X-ray HV Currents and Future Plans

PXD Workshop and 24th International Workshop on
DEPFET Detectors and Applications
16.05.2022

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OVERVIEW

- Investigation and problem tackling of high HV currents at KEK
- Effect reproduction in the lab
- Current understanding of the mechanism
- Future irradiation plans and progress
- Outlook

HIGH HV CURRENTS AT KEK

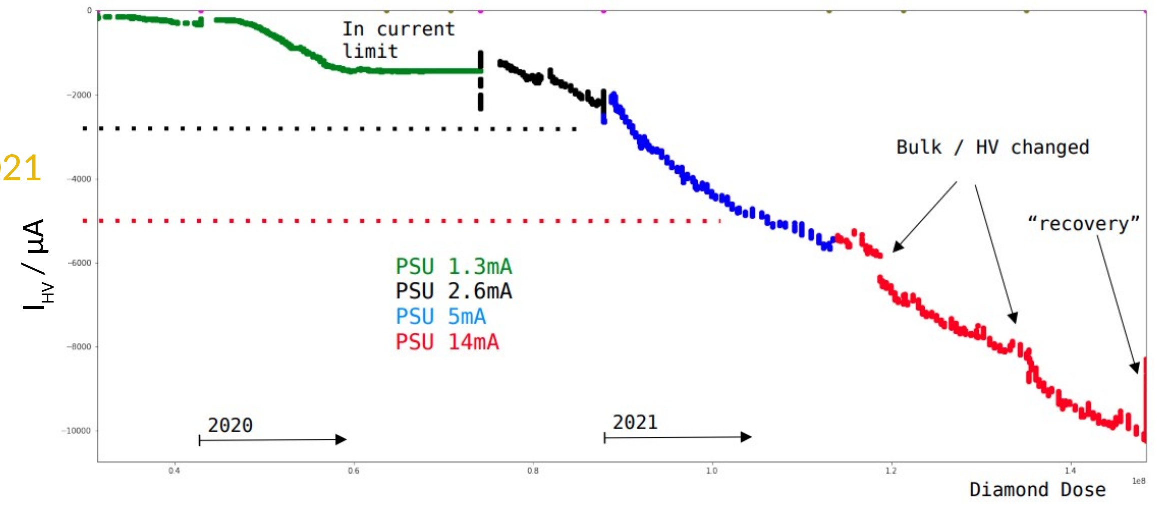
- High HV currents were observed for the first time at KEK
- Initially HV channel only supplied ~1.3 mA current channel limit
  - Reduce HV current by tweaking other matrix voltages, e.g. BULK
- Modify HV channel on LMU PS to supply more current
  - Currently tested up to 28 mA
  - Temperature will be a limitation
- Tests still ongoing

March/April 2020

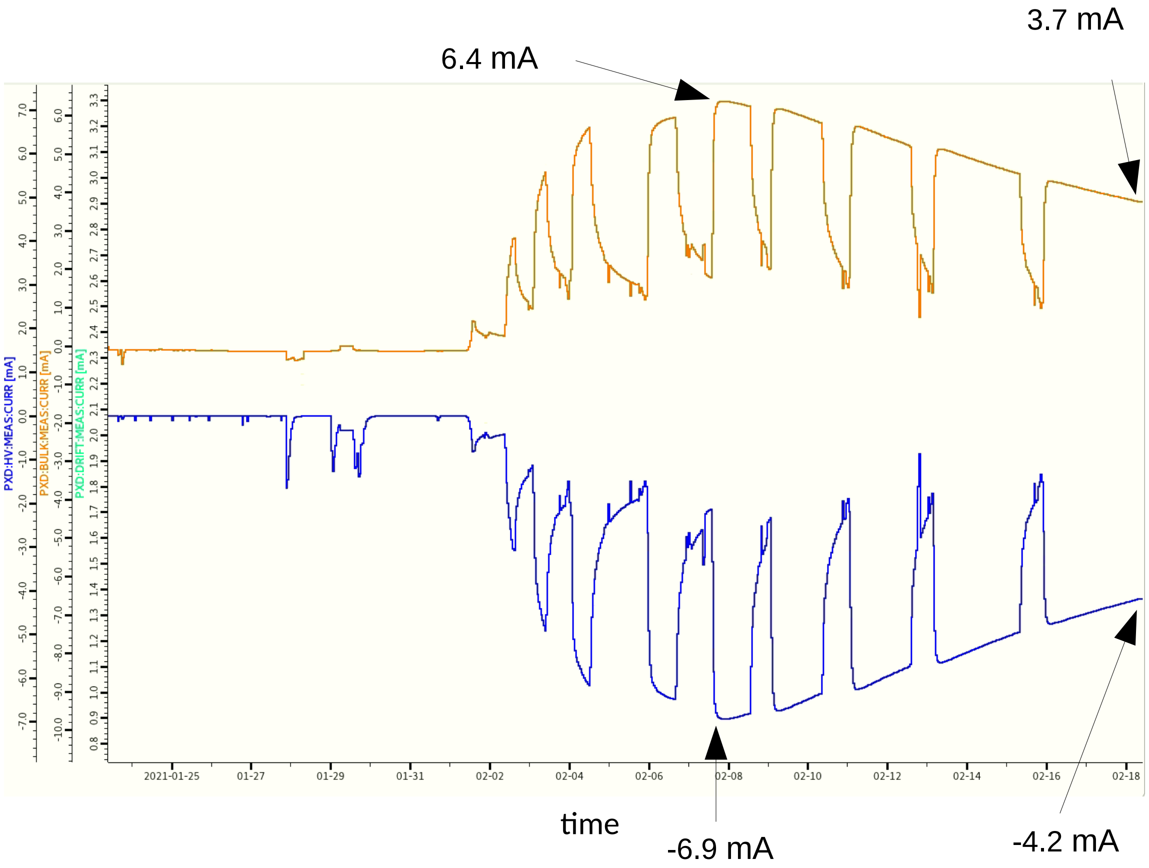
April/May/June 2020

November 2021

…

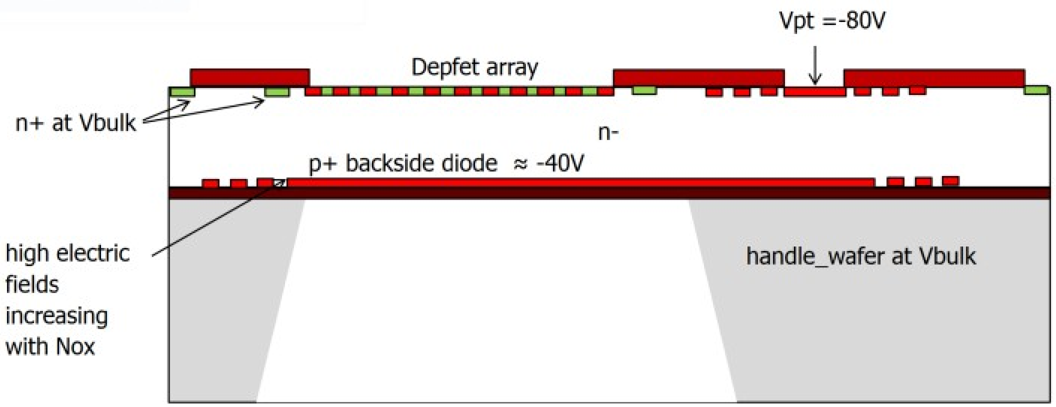


X-RAY IRRADIATION AT BONN



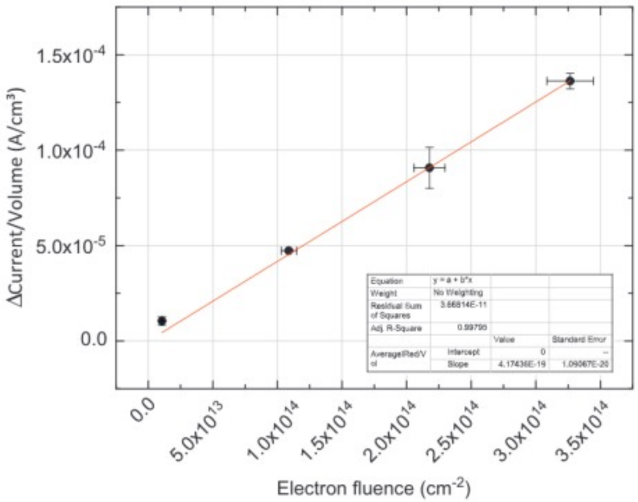
- Two irradiation campaigns in Nov 2020 and Jan 2021
- Irradiation of the DUT is done in steps to allow for characterization in between
- Correlated trends → parasitic channel between BULK and backside
- Saturation point around -7 mA
- Currents anneal with irradiation beyond this point
- Origin of the current?

