Characterisation of the silicon oxide quality in CMS HGCAL sensor prototypes

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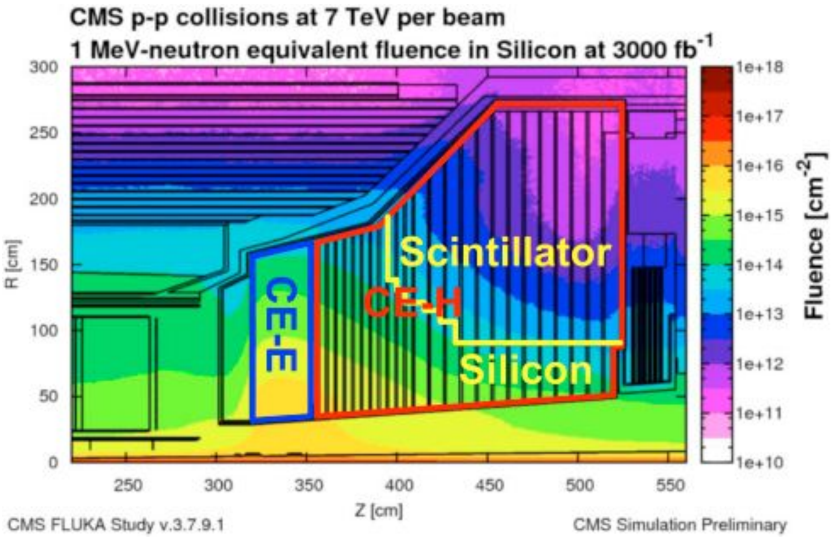
The case for the High Granularity CALorimeter

Sampling EM and H calorimeter to be installed in CMS endcap in Phase II upgrade -> silicon

- Granular, 3D sampling of showers
- Good timing resolution (~50 ps)
- Radiation hardness (EM, hadronic)

-> unprecedented project that requires significant **development** of sensor technology

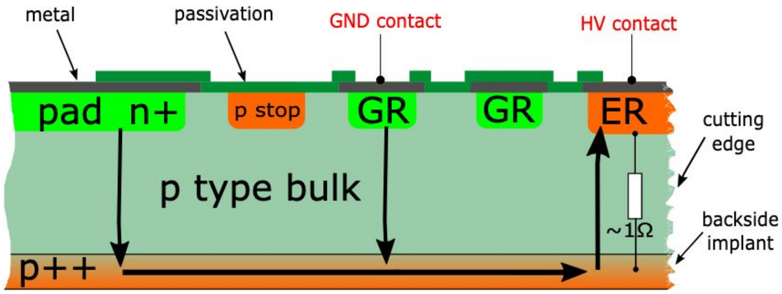
-> significant investment of financial resources: careful **testing and validation** are key



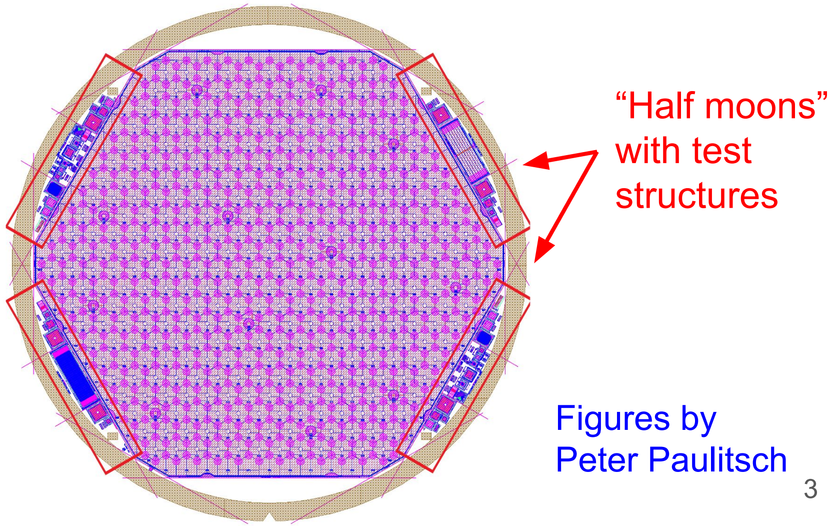
Goal of this work: study of quality of SiO_2 layer in HGCAL sensors for different production variants

Silicon sensors for HGCAL: a world in hexagons

- Hexagonal geometry to optimize usage of circular silicon wafer (**Hamamatsu**)
- First time that 8'' wafer is used in HEP
  -> economical / practical advantage
  -> new production line challenges



- pad = diode in p-type silicon bulk
- Inter-pad isolation increased by dedicated p+ implants (p-stops)
- SiO_2 used as passivation layer



Dedicated test structures can be used to perform destructive tests -> **X-ray irradiation** used to study EM radiation damage in SiO_2

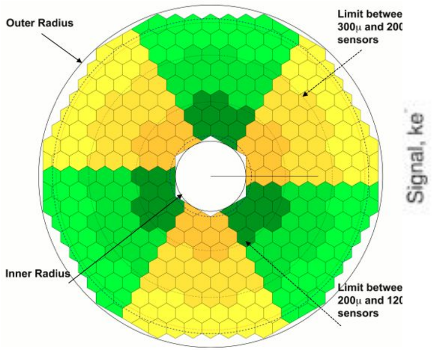
Figures by Peter Paulitsch

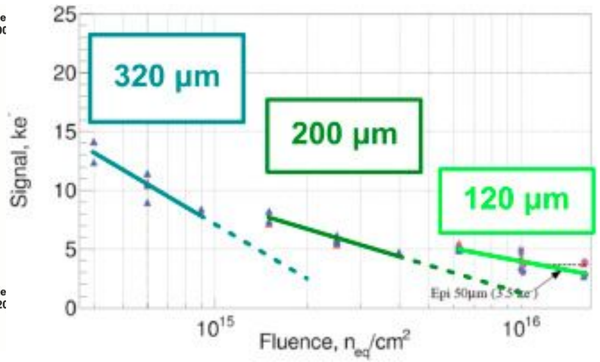
Different sensors for different fluences

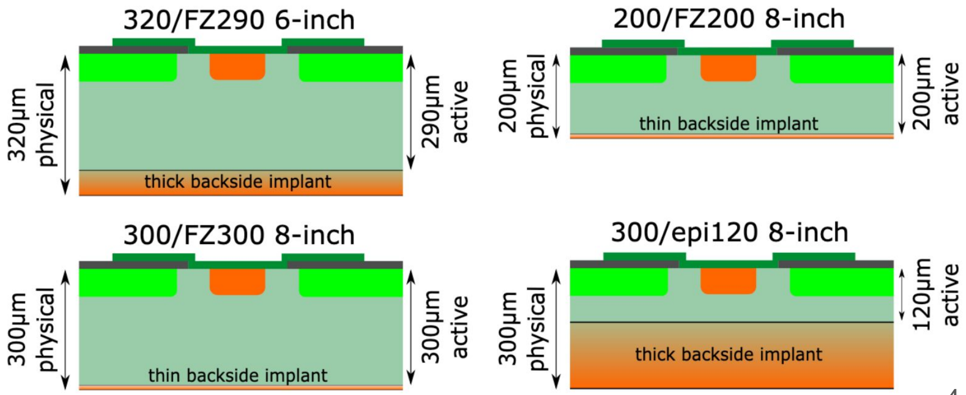
Sensors in inner radius (**forward**) are exposed to much higher fluence

- Different active thickness in different pseudo-rapidity regions
  (300, 200, 120 μm)
- 120 μm: high-density sensors
  (smaller pads = higher granularity)

- **epitaxial** material used for 120 μm, while **float-zone** for 200 and 300 μm
  -> crucial to test different materials



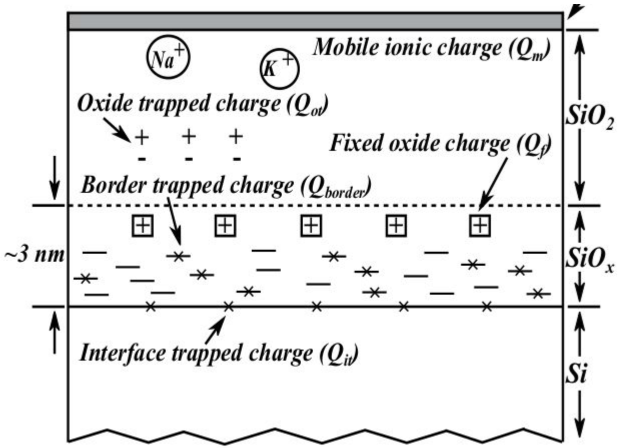




Damage from electromagnetic radiation

- EM radiation creates e/h pairs in the SiO_2 layer
- Initial recombination -> e/h yield
- Electrons quickly collected at the electrodes
- Holes slowly diffuse -> can be **trapped**

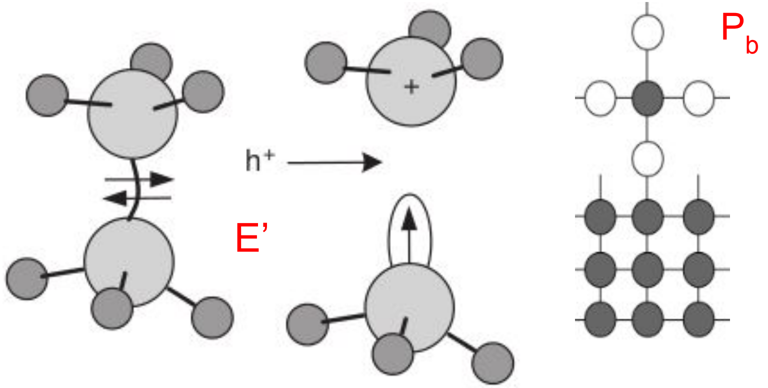
Border + interface region -> SiO_X



Border traps: E’ centers due to O vacancy

Interface traps: P_b centers = dangling bonds (partially passivated with H^+)

H^+ passivation altered by radiation -> increase in the number of interface traps



MOS and GCD measurements

Effect of trapped charge:

1. Increase in $\mathbf{V_{fb}}$
   -> total oxide charge N_{ox}

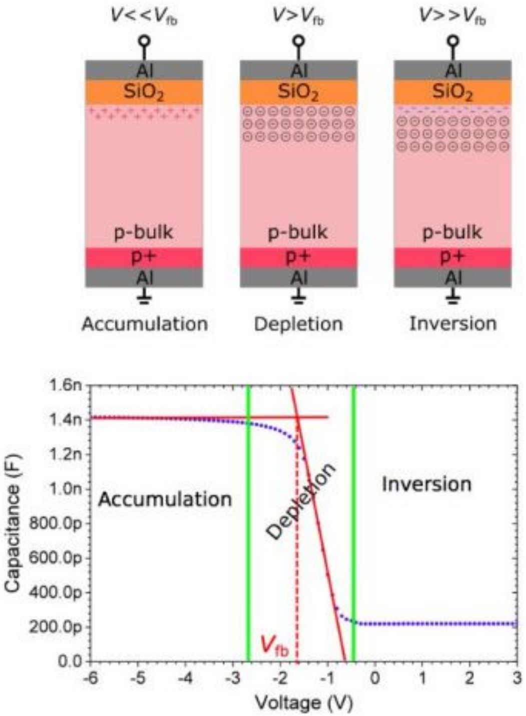
$$N_{oxide} = \frac{C_{oxide}}{qA_{gate}}(\phi_{ms} - V_{FB})$$

2. Increase in **surface current**
   -> interface charge

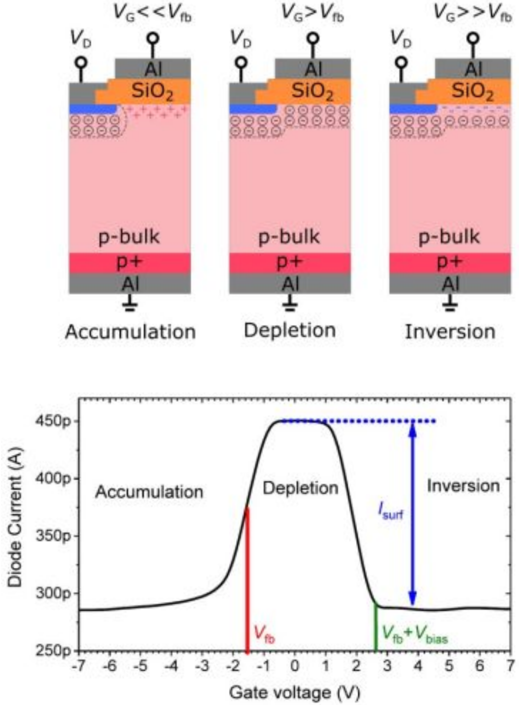
$$s_0 = \frac{I_{surf}}{qn_i A_{gate}}$$

