Investigation of LGAD performance dependence on neutron flux

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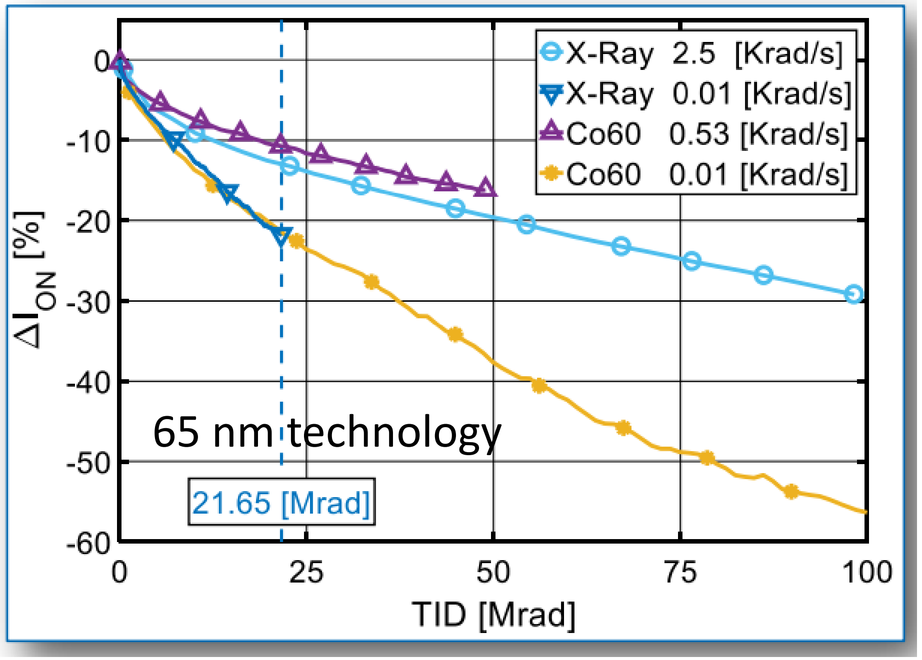
A BROAD COLLABORATION WITH ATLAS-HGTD GROUPS

Motivation

- LGADs will at HL-LHC be exposed to fluxes of particles around 10^7-10^8 cm^2 s^{-1}
- Most of the irradiation studies done so far use fluxes which are much larger than that (typically ~10^{12} cm^2 s^{-1} at JSI reactor)
- Dose rate effects observed in electronics and present a major problem (depends on bias/temperature/annealing) – safety factors
- Question do we see that also in the bulk?
  - studies showed no flux effect on N_{eff} and I_{leak} (D. Zontar PhD thesis)
  - effects to removal of initial dopants was not studied to our knowledge
- Possible dependence of initial acceptor removal rate would have a large implication to operation of LGADs at HL-LHC
  - positive in case of smaller removal at low rates
  - negative in case of larger removal at low rates



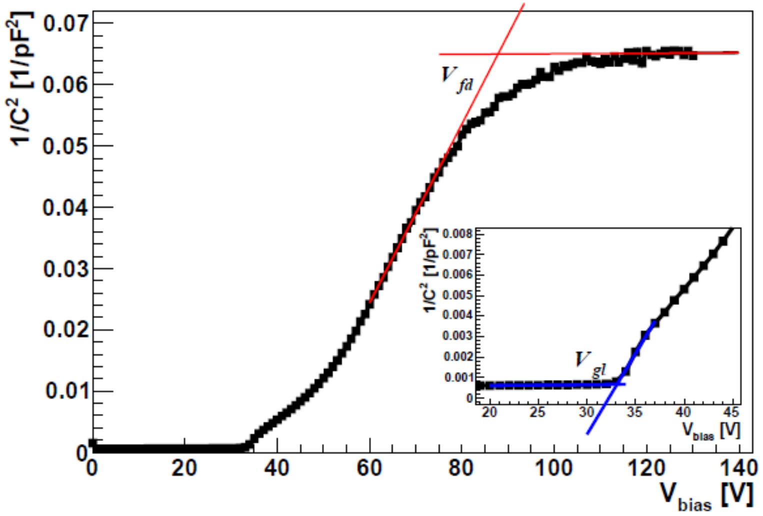
F. Faccio, HSTD11, Okinawa, 2017

Reasons for possible flux effects

- The main channel for removal of initial acceptors is: B_s+Si_i->B_i which is followed by reactions of B_i with other impurities and defects
- Different mobilities of Vacancies (V) and Interstitials (I) can lead to different recombination rate of V-I if more are created close in space and time and don't have time to react with other impurities/defects
- Smaller recombination could effectively lead to larger removal at low fluxes ☹
- As the mechanisms are not fully known checks are required.