HIGH HV CURRENT MECHANISM



- *Current understanding*: High electric fields at guard-ring structures, which results in avalanche current multiplication and consequently increased currents

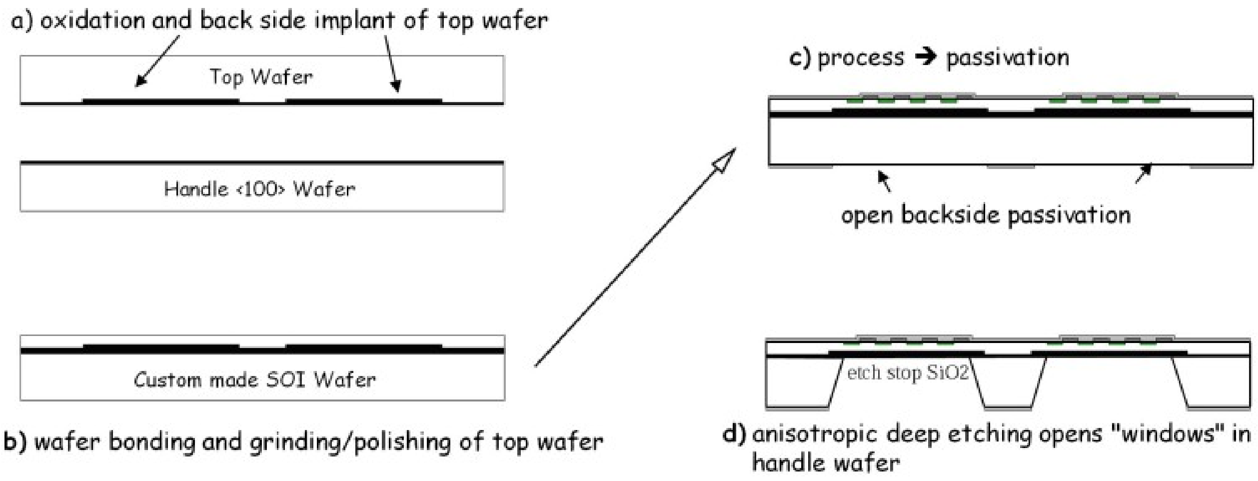
- Different dose rate and radiation damage
- HV currents at KEK should have reached saturation, but they keep increasing!
- Maybe additional HV current due to bulk damage?
  - Electrons can damage the crystal lattice → increase in leakage current
- Further investigation is needed with dedicated test structures



Investigations on radiation hardness of DEPFET sensors for the Belle II detector, NIMA 2013

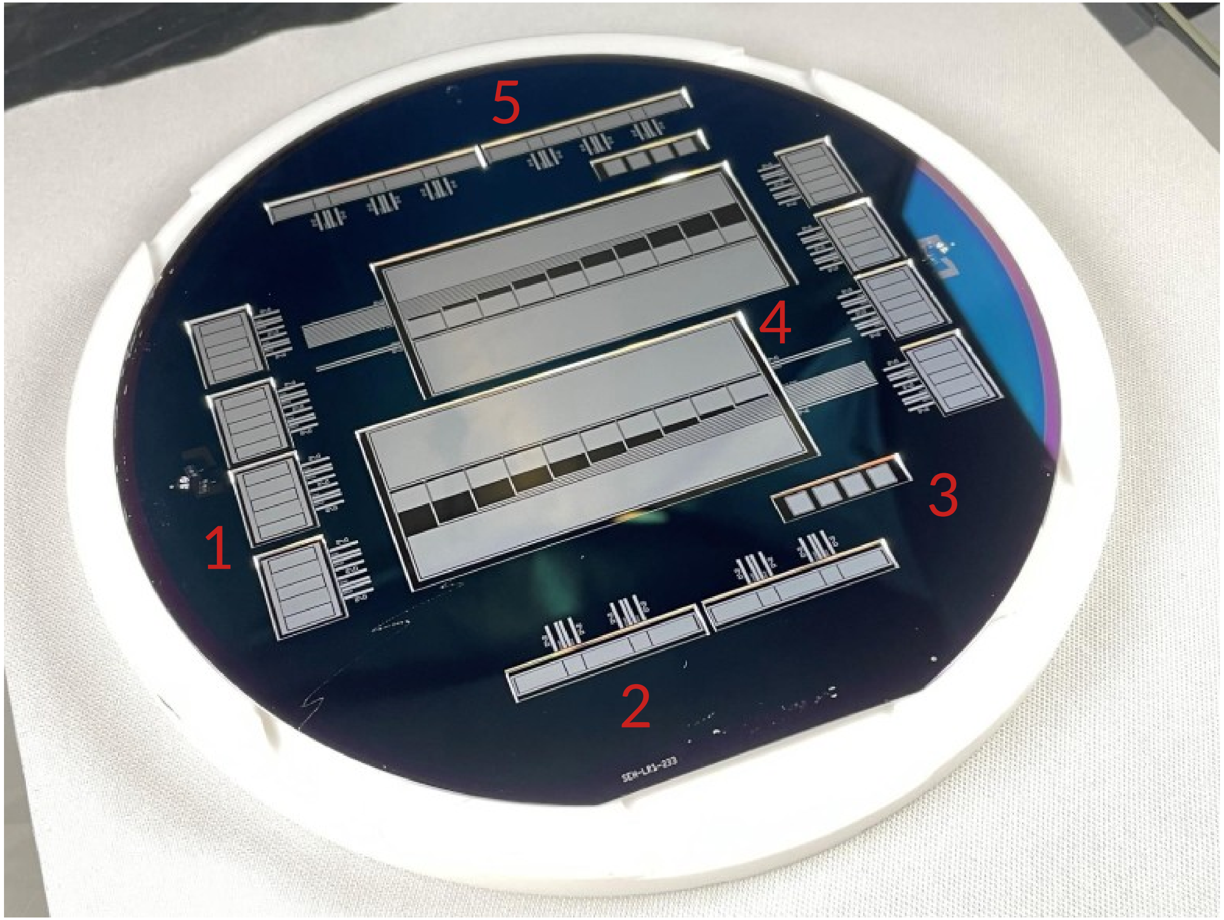
MOS CAPS AND MOSFET STRUCTURES

- Processing similar to DEPFET
  - Backside implantation of the Top Wafer
  - Oxidization of the Top and Handle Wafer
  - SOI bonding of the two Wafers (Shin-Etsu and IceMOS)
  - Passivation
  - Unstractured n-type substrate on the topside of the Top Wafer
  - Etching

