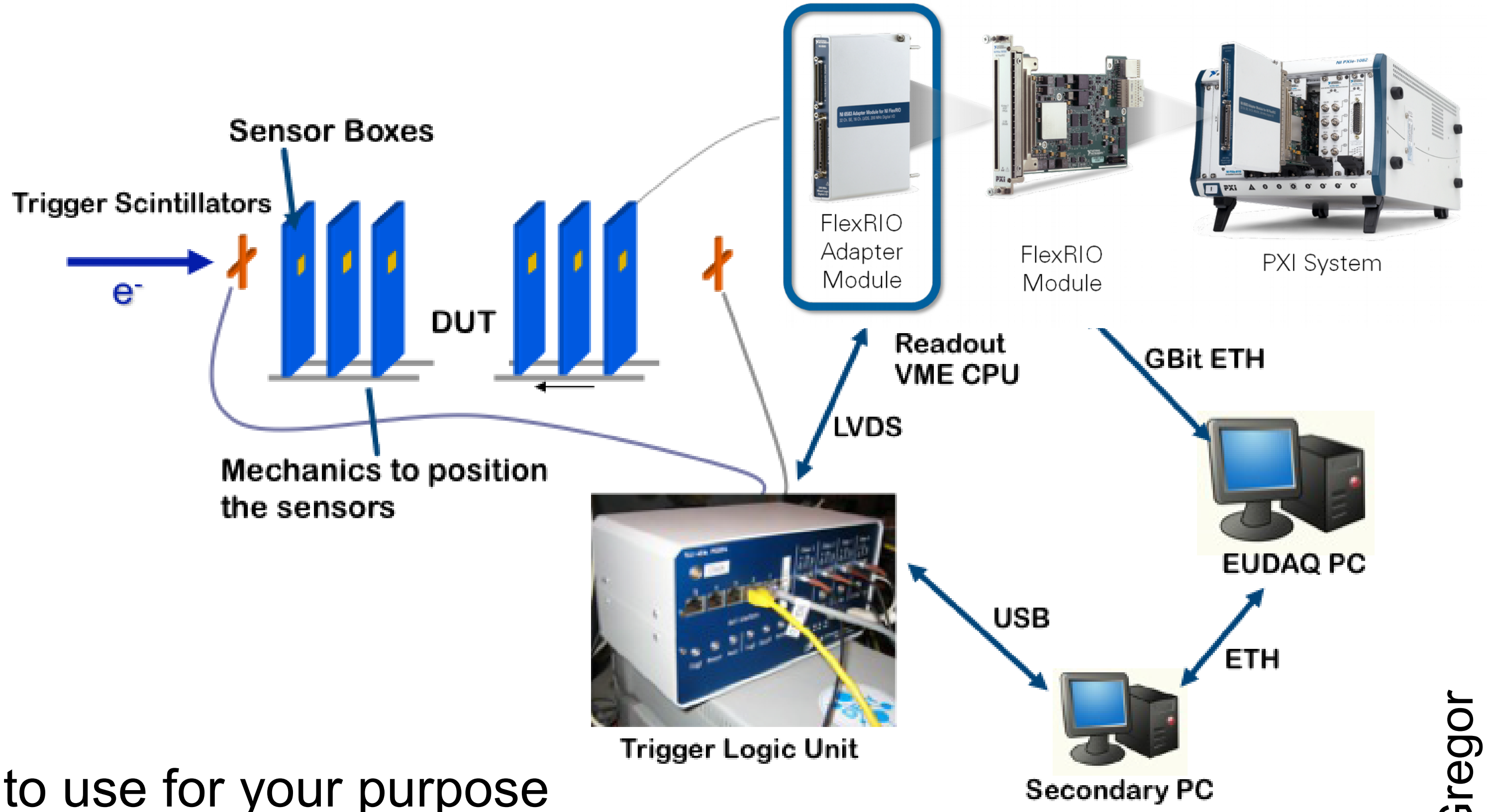
- Two possibilities
  - Many layers of same sensor (choose middle one to be DUTs)
  - An independent reference system: “Beam telescope”



Slide from I. Gregor

Telescope ingredients

- ✓ **Sensors (Mimosa26)**
- ✓ **Readout System**
- ✓ **EUDAQ**
- ✓ **Trigger Logic Unit**
- ✓ **Mechanics**

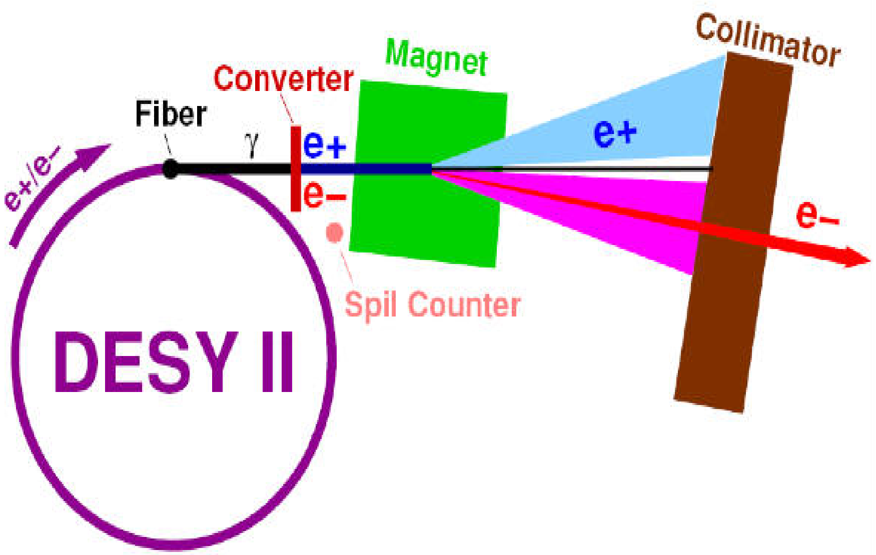


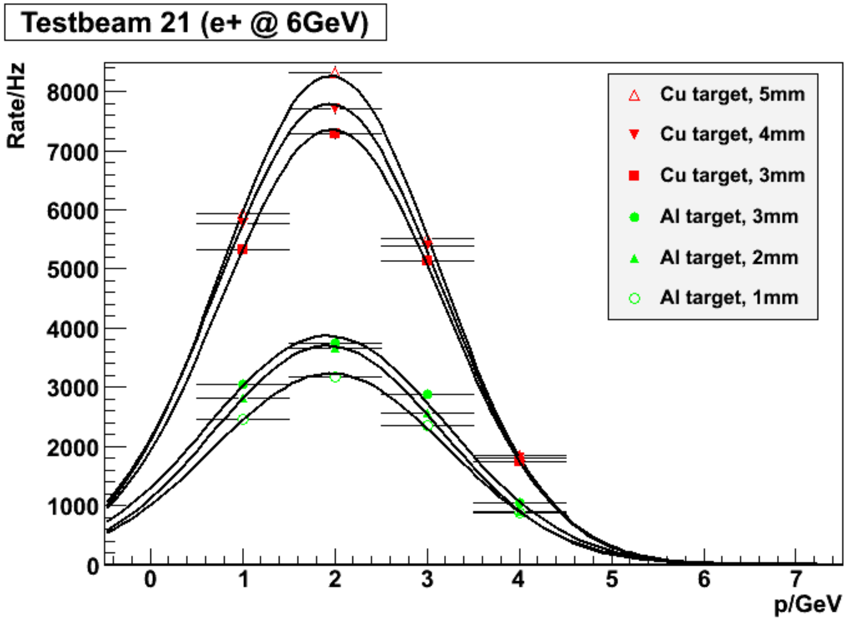
Nota bene:

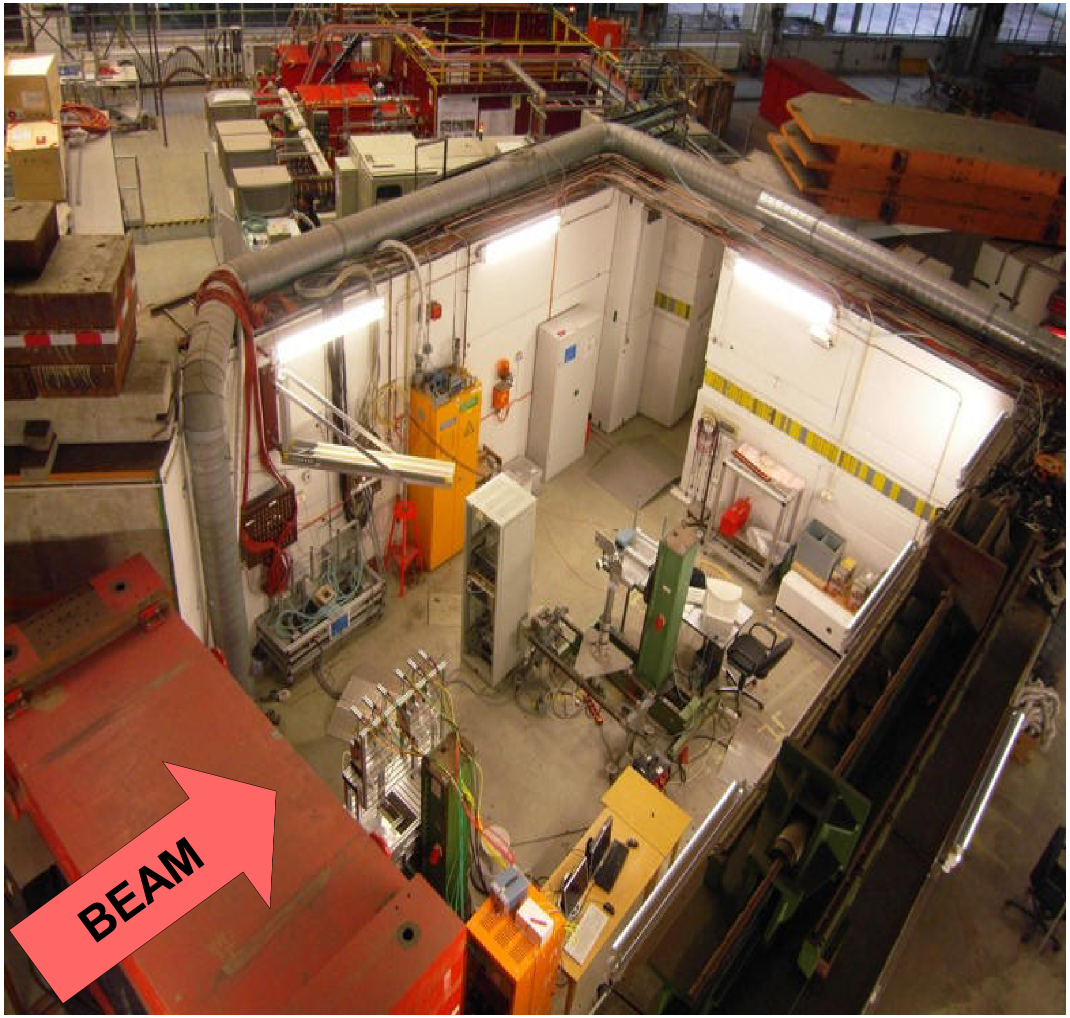
- Use a DAQ that is
  → easy enough to use for your purpose
  → generic enough to accommodate your needs
- Reconstruction software for track reconstruction
  → e.g. EUTelescope based on ILCSoft
- You'll need time to get acquainted with the tools

Slide from I. Gregor

Test beam studies







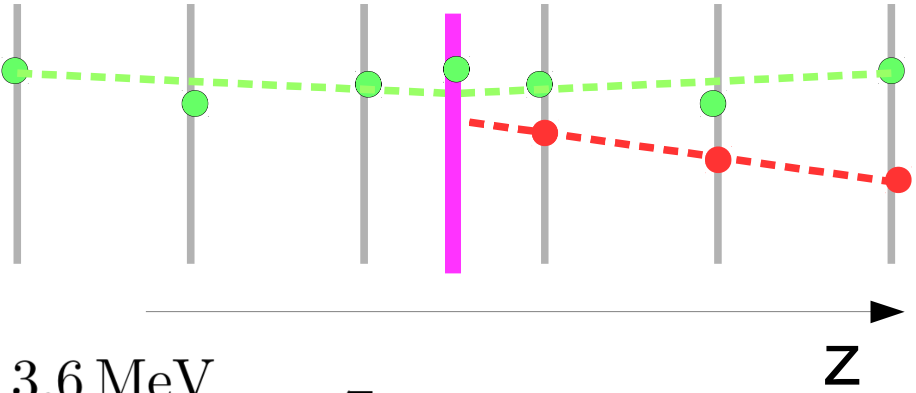
Slide from J. Dreyling

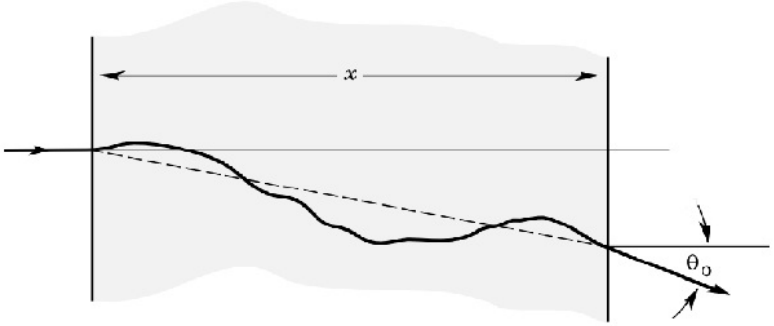
Test beams around the world

Slide from I. Gregor

Test beam studies

- Know precisely the resolution of your telescope sensors
- Measure many particle tracks (hits in telescope + DUT)
  - Find hits that belong together (track finding)
  - Fit/Extrapolate track to DUT (for good fit, need estimate of material budget in beam)





$$\Theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} \cdot Z\sqrt{\epsilon} \cdot \left(1 + 0.038 \ln(\epsilon)\right)$$

