First measurements with silicon detectors irradiated above 3e17 n/cm^2

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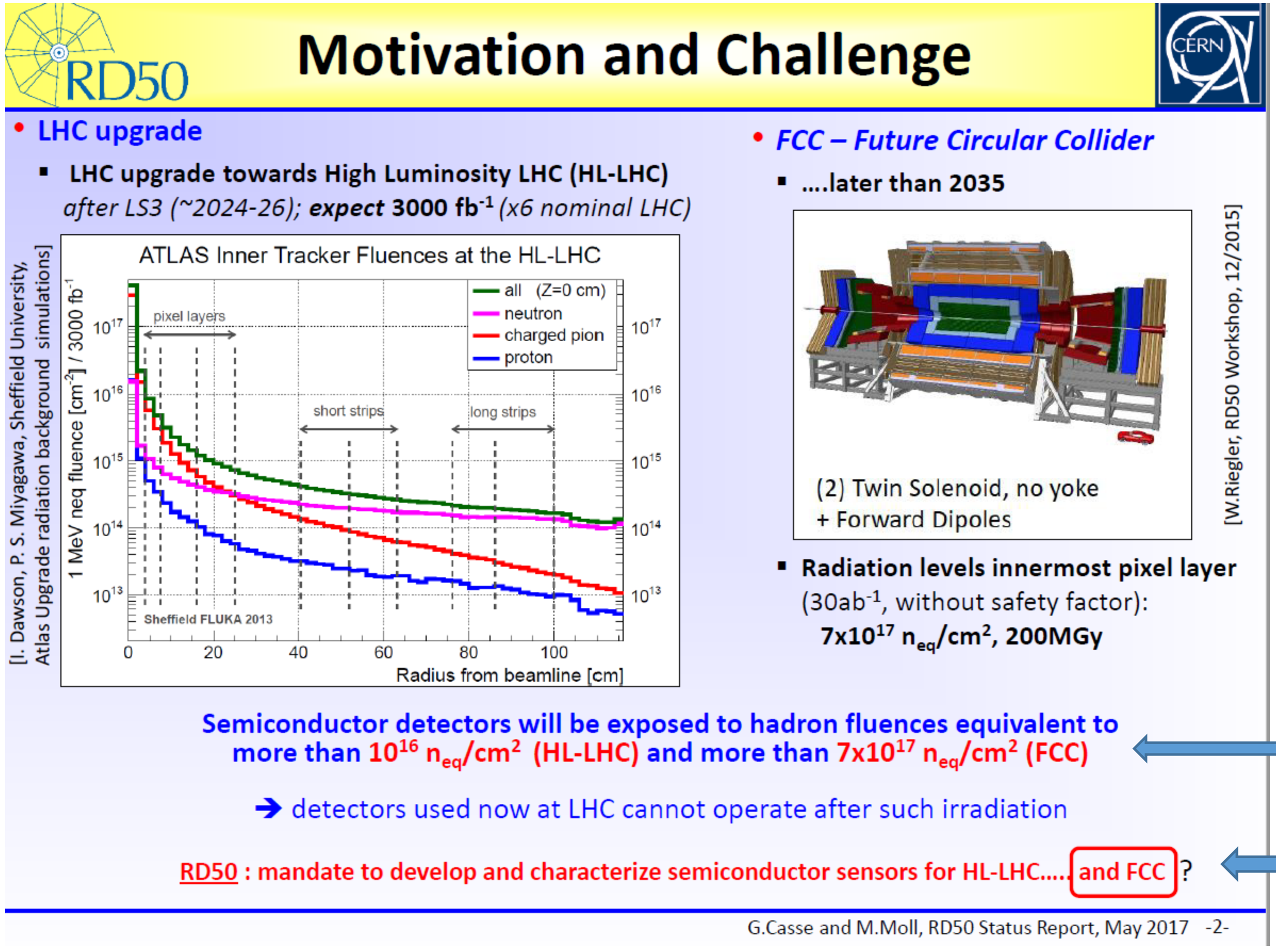
Motivation

RD50 status report May 2017:



RD50 Prolongation Request: May 2018

5.2.2 Extreme fluences:

Explore the macroscopic device properties (I-V, C-V-f, CCE) on different p-type silicon materials up to fluence values ranging from **1e16 to 5e17 neq cm-2 and beyond** with neutrons and protons of different energies.

Continue previous work:

- G Kramberger et al., *Charge collection studies on custom silicon detectors irradiated up to* ***1.6E17*** $\boldsymbol{n_{eq}/cm^2}$, **2013 *JINST* 8 P08004** (Charge collection with Sr-90 with spaghetti detectors up to **1.6E17** n_{eq}/cm^2)

- Marko Mikuž et al., *Extreme Radiation Tolerant Sensor Technologies",* The 26th International Workshop on Vertex Detectors, 10-15 September 2017, Las Caldas, Spain (E-TCT: electric field, mobility, trapping …. estimated up to **1E17** $\boldsymbol{n_{eq}/cm^2}$)

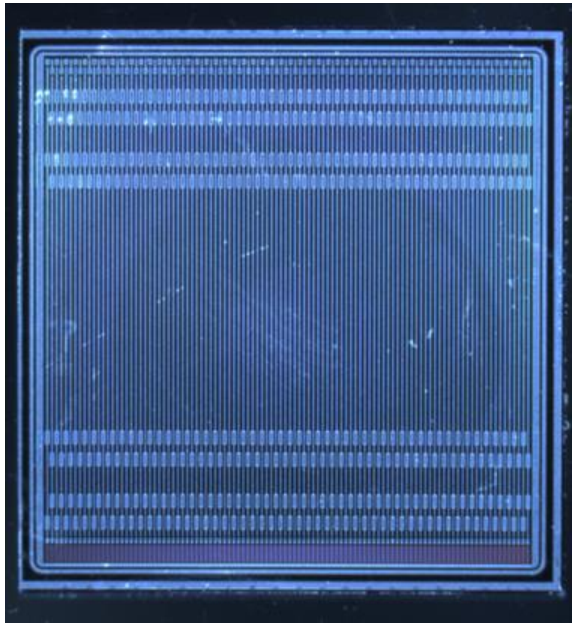
https://indico.cern.ch/event/627245/contributions/2676707/attachments/1523242/2380562/Extreme-Vertex-Sep17.pdf

Samples:

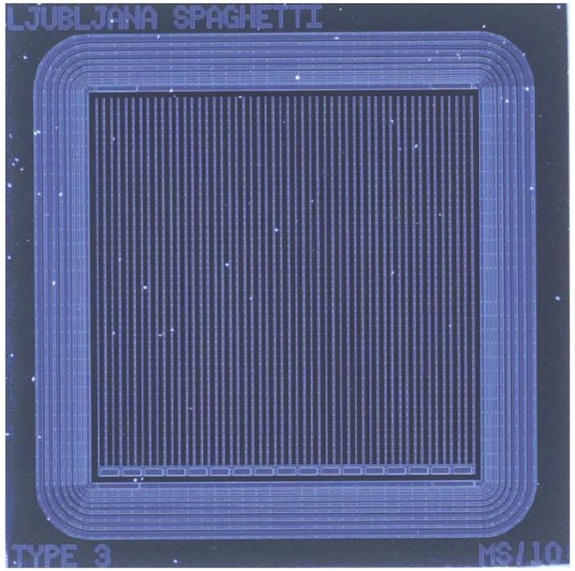
- A12 mini strip detector
- 50 um thick LGAD pad detectors from CNM
- “spaghetti” detectors

Irradiated in reactor in Ljubljana up to 3E17 n_{eq}/cm^2

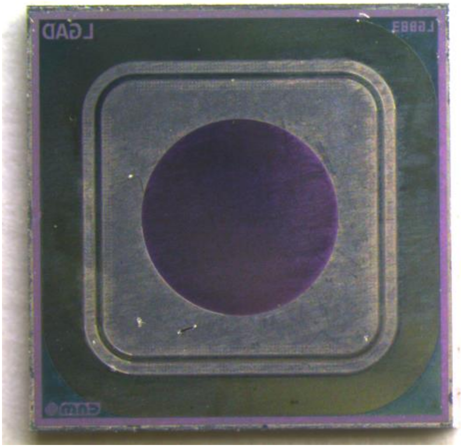
➔ spaghetti detectors were preirradiated with 1.6E17 n_{eq}/cm^2 in 2013 → **total fluence 4.6E17 n_{eq}/cm^2**