Measure V_{fb} and I_{surf} as a function of the absorbed dose

MOS



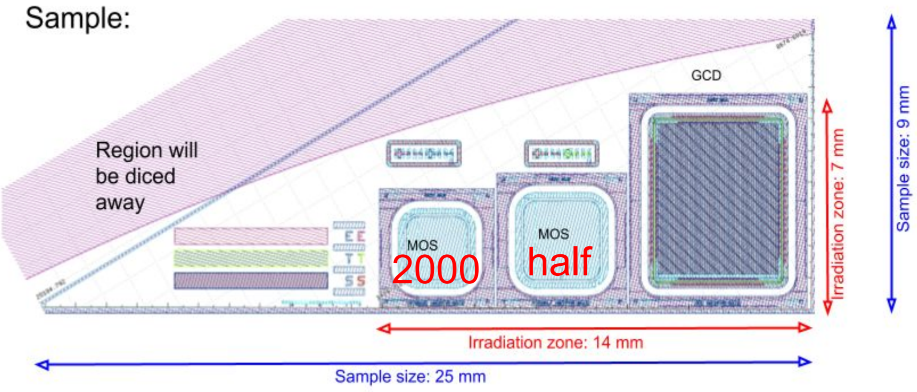
GCD

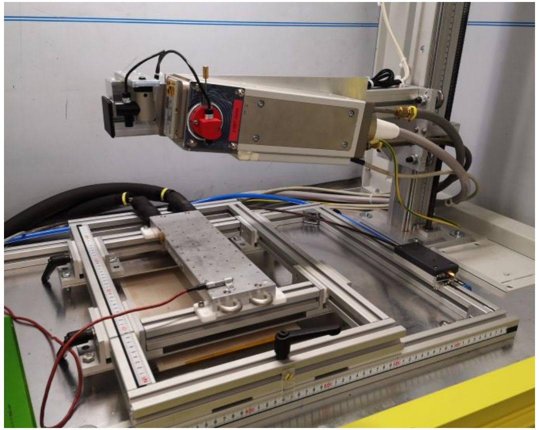


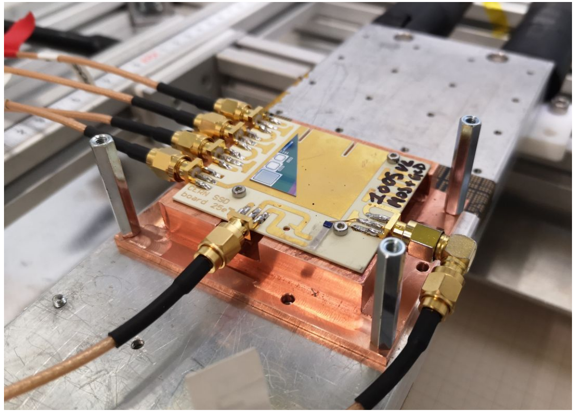
Illustrations by V. Hinger

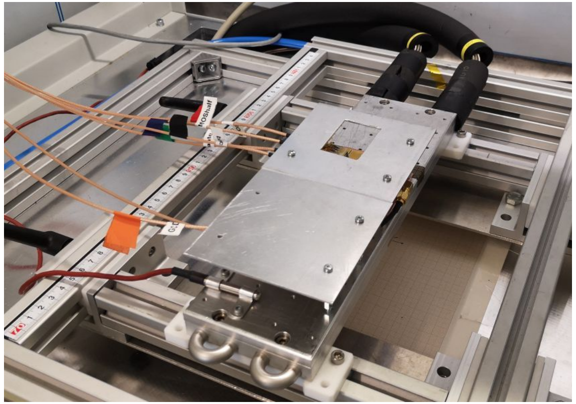
Sample irradiation at CERN

- MOS2000 biased with +10 V in order to study the radiation damage in the presence of an **electric field**
- measurements and irradiation at -20 °C -> **crucial to control annealing**
- Dose rate = 14 kGy/h

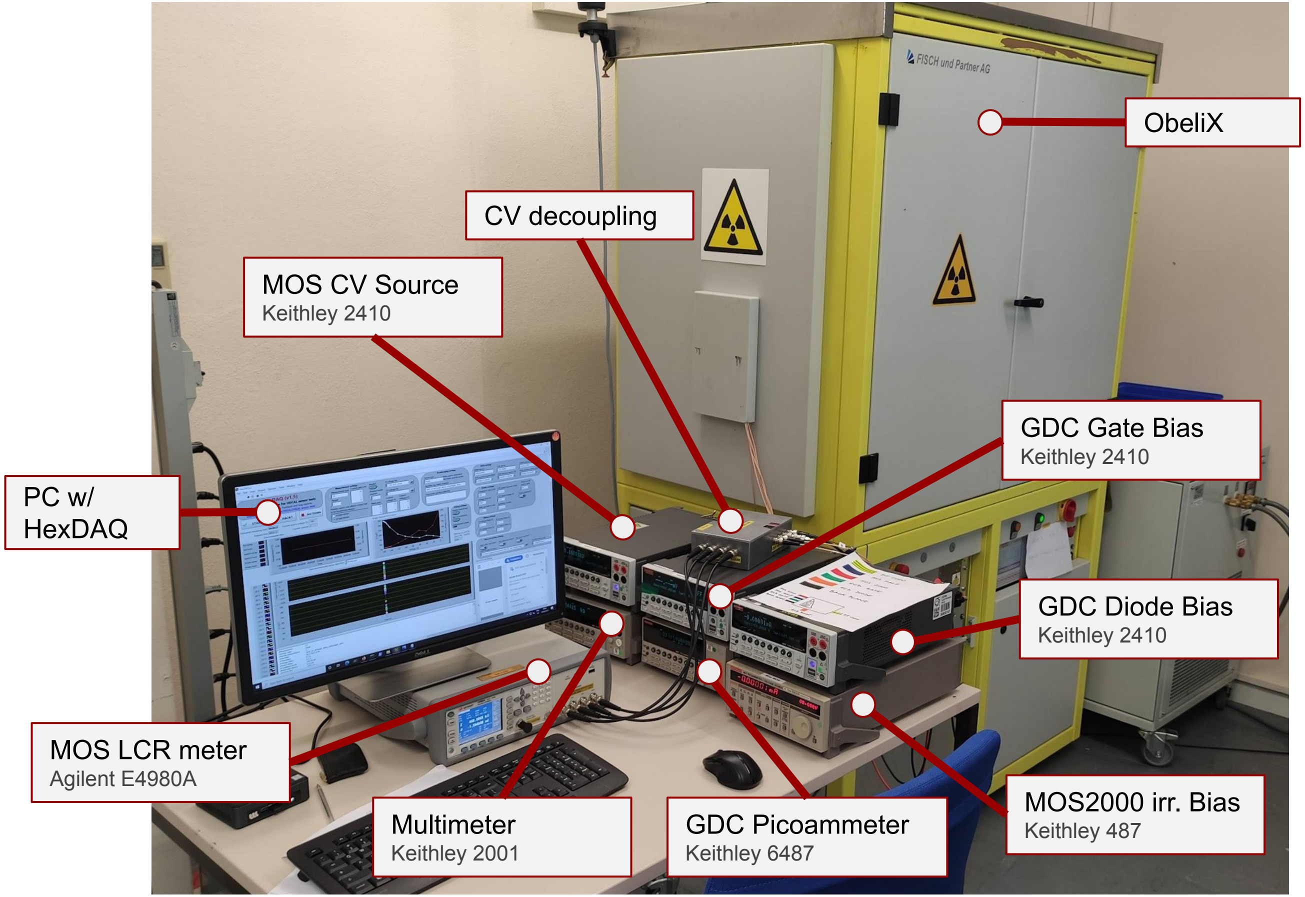








The X-ray setup @ ObeliX (CERN)



MD, Pedro Almeida,
Eva Sicking

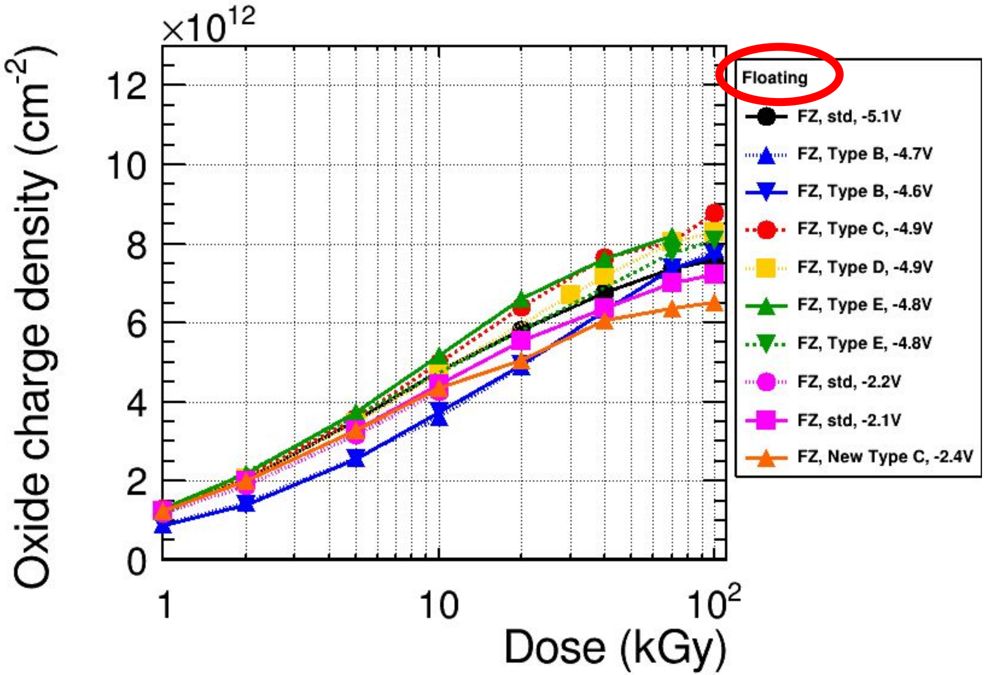
Entirely new setup developed between October and December 2020

Reliable and precise setup (~pF and ~nA) to be operated in combination of X-ray machine (ObeliX)

-> achieved high level of reproducibility (not trivial due to non-negligible annealing even at low T)

disadvantage: operated manually

Oxide variants from HPK: STD + type B-E



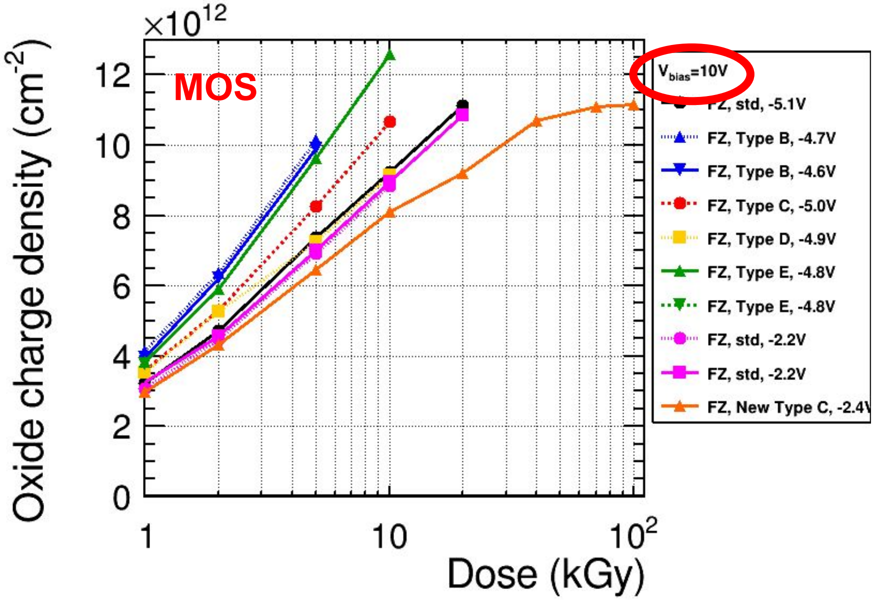
Tested different oxide variants provided by Hamamatsu, of which we don't know production details