Samples used in the study

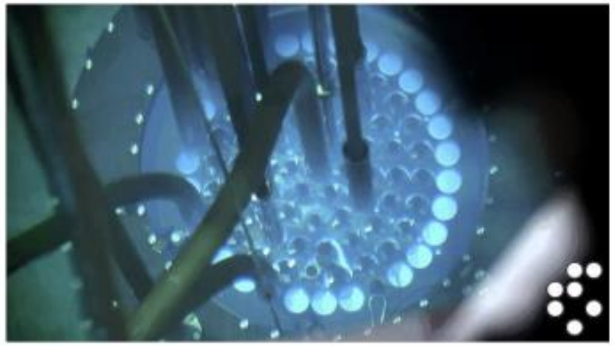
- LGADs from ATLAS-HGTD prototype run with HPK were used – they're different in implant dose and also in depth profile of the implant



Sample name	Thickness	Vgl [V]	Vfd [V]
HPK-3.1-50	50 μm	42	49
HPK-3.2-50	50 μm	56	64

- Samples were studied with
  - CV/IV at 20°C and 10 kHz to determine V_{gl}, V_{fd}
  - Timing setup to verify that there is no impact to timing performance as well
- All samples were annealed for 80min @ 60°C after irradiation to wipe out different history during irradiations
- The temperature during irradiations in not controlled – at full power in F19 irradiations <50°C