- Residual = fit – measured
→ Fill residual distribution

$$r_{\mathrm{u}}{}^{2}(z) = \sigma_{\mathrm{int}}{}^{2}(z) + \sigma_{\mathrm{t,u}}{}^{2}(z)$$

Test beam studies

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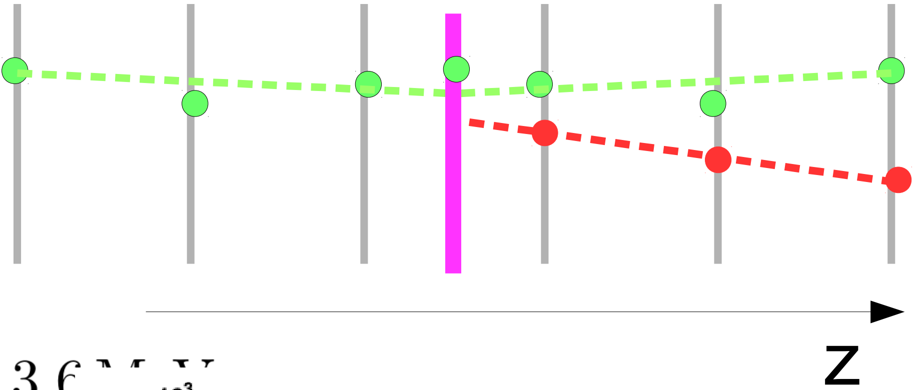
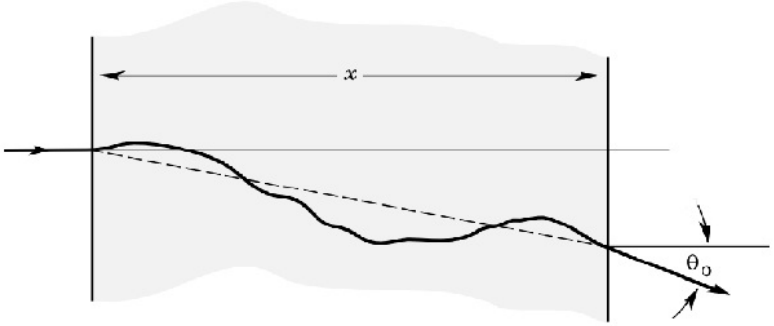
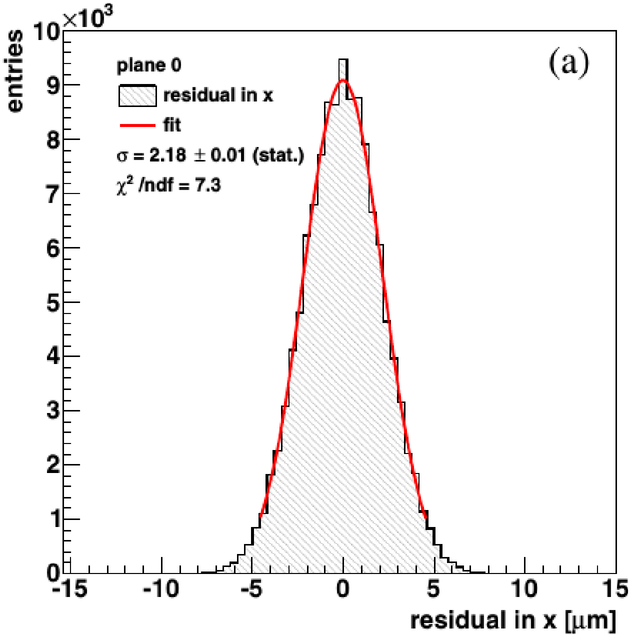




$$\Theta_0 = \frac{13.6}{} \qquad (\epsilon))$$



- Residual = fit – measured

→ Fill residual distribution

$$r_u^2(z) = \boxed{\sigma_{int}^2(z)} + \sigma_{t,u}^2(z)$$

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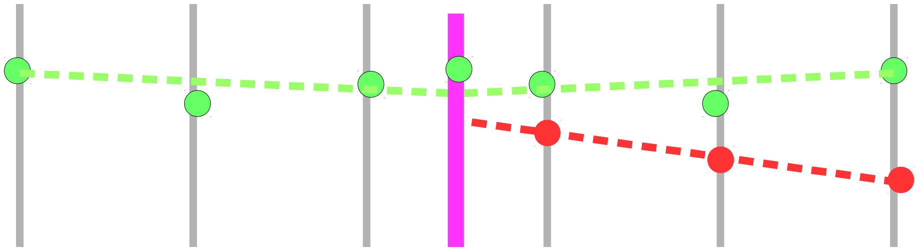
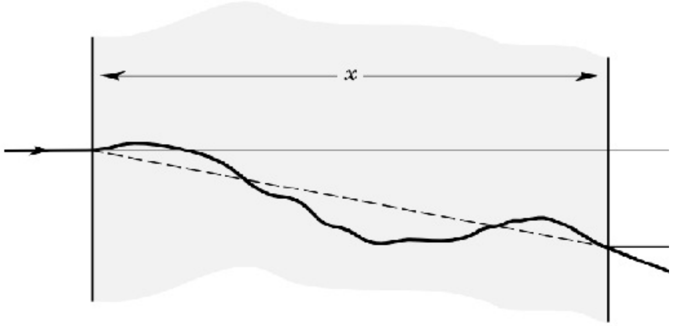
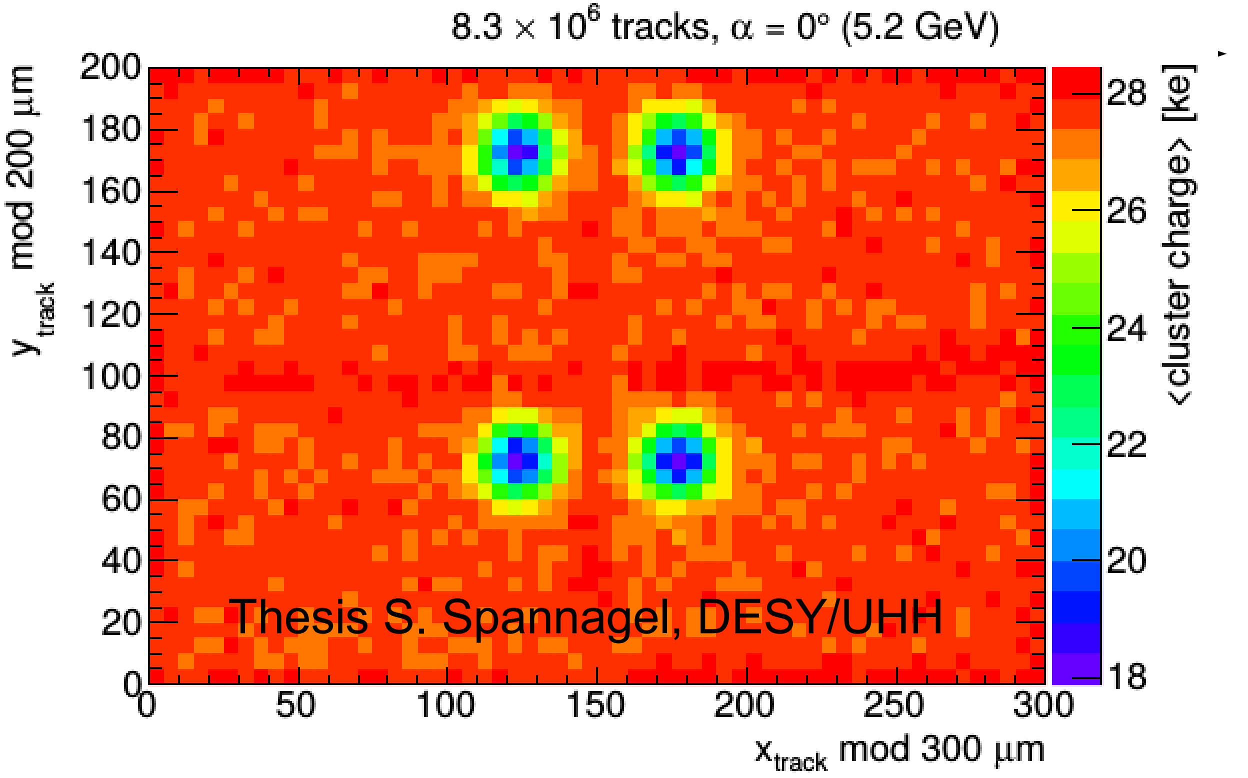


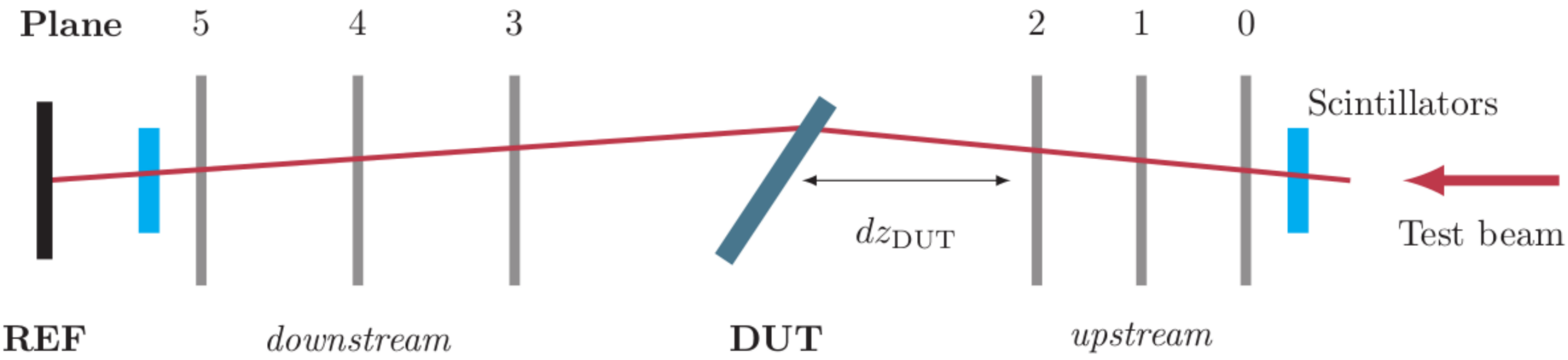


- Residual = fit – me
→ Fill residual distri

$$r_\mathrm{u}{}^2(z) = \boxed{\sigma_\mathrm{int}{}^2(z)} + \sigma_{\mathrm{t,}}$$