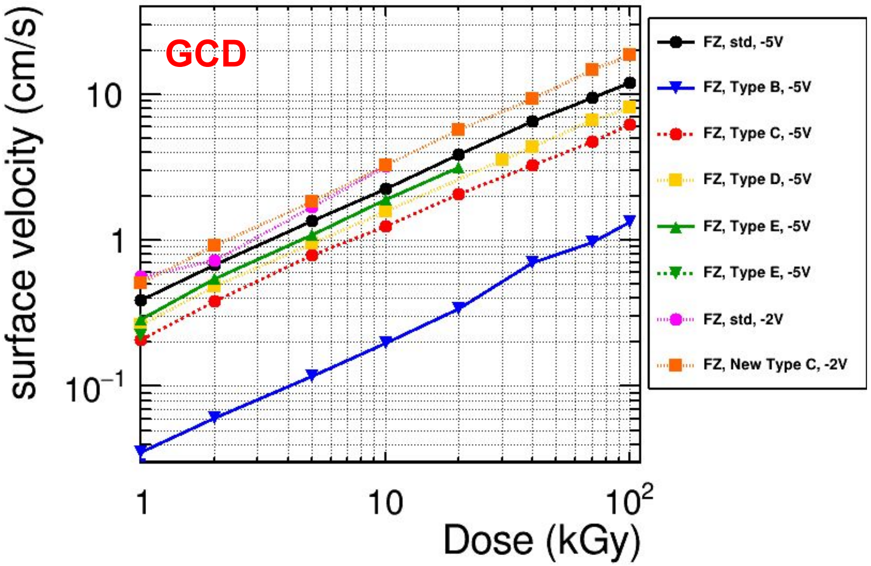
The producer attempted to "*improve the oxide layer quality by changing the condition thermally and/or environmentally*"

The new type C is also referred to as "*thermal oxide condition*"

- Results shown refer to the MOS structure kept floating during irradiation
- Marked preference for new type C, especially at higher doses

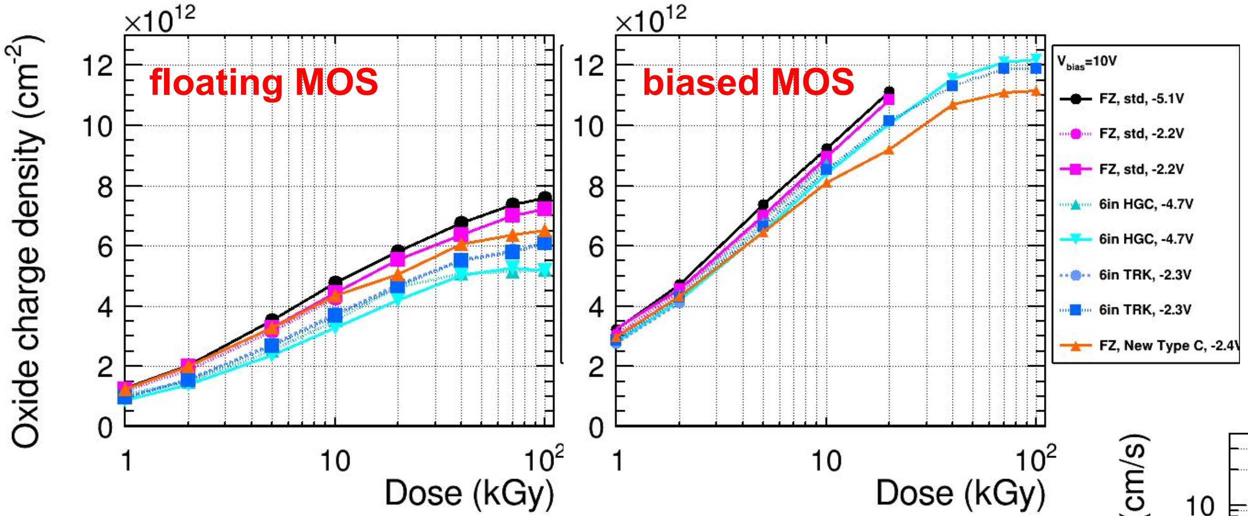
Biased MOS and GCD results





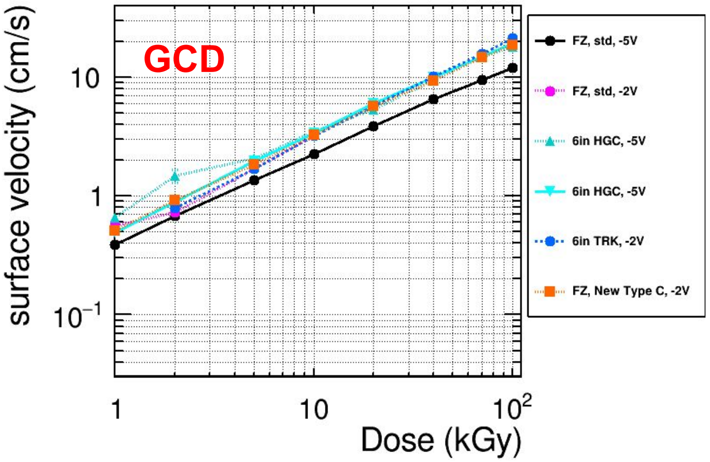
- Marked preference for new type C in biased MOS structure
- Higher surface current observed for new type C. However, similar performance as in benchmark HGCAL 6” prototypes and CMS outer tracker (next slide)

Comparison to benchmark samples



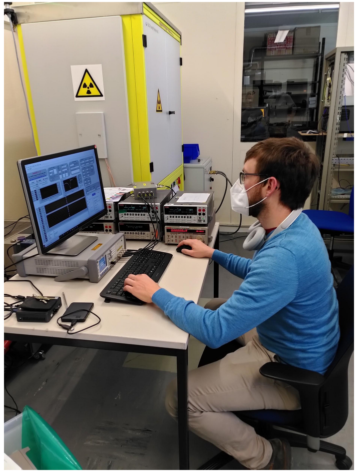
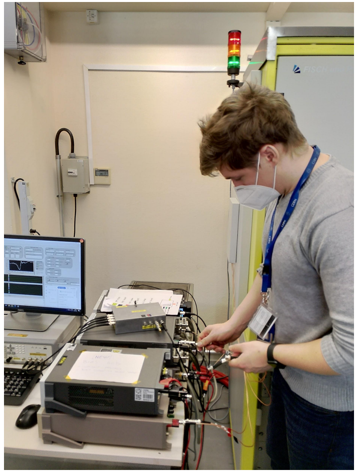
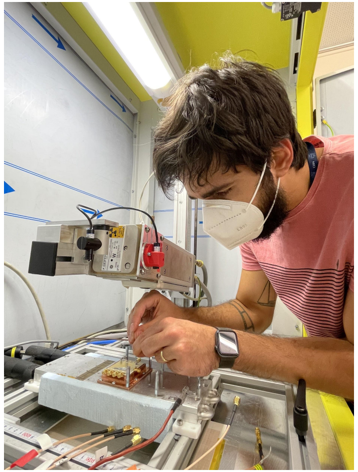
Compared to HGCAL 6” prototypes and CMS outer tracker (benchmarks), obtained with the same procedure

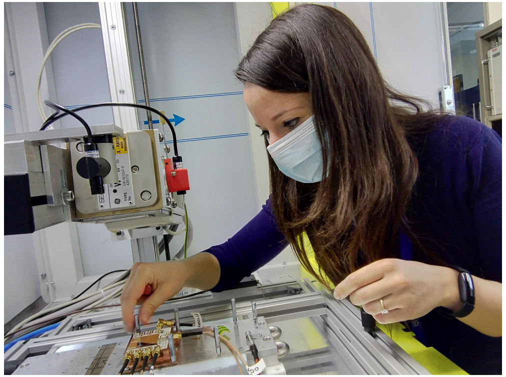
- New type C performs better in the presence of an electric field, slightly worse otherwise
- **Similar performance in case of GCD**



-> second round of prototypes produced by HPK based on these results (new types A-D)

Some of the team members during the campaigns


Long shifts involving 6-8 people per campaign

2 weeks/campaign, 6h shifts, 2 persons/shift

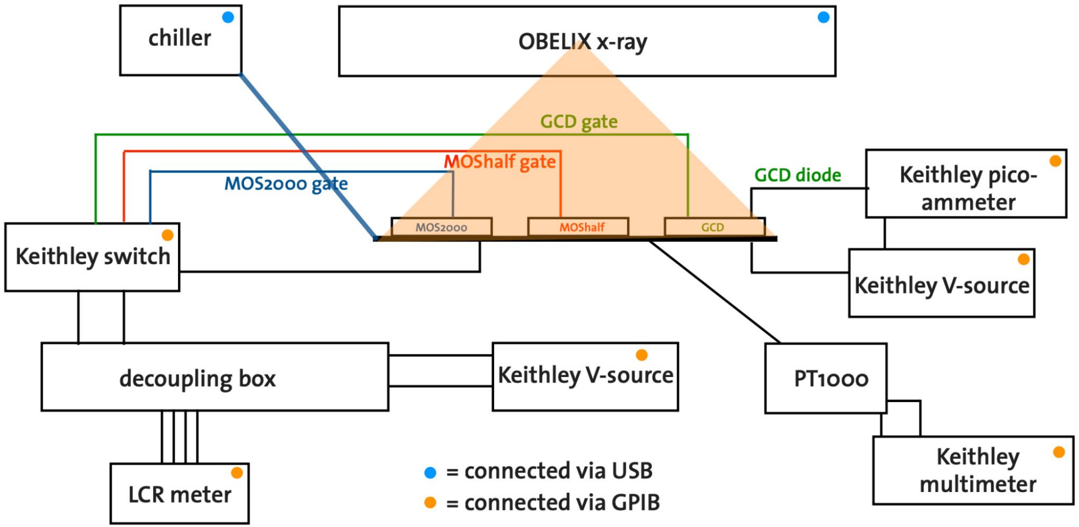
2 weeks/month from Jan to Mar 2021 (including w/e)

- Very demanding (and exhausting) for the group
- Dire need for improved (automated) setup

The new *AXIOM** setup

Marc Dünser, MD,
Marco Cipriani, Vitor Sousa

*Automated X-ray Irradiation and Oxide Measurements



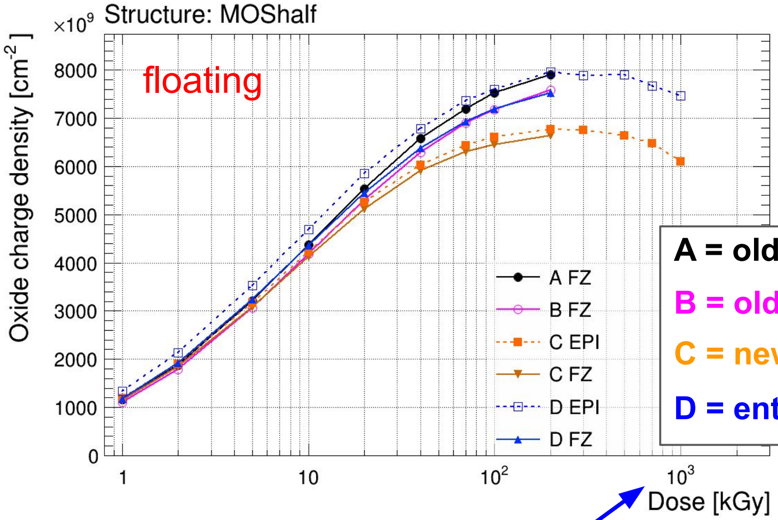
All components of the setup are now computer-controlled, switch system allows to measure different structures without manual intervention

Automatic setting and control of ObeliX, including monitoring of correct operation

Fully automatic dose steps setting and measurements, **no supervision needed** after installing the test structure -> efficient use of nights and weekends

Previous setup: 0 -> 100 kGy = 3 days FTE
New setup: 0 -> 100 kGy = 3 hours FTE
} *x8 improvement!*