A12 mini, 7x8 mm², 75 um pitch, 300 um thick



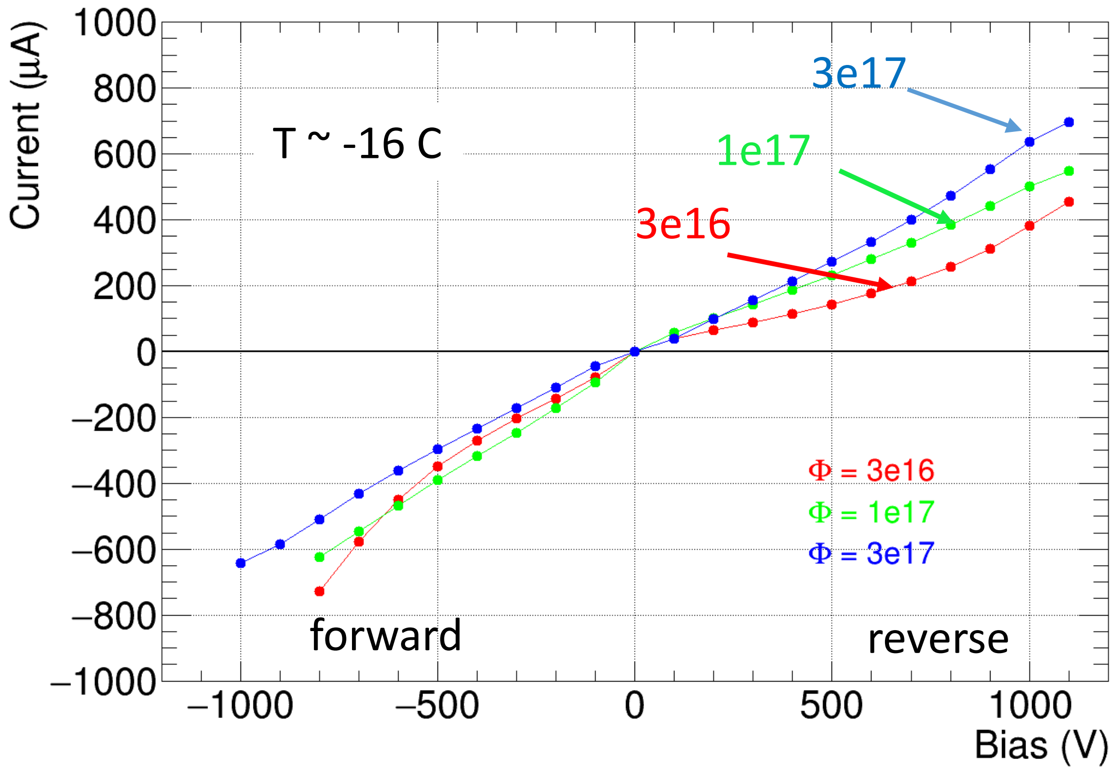
4x4 mm2, n-on-p, strip pitch 80 um
300 um thick, all strips connected together on one side



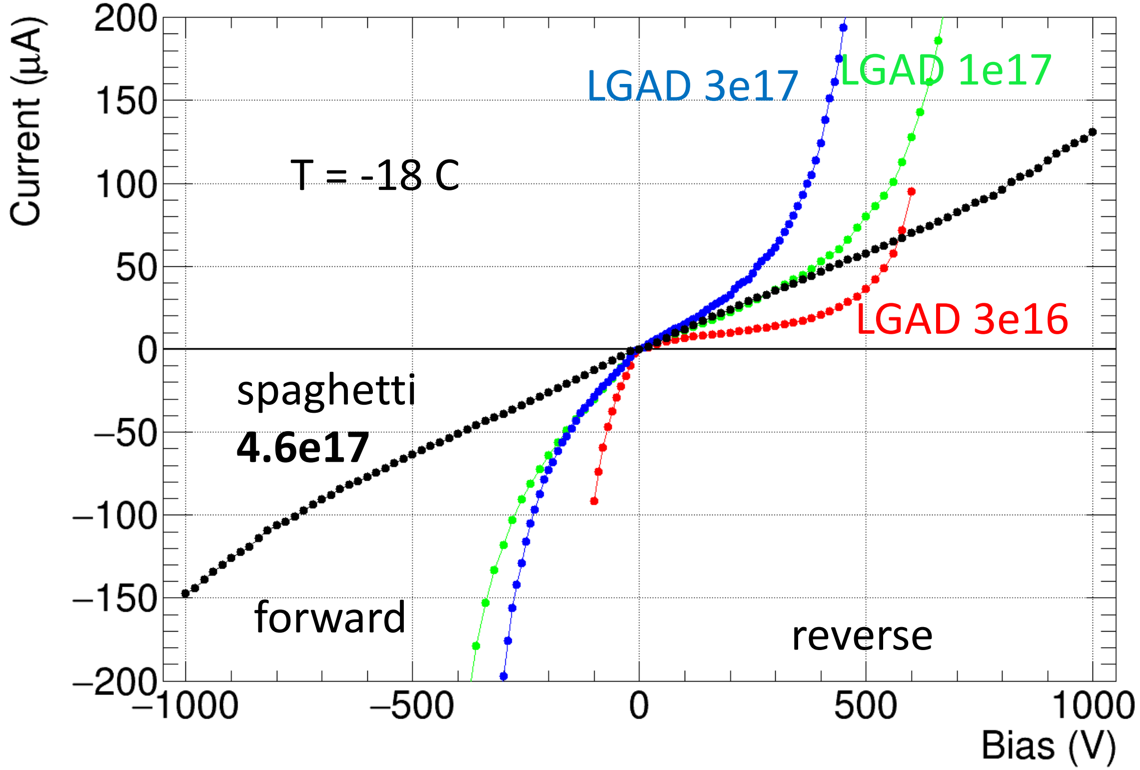
LGAD, 50 um thick, CNM, 3x3 mm2

Current

I-V, A12 strip detectors measured on E-TCT setup



I-V, LGAD and spaghetti measured on probe station

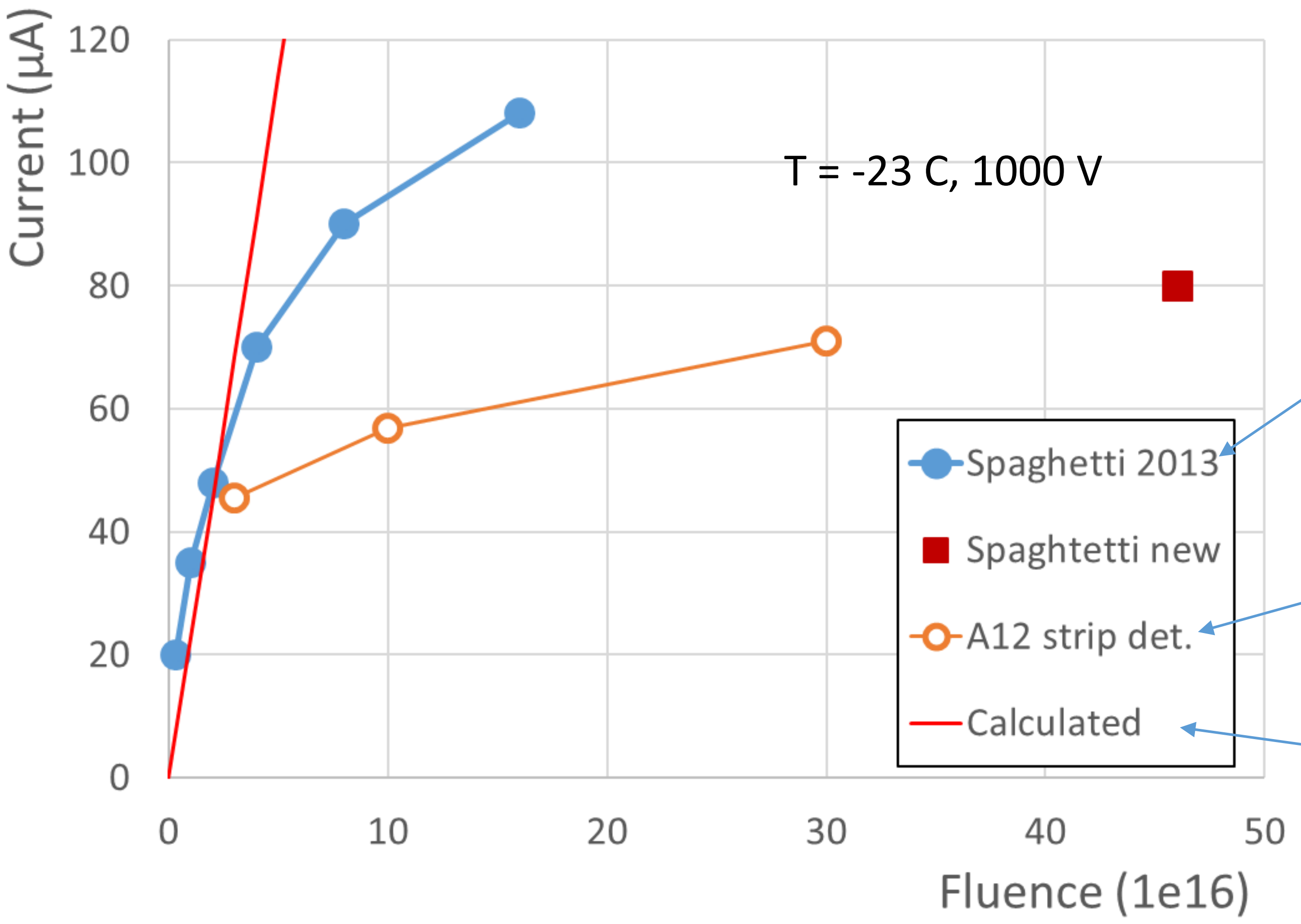


- strip detectors:
  - ➔ small increase of current with fluence
  - ➔ not much difference between reverse and forward current