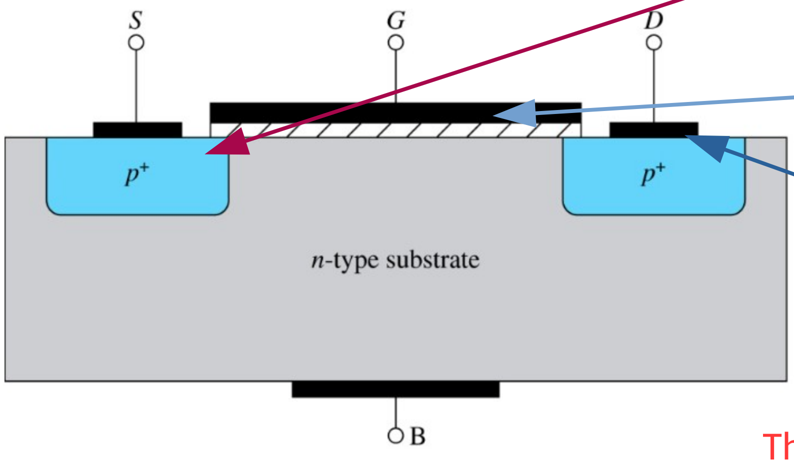


NEW TEST STRUCTURES

- Six (6) wafers in total
  - Three (3) IceMOS bonded SOI
  - Three (3) Shin-Etsu bonded SOI
- Five (5) different structures
  - Four (4) MOSFET
  - One (1) MOS CAP
- Structures have been cut, tested and sent to Bonn