Results for new types A-D

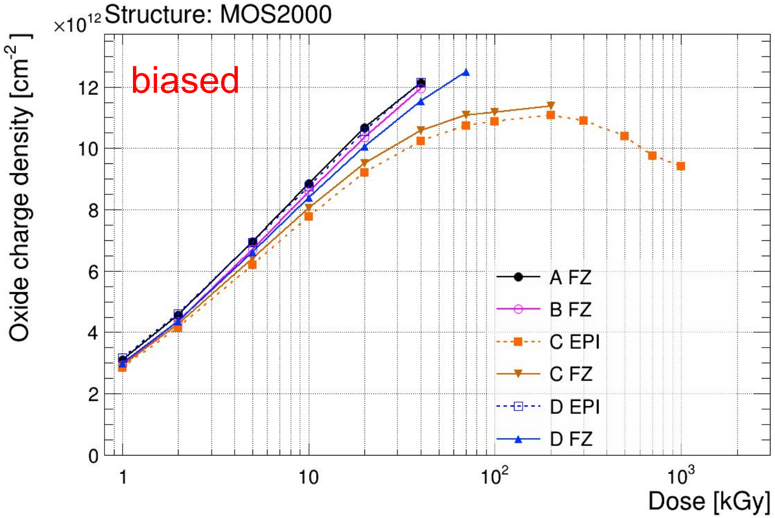


A = old STD -5V

B = old STD -2V

C = new type C

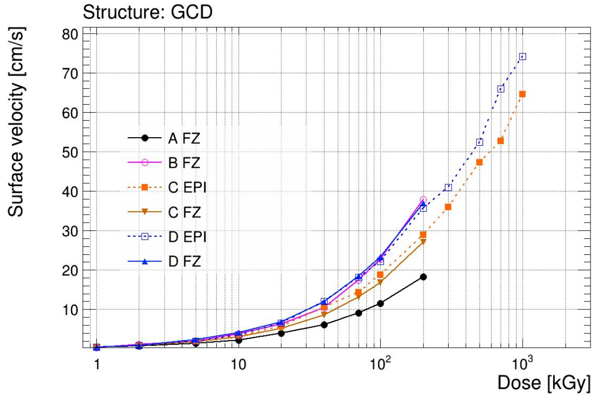
D = entirely new type



EPI material irradiated up to 1MGy (expected dose in forward region of the calorimeter at the end of HL-LHC)

confirmed preference for new type C -> will be used by HPK for next round prototypes (larger scale testing)

-> similar performance in FZ and EPI samples

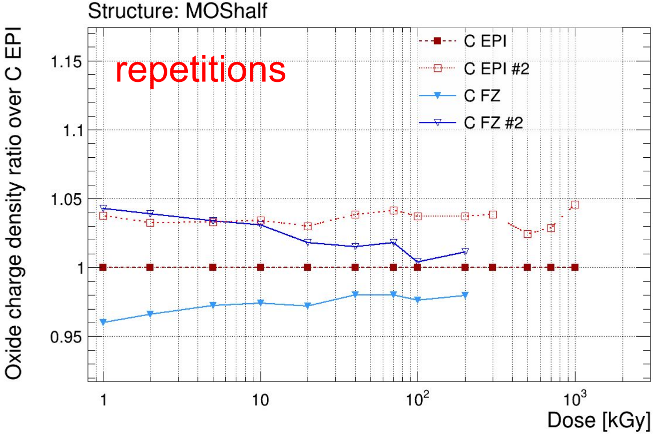


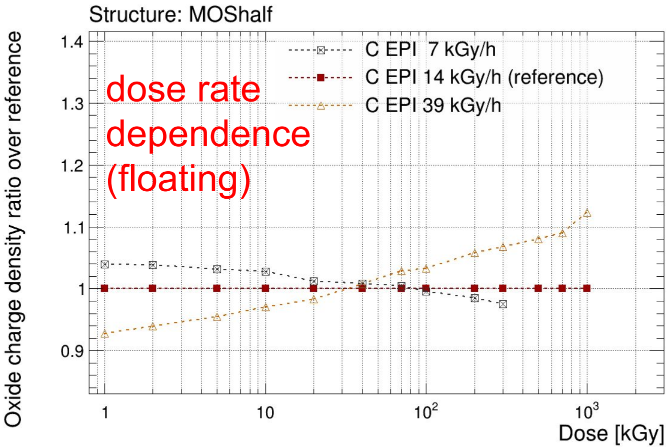
On reproducibility and dose rate dependence

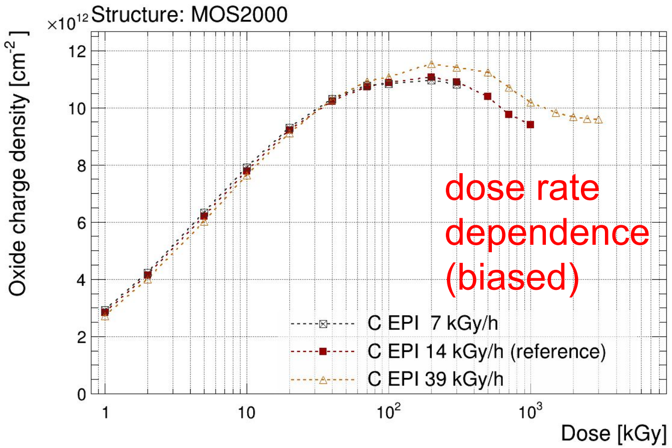
Reproducibility of measurements across different campaigns achieved at the ~5% level

Differences between different oxide types exceeding 10% level -> confidence that our results are conclusive

Hints for **mild dose rate dependence** + saturation at ~3 MGy also observed





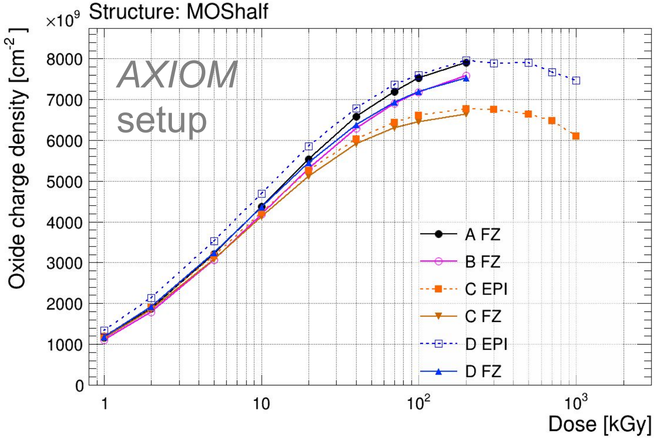


Uninterrupted irradiation up to 3 MGy only possible thanks to *AXIOM* setup

Summary and outlook

- The EM damage of the SiO_2 layer has been studied in HGCAL 8'' silicon sensors by means of X-ray irradiation of dedicated test structures at the CERN ObeliX facility
- A **fully-automated setup**, called ***AXIOM***, was developed for this purpose, which can be used in the future for larger scale testing, including production quality monitoring

- **Different oxide variants** provided by Hamamatsu have been tested, and a clear preference for so-called new type C (thermal oxide condition) has emerged
- The performance was found to be in satisfactory agreement with HGCAL 6'' prototypes and with sensors of the CMS outer tracker
- Based on these (and other) results, new type C was chosen for next round of prototypes, which will undergo larger scale testing



In order to provide a complete picture of the oxide behaviour in real operating conditions, annealing studies of irradiated structures are now ongoing at CERN

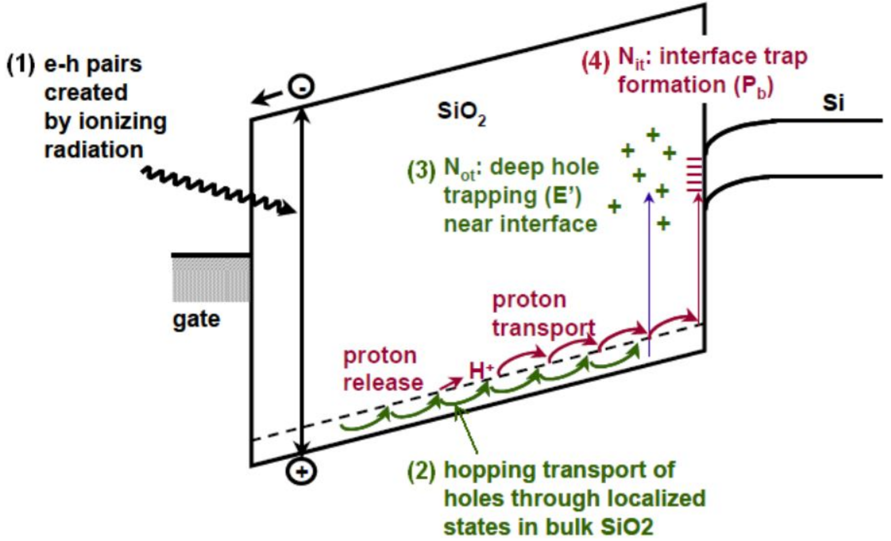
Thank you

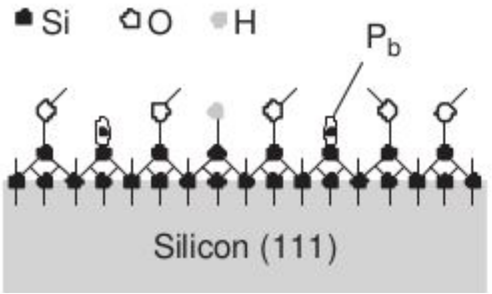
Irradiation with an electric field

- **Intensity**: initial e/h yields
- **Direction:** how much positive charge reaches the Si-SiO_2 interface

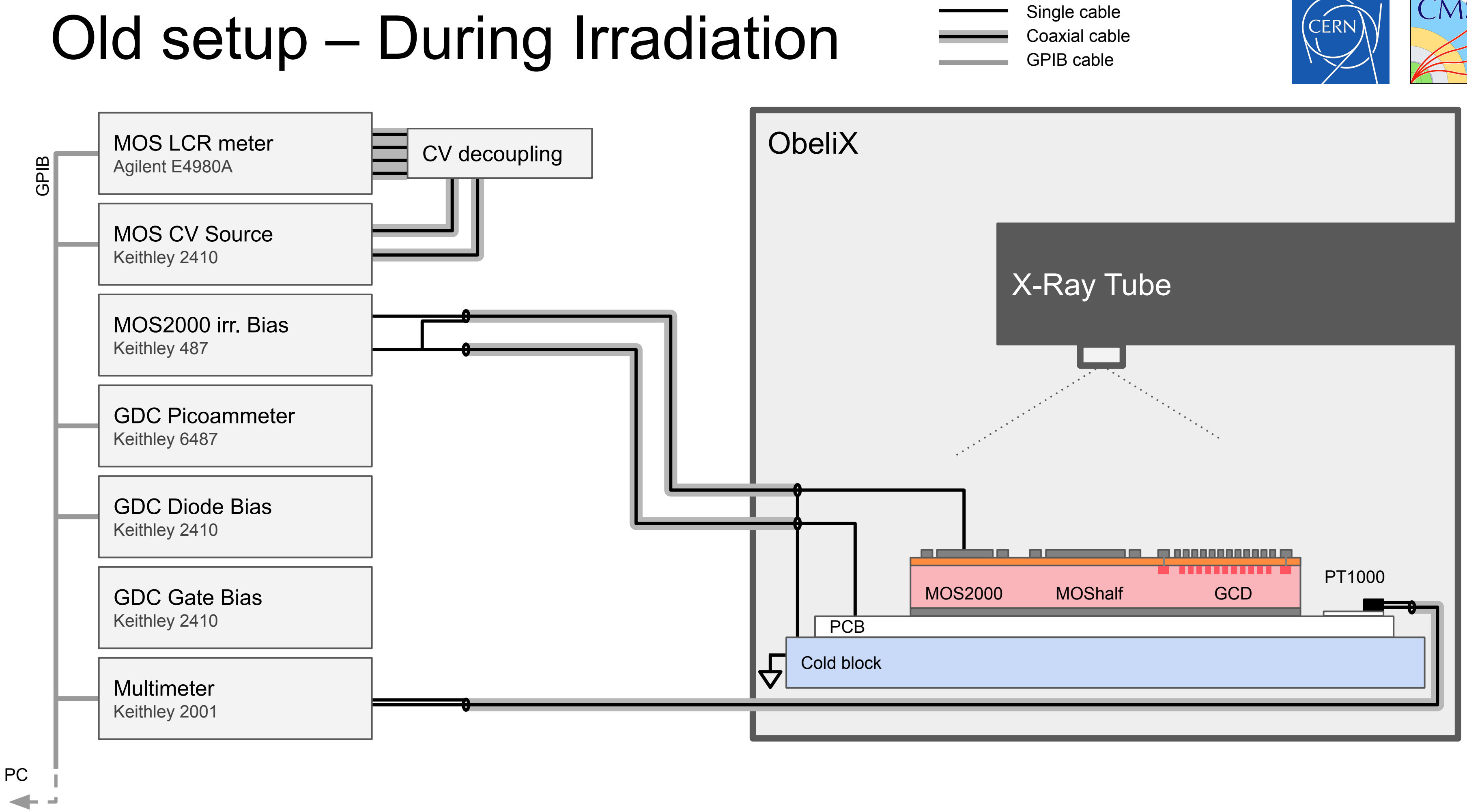
Interface trap formation

1. H^+ ions liberated during irradiation
2. Ions travel to the interface ($V_{gate} > 0$) where they can pick up an electron
3. H^0 is very reactive, and can combine with one H of the passivation to form H_2, thus creating a dangling bond (P_b)