- LGAD:
  - ➔ current increases with fluence more than in thicker strip detectors
  - ➔ larger difference between reverse and forward bias current at 3e16
  - ➔ breakdown (multiplication)?

Current

Current at 1000 V, 300 um thick detectors



Spaghetti 2013 from:
G. Kramberger *et al,*
2013 *JINST* **8** P08004

Normalised to spaghetti volume

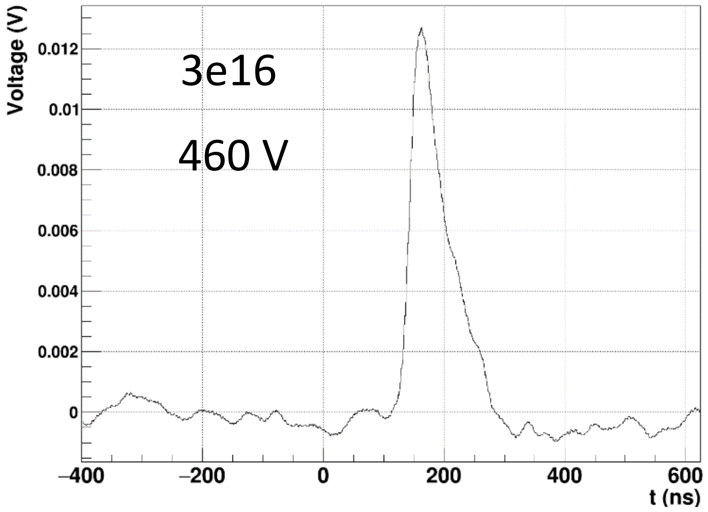
I = α·Φ·V
α =4E-17 A/cm2, scaled to -23 C,
spaghetti det. volume

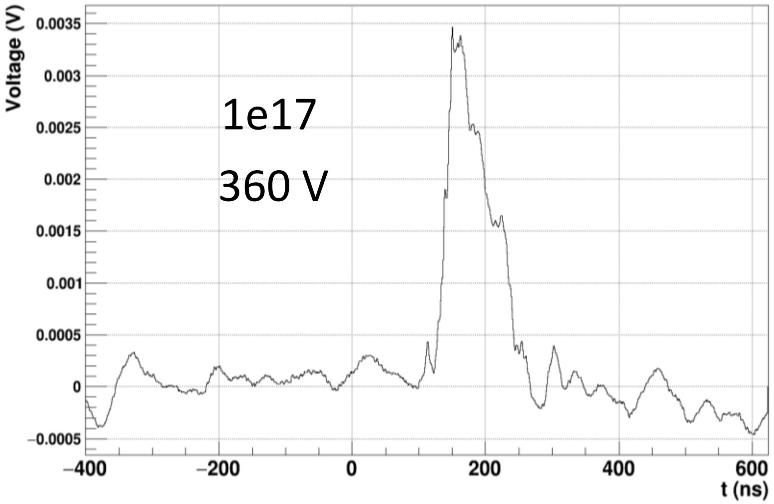
➔ slow increase of current with fluence

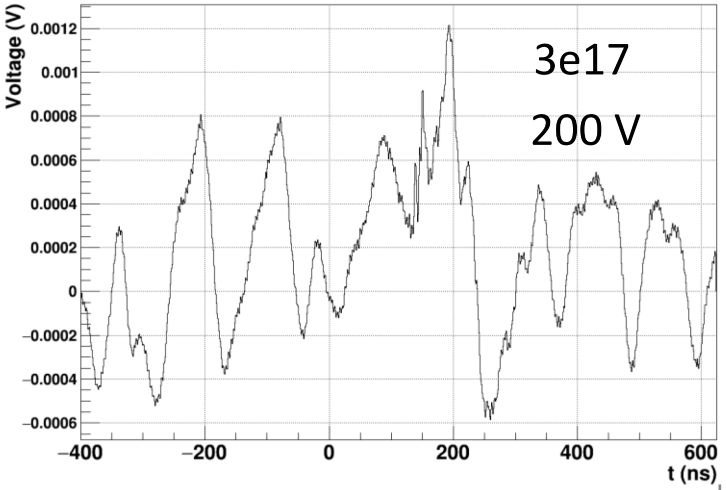
Warning: temperature uncertainties significant

Charge collection

- average waveform from **Ortec142 + 25 ns shaper** caused by fast electron from Sr- 90 source
- measured up to bias voltage at which current ~ 90 uA (900 V voltage drop on 10 MOhm bias resistor)