Irradiations



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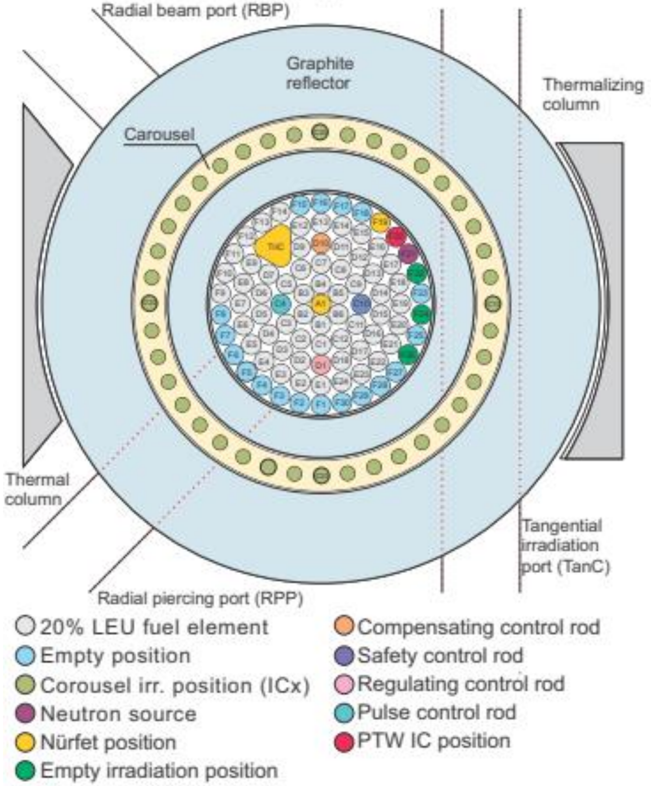
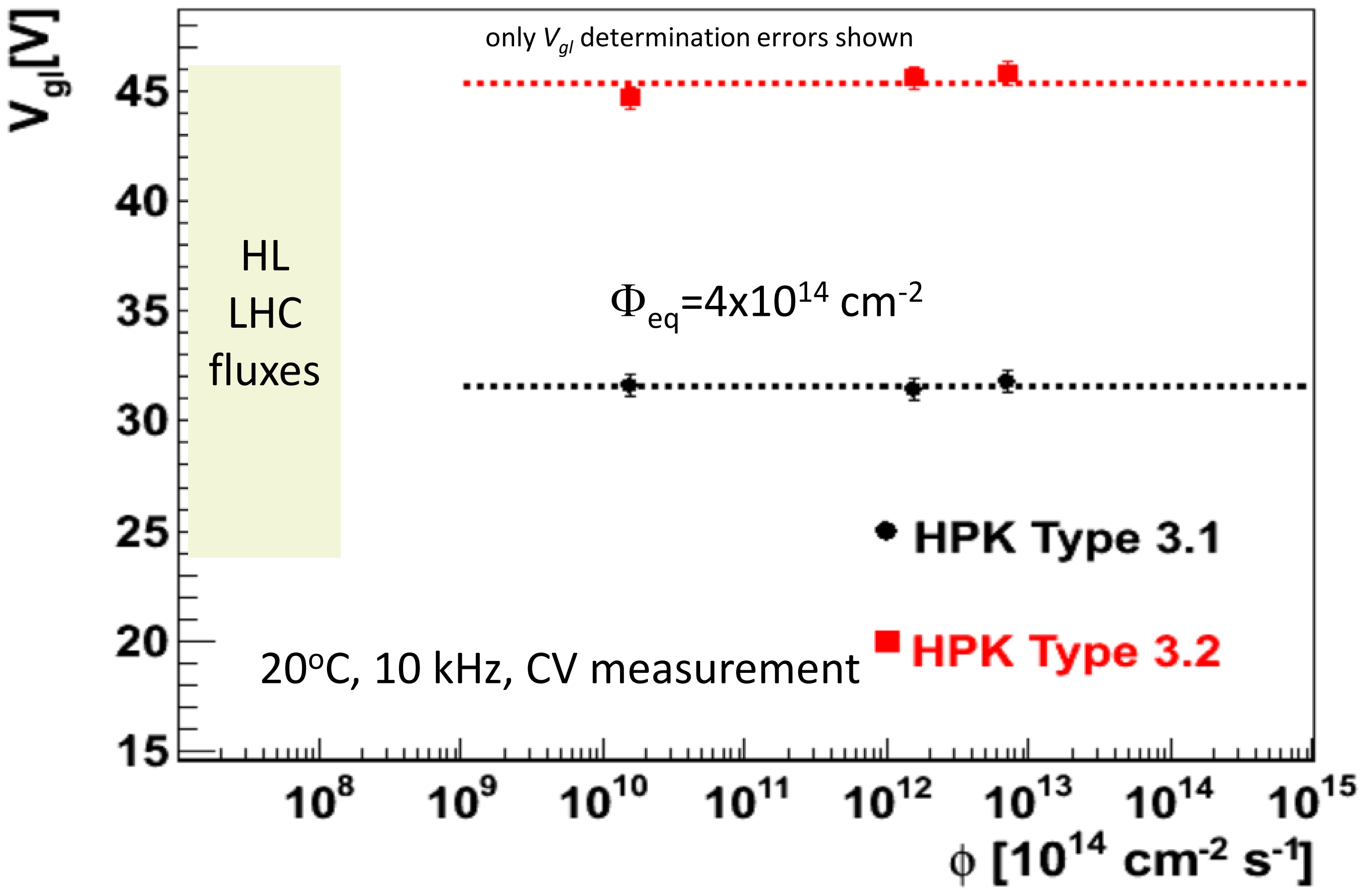


- Samples were irradiated with reactor neutrons at three different fluxes
  - 1.55e12 cm^{-2} s^{-1} (250 kW, F19 channel – our standard irradiation flux)
  - 1.55e10 cm^{-2} s^{-1} (2.5 kW, F19 channel)
  - 7e12 cm^{-2} s^{-1} (250 kW, Central channel)
- All samples were irradiated to the **same fluence of 4e14 cm^{-2}**
  - Effects on V_{gl} are clearly visible
  - Timing measurement can be accurately performed
  - A wide flux range can be practically studied
    - 26000 s for slow (F19)
    - 260 s for standard (F19)
    - 57 s for fast (CK)