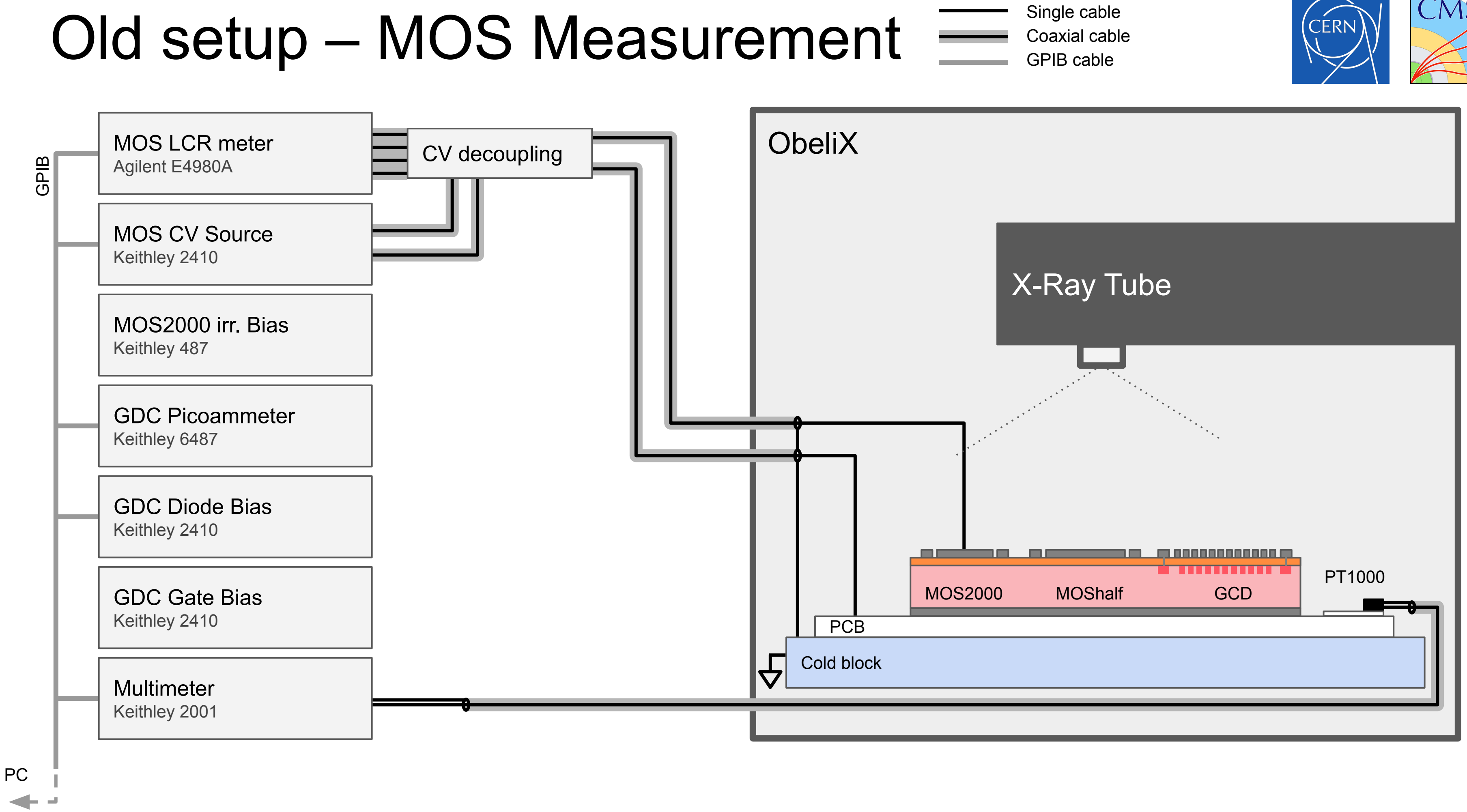




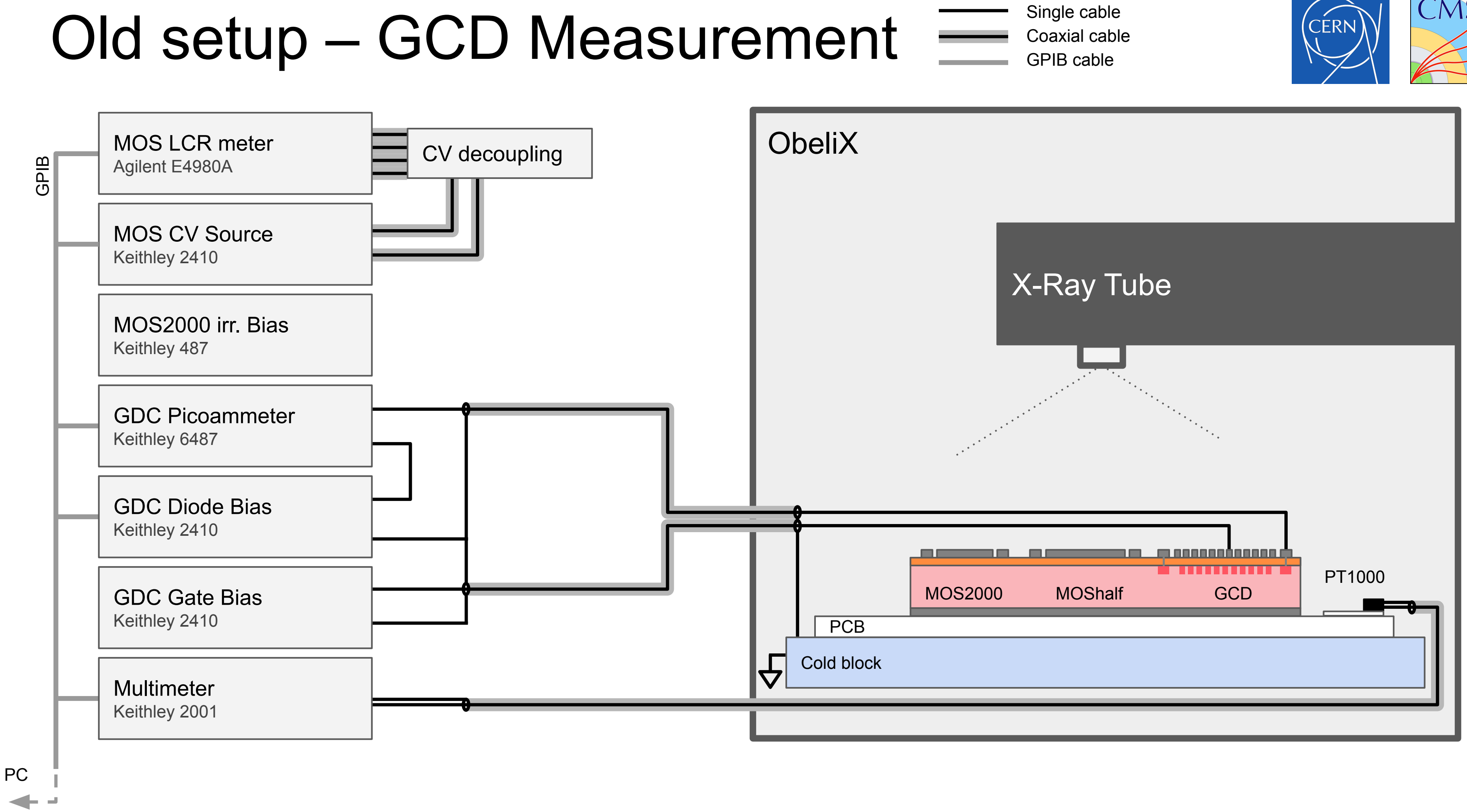
Old setup – During Irradiation



Old setup – MOS Measurement

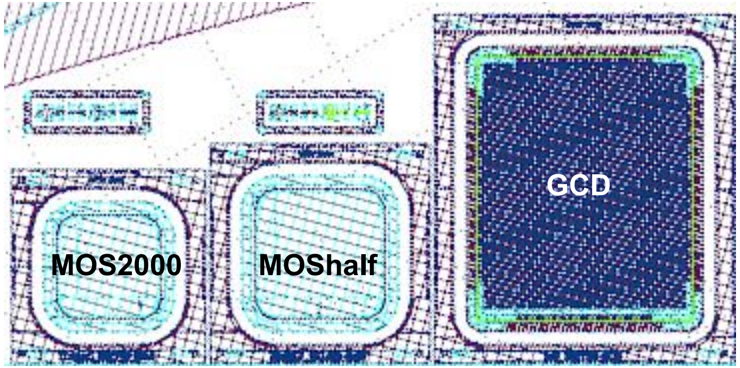


Old setup – GCD Measurement



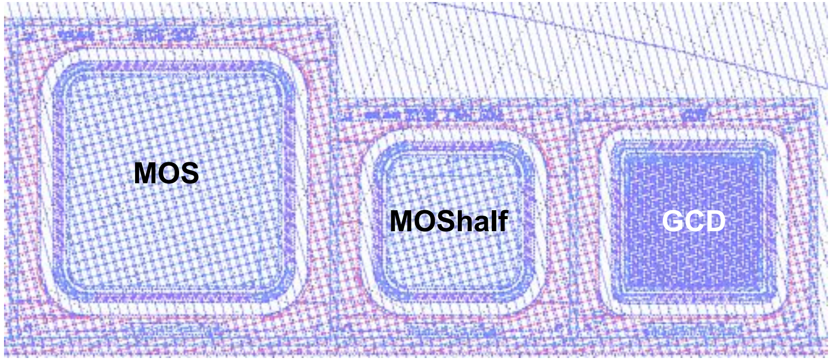
MOS/GCD gate surface / MOS biasing

8-inch



MOS2000 8-inch: 3.86 mm^2
MOShalf 8-inch: 6.11 mm^2
GCD gate 8-inch: 9.61 mm^2

6-inch HGCal

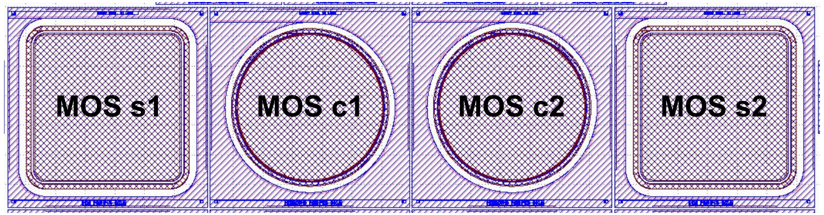


MOS 6-inch: 15.86 mm^2
MOShalf 6-inch: 6.11 mm^2
GCD gate 6-inch: 2.85 mm^2

MOS biasing configuration during irradiation:
MOShalf: floating
MOS2000/MOS: biased

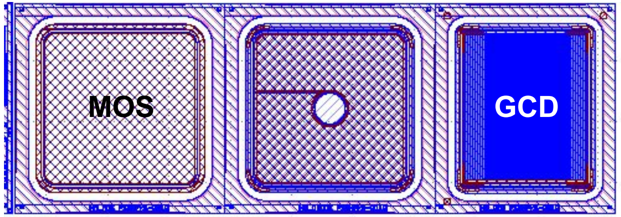
MOS/GCD gate surface / MOS biasing

6-inch tracker
(E halfmoon)



MOS square: 24.86 mm^2
MOS circle: 19.63 mm^2

6-inch tracker
(SE halfmoon)