TEST STRUCTURE 1



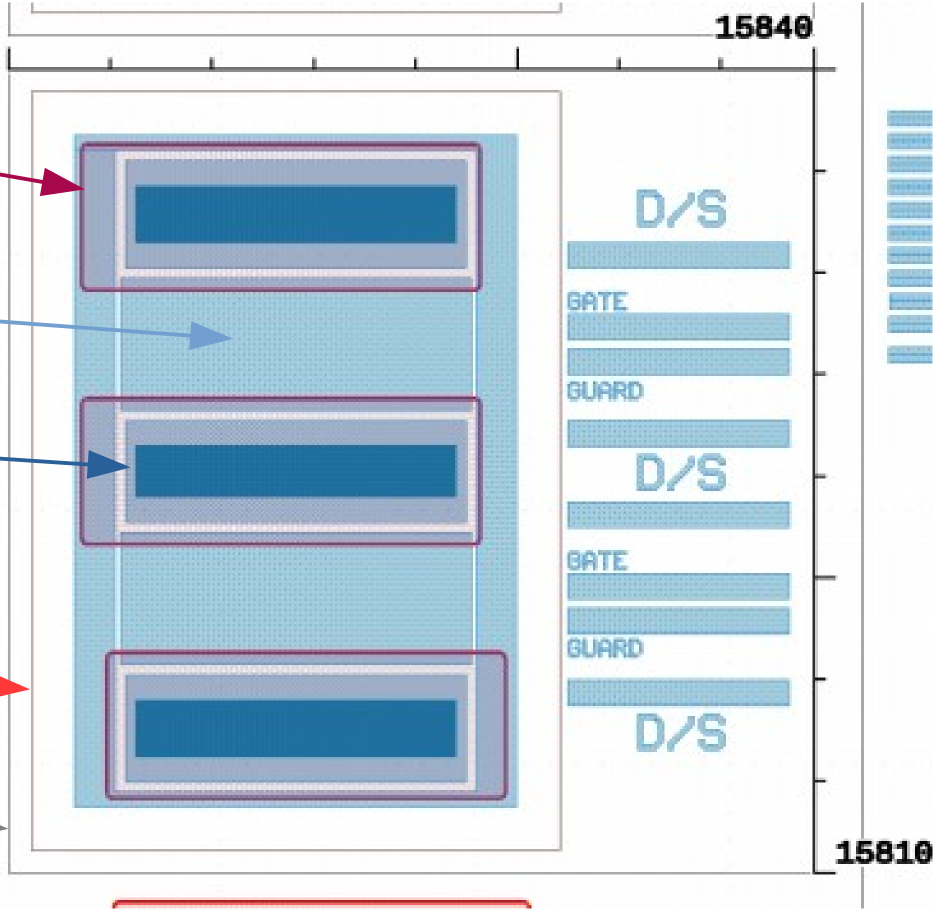
Backside p+ implants as source or drain

Aluminium as gate

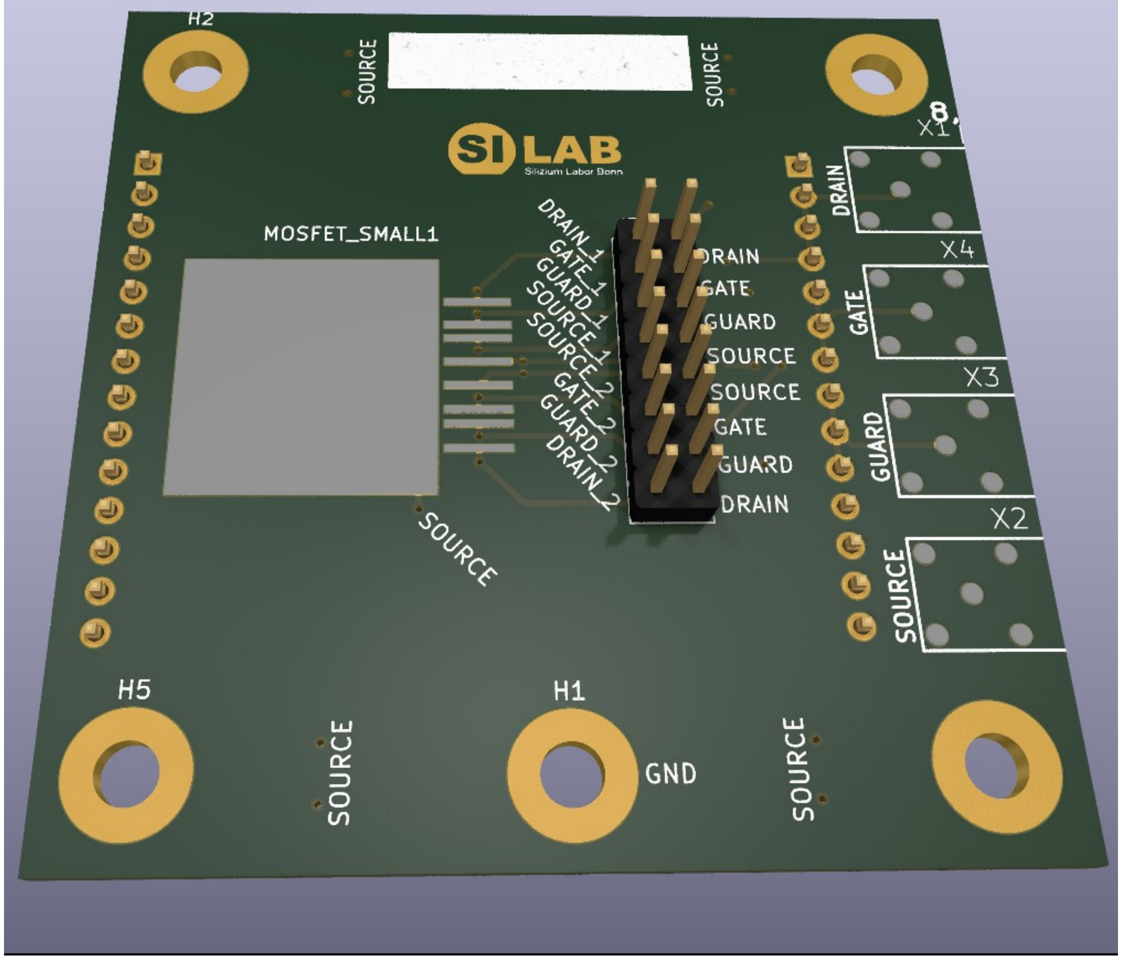
Contact through BOX

Thinned area

Suggested chip margins

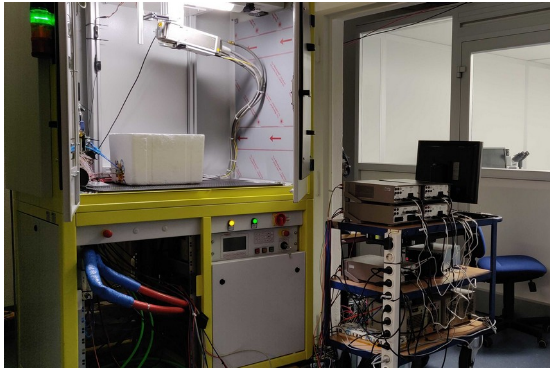


PCB DESIGN

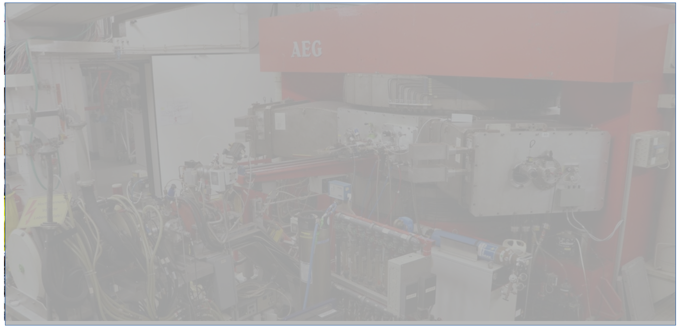


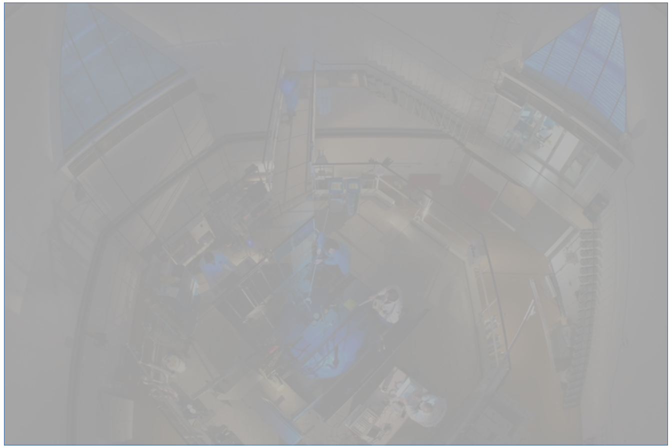
- Four layer passive component PCB
  - Voltage lines (F.Cu)
  - Source layer
  - GND layer
  - Voltage lines (B.Cu)
- Decoupling capacitors at the backside
- Small area (6x6 cm^2) to account for environment specifications of irradiation sites
- PCB v0, review before submission

FUTURE IRRADIATIONS



- X-ray irradiation at Bonn (starting 15.07)
- Electron irradiation at MAMI
- Proton irradiation at HISKP cyclotron in Bonn
- Neutron irradiation at the light water reactor in Ljubljana (?)





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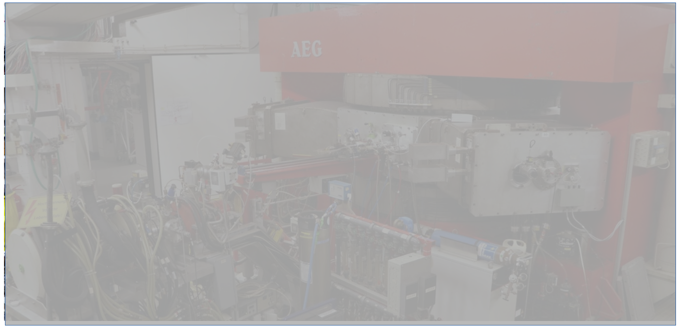

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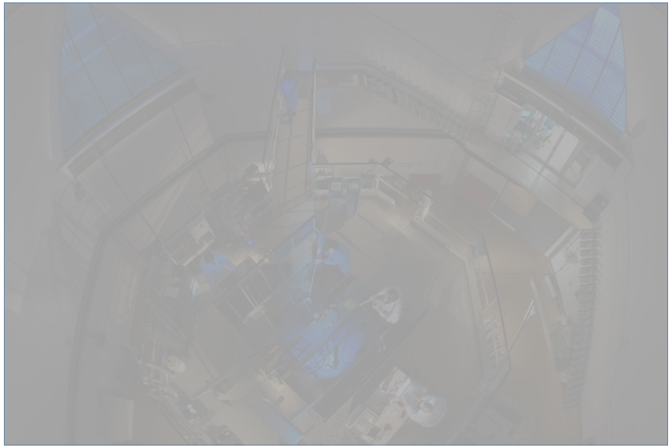

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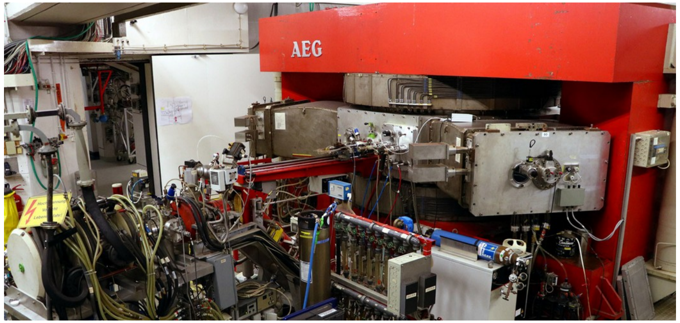

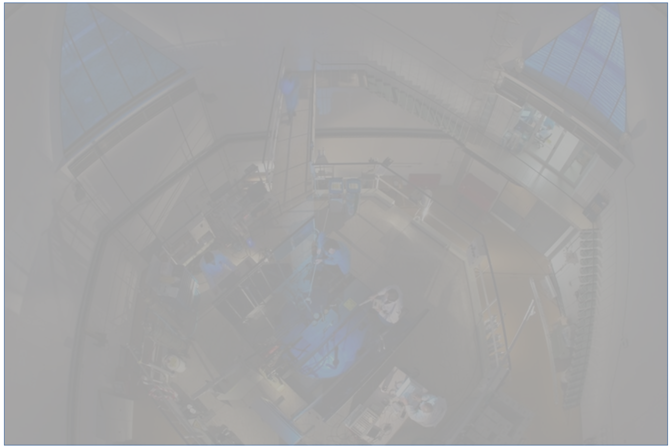

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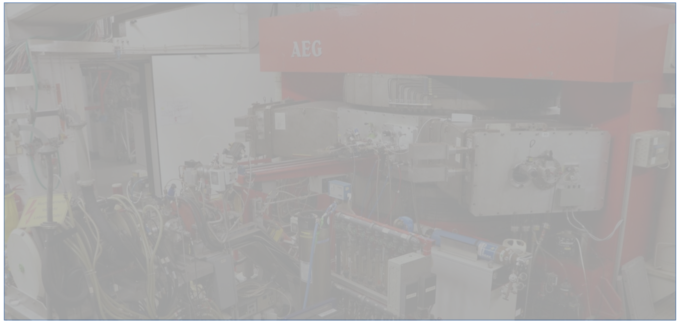

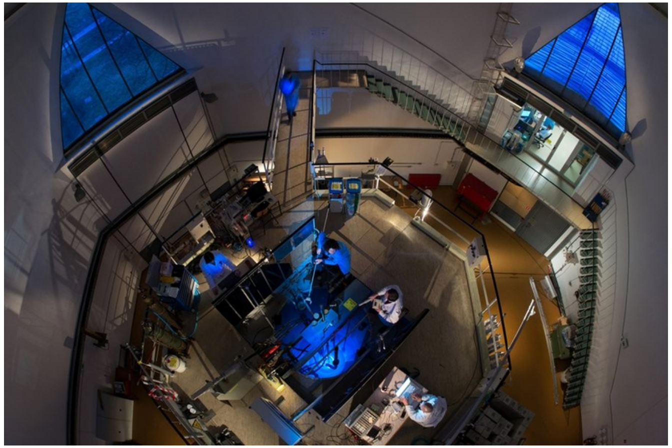

OUTLOOK

- High HV currents at KEK since April 2020
  - LMU PS modifications to keep supplying the needed current
- Effect was reproduced during X-ray irradiation in Bonn
- Discrepancy between KEK and irradiation campaign observations
  - Dose rate
  - Particle type → different radiation damage
- Test structures to probe the mechanism already received
- First version of PCB to mount the structures already designed
- First irradiation campaign (X-rays) already scheduled for mid-July 2022