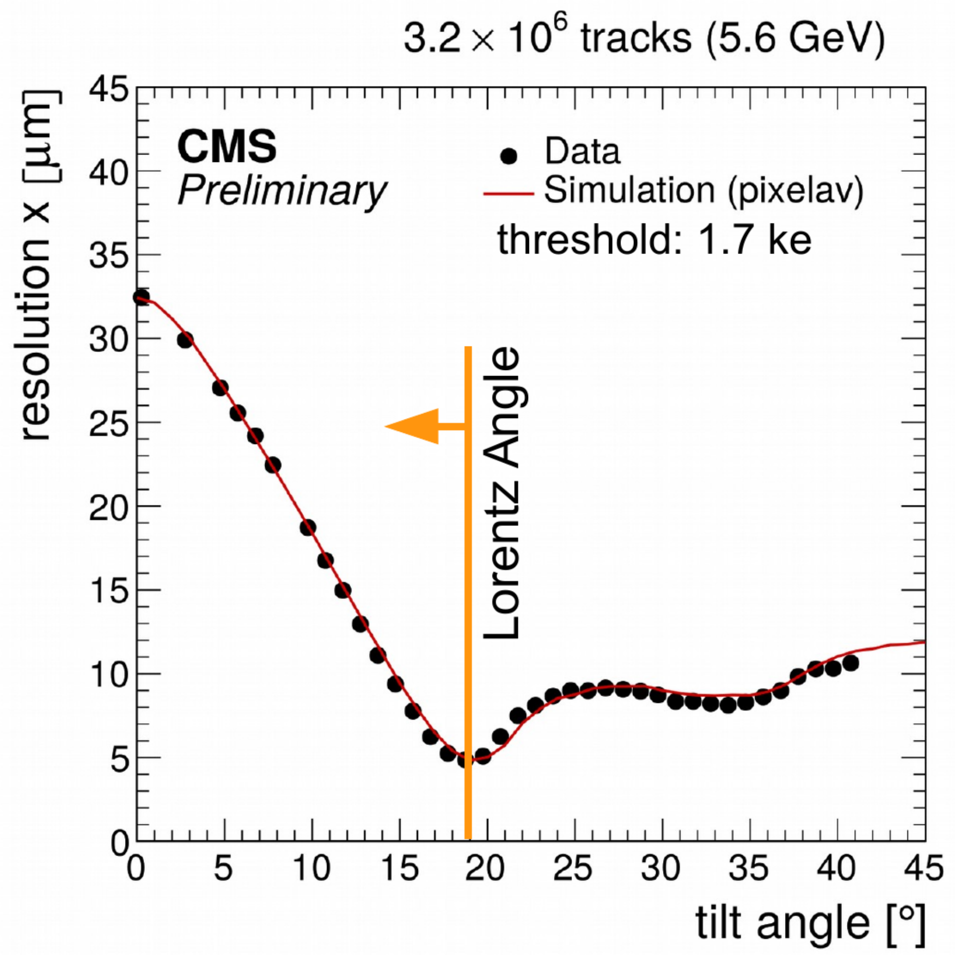
Thesis S. Spannagel, DESY/UHH

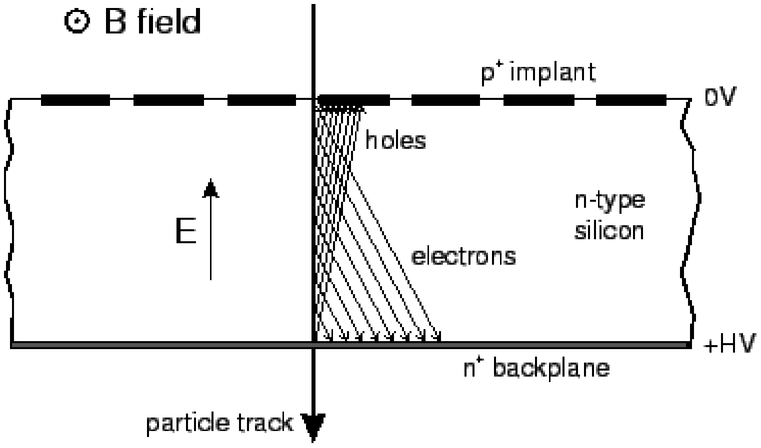


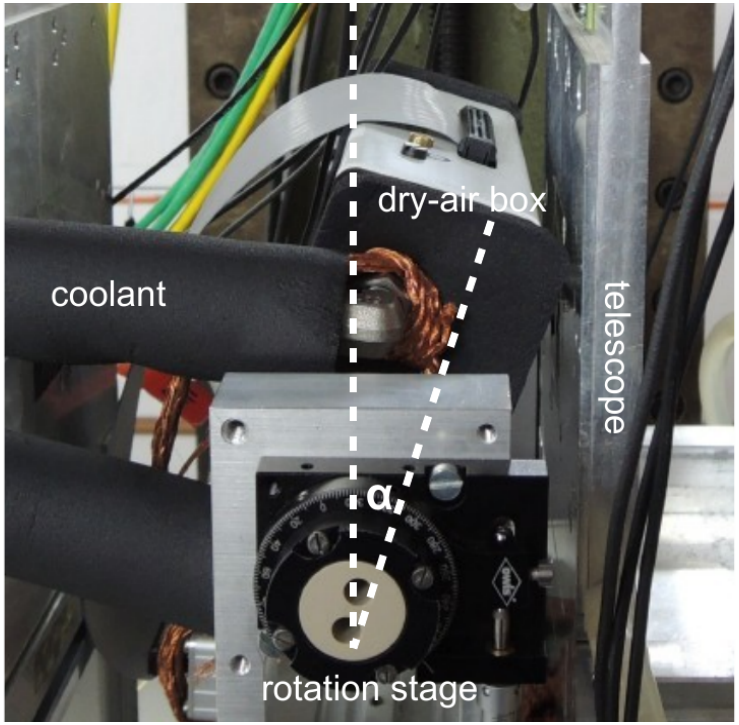
test beam measurements
-
Resolution studies with CMS pixel detectors

Spatial Resolution

- Mimic Lorentz drift by rotating ROC
- Very good agreement with simulation
- Best resolution: 5 µm





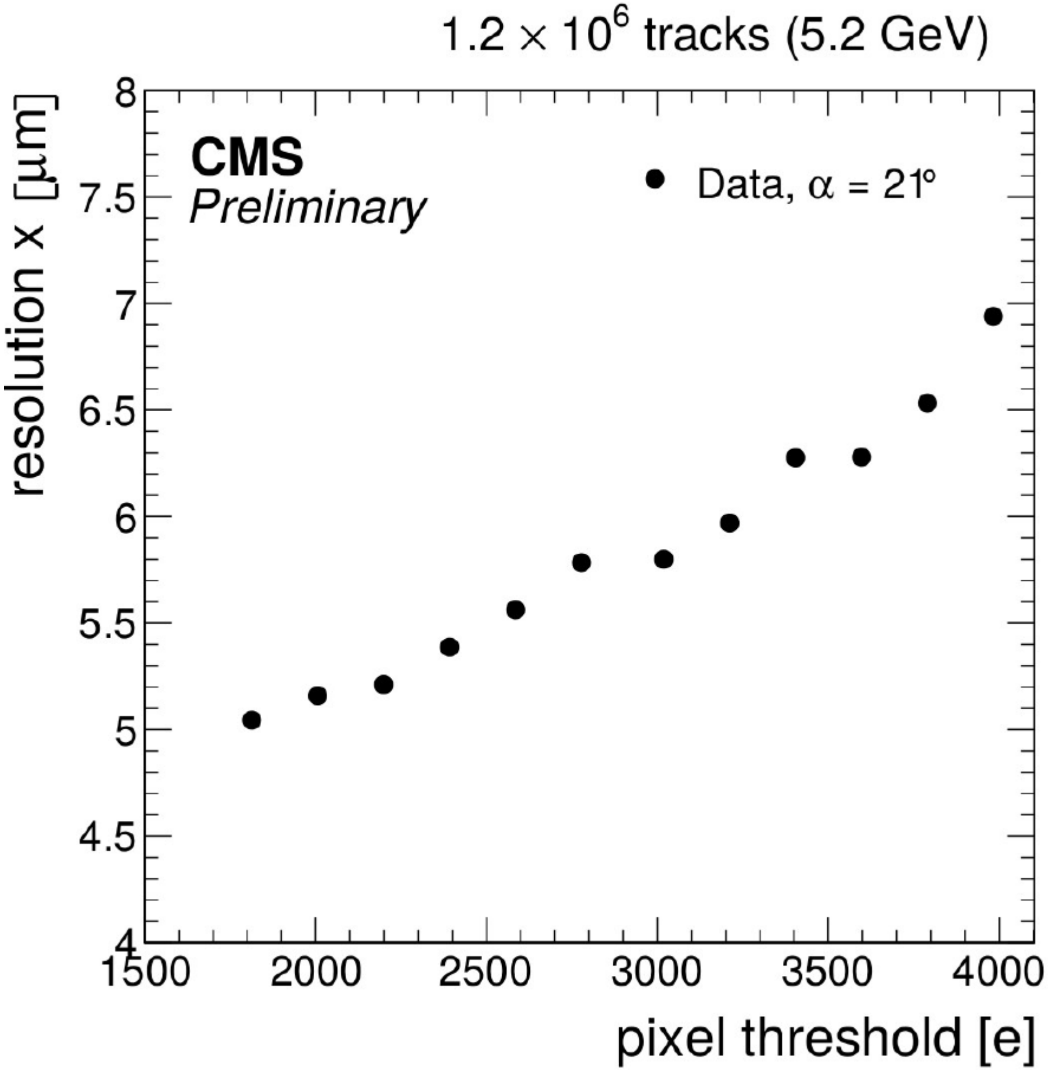


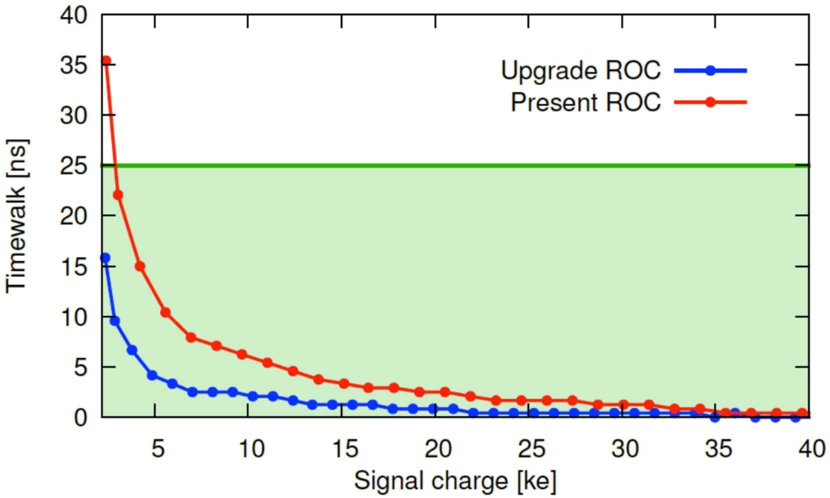
Slide from S. Spannagel

ROC Analogue performance

- Improved analogue circuitry
- Lower absolute & in-time threshold

  ~1.5 ke
- Current ROC:
  - 2.5 ke- minimal threshold
  - 3.2 ke in-time threshold
- Reduced time walk due to faster comparator





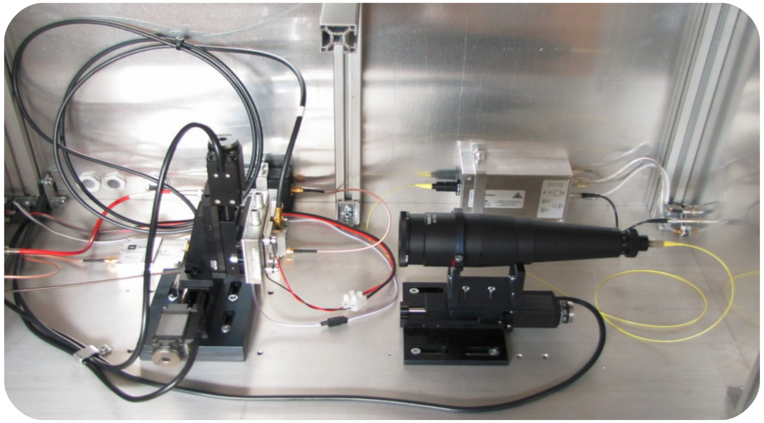
Slide from S. Spannagel

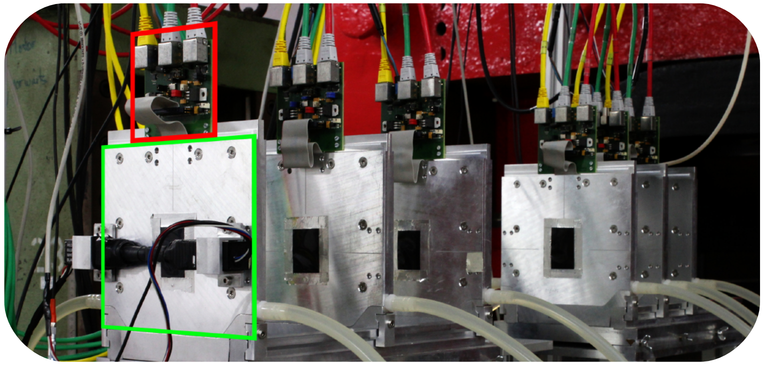
Intermediate summary

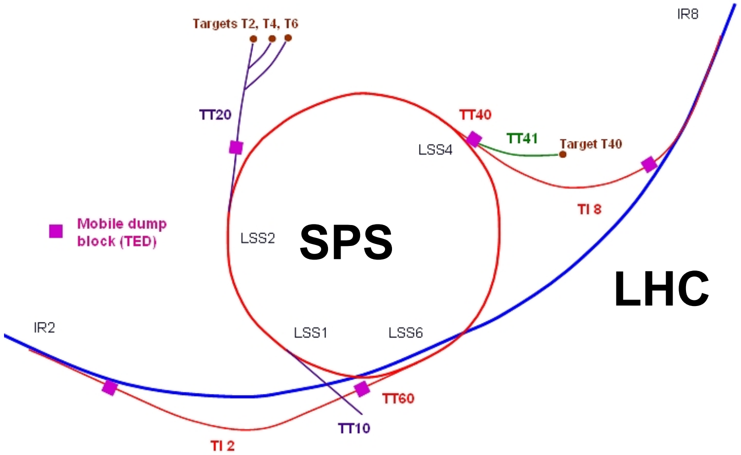
- We reviewed different techniques to study electrical properties of semiconductor sensors
- There is more …
- Radiation damage in
  - front-end ASICs (read-out of sensor)
  - periphery: opto-electronics (laser, receiver)
  - passive components: thermal connections, …
- Time to short to talk about more techniques, but some ideas of mitigating rad. damage in passive components are given in the next part.

Outline

- HEP detector overview
  - what we have and
  - why we need to do better
- Radiation damage in semiconductor sensors
- Characterisation techniques
  - lab-based
  - with beams
- **Clever ideas confronting radiation damage**

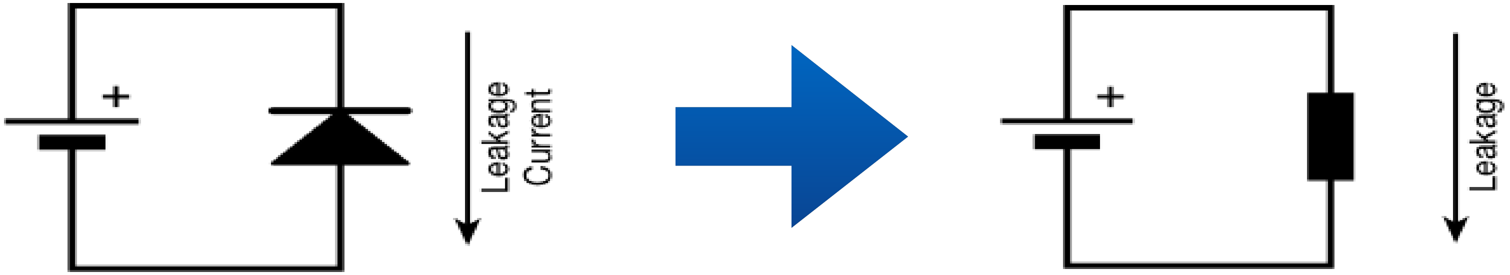






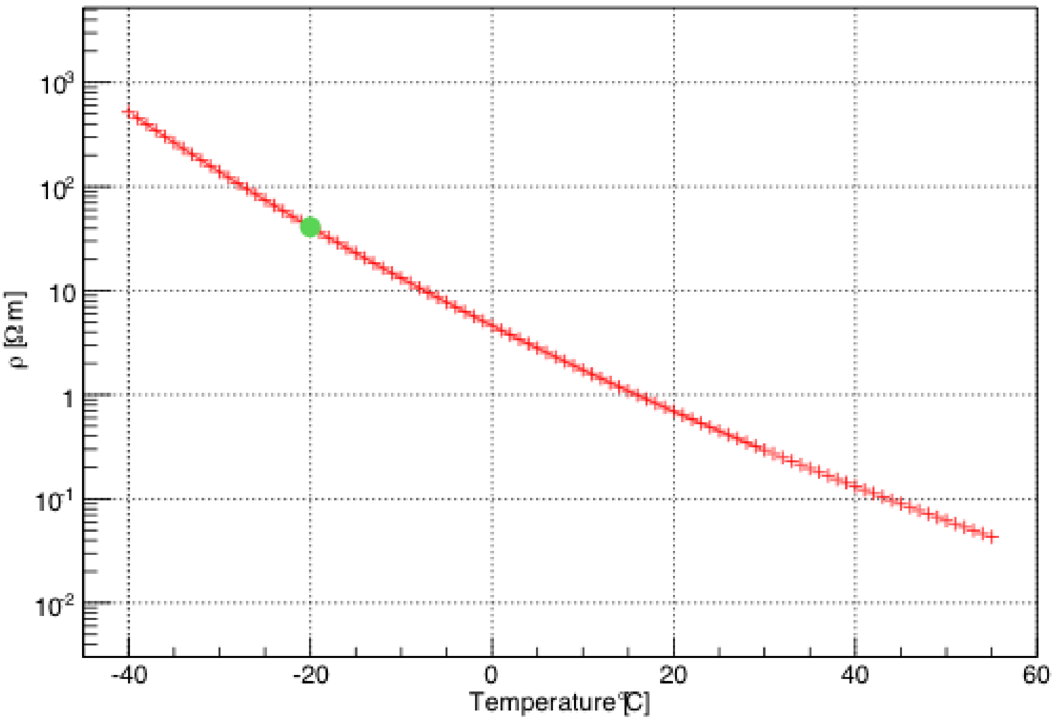
Smarter cooling

- Radiation damage increases leakage current
- Reversed biased diode acts as resistor heat-wise