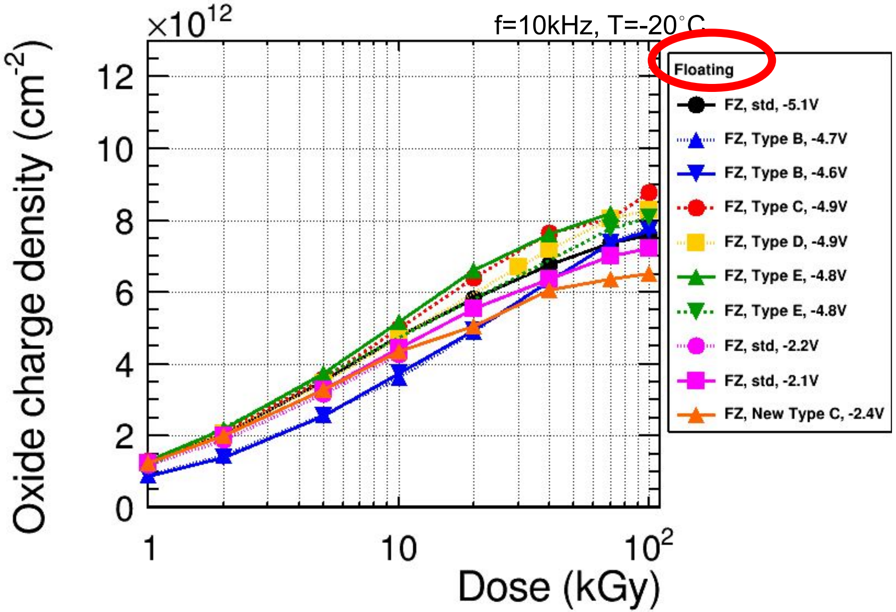


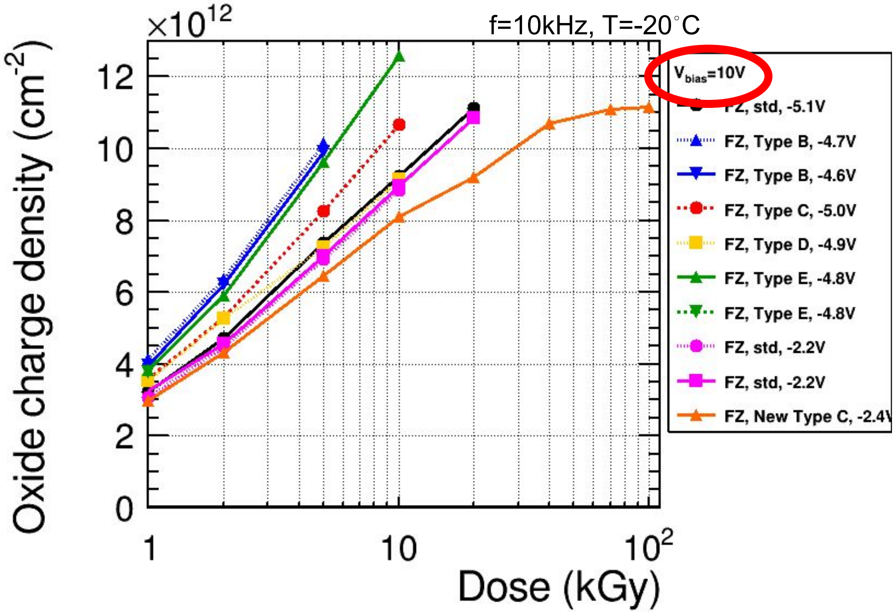
MOS square: 24.86 mm^2
GCD Gate: 9.60 mm^2

MOS biasing configuration during irradiation

E halfmoon		SE halfmoon	
MOSs1	Not used	MOS	biased
MOSc1	floating	GCD	—
MOSc2	biased		
MOSs2	floating		

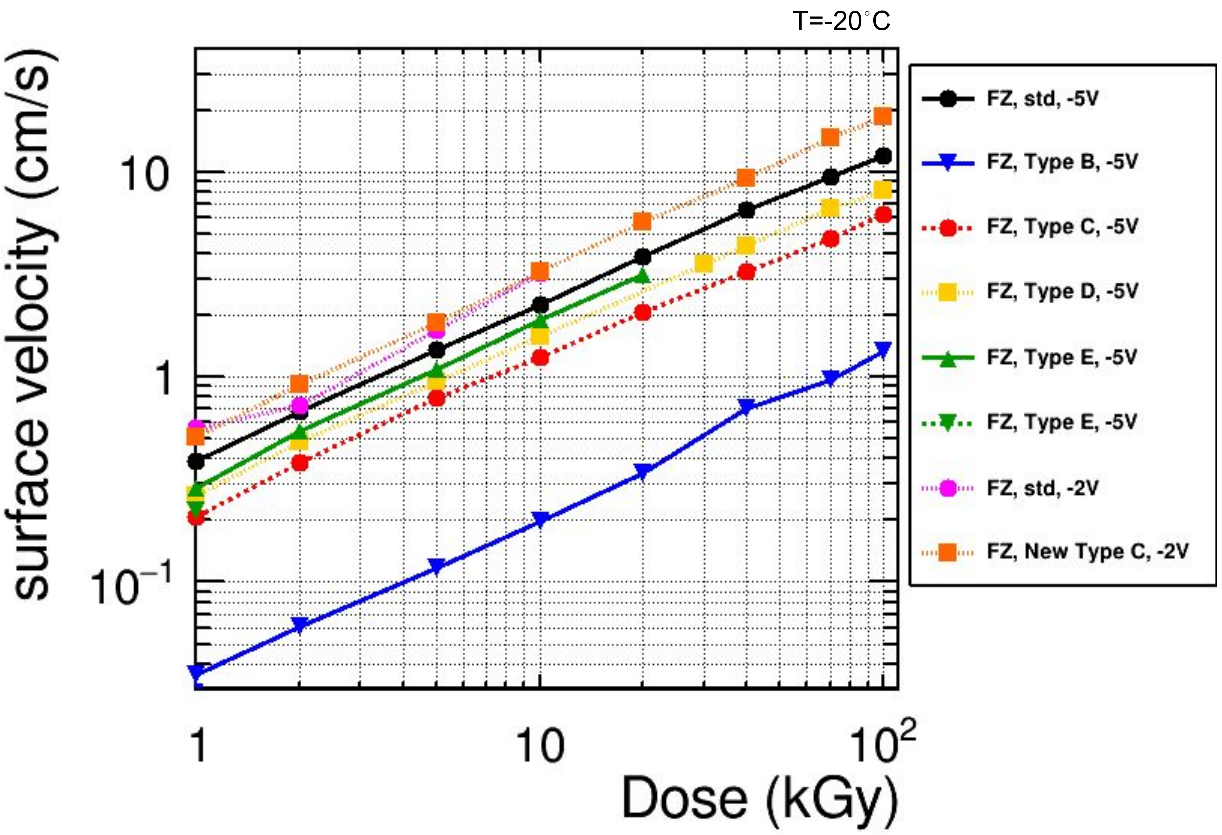
8-inch, FZ, -5V, -2V, all oxide types (MOS)





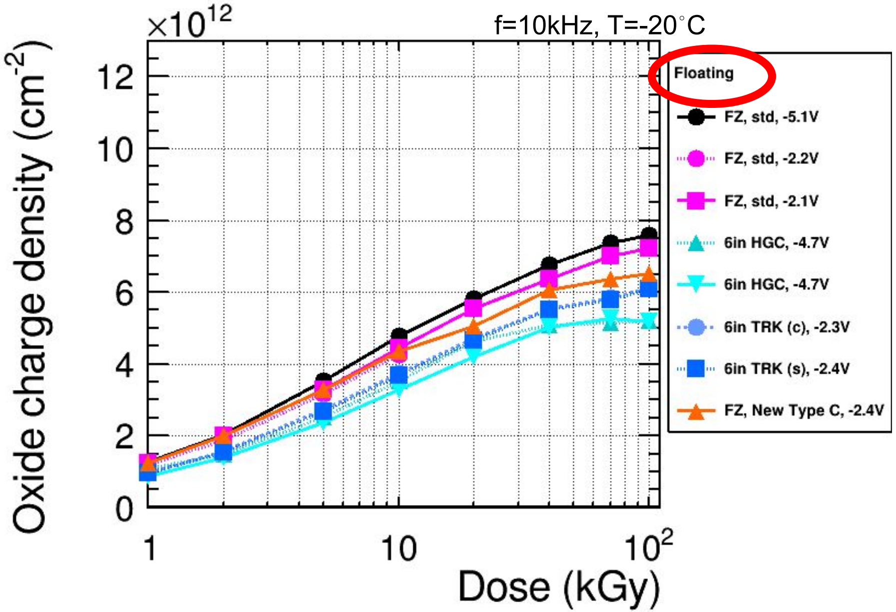
- Type B best at lowest dose steps for floating sample
- New Type C best at high dose steps for floating sample
- New Type C overall best under bias

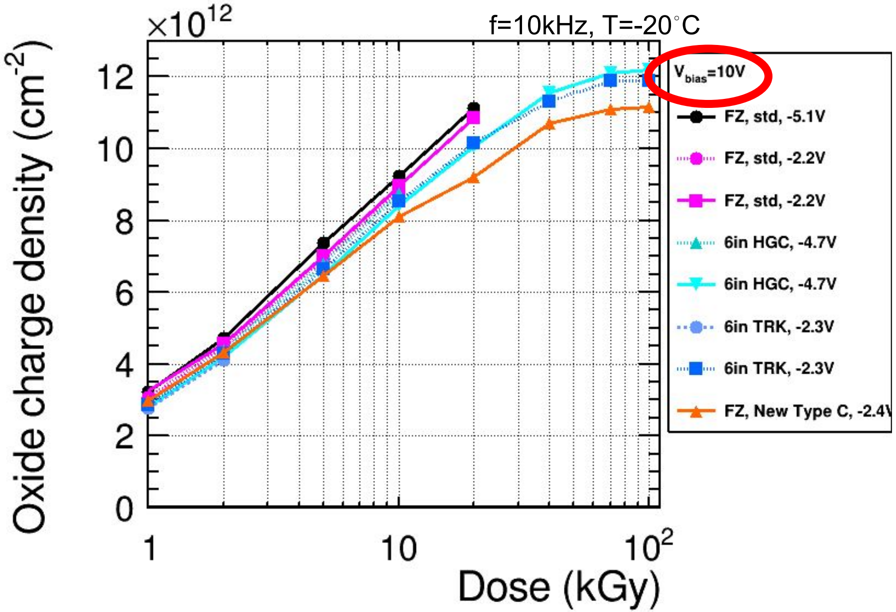
8-inch FZ, -5V, -2V, all oxide types (GCD)



- New Type C -2V and standard -2V have higher surface velocity than all -5V oxide variants

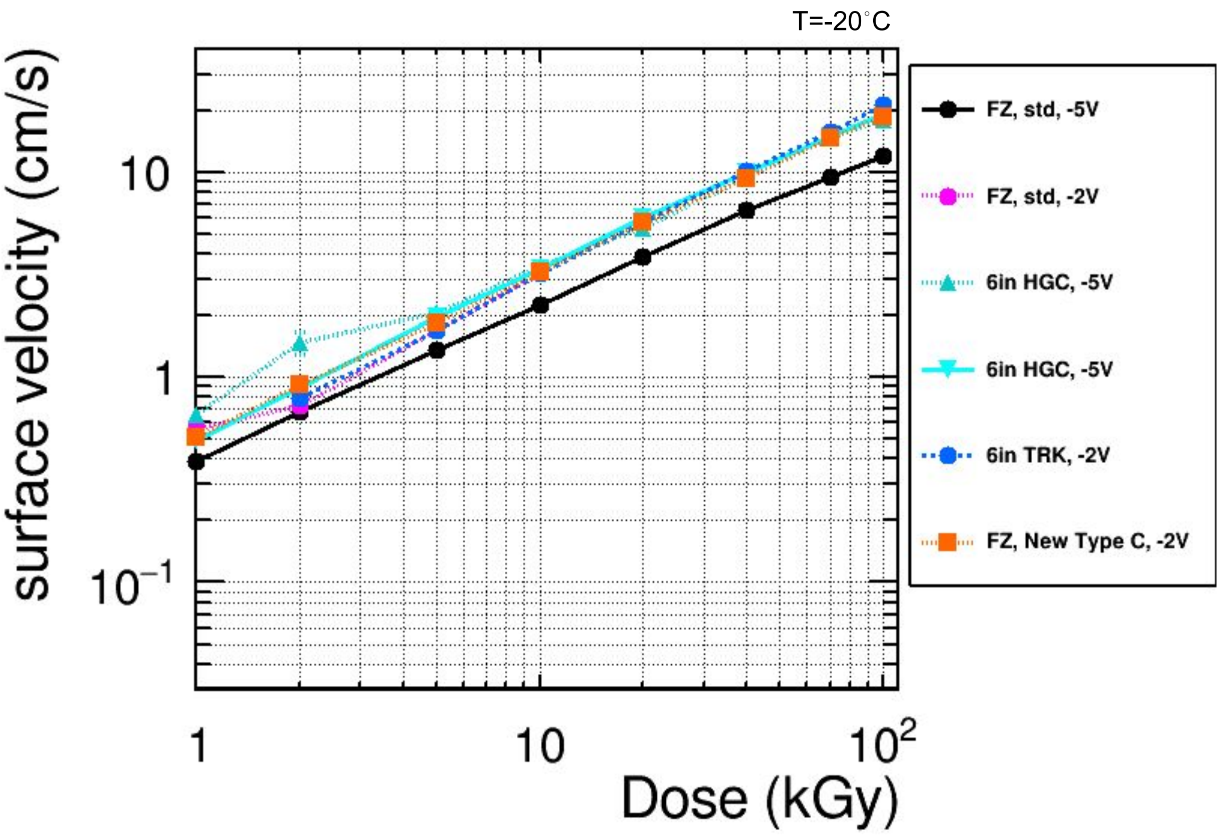
8-inch vs. 6-inch samples (selection, MOS)