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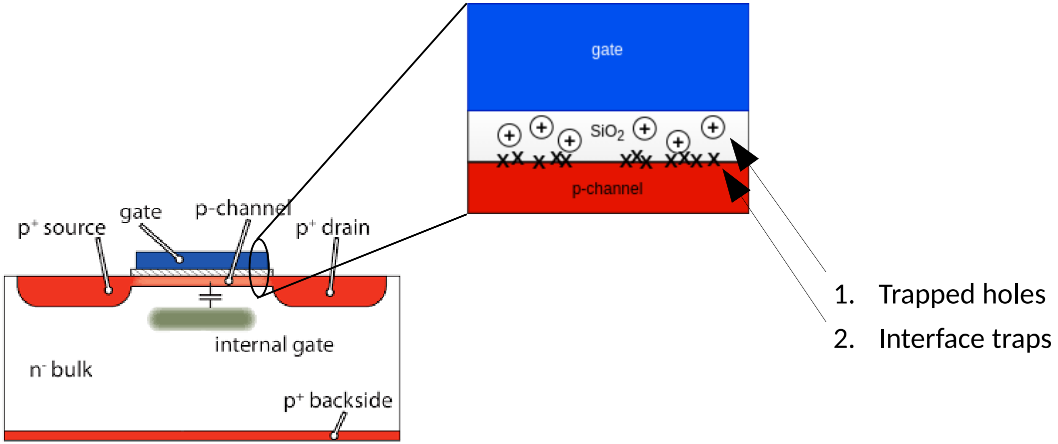
THANK YOU!

BACKUP

SURFACE RADIATION DAMAGE ON DEPFET

DEpleted P-channel Field Effect Transistor (DEPFET)

- X-ray irradiation → e-h pairs → Oxide damage
  1. Trapped holes at SiO_2 / Si border due to their low mobility
  2. Interface traps
     - Moving holes in the lattice release protons
     - Protons drift towards the SiO_2 / Si interface
     - Reaction with hydrogen-passivated defects → H_2 molecules
     - H_2 molecules diffuse out and charge defect is left behind



- Effect on V_{th} of a FET
  - Negative threshold shift for p-channel MOSFET
  - **DEPFET gate (V_G)** and **Common Clear Gate (V_{CCG})**

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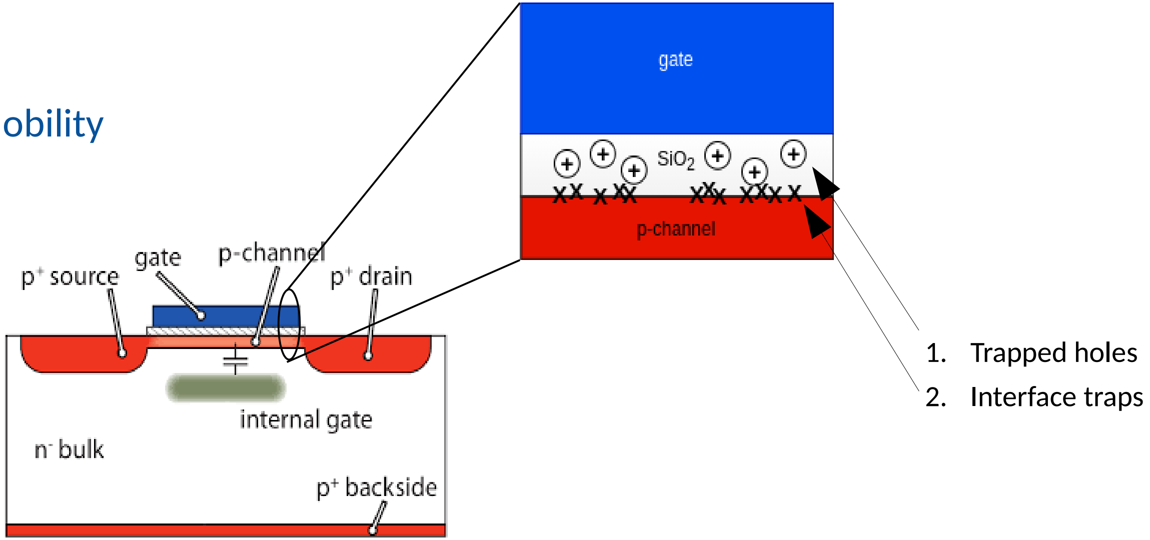
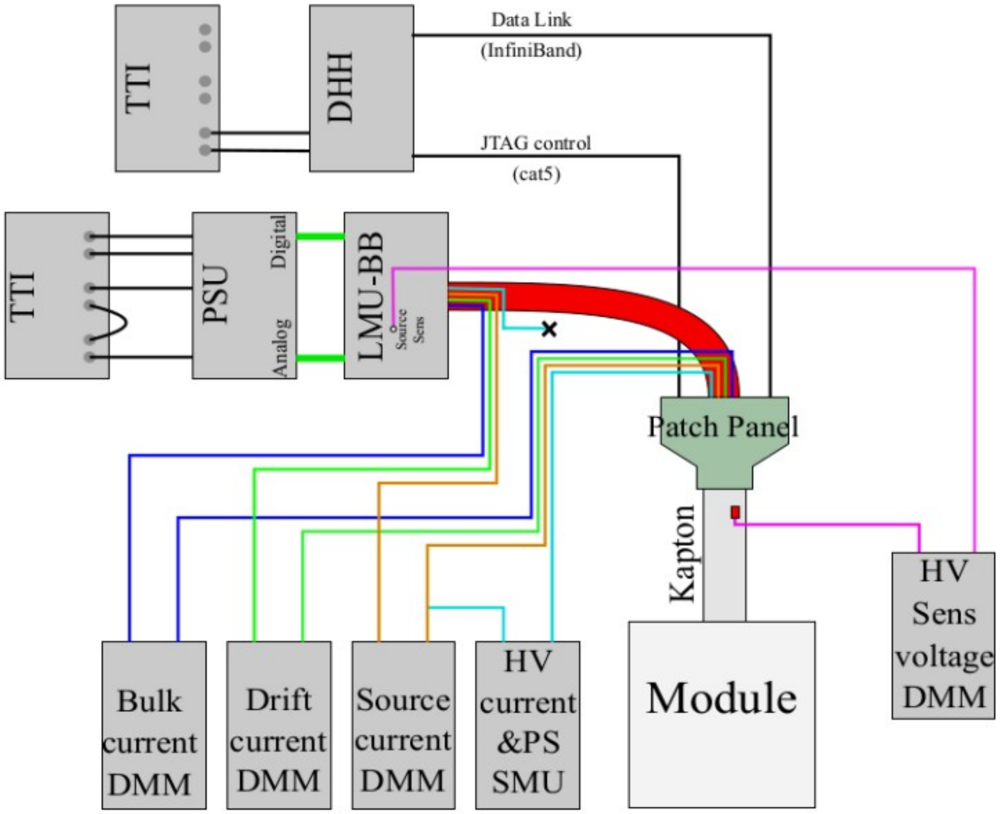
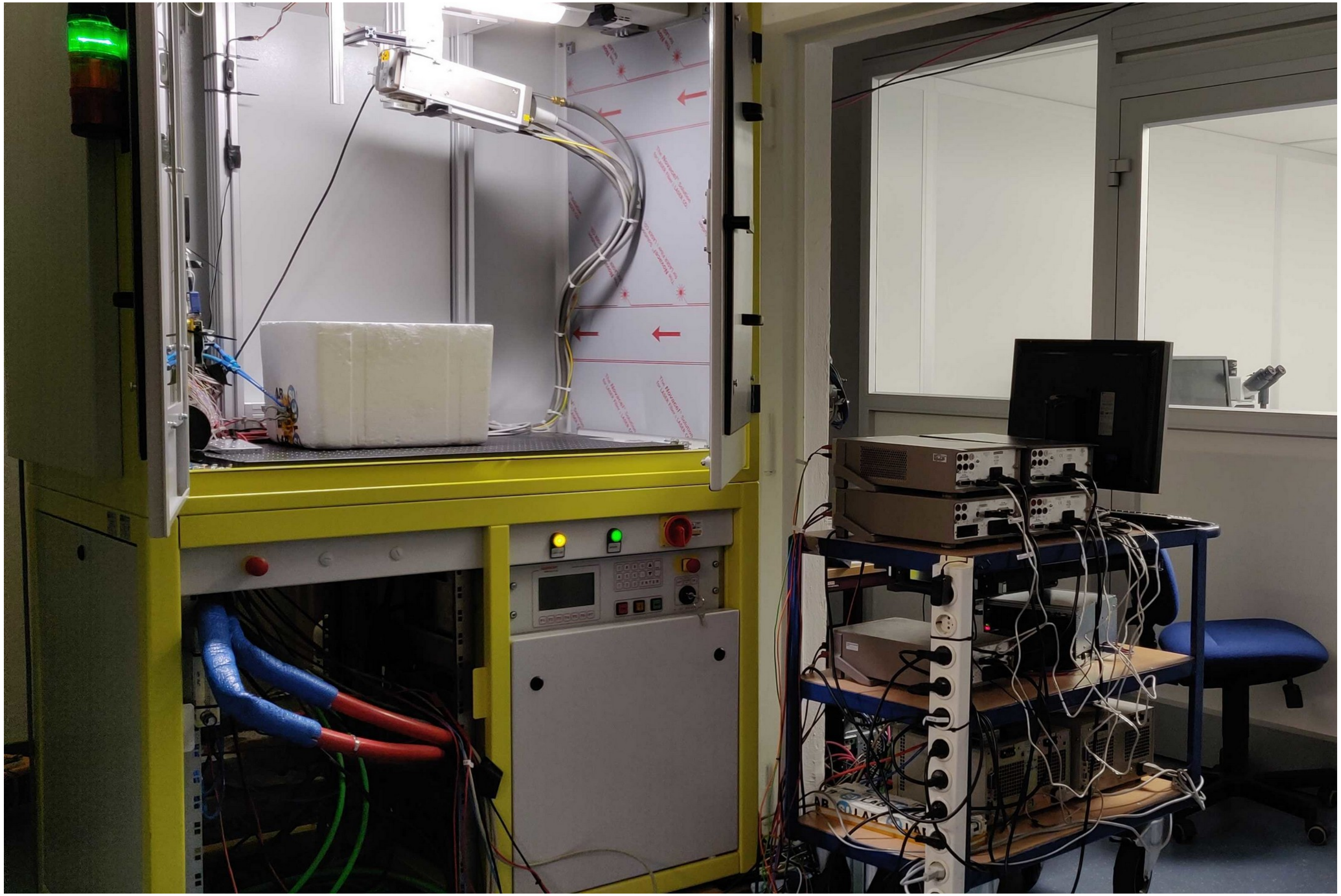