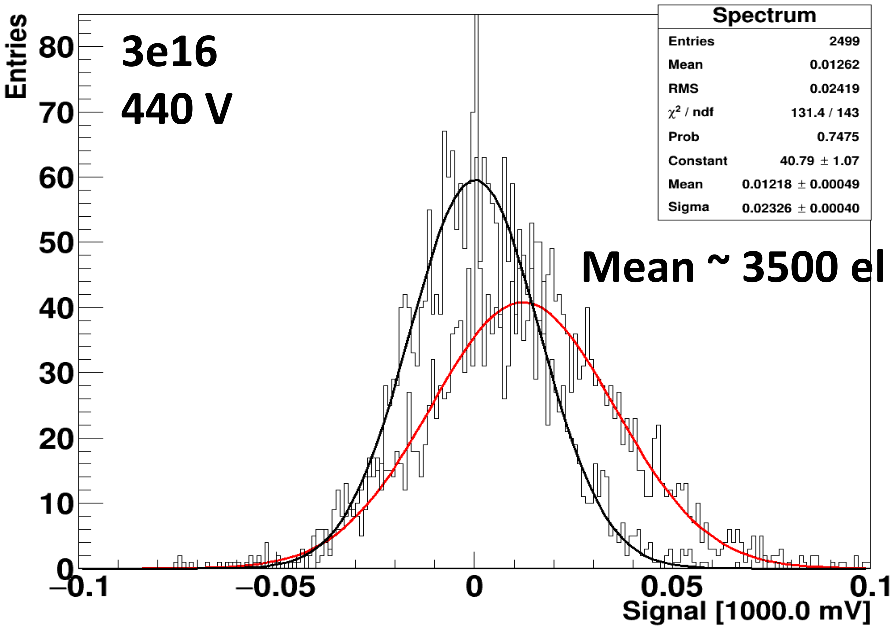


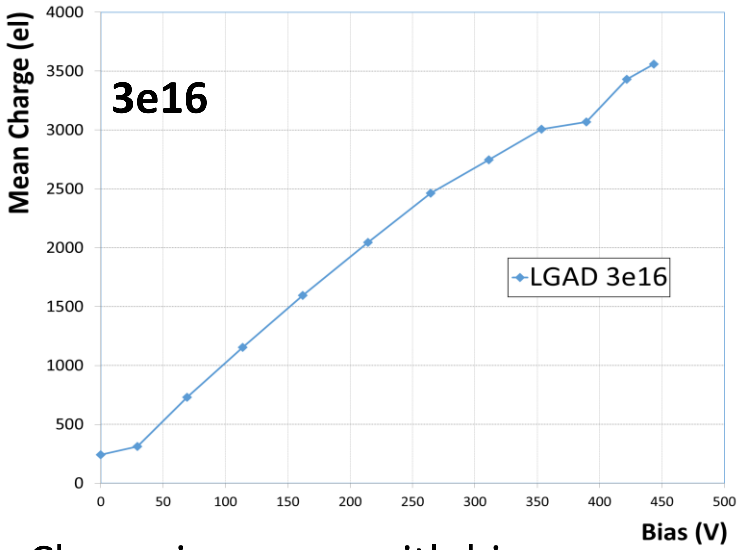




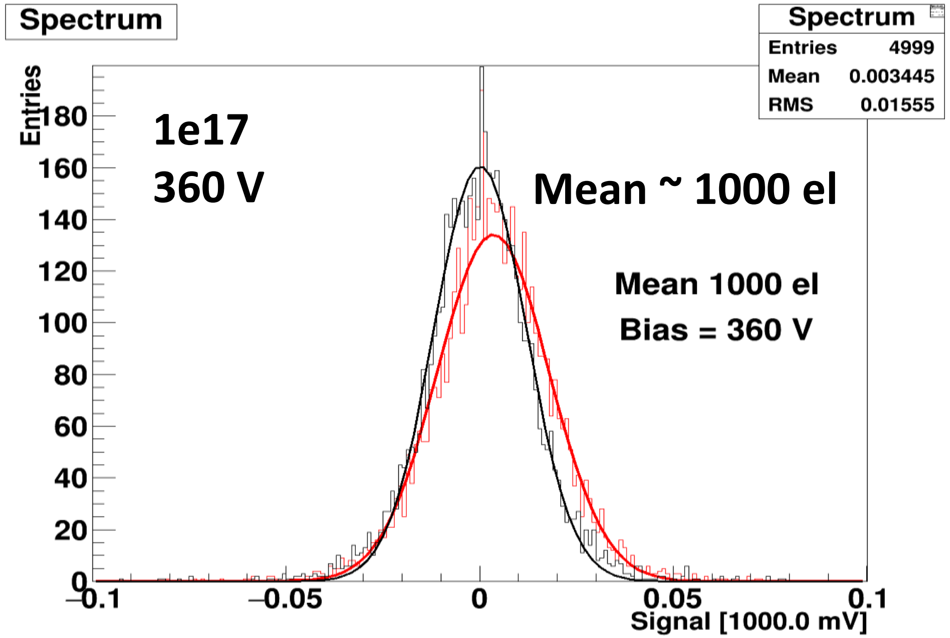
No signal seen in spaghetti detector irradiated to 4.6e17 up zo 320 V bias

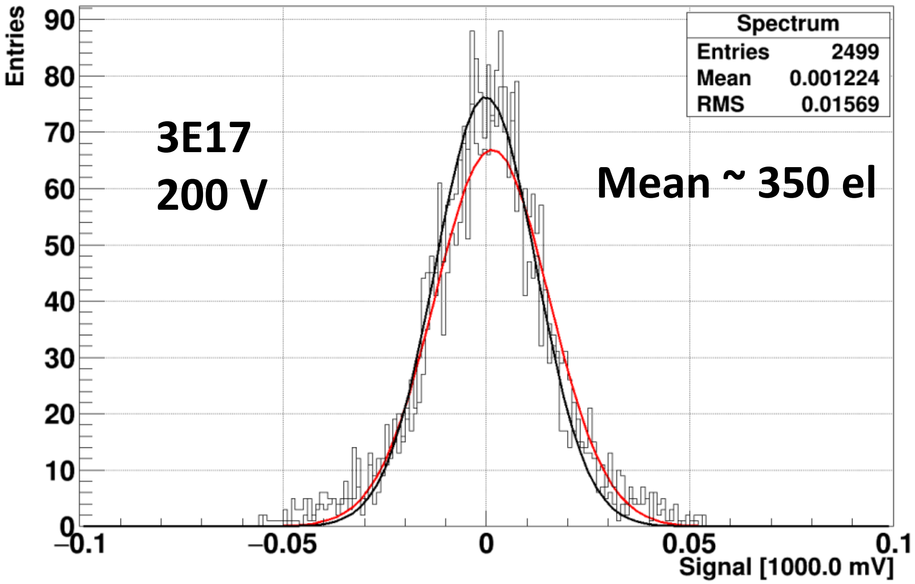
Charg





Charge increases with bias





Spaghetti, 4.6e17: no signal above noise.

Charge collection

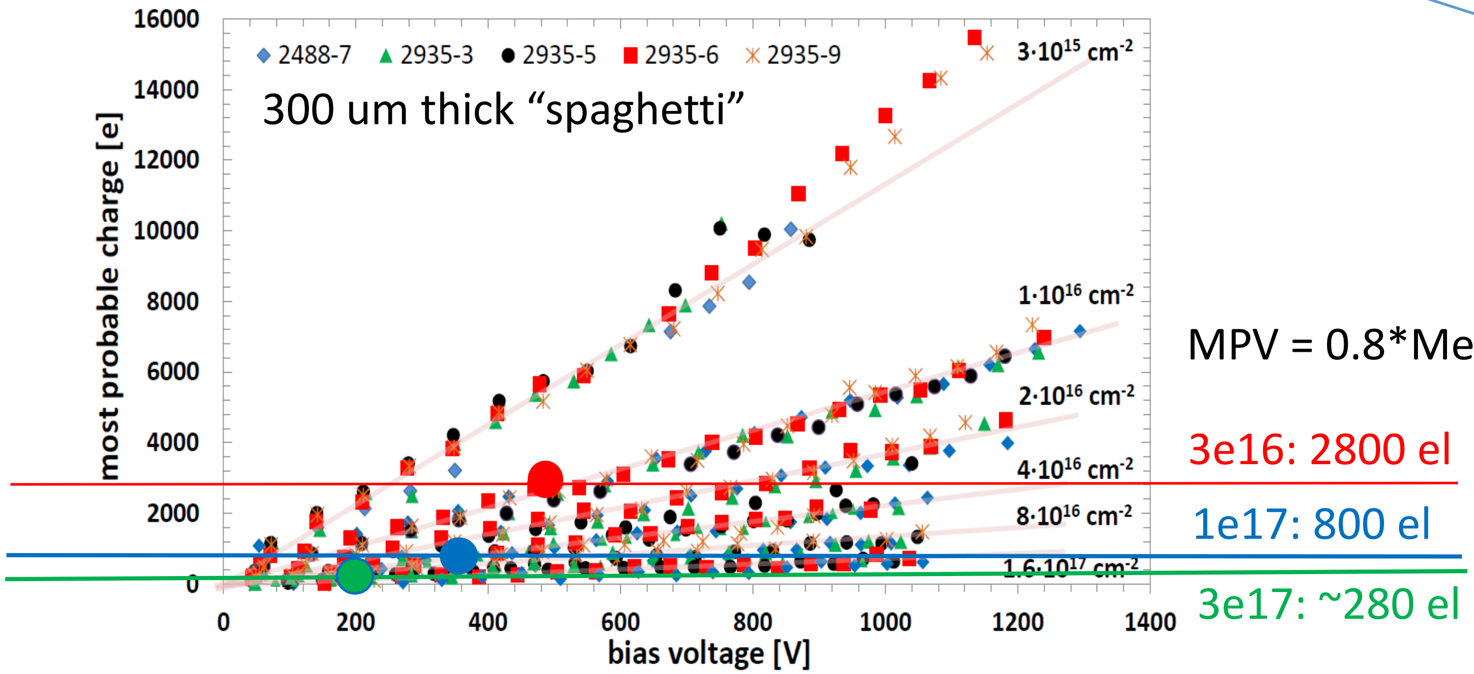
Compare 50 um thick LGAD with 300 um Spaghetti detectors

➔ at 3e16 n/cm2 at 460 V LGAD gives similar charge as spaghetti at 1000 V

- ➔ at high fluence in pad detector thickness *D* cancels with weighting field factor
- ➔ In 50 um thick detector larger *E* field at same voltage than in 300 um

Q ~ (dq/dx·D)·(1/D)·L,
L = v·τ, charge collection distance
v increases with *E* (until saturation)
At high *Φ*, saturation at higher *V*

"spaghetti" from G Kramberger *et al*, 2013 *JINST* **8** P08004



MPV = 0.8*Mean

Magic formula (300 um spaghetti Φ > 1e15):

$$Q_{MPV} = k \cdot \Phi^{b} \cdot V,$$

k = 26.4 el/V, b = -0.683
Φ in 1e15 n/cm2, *V* in volts

At *V* = 1000 V for 300 um detector magic formula predicts:

Φ = 3e16: Q_{MPV} = 2600 el
Φ = 1e17: Q_{MPV} = 1100 el
Φ = 3e17: Q_{MPV} = 500 el

E-TCT

C. Scharf et al., RD50 workshop, Krakow, June 2017
https://indico.cern.ch/event/637212/contributions/2608643/

Absorption coefficient increases with irradiation:

- light absorbed in the material before the sensitive region
  ➔ small signal!