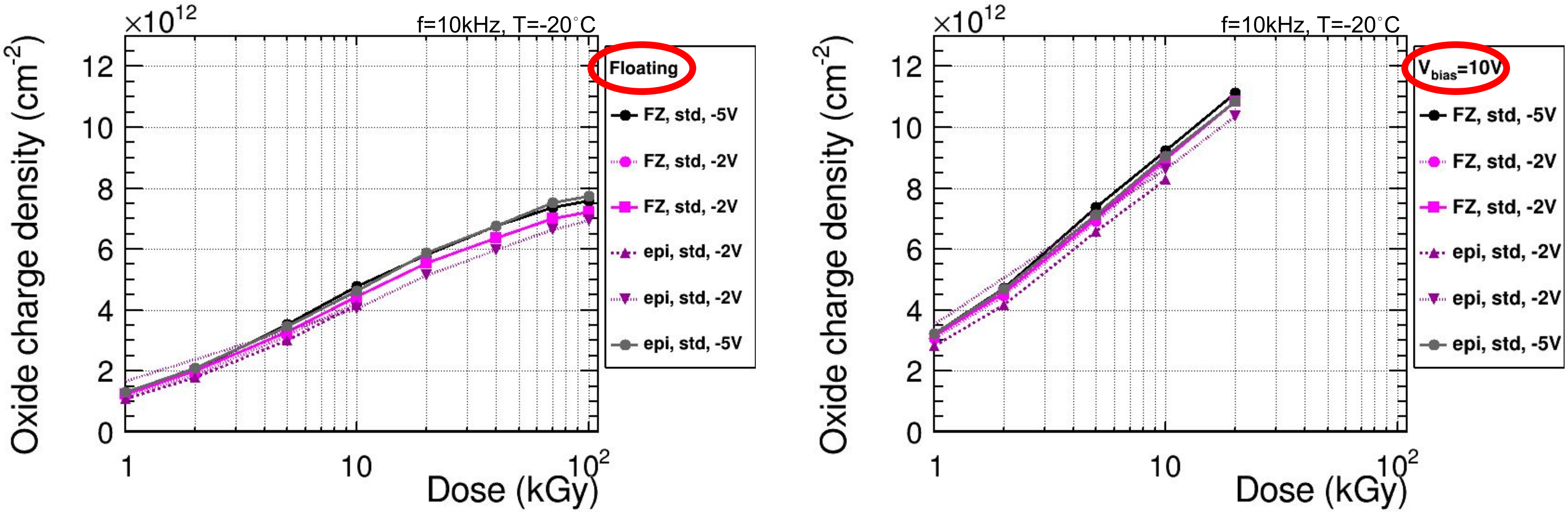
- **New:** 6-inch tracker sample newly added (including circular (c) and square (s) MOS)
- 6-inch HGCal sample better than 6-inch tracker sample for floating sample
- 6-inch tracker samples and 6-inch HGCal samples very similar under bias
- Both 6-inch samples and the New Type C sample saturate
- New Type C better than both 6-inch samples under bias

8-inch vs. 6-inch samples (selection, GCD)



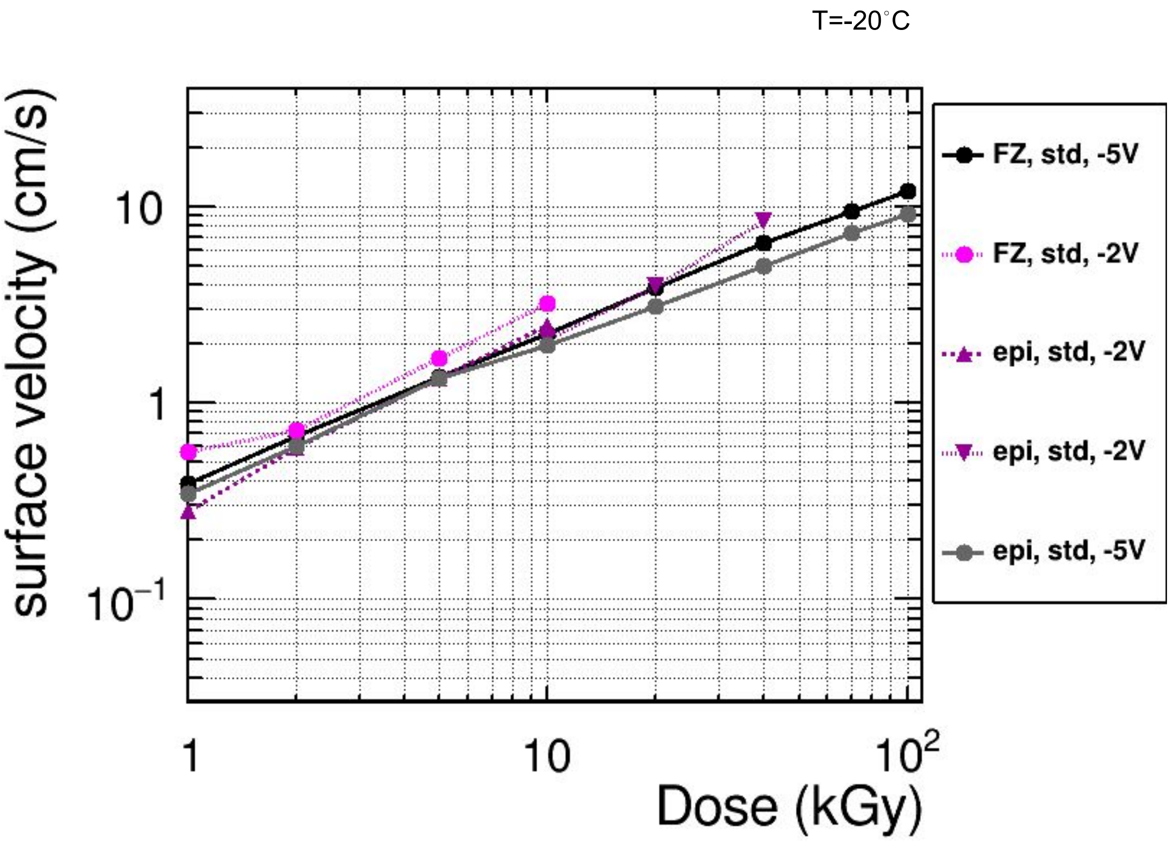
- 6-inch samples (tracker and HGCal) and HGCal -2V samples (masking and thermal condition) are very similar in terms of surface velocity

FZ vs epi and V_{fb}=-2V vs V_{fb}=-5V (MOS)



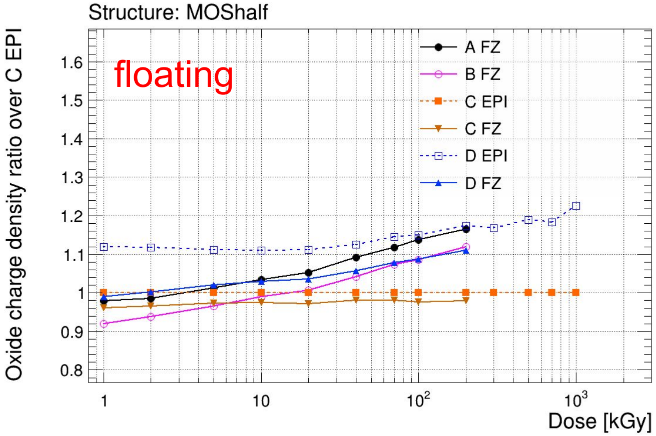
- Slightly lower oxide charge in -2V samples, for both FZ and EPI
- True in particular for EPI

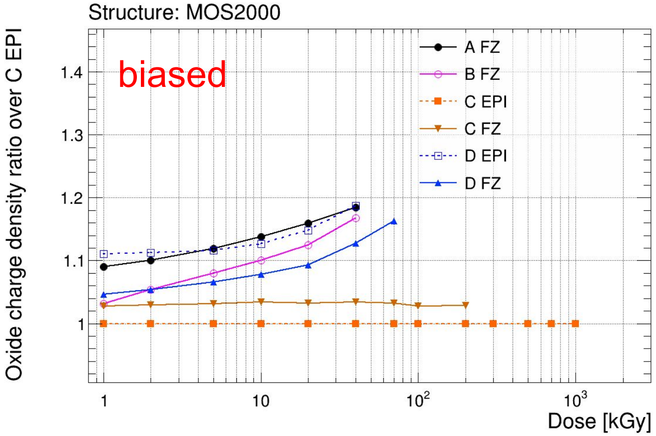
FZ vs epi and V_{fb}=-2V vs V_{fb}=-5V (GCD)



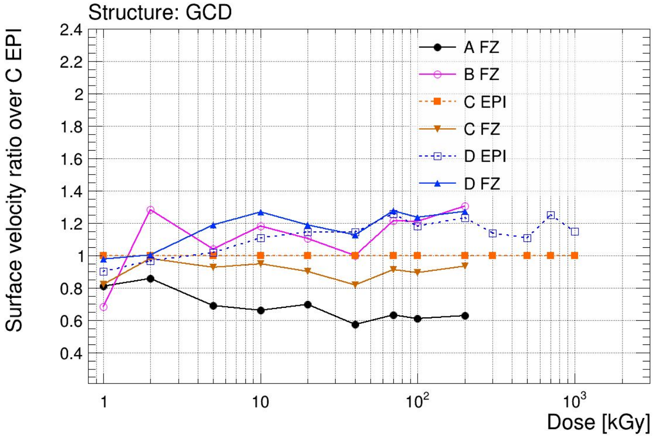
- Samples of -2V flatband voltage show slightly larger surface velocity than **-5V flat band voltage** samples
- True for both FZ and epitaxial samples
- Epitaxial samples have slightly lower surface velocity than FZ samples

Ratios of results for new oxide types

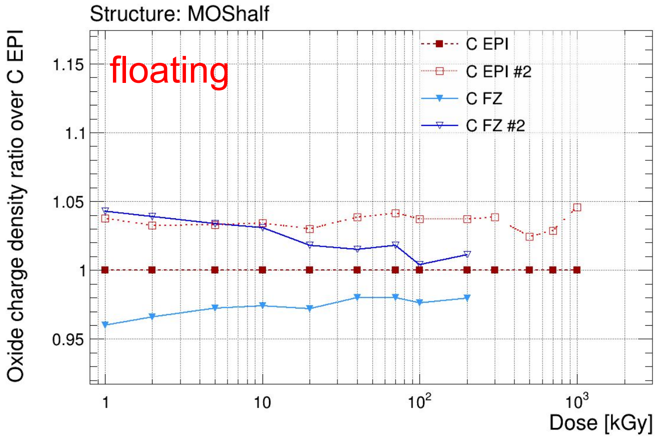


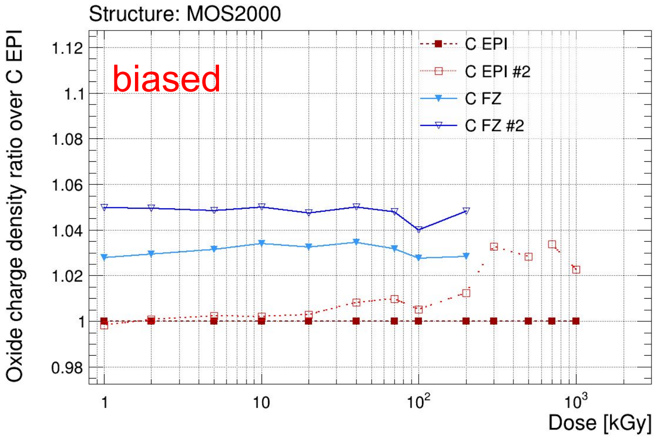


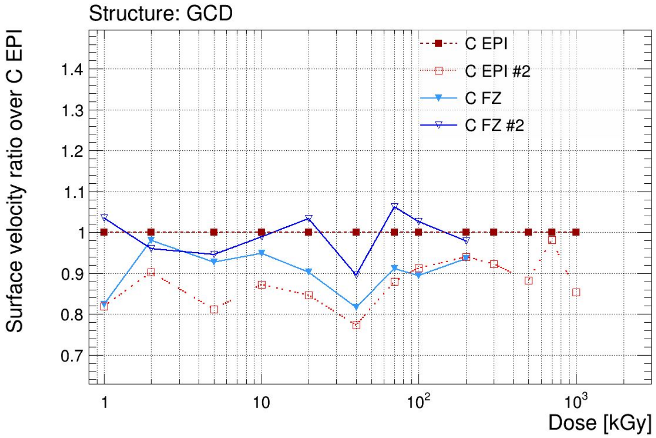
- Clear trends observed in the case of the MOS measurements
- Large variations in the case of the GCD, which however is more susceptible to noise and temperature instabilities