X-RAY IRRADIATION SETUP

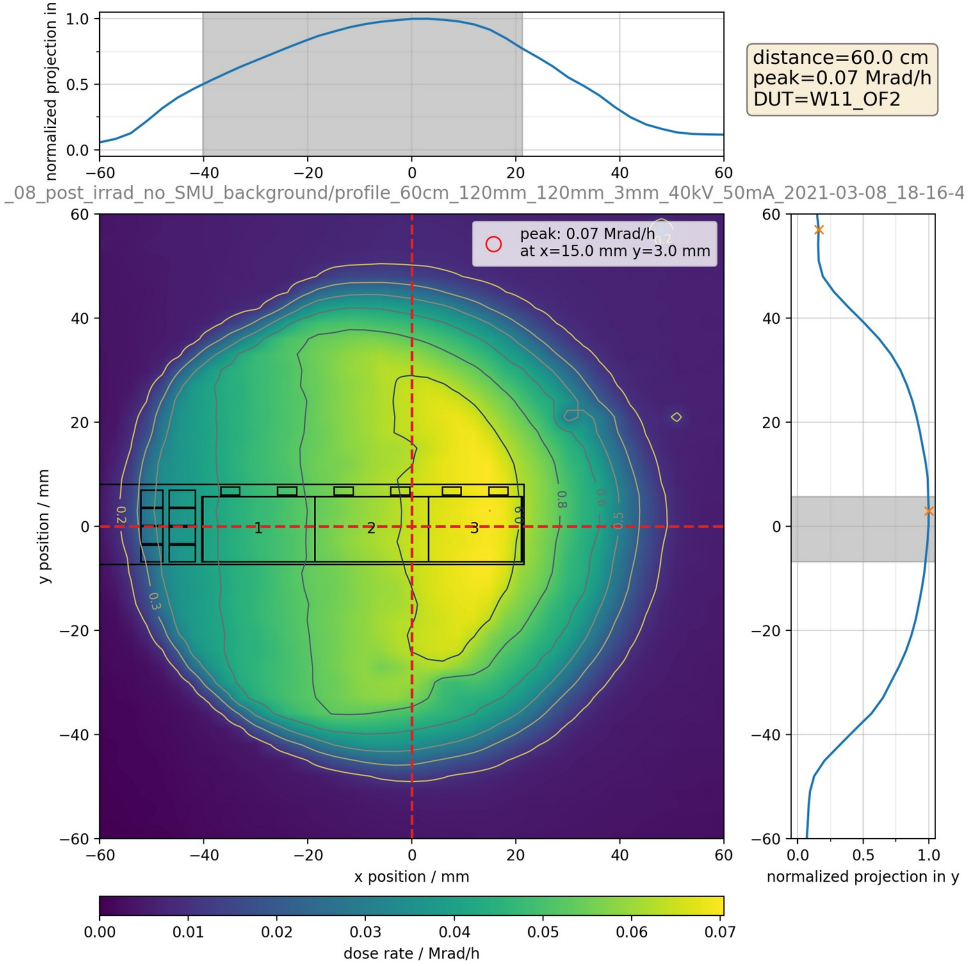


X-RAY IRRADIATION SETUP

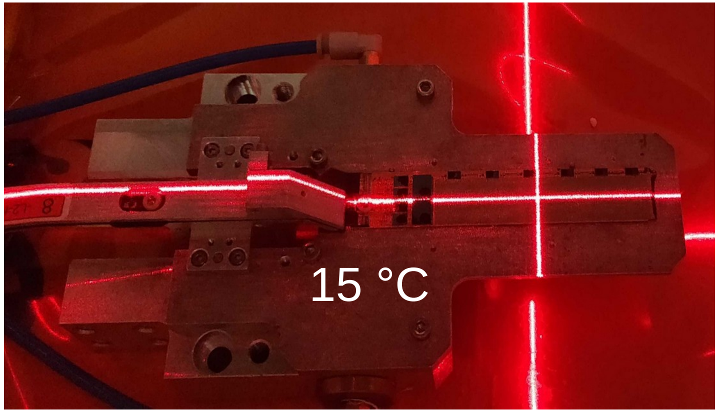
- X-ray setup in Bonn
- X-ray tube settings:
  - V_{tube} = 40 kV
  - I_{anode} = 50 mA
- Characteristics:
  - Tungsten target
  - Al filter (150 µm)
- Water-cooled
- Two irradiation campaigns
  - November 2020: 3 DUTs (prototypes)
  - January 2021: 2 DUTs (full-scale, **1 prev. unirradiated**)