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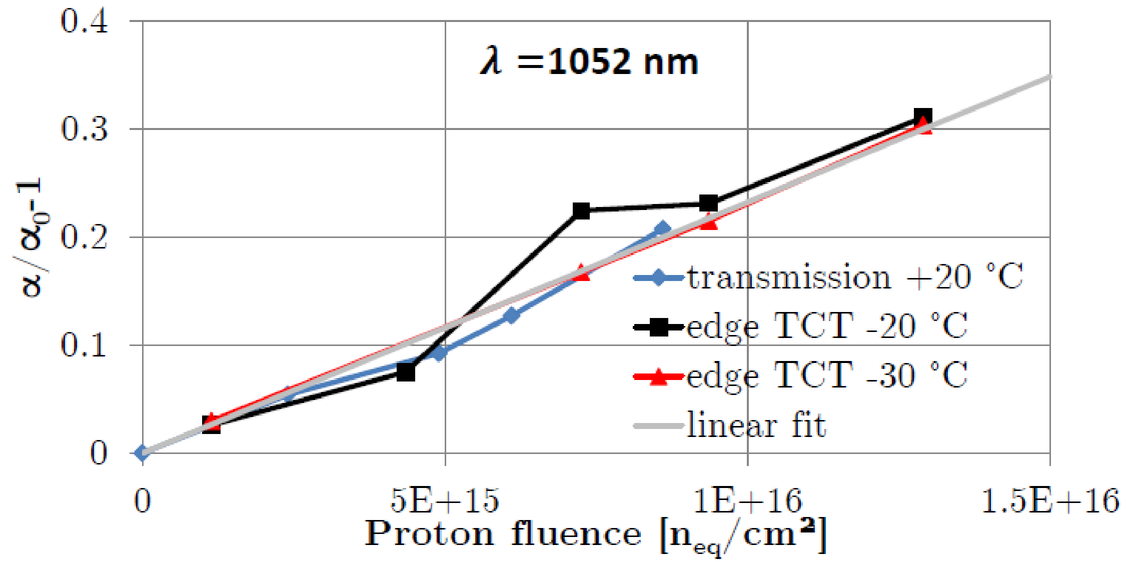
Absorption of light in irradiated silicon



Absorption coefficient $\alpha \propto n_{abs}(\Phi)$ → Plot $\frac{\alpha(\Phi,T)}{\alpha_0(T)} - 1$ vs. Φ

- ***T* dependence for damage induced absorption = interband absorption**

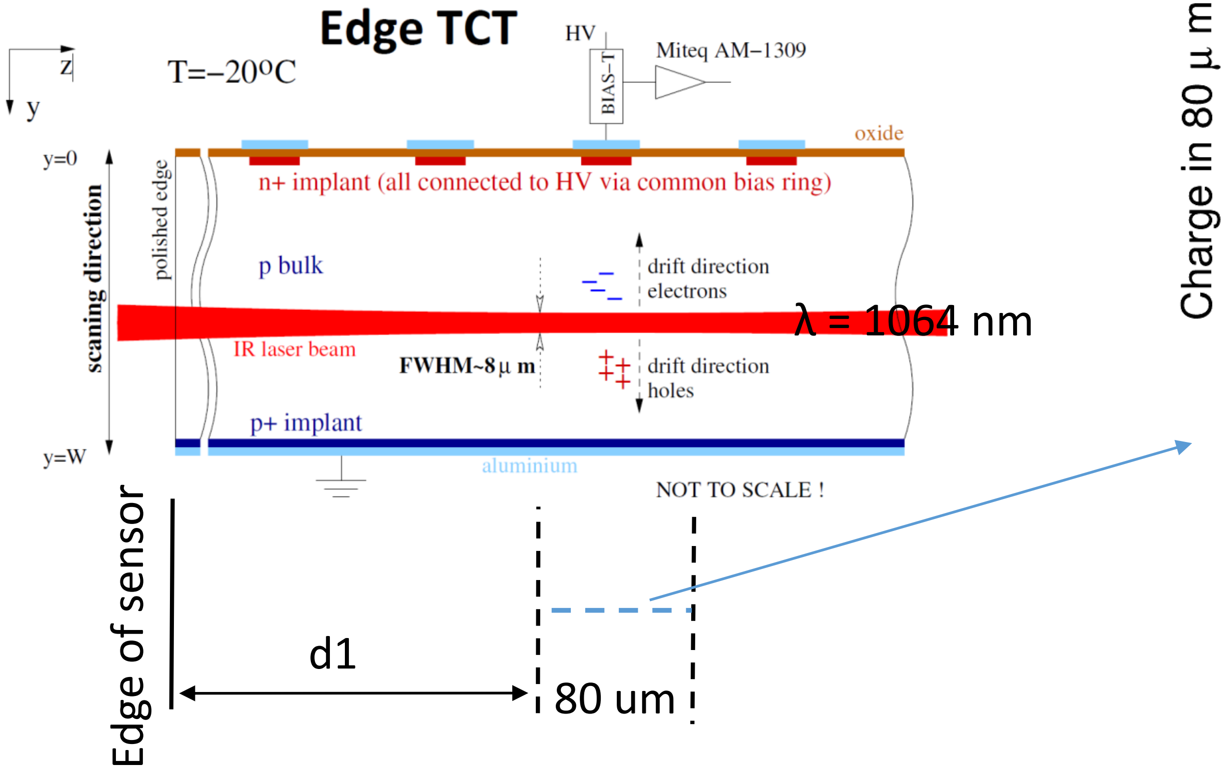
$$\rightarrow \boldsymbol{\alpha(\Phi,\lambda,T) = \alpha_0(\lambda,T) \cdot \left(1 + \frac{\Phi}{\Phi_{abs}(\lambda)}\right)}$$

$\Phi_{abs}(1052\ nm) = 4.30E16\ /cm^2$
$\Phi_{abs}(1064\ nm) = 3.32E16\ /cm^2$

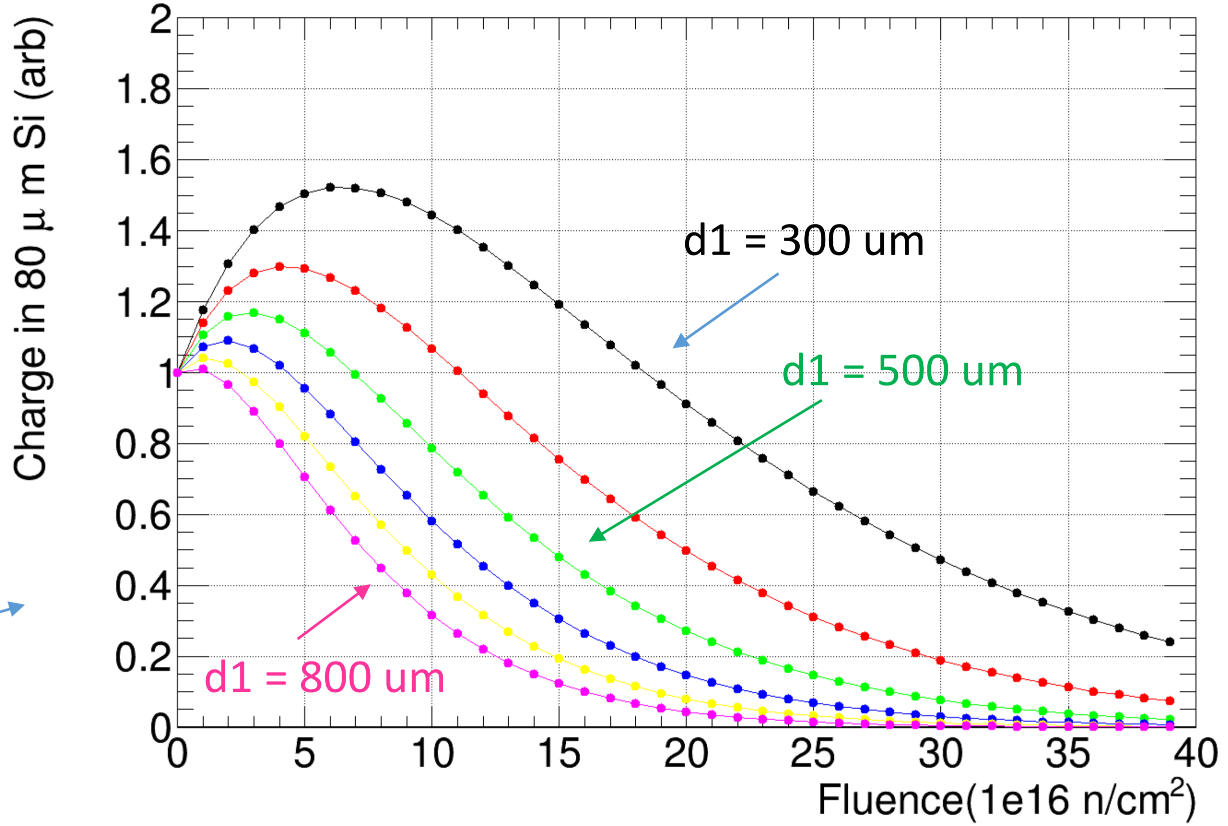
E-TCT

Light λ = 1064 nm, absorption length *X* in Si:

- before irradiation: *X* = 1 mm
- at Φ = 3.3e16: *X* = 0.5 mm
- at Φ = 3e17: *X* = 0.1 mm



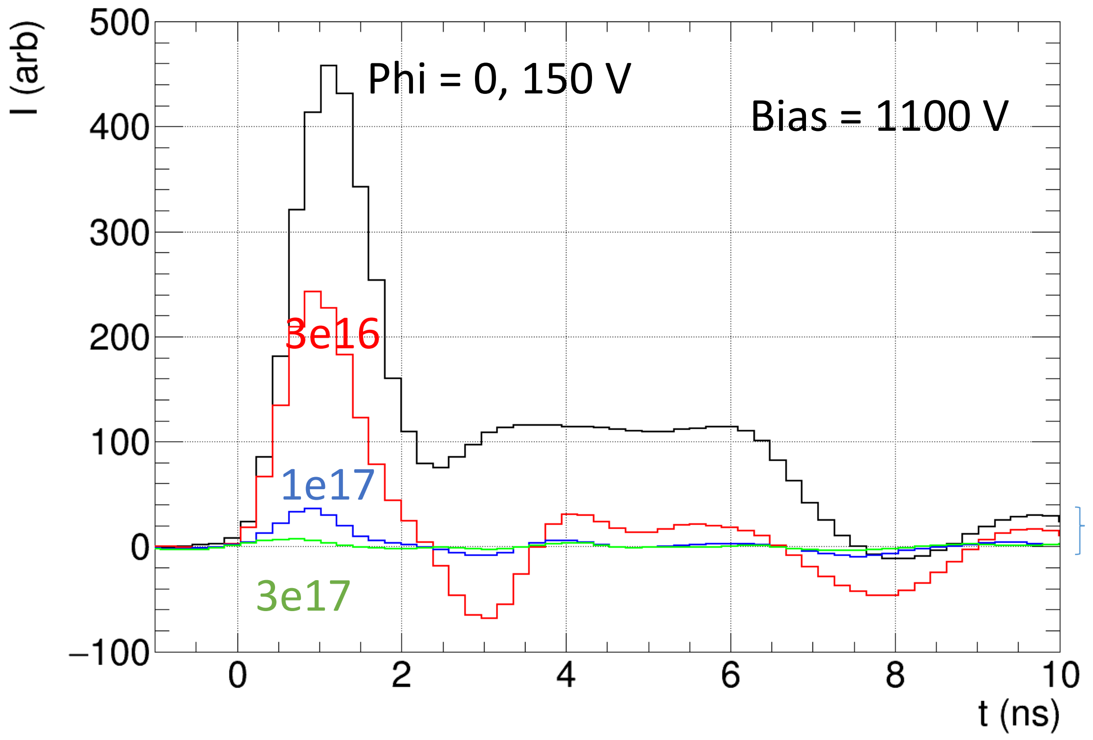
Absorption in 80 um silicon vs fluence at different d1 (distance from the edge of the strip detector), linear increase of absorption coeff. with fluence (C. Scharf et al.)

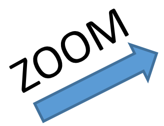


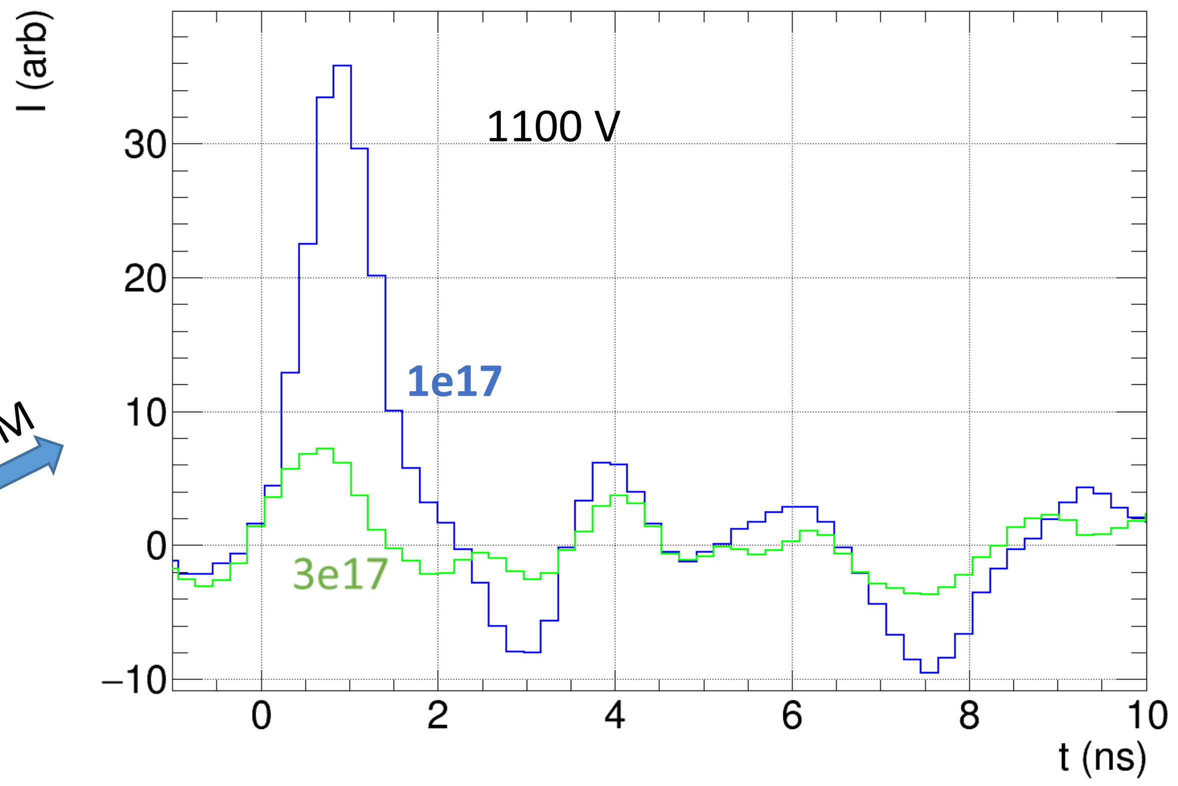
A12 strip detectors – readout strip (3rd)
~ 800 um from the sensor edge