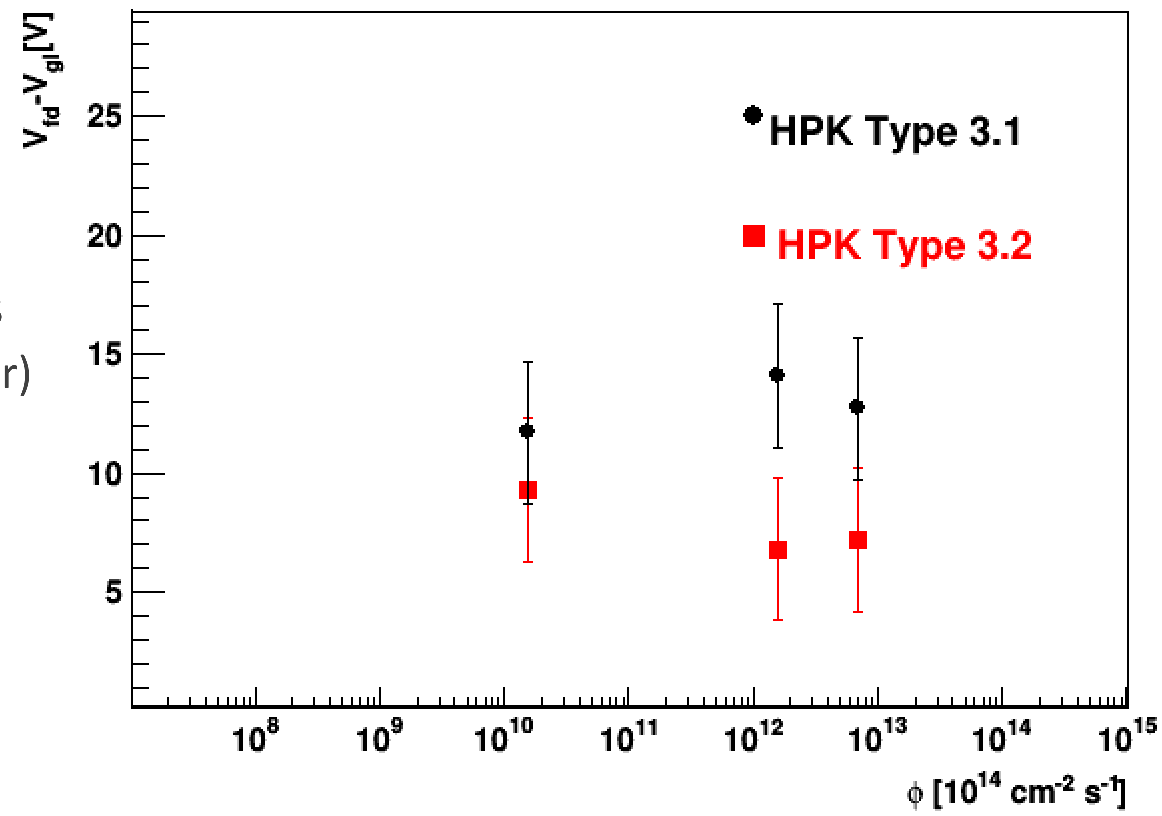
Measurements of gain layer depletion V_{gl}

- There is no flux impact on V_{gl} for both investigated samples with different implant profiles
- We are still two orders of magnitude away from HL-LHC fluxes, but the flux rate seem not to play a role on effective acceptor removal
- Estimation of V_{gl} uncertainty:
  - uncertainty due to 10% in fluence -> δV_{gl} ~1V
  - uncertainty due to V_{gl} determination -> δV_{gl} ~0.4 V
  - uncertainty due to initial material ~1%-> δV_{gl} ~0.5 V
- Fits are compatible with hypothesis of acceptor removal not depending of flux.



Depletion of the bulk

- There is no flux impact on bulk depletion voltage for both investigated samples with different implant profiles
- The result is in agreement with previous observations
  - more difficult to determine the V_{fd} (larger systematic error)
  - if full initial acceptor removal is assumed deep acceptor introduction rate g_{eff}=0.01-0.016 cm^{-1} is compatible with standard introduction rate in FZ