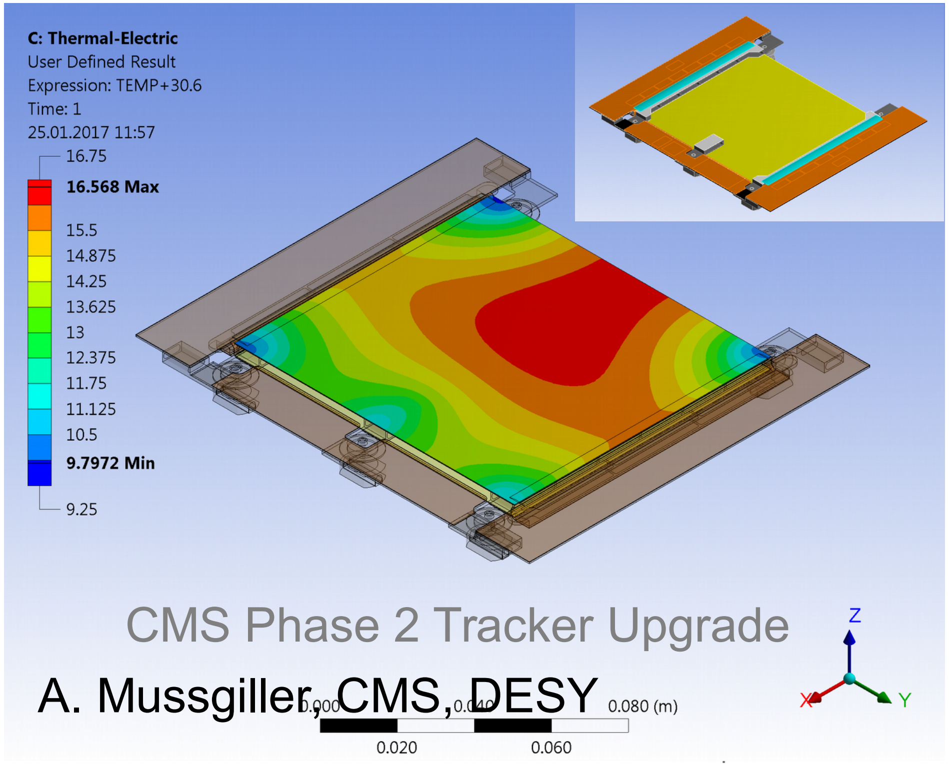
$$\text{Power} = U_{\text{bias}} * I_{\text{leakage}}(T)$$

- Temperature dependence of power dissipation for each given fluence



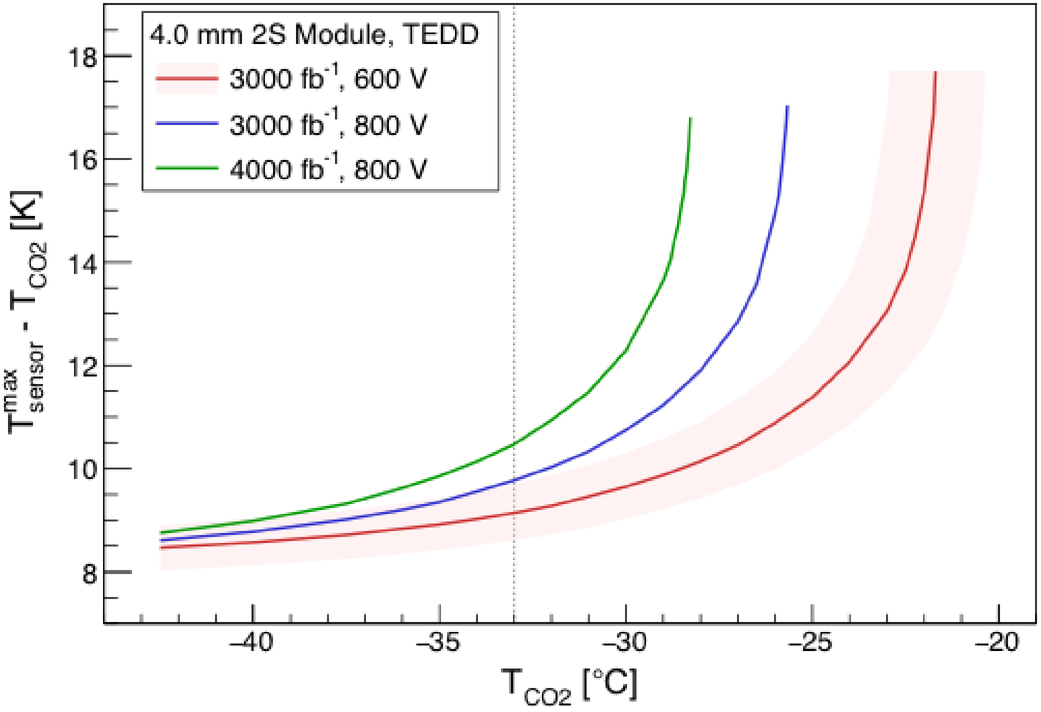
Minimise current / avoid hot spot

- Increased current due to irradiation can be mitigated by carefully designing your cooling system
- Thermal performance of CMS Phase 2 Tracker Upgrade is characterised in terms of T at which thermal runaway occurs ($I_{leakage}$ increases T, which increases $I_{leakage}$, ...)



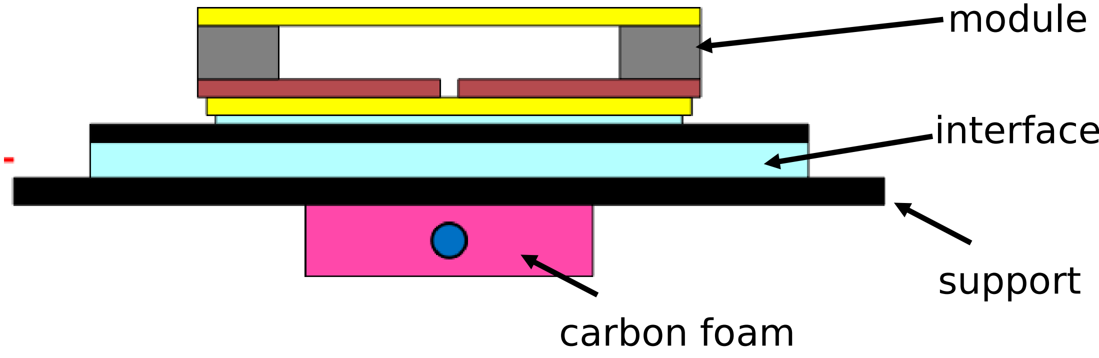
CMS Phase 2 Tracker Upgrade

A. Mussgiller, CMS, DESY



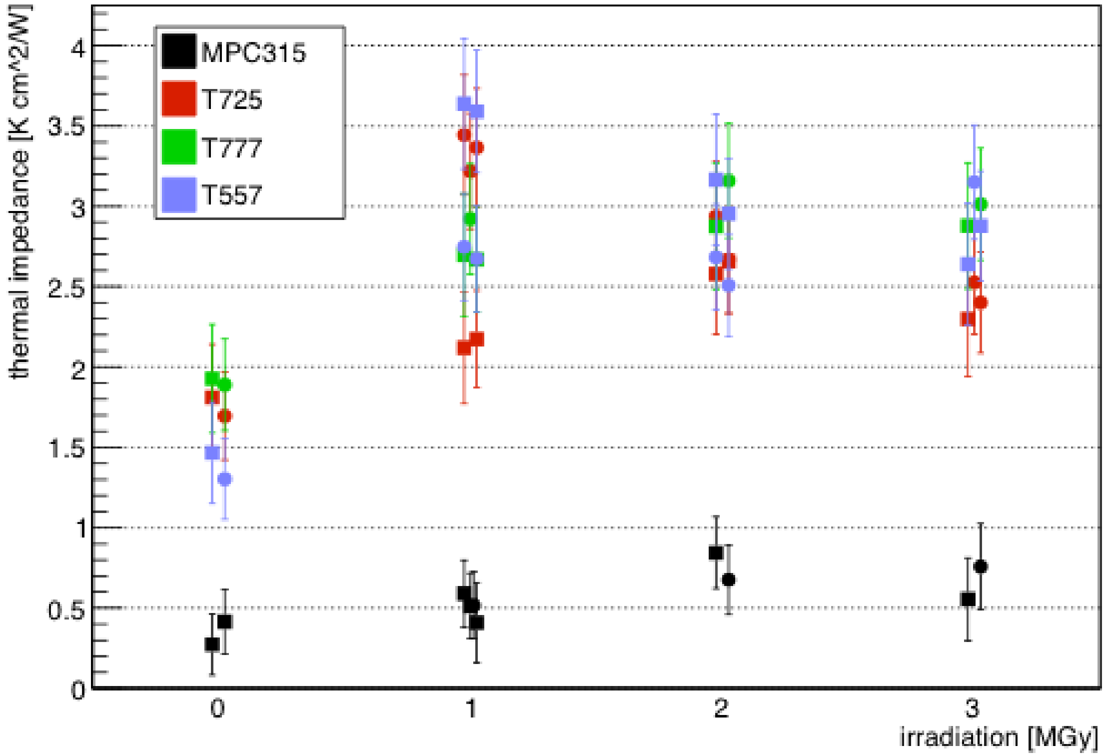
Glue!

- Glue? Yes.
- Need to glue module to cooling system



- Is the thermal connection affected by radiation damage?

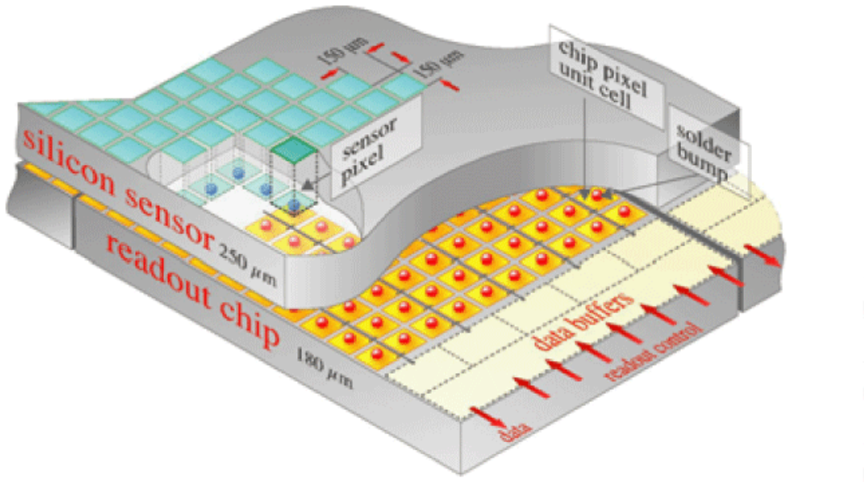
- Glue test sample, measure, irradiate, measure, …, compare

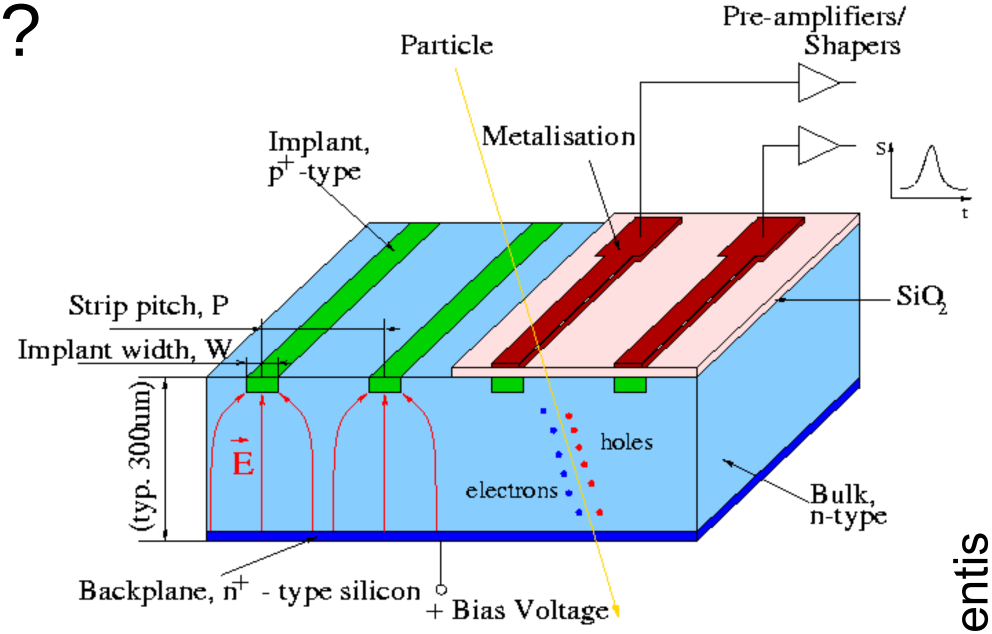


Test beam measurements
-
Sensor R&D for material choice

Material study for phase 2 pixel ...