DOSIMETRY

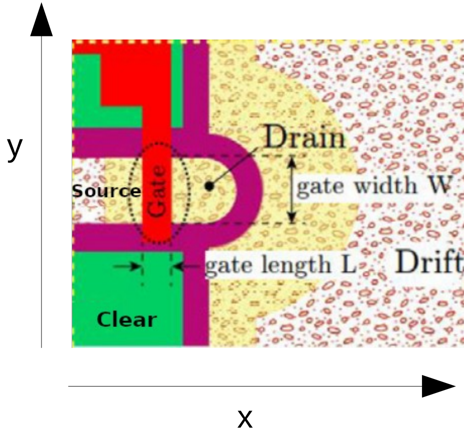


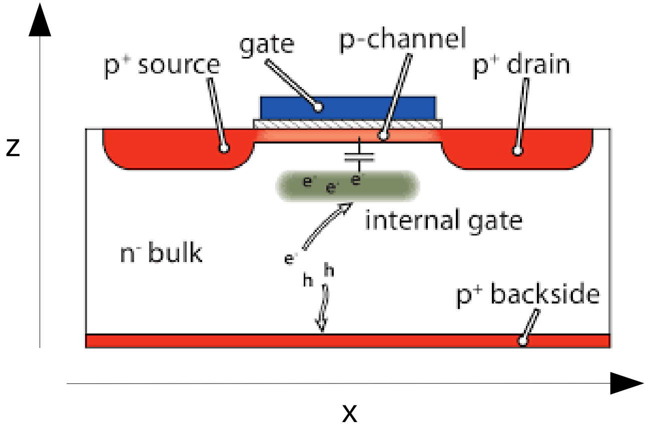
- Beam profile measured with a pre-calibrated diode
- Anode heel effect → Inhomogeneous beam profile
  - Different dose for different module area → Different ΔV_{th}
- Independent V_G and V_{CCG} steering in three regions
- Total Ionizing Dose (TID) up to **18.6 Mrad** in the DEPFET SiO_2
  - **Expected lifetime (10 years) exposure of the PXD is ~20 Mrad**

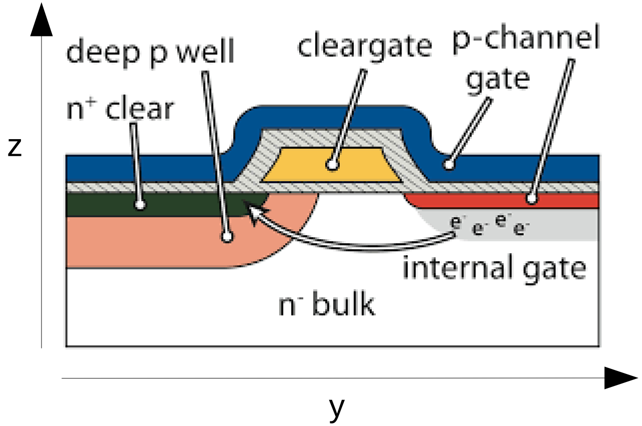


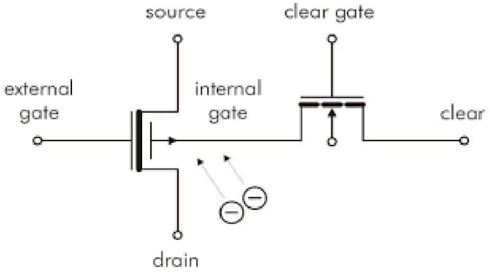
THE DEPFET STRUCTURE AND WORKING PRINCIPLE

DEpleted P-channel Field Effect Transistor (DEPFET)









1. p-channel MOSFET operated in saturation
   - $V_{GS} > V_{th}$ and $V_{DS} \geq V_{GS} - V_{th}$
   - V_{GS} modulates I_D
2. Internal gate
   - Charge collection
   - Additional I_D modulation → Signal
   - $g_q = \frac{\partial I_D}{\partial q} \approx 500 \frac{pA}{e^-}$ (see talk T.95.7 from Larissa von Jasienicki)
3. Additional FET for clear mechanism
   - Directly connected to internal gate
   - Large positive voltage applied to clear → empties internal gate

V_{GS}: gate voltage
V_{th}: threshold voltage
V_{DS}: drain-source voltage
I_D: *drain* current

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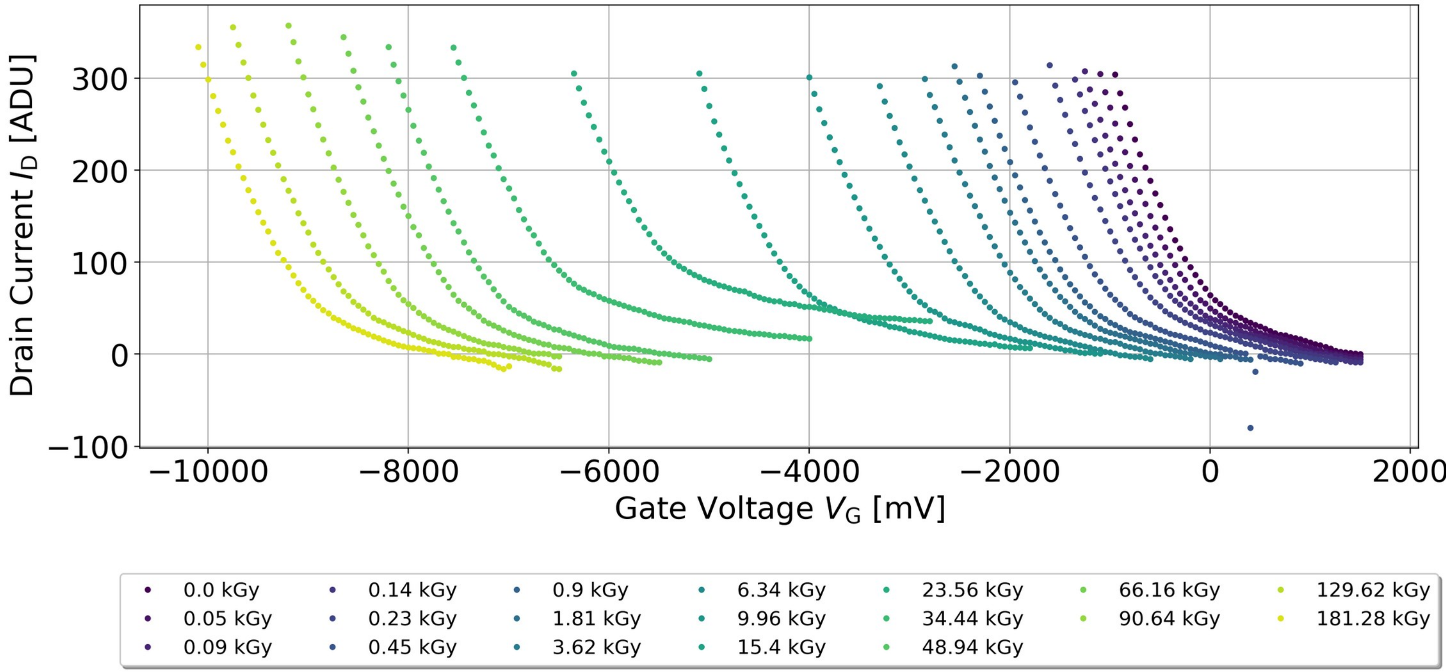
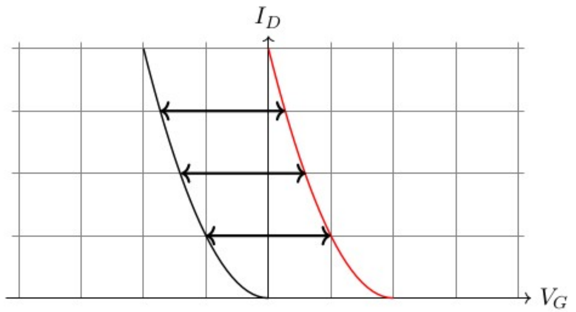
DEPFET I-V CURVE