Charge and Timing measurements

JSI
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Research
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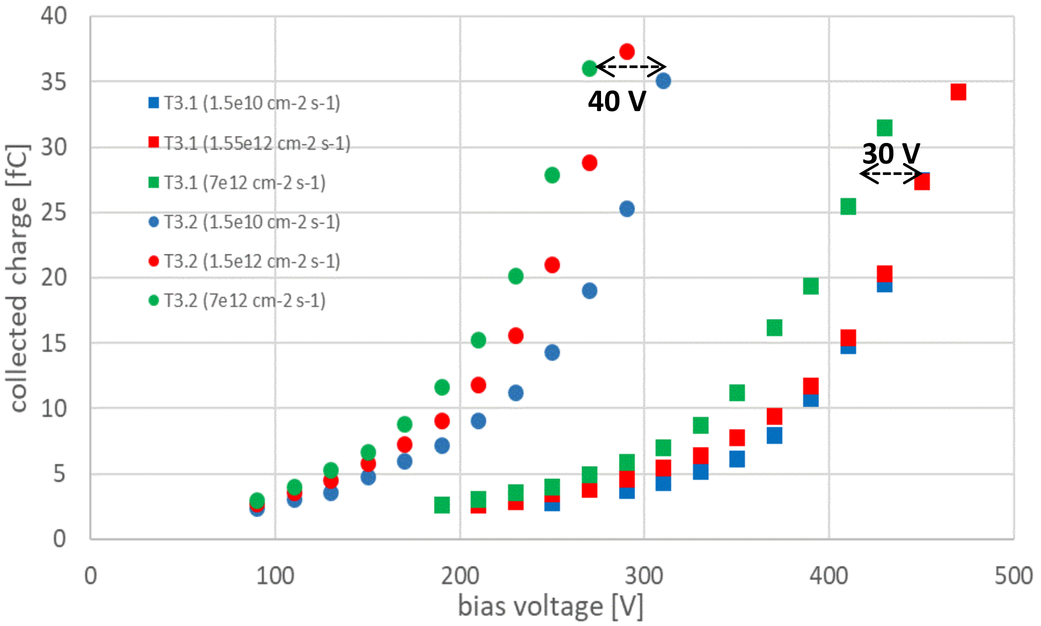
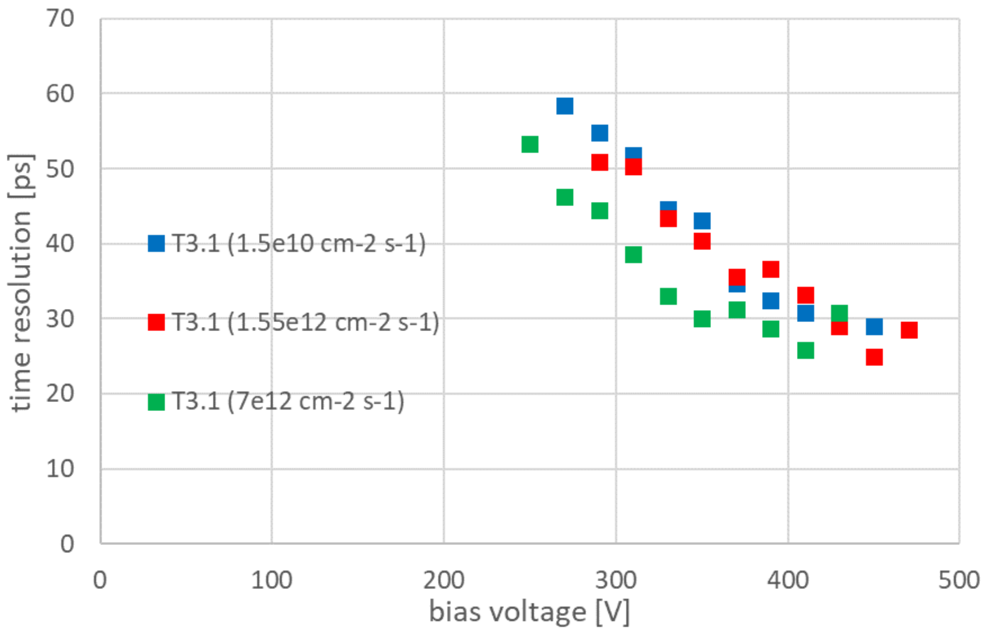
- At high voltages there may be effects not revealed by V_{fd} and V_{gl} measurements and may impact timing resolution and charge collection
- CC and timing measurements are the ultimate benchmark, therefore all detectors were tested with ^{90}Sr setup to very high bias voltages for performance
- The performance differs slightly for different samples, but the difference is compatible with known uncertainties:
  - T3.2: ΔV(35 fC)~40V -> ΔV_{gl}(2 μm) ~1.4-1.6 V are required to increase the field in gain layer by 0.8 V/μm -> measured difference is ΔV_{gl} =1.1 V
  - T3.1: ΔV(30 fC)~30V -> ΔV_{gl}(1 μm) ~0.6 V are required to increase the field in gain layer by 0.6 V/μm -> measured difference is ΔV_{gl} =0.4 V
- **Small difference between the samples can be to large extent explained by the small difference in V_{gl}**