- … using strip sensors. Why?





- Noise level ~100 e^- before irradiation
- **Bump bonding**
- Heat treatment to achieve connection between sensor and readout
  → modification of sensor properties
- Irradiation of sensor and electronics
  → modification of electronics

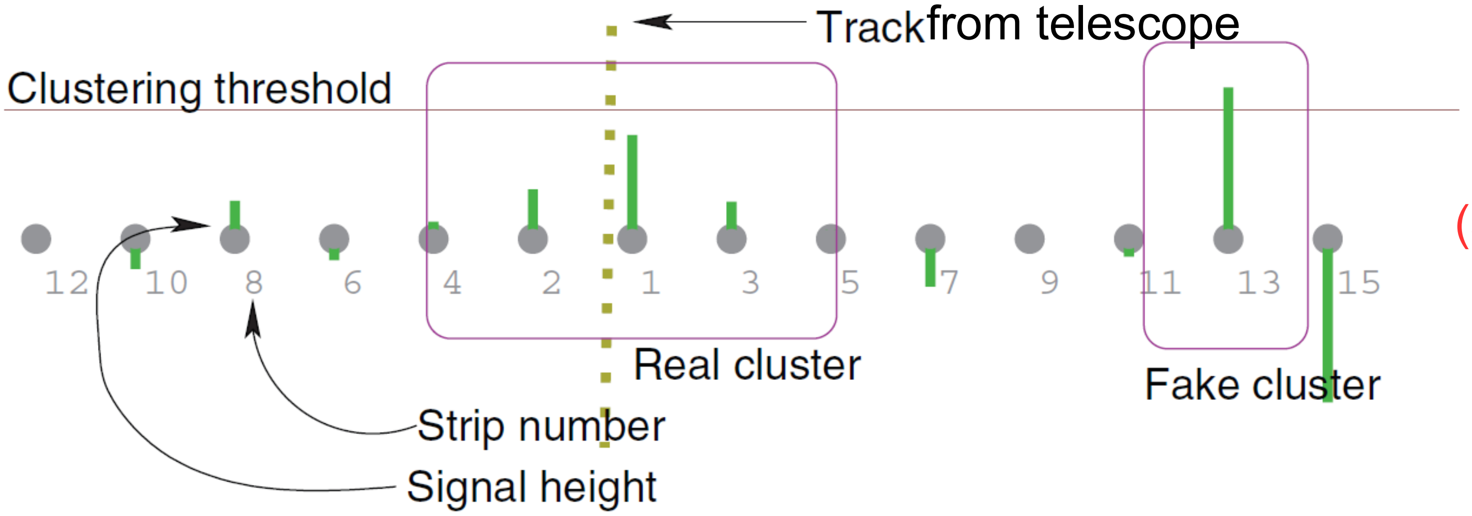
- Noise level ~800 e^- before irradiation
- **Wire bonding**
- No heat treatment for connection with readout electronics
- Separate irradiation
- No modification of electronics

Beam telescope to reconstruct hit position
→ **separation of noise from signal**

Slide from M. Centis

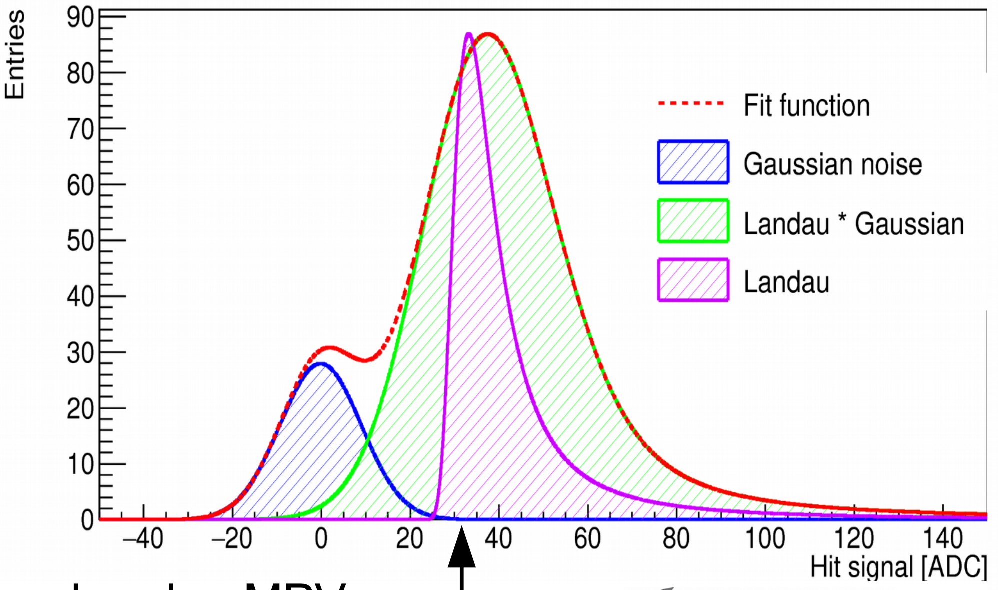
Cluster definition

T. Mäenpää et al, IEEE 2009



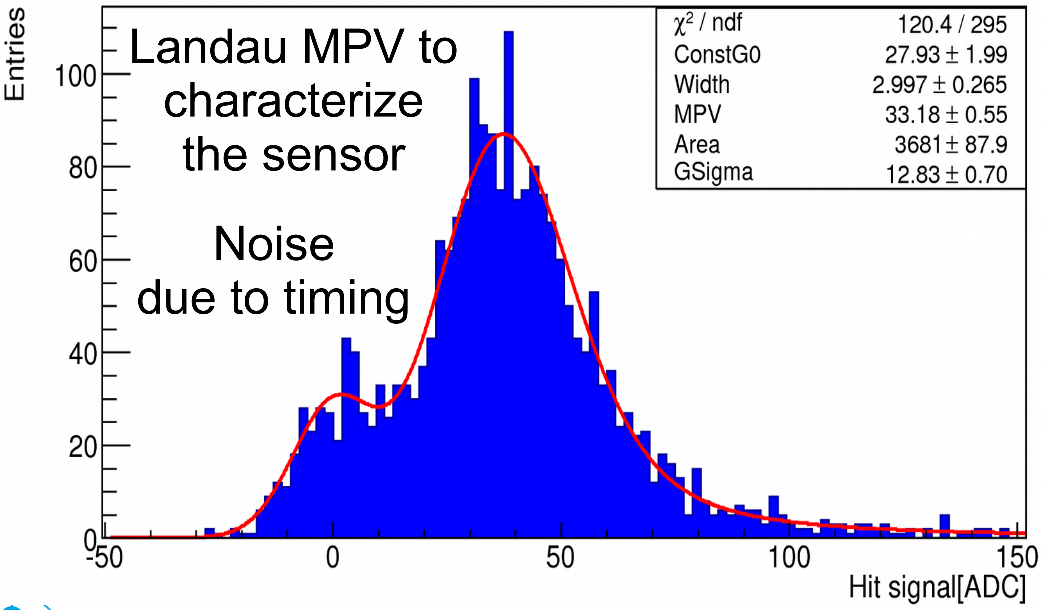
No threshold used in this analysis! (since track is known)

Slide from M. Centis



Landau MPV

Cluster charge distribution



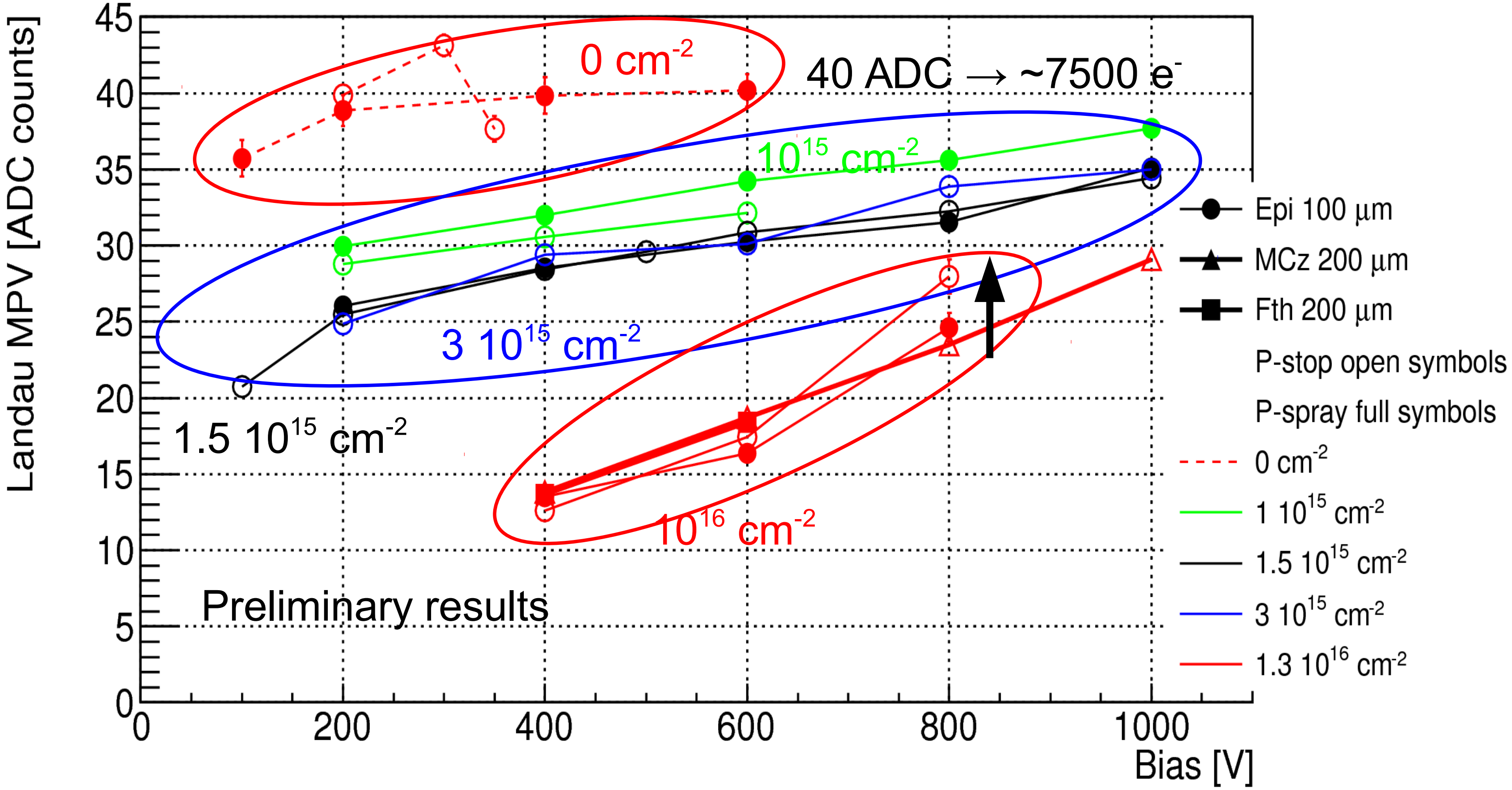
Landau MPV to characterize the sensor

Noise due to timing

Epi100P, 23 GeV p, 3 x 10^{15} cm^{-2}, -800V, -20 °C

Material study for phase 2 pixel

3 groups: unirradiated, ~10^{15} cm^{-2}, ~10^{16} cm^{-2}



Slide from M. Centis

- **Charge collection degrades with irradiation**
- **Charge collection increase with bias after irradiation**
- **At 10^{16} cm^{-2}:**

  100 µm sensors → **faster signal recovery** with bias

  200 µm sensors → operation at **higher bias**

  Similar MPV achieved for both thicknesses!