E-TCT

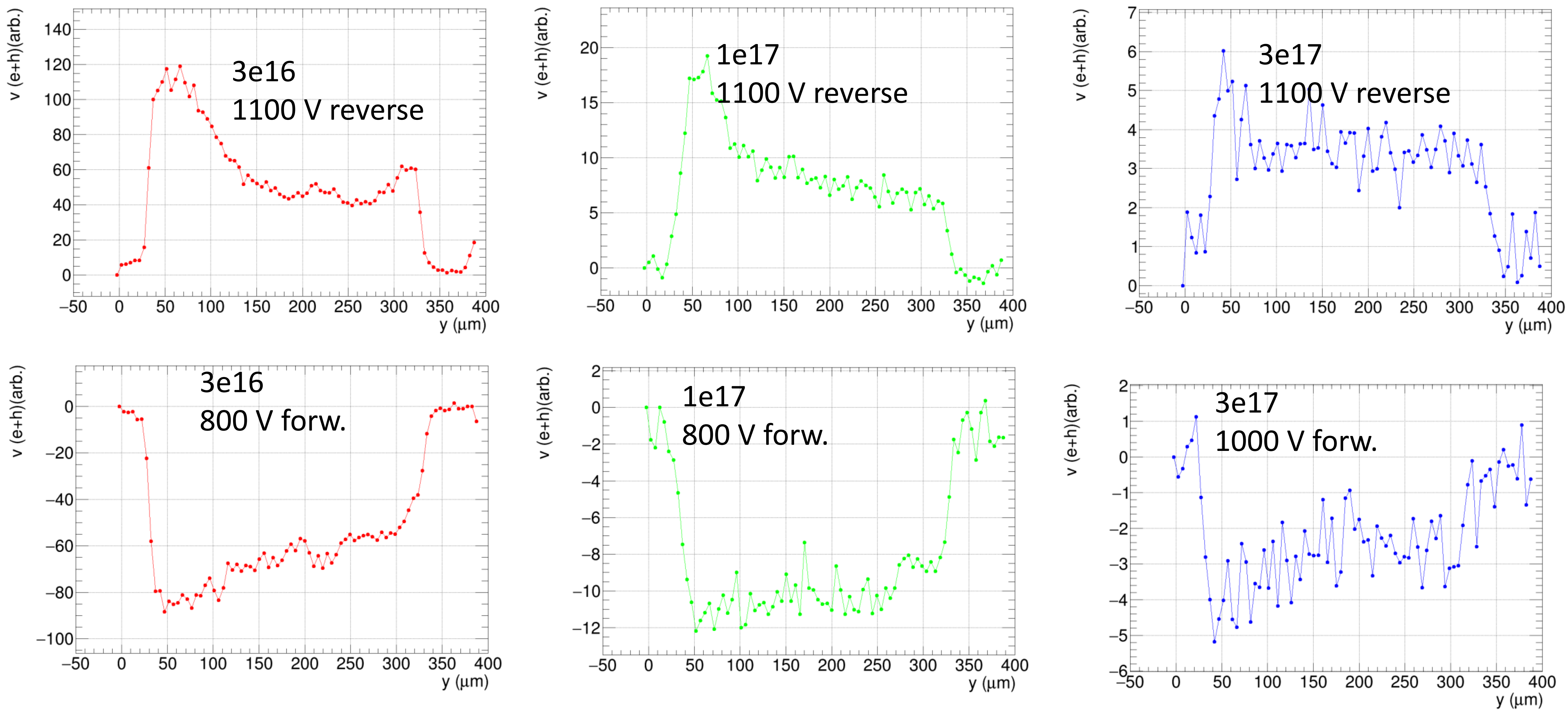
- E-TCT pulses normalized to same laser light intensity. Laser beam position close to the strip (depth *y* ~ 20 um)
  - ➔ very small pulses at 1e17 and higher
  - ➔ pulses are short (no need to integrate for 25 ns at high fluences)







Velocity profiles



- *E* field in whole detector → high field in the neutral bulk
- not much difference between reverse and forward at 3e17

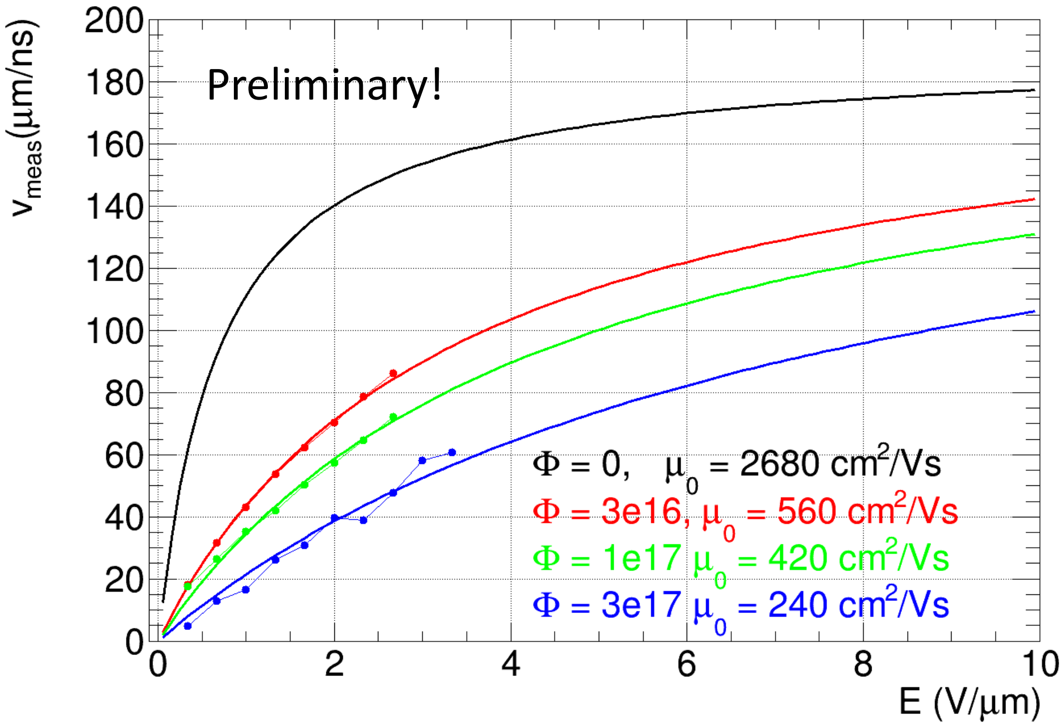
Mobility

Method from M. Mikuž et al.: mobility estimated from velocity profiles in forward bias

Assumptions: 1) electric field in forward bias: ***E = V/D,*** (*V* bias voltage, *D* detector thickness)

2) saturation velocity v_{sat} **= 190 µm/ns** does not change with fluence,

3) fit with: $v = \mu_0 \cdot E/(1+\mu_0 \cdot E/v_{sat})$



Good agreement with values from M. Mikuž et al.:

Φn	$\mu_{0,sum}$
[10^{15} n_{eq}/cm^2]	[cm^2/Vs]
non-irr (model)	
5	1661 ± 134
10	1238 ± 131
50	555 ± 32
100	407 ± 40

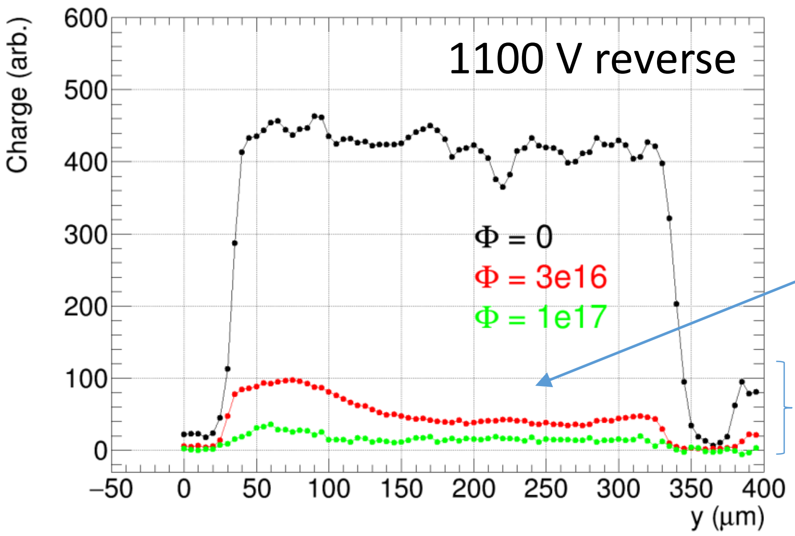
Value at 3e17 uncertain → should be interpreted as upper limit