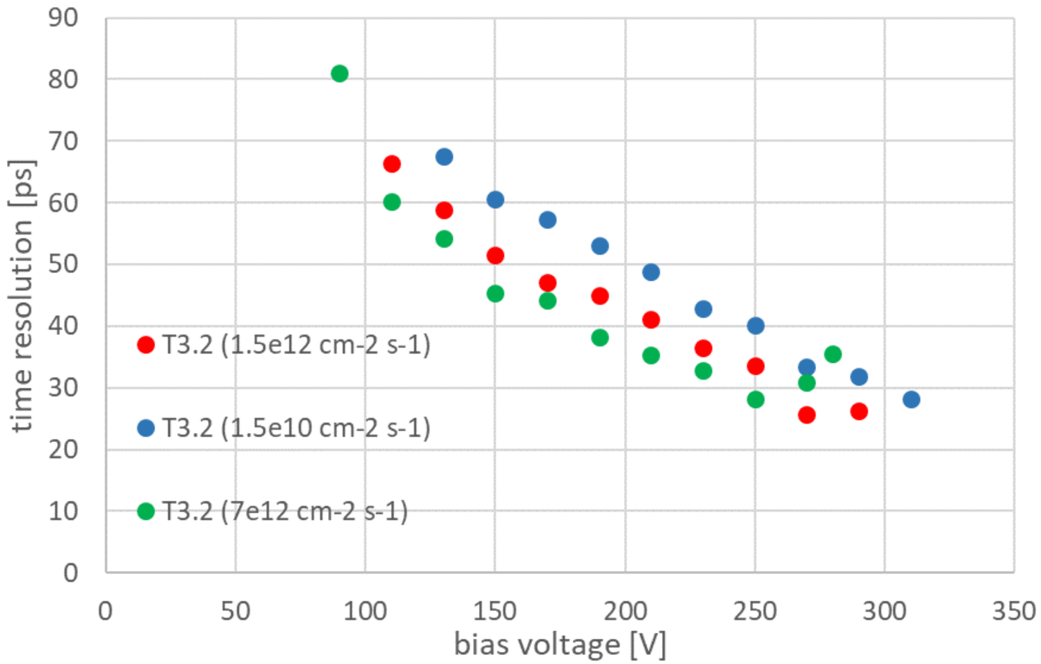


Note the error on fluence may be larger for central channel:
- 57s irradiation time – few s already mean sizeable effect
- less calibration runs were performed – not so well calibrated