Material study for phase 2 pixel

The thin sensors show promising results:

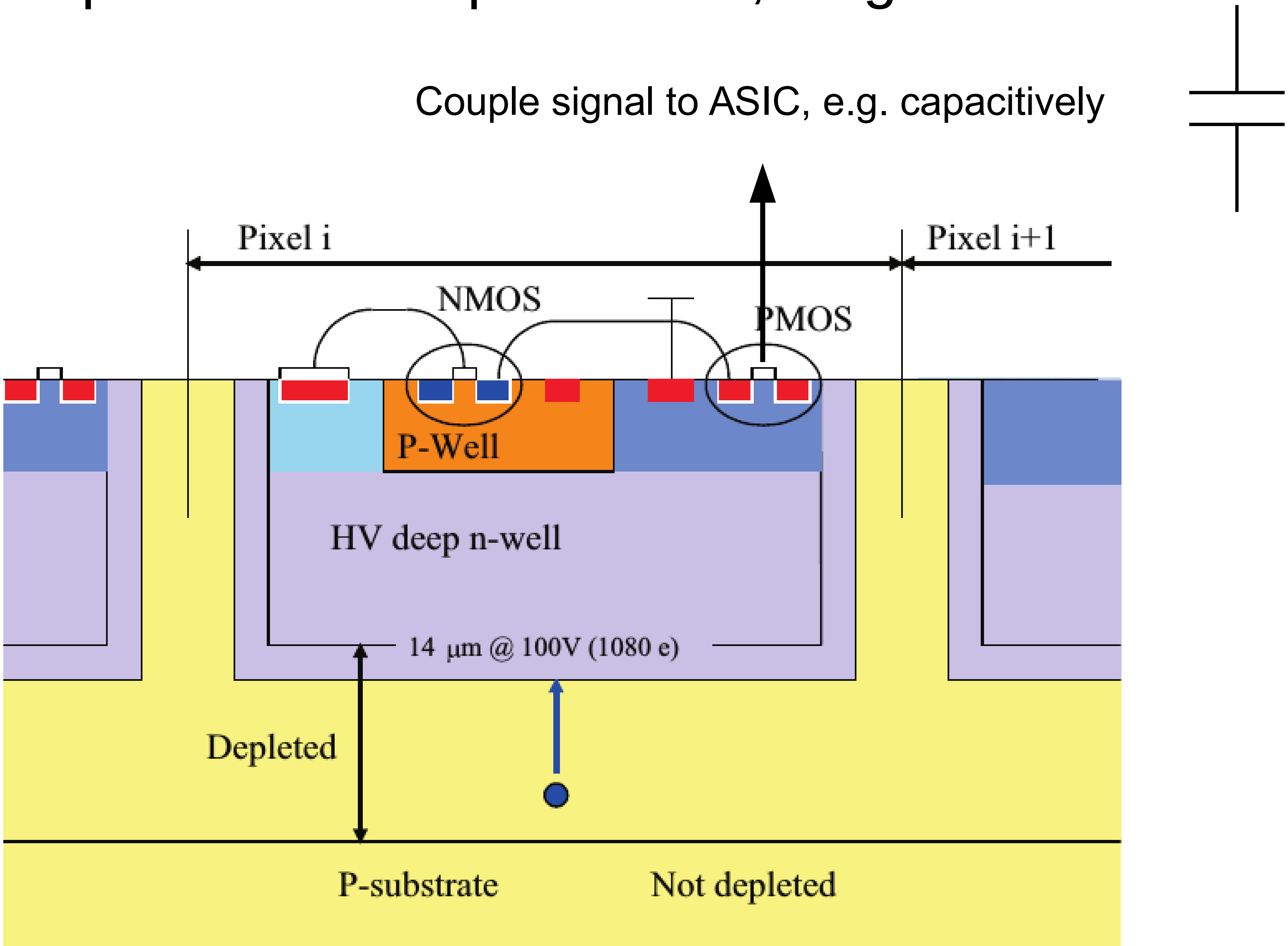
- 100 µm, p-bulk
  - Charge collection efficiency of ~65% after a fluence of 10^{16} cm^{-2}
  - Signal increase with bias
  - Good candidates for outer pixel layers (fluence ~10^{15} cm^{-2})
  - Further studies needed for operation after a fluence of 10^{16} cm^{-2}
- 200 µm, p-bulk
  - Charge collection efficiency of ~35% after a fluence of 10^{16} cm^{-2}
- Comparison to 100 µm sensors:
  - Slower signal increase with bias
  - Smaller noise

→ **150 µm might be worth looking at!**

Slide from M. Centis

HV-CMOS

- Use cheap commercial processes, singles-sided



Couple signal to ASIC, e.g. capacitively

I. Peric, NIMA650 (2011) 158

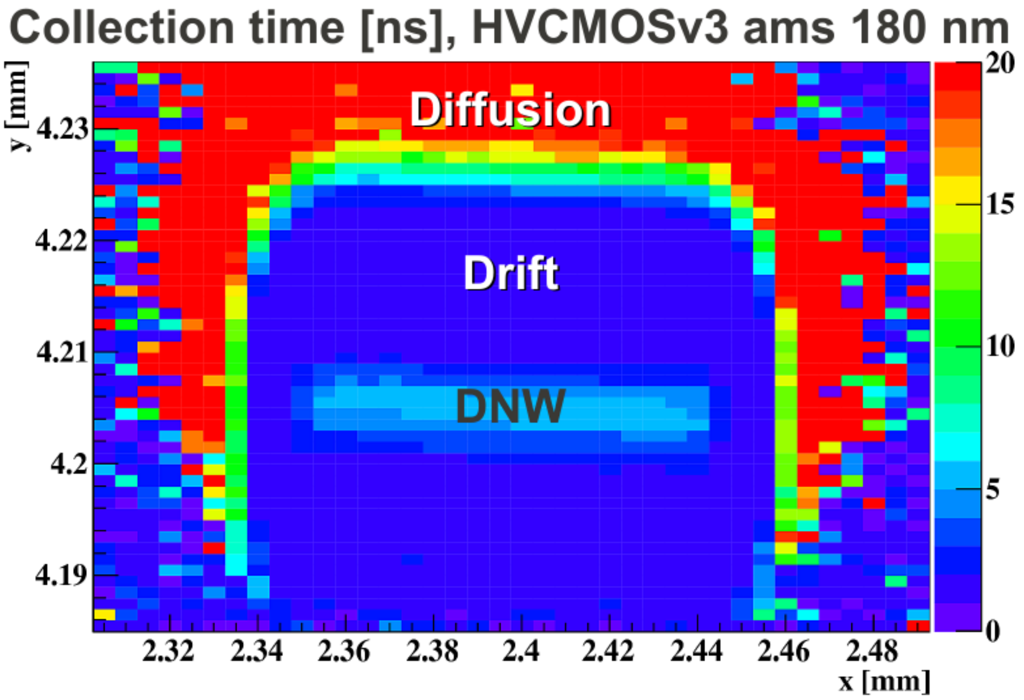
TPA-TCT with HVCMOS

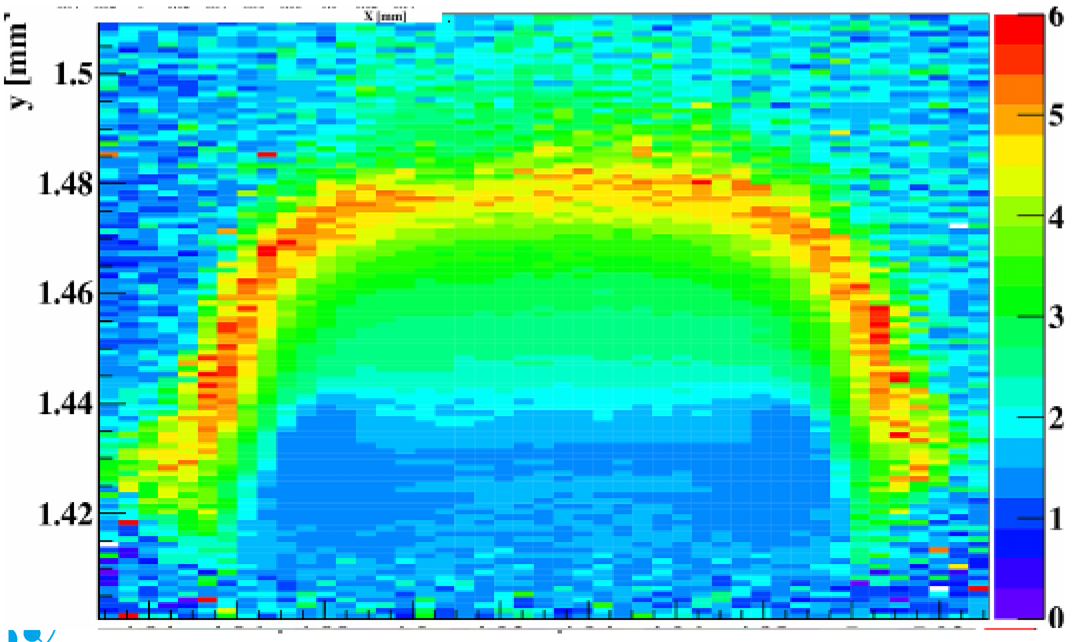
- Study the collection time of HVCMOS sensors with the TPA-TCT technique

un-irradiated

Irradiated
7e15 1/cm^2

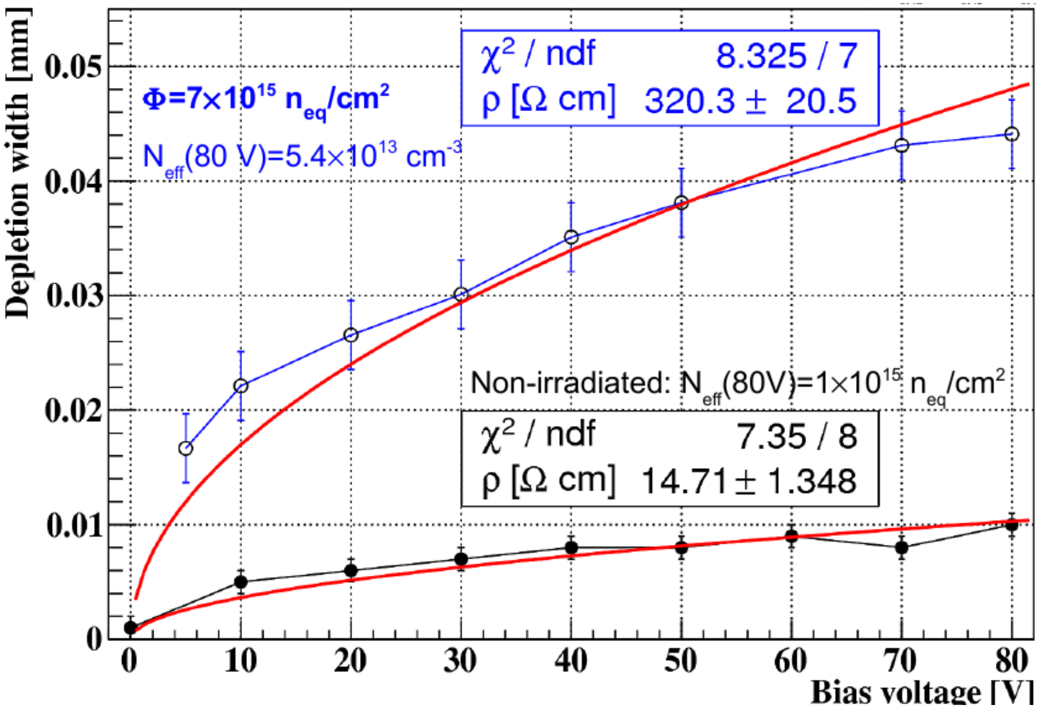
M. Fernandez, 29th RD50





TPA-TCT with HVCMOS II

- Extract the depletion width of the sensors, and compare for different fluences

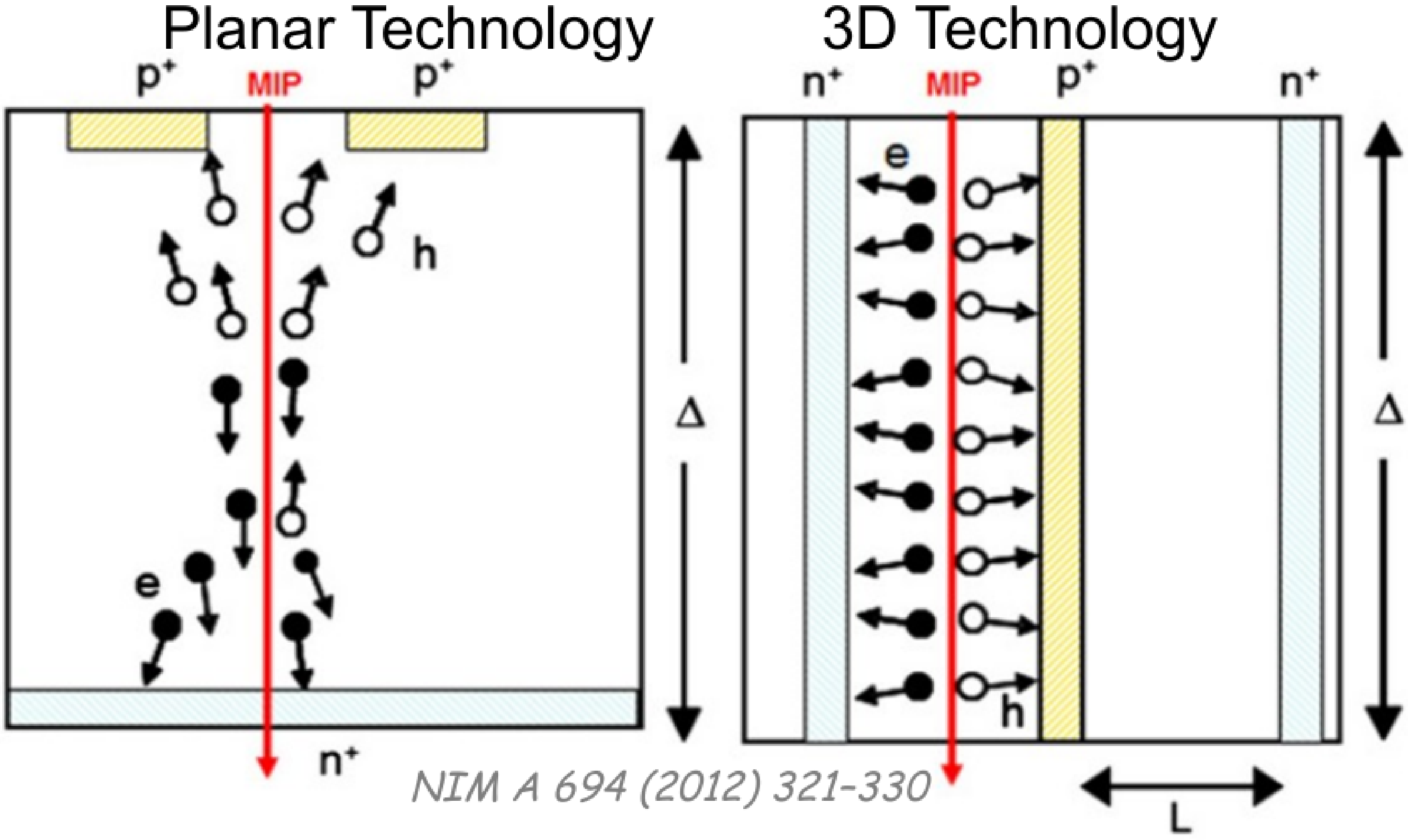


- The performance INCREASES up to a certain flux!
- Then degrades again: Acceptor removal vs. trapping time

M. Fernandez, 29th RD50

3D sensors

- We saw many examples of standard 2D sensors
- Long drift path problematic at high radiation damage (short trapping times, charges don’t reach electrode)
- How to achieve shorter drift paths?