➔ zero field mobility decreases with fluence

➔ velocity increases linearly with field up to high *E*

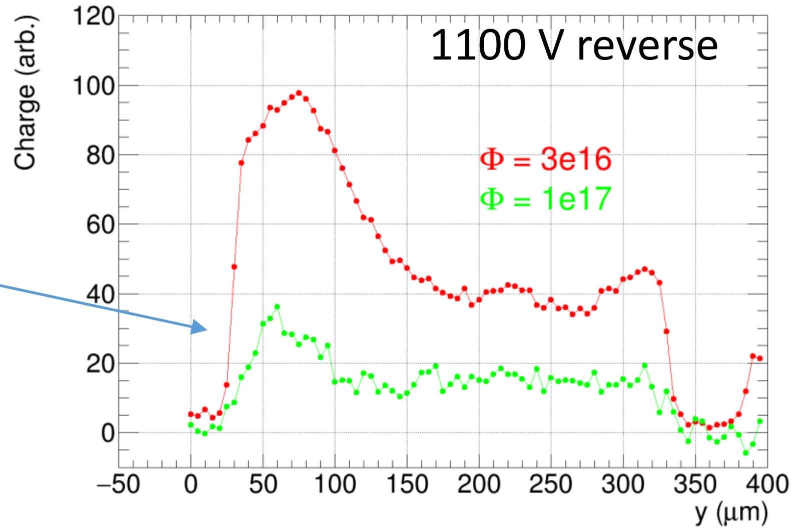
E-TCT Charge collection profiles

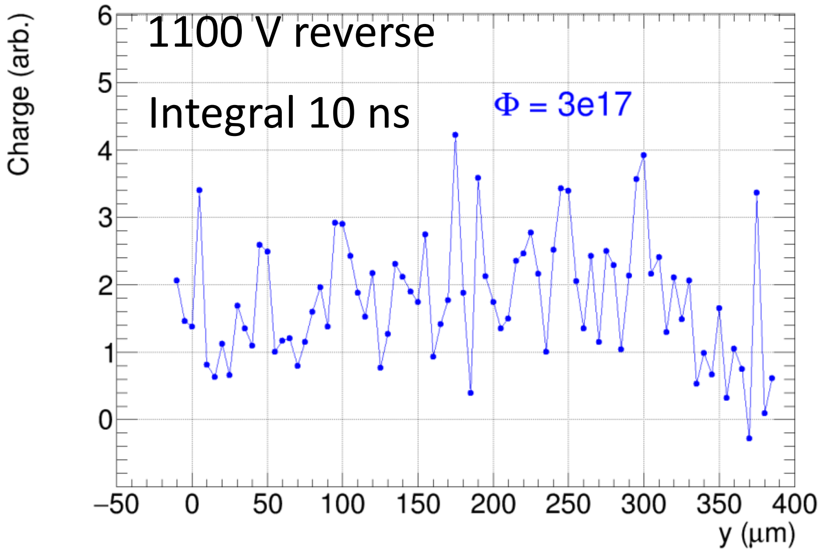
Charge: pulse integral 0 to 10 ns



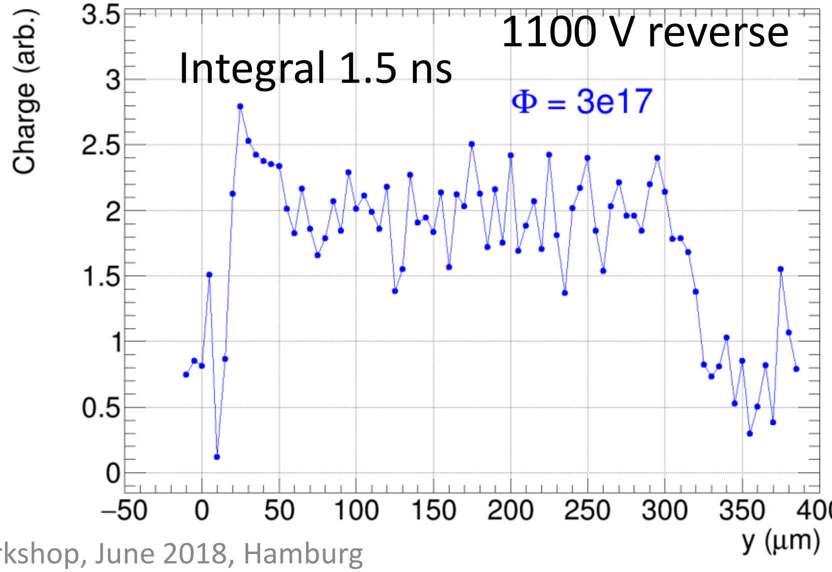
Corrected for light absorption (d1 = 800 um)

zoom





3e17:
no correction for absorp.
(correction factor too large)



E-TCT Charge collection

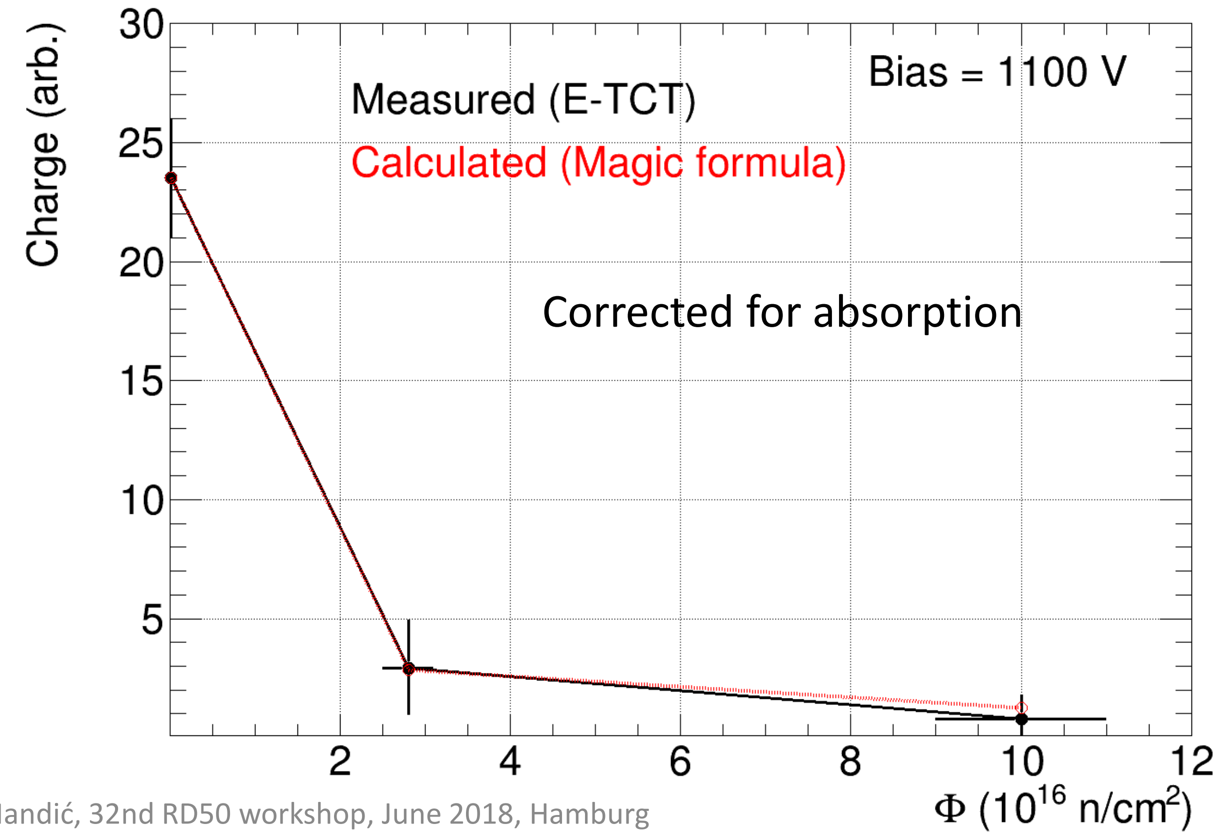
- Integrate charge profile along detector depth (*y*) and get charge → estimate of charge collected from a MIP
- correct for change of light absorption with fluence
  ➔ doesn't work for 3e17 because correction factor very high (~ 200) and uncertainty large
- plot the charge vs fluence

➔ consistent with "magic formula" for collected charge measured with Sr-90 with spaghetti detectors at 1100 V
(warning: spaghetti detector and E-TCT weighting field as in pad detector. Charge could be different in real strip or pixel geometry)

Magic formula (300 um spaghetti):
G Kramberger *et al*, 2013 *JINST* **8** P08004

$$Q_{MPV} = k \cdot \Phi^{b} \cdot V,$$

k = 26.4 el/V, b = -0.683
Φ in 1e15 n/cm2, V in volts



Summary: measurements with silicon detectors irradiated up to 4.6e17 n/cm²

Current:
- difference between forward and reverse bias up to about 1e17 in 50 um LGAD detectors
- in 300 um thick detectors not much difference between forward and reverse bias already at 3e16 n/cm²
- current increase with fluence in 50 um LGAD larger than in 300 um strip detector**s**
- In LGAD breakdown at relatively low voltage, breakdown voltage decreases with fleunce

Charge collection with Sr-90
- Collected charge with Sr-90 source measured with 50 um thick LGAD detectors up to 3e17 n/cm²
- no signal seen in detector irradiated to 4.6e17 n/cm²

  ➔ larger collected charge measured with thin detectors at lower bias voltage compared to 300 um devices

E-TCT

➔ small signals because of increase of light absorption coefficient with fluence
- electric field in whole detector volume at all bias voltages
- zero field mobility decreases with fluence
- dependence of collected charge on fluence agrees with "magic formula"

About 1000 el collected charge at 1e17 n/cm², less at higher fluence

➔ using Si as detector material above 1e17 n/cm² will be a great challenge