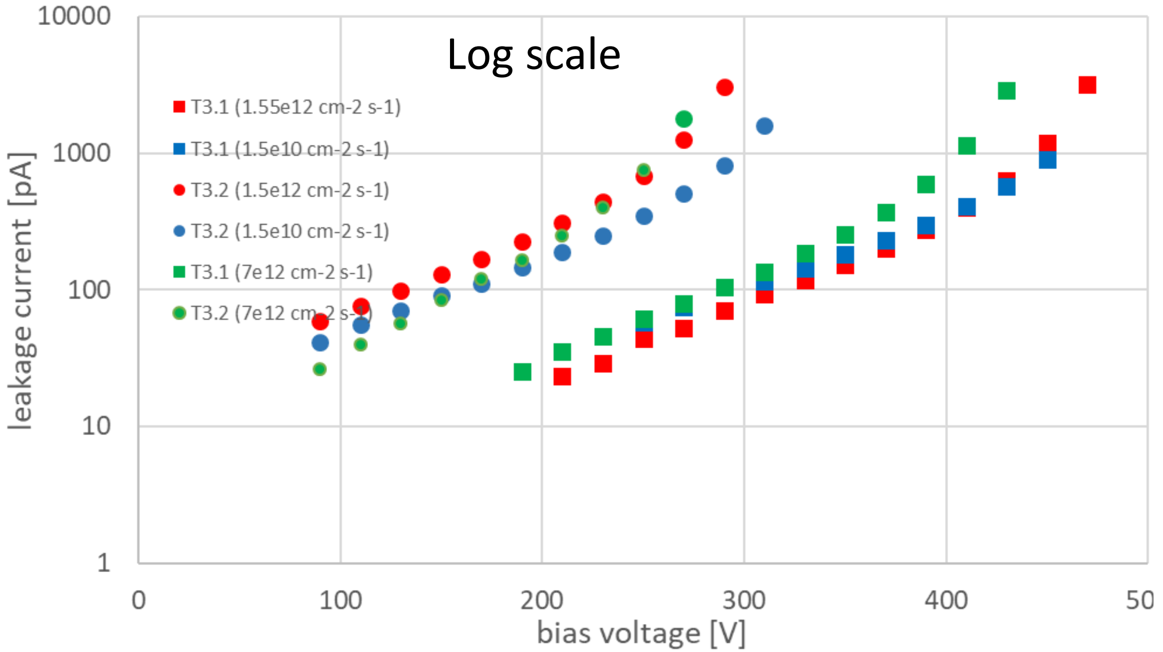
Charge and Timing measurements

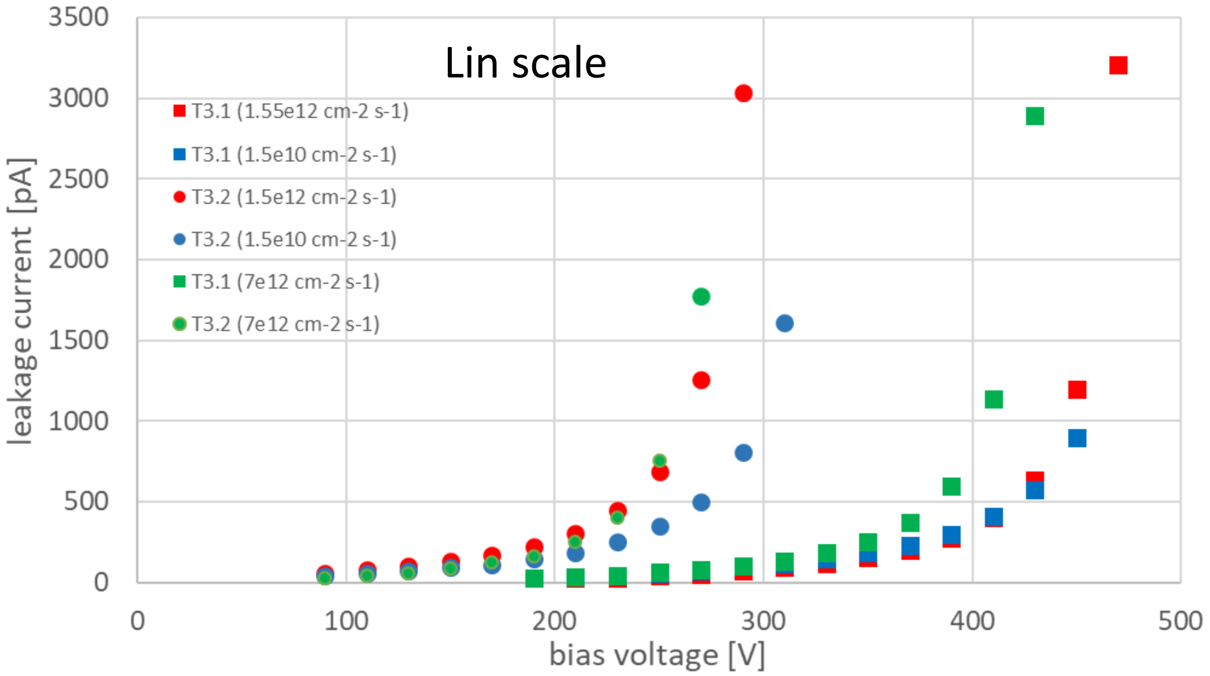
- Timing measurements confirm charge collection measurements – a small difference in voltage is required to achieve the same time resolution.





Leakage current





Leakage currents at low voltages (generation current) are similar for all three fluxes.

At large bias voltages where *G(V)* dominates:

- Same difference in bias voltage for a given current is observed as for the charge: $V(\phi_1,I)-V(\phi_2,I) = V(\phi_1,Q)-V(\phi_2,Q)$
- Similar relative ratio of current and charge $I(\phi_1,V)/I(\phi_2,V) = Q(\phi_1,V)/Q(\phi_2,V)$

Conclusions and future work

- In the investigated flux range of $10^{10} – 10^{13}$ cm^{-2} s^{-1} no flux dependence on the damage was found – gain layer and bulk
- The gain and timing performance of all the sensors at high operation voltages was similar – no effects of different flux observed
- This is still 2 orders of magnitude larger than rates at HL-LHC, but it is very probable that the flux effects are not present
- Plans:
  - we can't irradiate for months, so it is not possible to go to much lower fluxes
  - We will go to high fluxes 10^{15}-10^{16} cm^{-2} s^{-1} with reactor operating in pulse mode (above critical for very short amount of time) in the following months