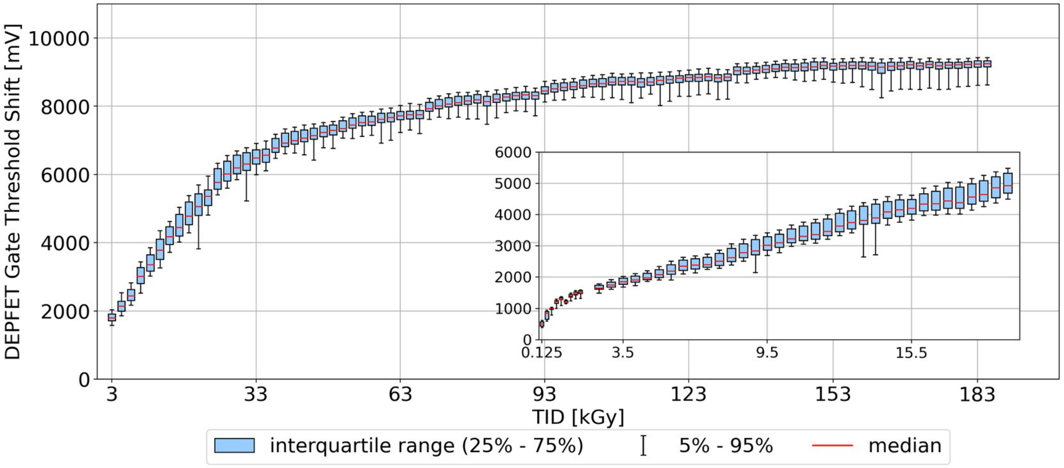


- I-V curve per pixel
- Drain Current vs Gate Voltage
- First measurement as reference (0 kGy)
- Only relative threshold shift calculated
  - Curves binned along I_D axis
  - ΔV_{th} = mean difference over all bins wrt the reference

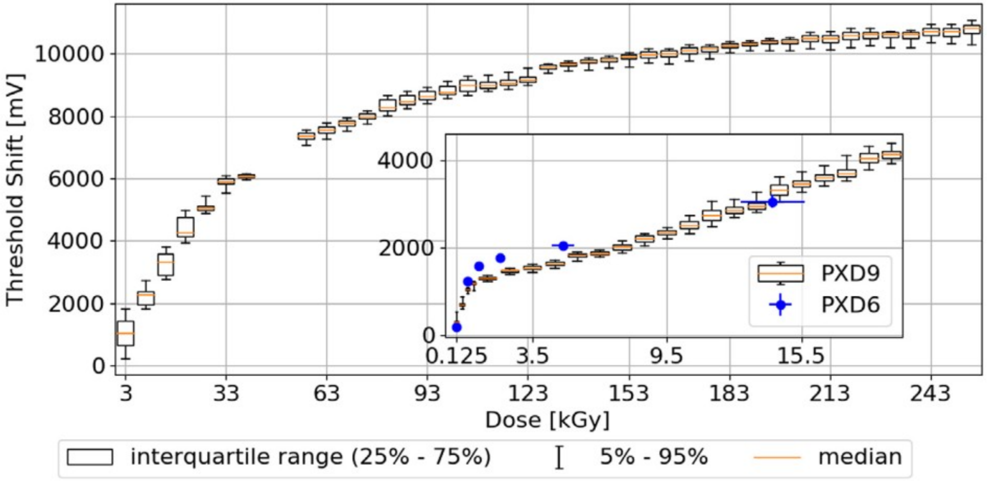


DEPFET GATE THRESHOLD SHIFT

January 2021 campaign



January 2019 campaign



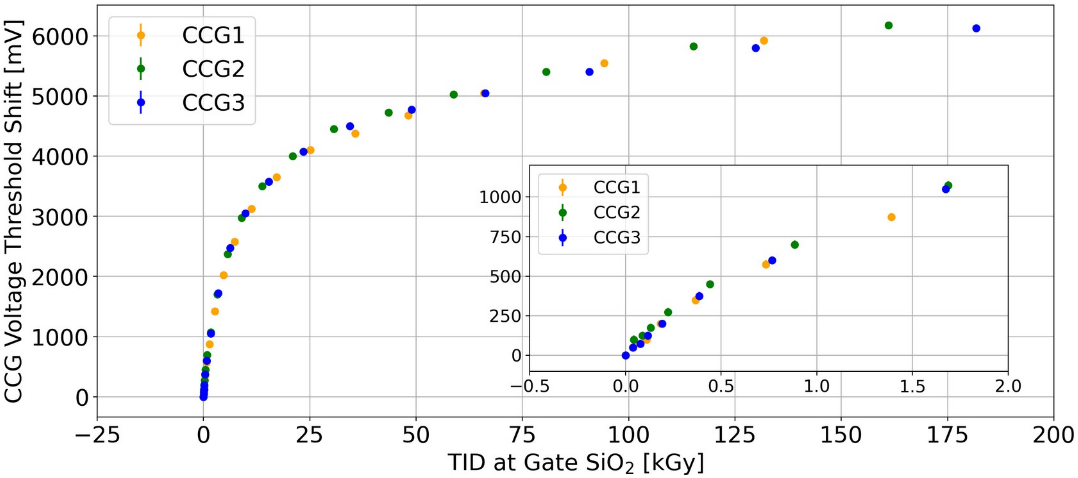
[Harrison Schreeck, Botho Paschen, et al (2020). *Effects of gamma irradiation on DEPFET pixel sensors for the Belle II experiment*]

- Boxes contain measurements from different pixels and irradiation steps
- Jumps due to large irradiation steps

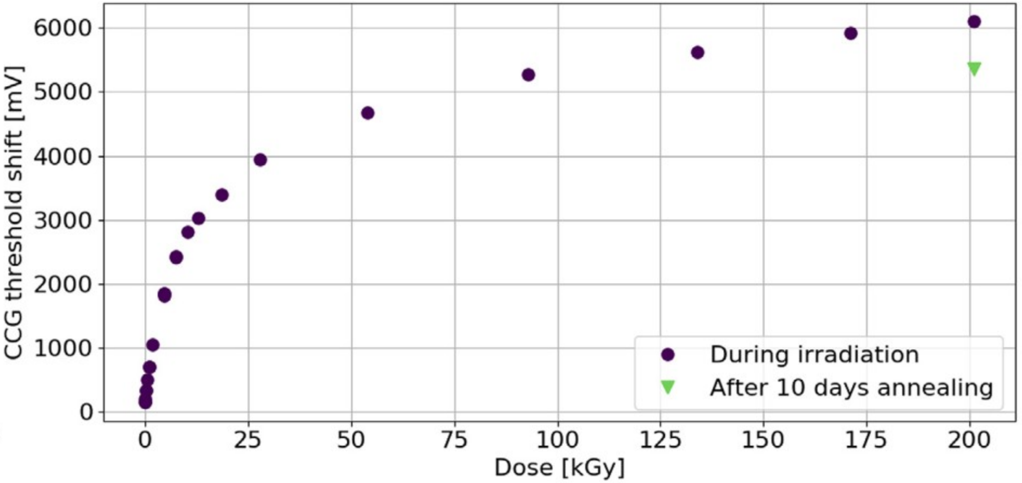
- Full-scale DEPFET modules in both cases
- Similar threshold evolution

COMMON CLEAR GATE THRESHOLD SHIFT

January 2021 campaign



January 2019 campaign



[Harrison Schreeck, Botho Paschen, et al (2020). *Effects of gamma irradiation on DEPFET pixel sensors for the Belle II experiment*]

- Not per pixel, but per region (1, 2, 3)
- Taking into account inhomogeneous irradiation → 3x more data points

- Full-scale DEPFET modules in both cases
- Similar threshold evolution