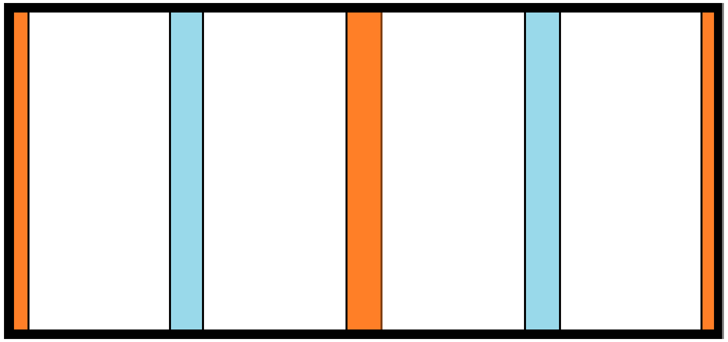
NIM A 694 (2012) 321-330

Picture: U. C. DaVia

ATLAS 3D sensors

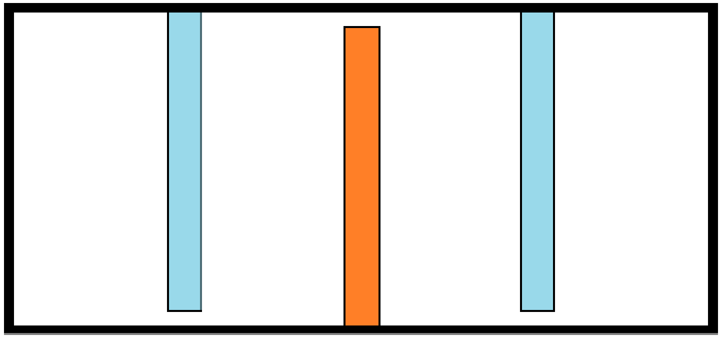
- They exist in different versions

Full 3D technology:



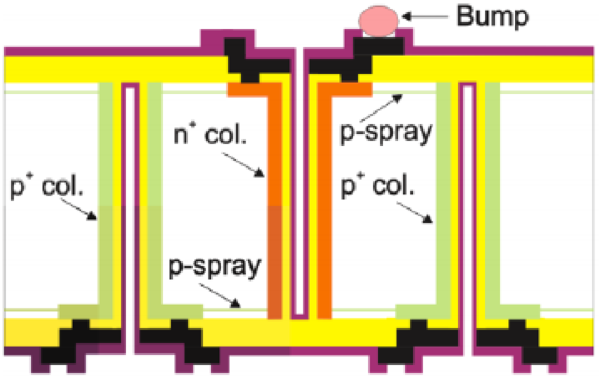
SNF (SLAC) and Sintef

Double-sided 3D technology:

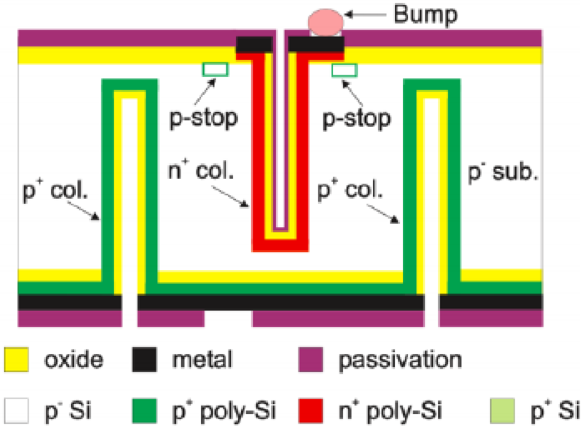


CNM and FBK

FBK



CNM



J. Lange 29th RD50, S. Grinstein, Vertex14,

3D Sensors

- Small inter-electrode distance
- Development of new generation of HL-LHC 3D pixel sensor
  - less trapping due to small L

  → radiation hardness of up to 2e16 n_{eq}/cm^2 required
- Drawback: Larger capacitance

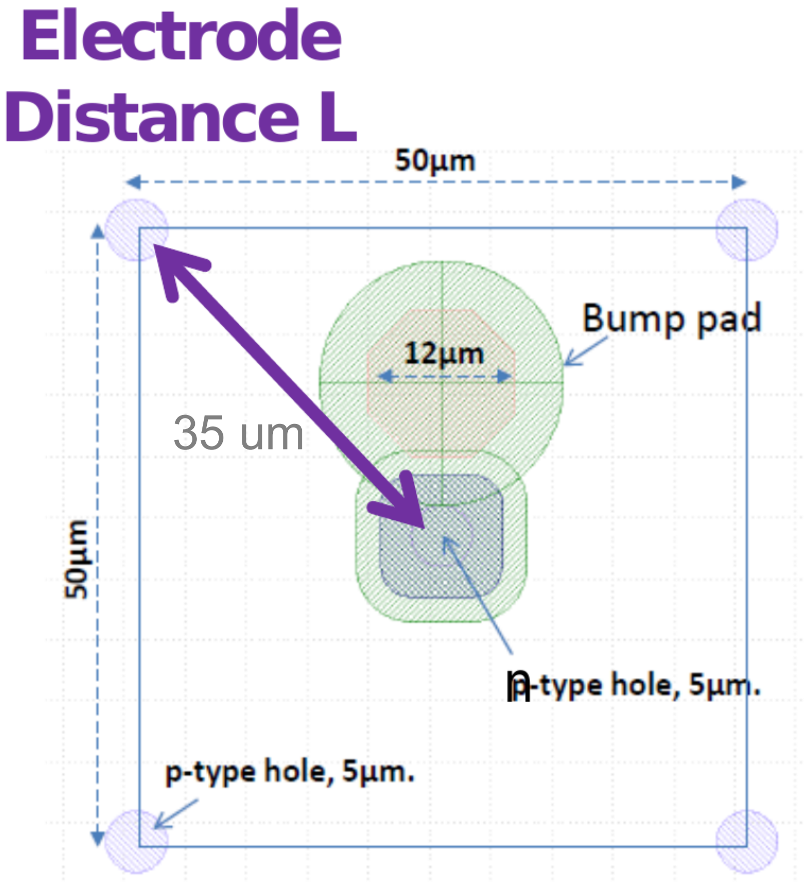
  → more noise
- Possibility to reduce thickness

  → decreases the noise

  → decreased leakage current (less volume)

  → but also less charge!

  → it is always a trade-off, need also better ASICs!

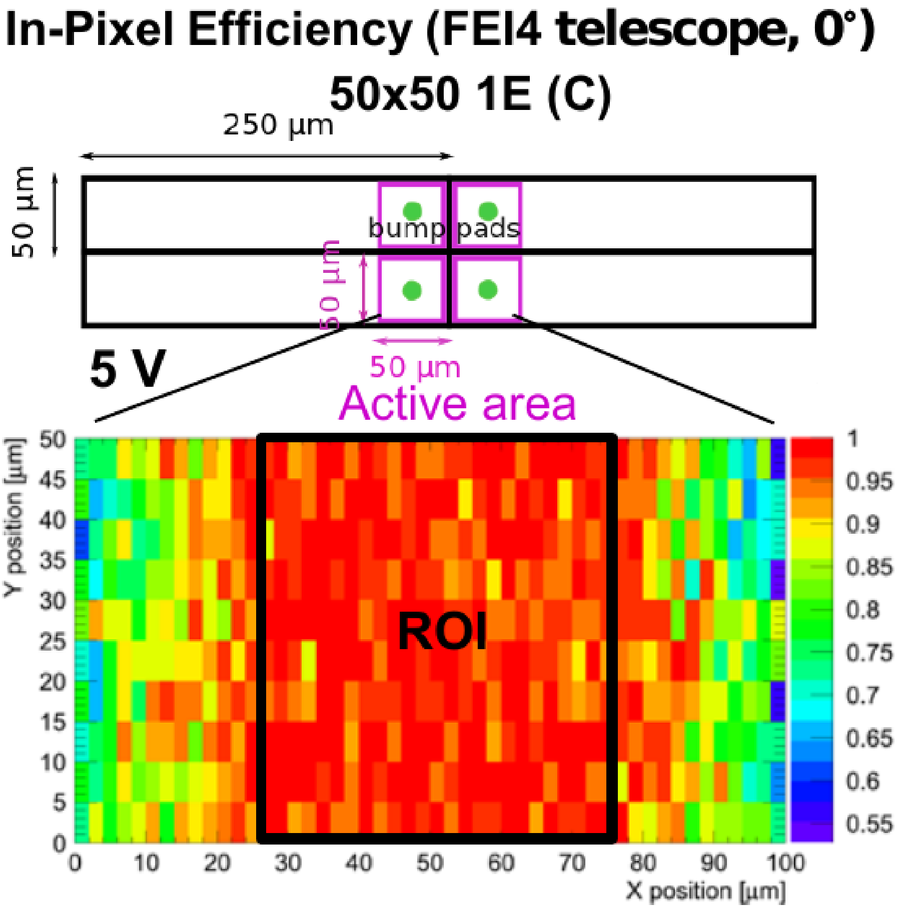


J. Lange 29th RD50, S. Grinstein, Vertex14,

3D sensor in a test beam

- Test beam with a 50 x 50 um2 sensor

un-irradiated **irradiated**

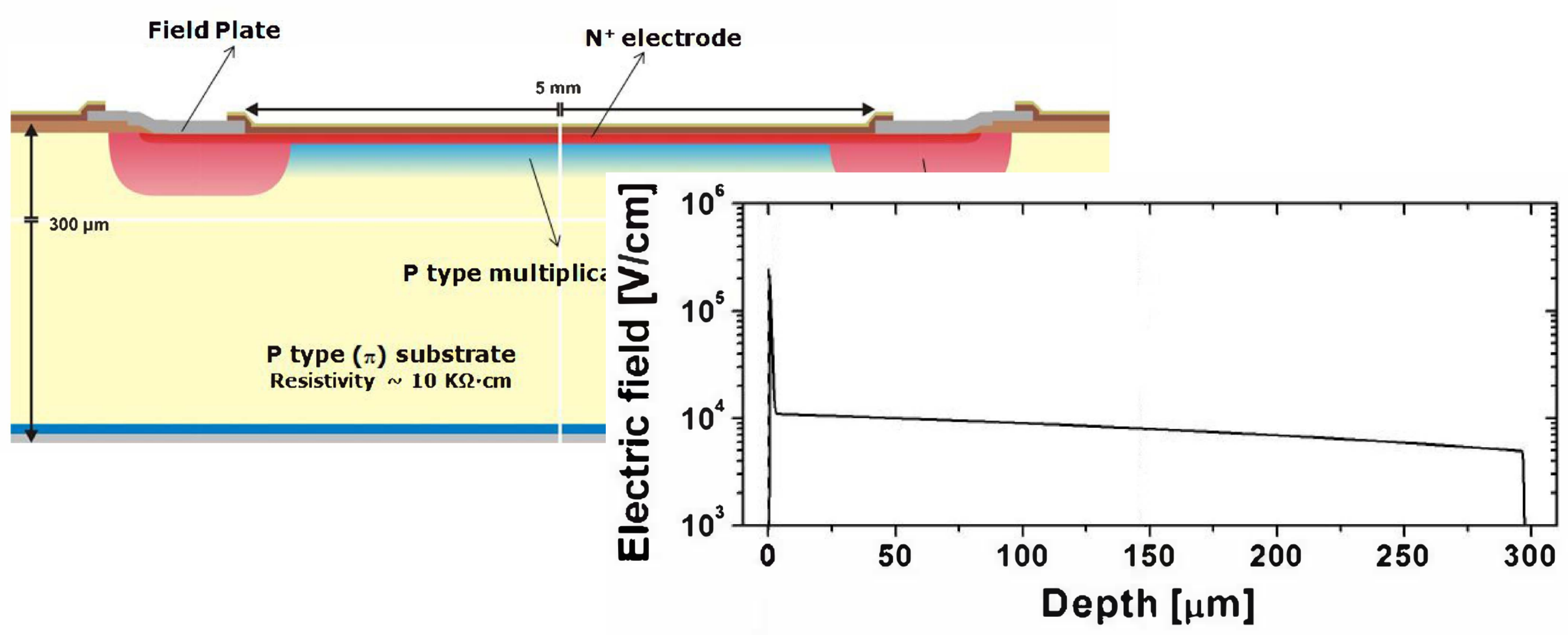


?

J. Lange 29th RD50, S. Grinstein, Vertex14,

Low gain avalanche diode

- Try to increase SNR of your (irradiated) sensor
- LGAD uses P-type multiplication layer below n+ electrode
- Use top-TCT (red laser) for scan



2015 10th Spanish Conference on Electron Devices, “Low gain Avalanche Detectors for HEP”, P. Fernandez-Martinez et al.