Measurements of gain layer depletion V_{gl}

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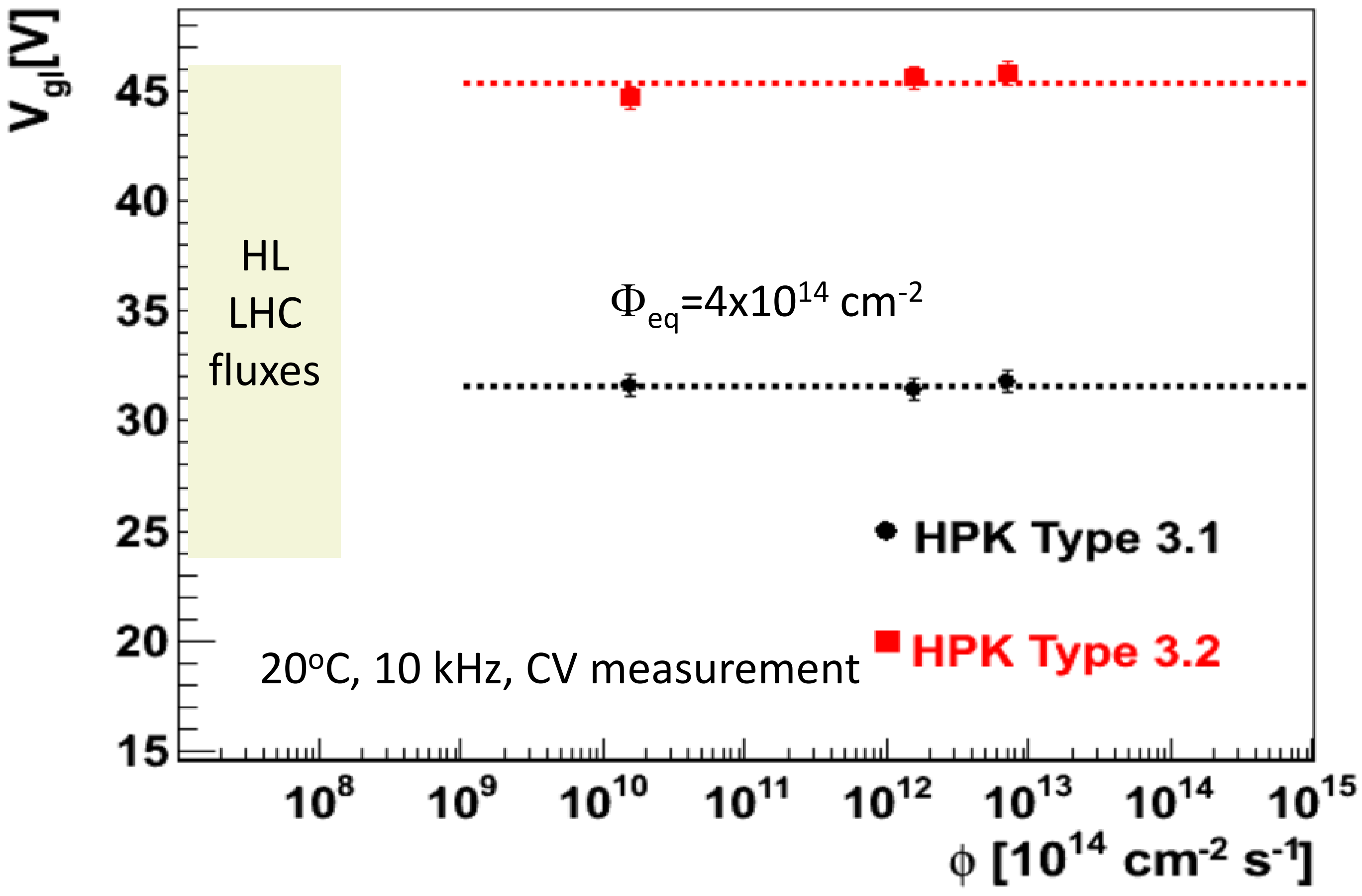

Estimation of V_{gl} uncertainty:

$$\sigma_V^2 = \sigma_{c\Phi}^2 + \sigma_{CV}^2$$
$$\sigma_V^2 = c^2 V_{gl}^2 \sigma_\Phi^2 + \sigma_{CV}^2$$
$$\sigma_V \sim 1.1 \text{ V}$$

$$\sigma_{CV} \sim 0.5 \text{ V}$$
$$\sigma_\Phi \sim 0.4 \cdot 10^{14} \text{cm}^{-2}$$
$$c \sim 0.04 \text{ cm}^2$$

The measured values are well within 1 V from the average – so compatible with uncertainty.