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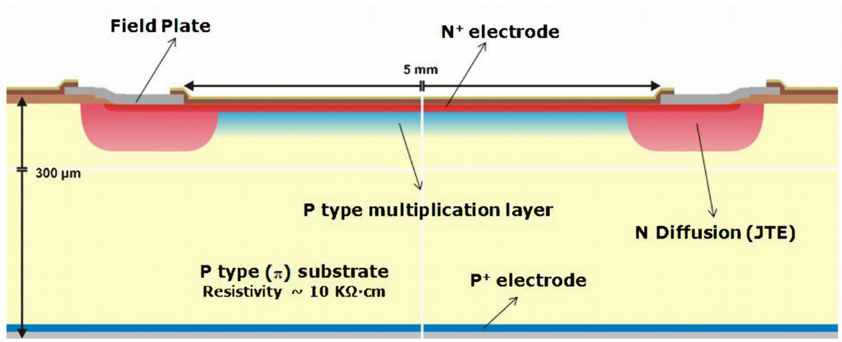
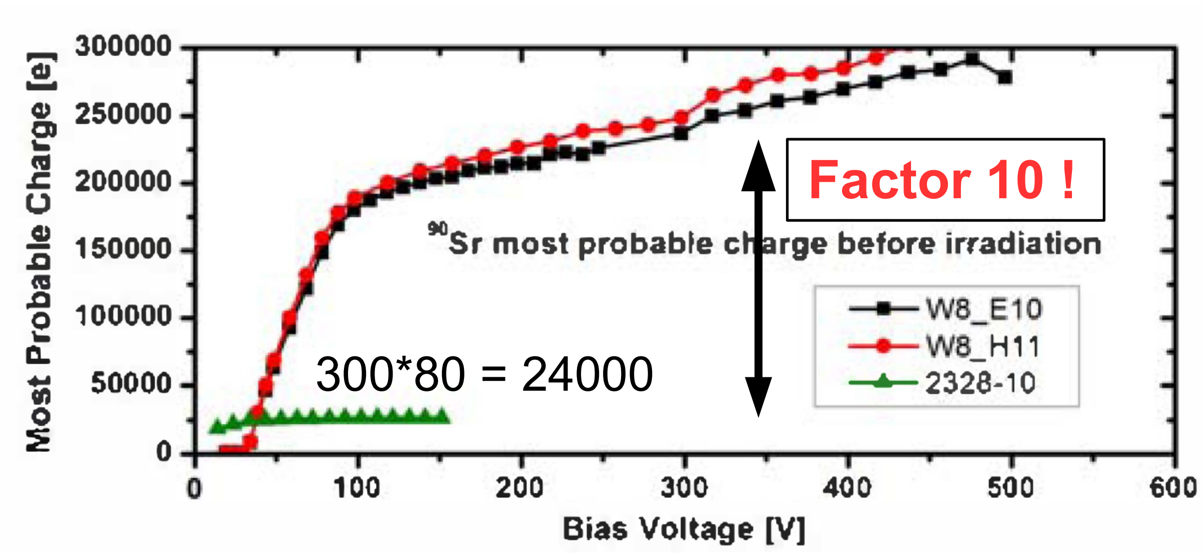
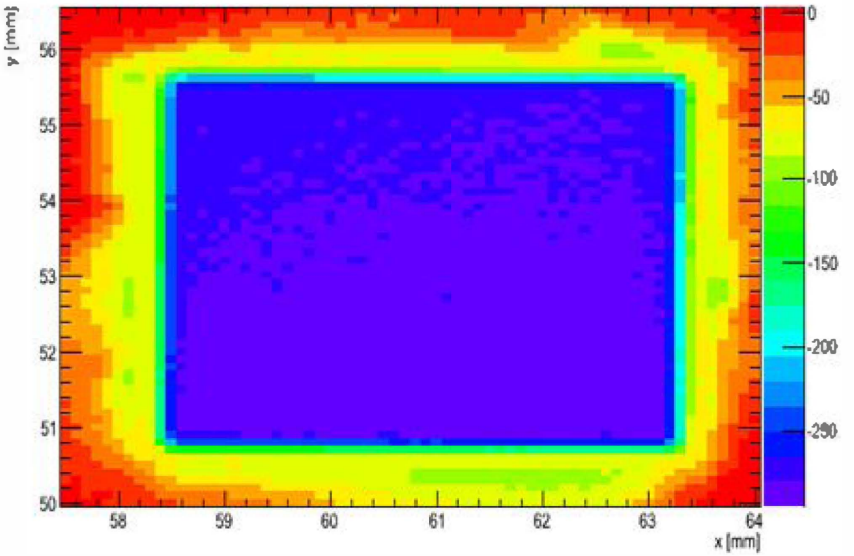




Factor 10 !

300*80 = 24000

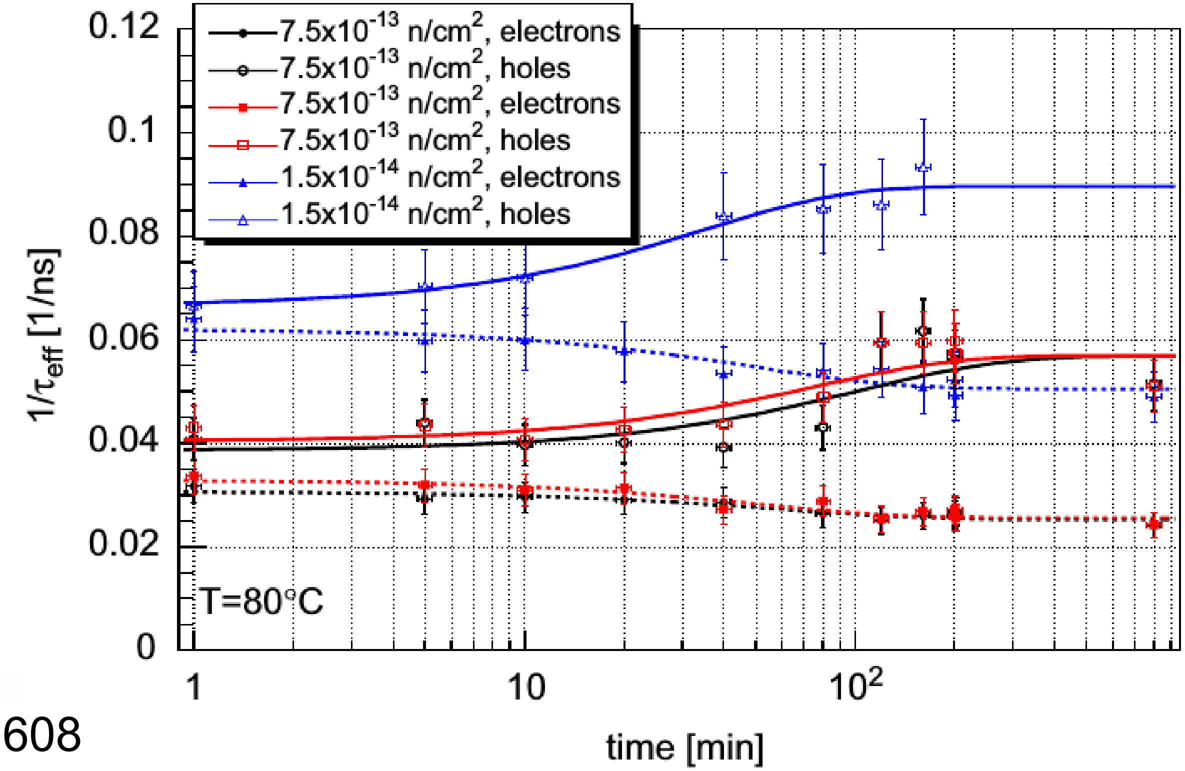


2015 10th Spanish Conference on Electron Devices, “Low gain Avalanche Detectors for HEP”, P. Fernandez-Martinez et al.

Annealing of defects

- Heating a damaged sensor has positive and negative effects
- Lifetime of charges at given flux is changed by heating:
  - heat → higher mobility of atoms/vacancies
  - new ‘configuration’ of defects

  → visible in TSC and DLTS
- Trapping probability increases for holes, decreases for electrons



G. Kramberger et al., NIMA 571 (2007) 608

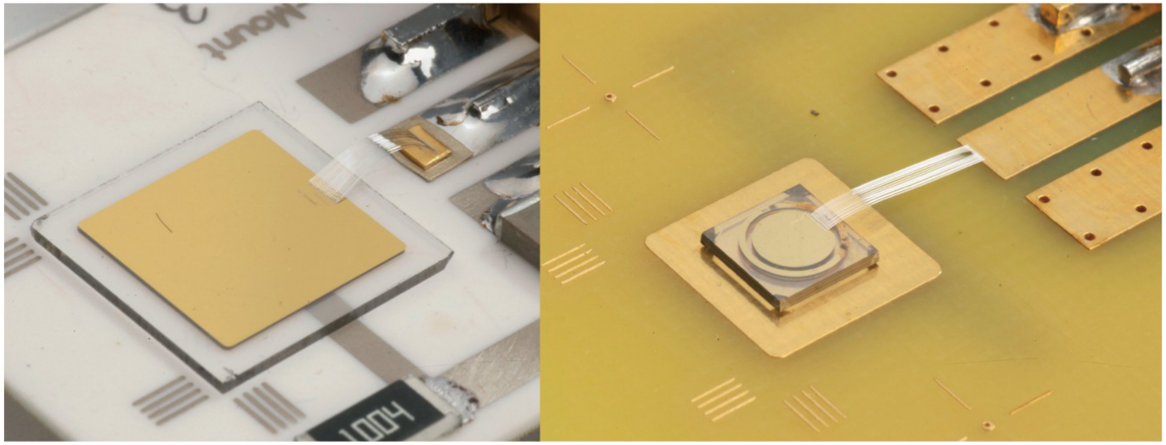
Maybe diamond?

Pros:

- High band gap (5.5 eV)
  → Very high breakdown field
  → Very low leakage current
- 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
- Very wide sensitivity range

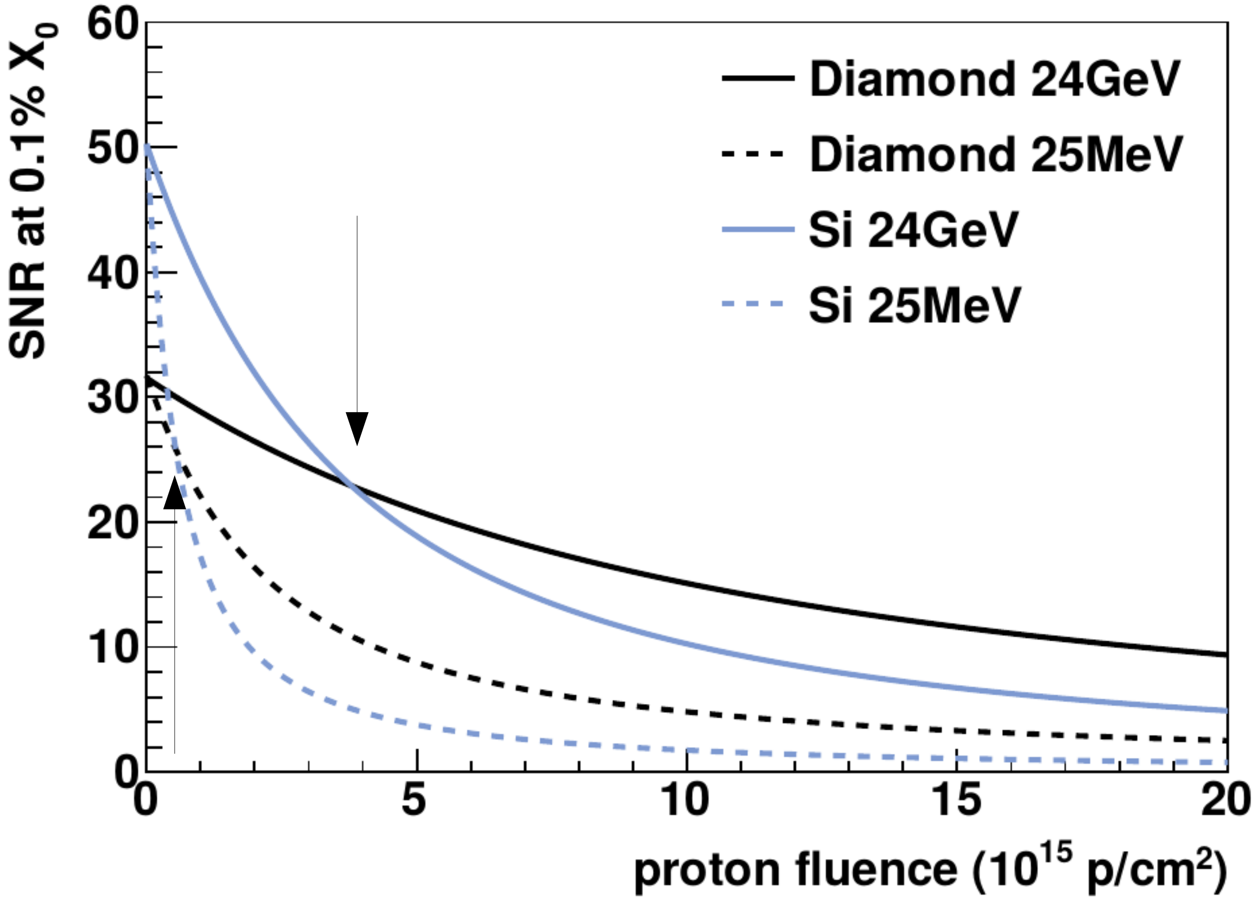
Cons:

- 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



Silicon vs. diamond

- Which material performs better over a time/fluence?



JW Tsung, et al, arXiv 1206.6795v2

There is more …

- Nitrogen, oxygen enriched wafers:

  Idea:
  specific impurities + vacancy (clusters) from damage
  better than vacancy alone

- Micro-channel cooling:
  Idea:
  optimised cooling by micro-channels inside the bulk sensor material (instead of cooling pipes)
  → very effective cooling

Résumé

- Radiation damage is challenging by itself
  - Need to understand the microscopic mechanisms and their macroscopic effects

  → Need various techniques for profound understanding

- Radiation damage influences detectors and their parameters in many ways
  - Need to understand which effect is important for my detector

- Overcoming radiation damage needs clever ideas!
  - New technologies, new geometries, new/modif

  material, engineered bulk regions,

+ your future ideas!