Reproducibility with new type C

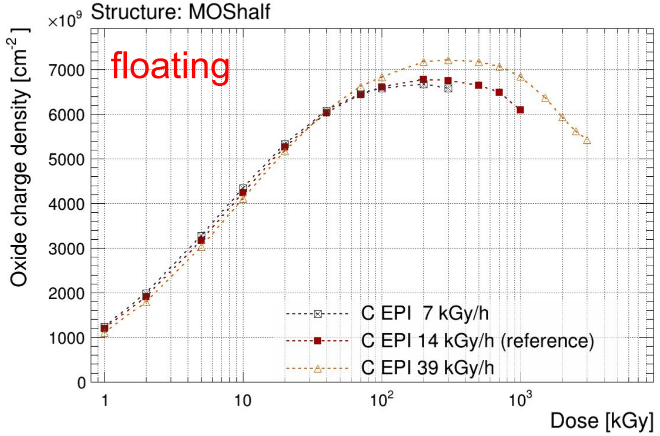


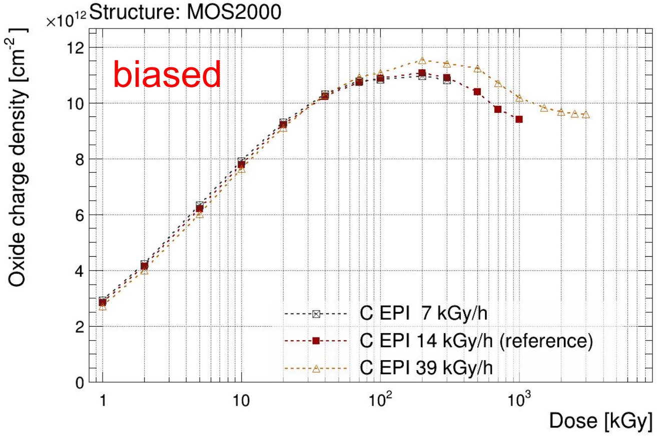




- Reproducibility of MOS measurements across different campaigns within ~5%
- Large variations in the case of the GCD, which is more susceptible to noise and temperature instabilities

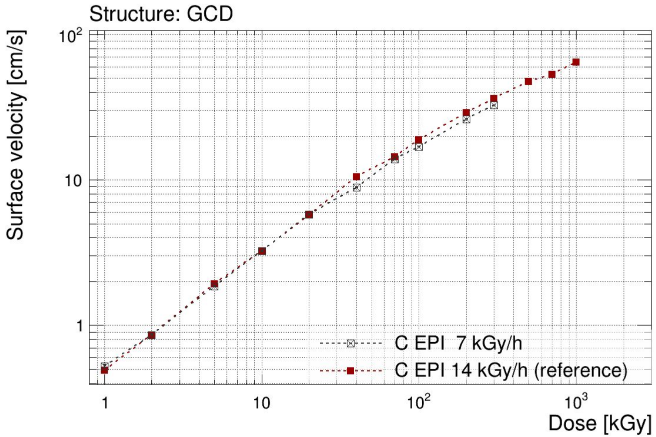
Dose rate dependence with new type C



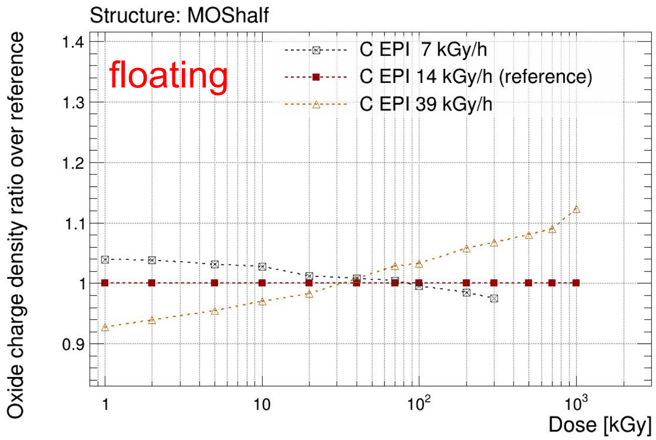


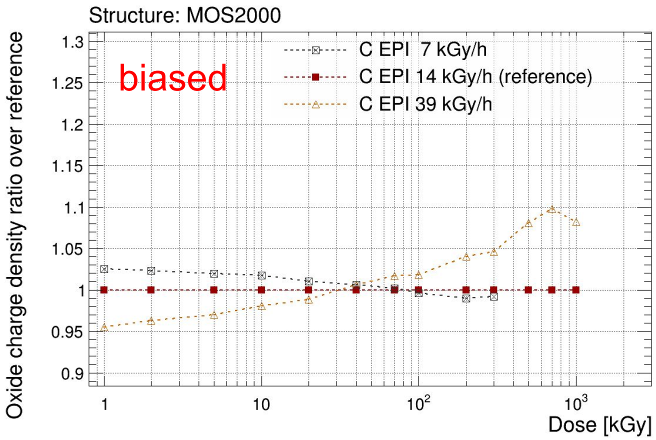
- Similar trend observed for floating and biased MOS structures
- Saturation of biased MOS at ~3 MGy

- GCD not measured at highest dose (reduced X-ray beam area)

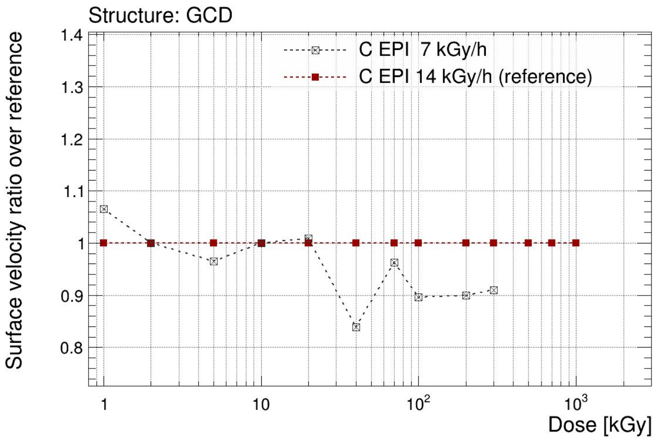


Dose rate depend. with new type C (ratios)

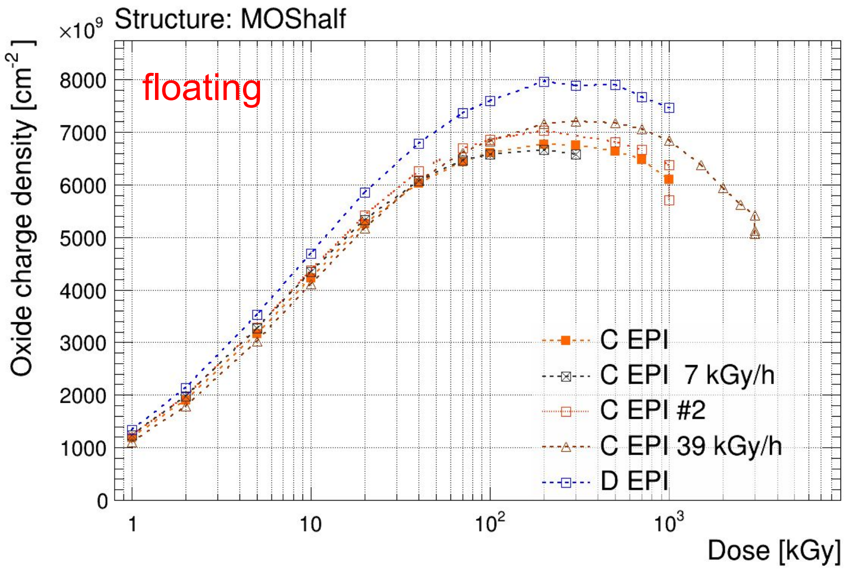


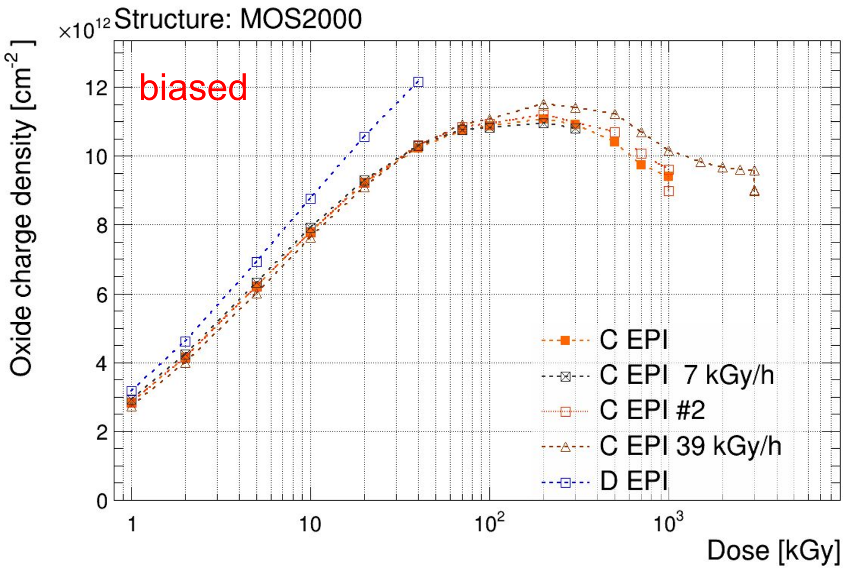


- Similar trend observed for floating and biased MOS structures
- GCD result not conclusive due to large fluctuations



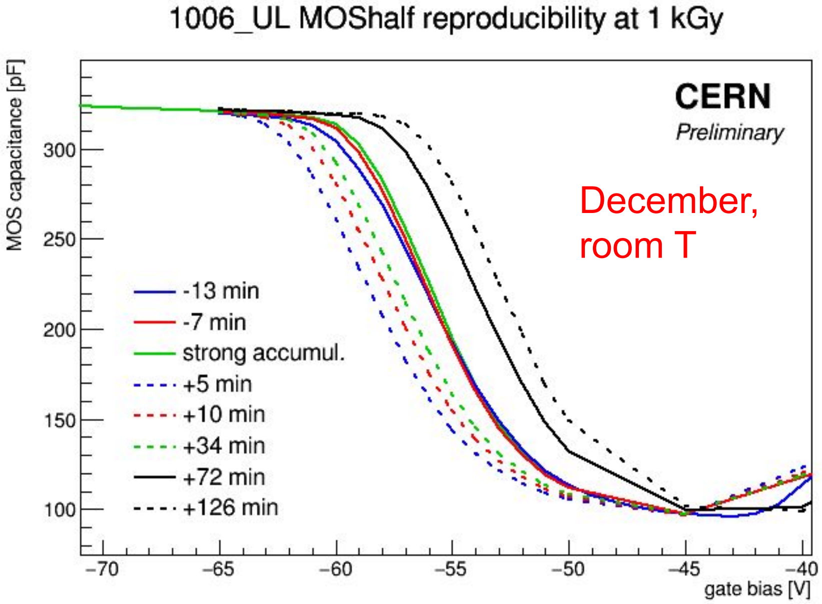
Annealing at -20 ºC

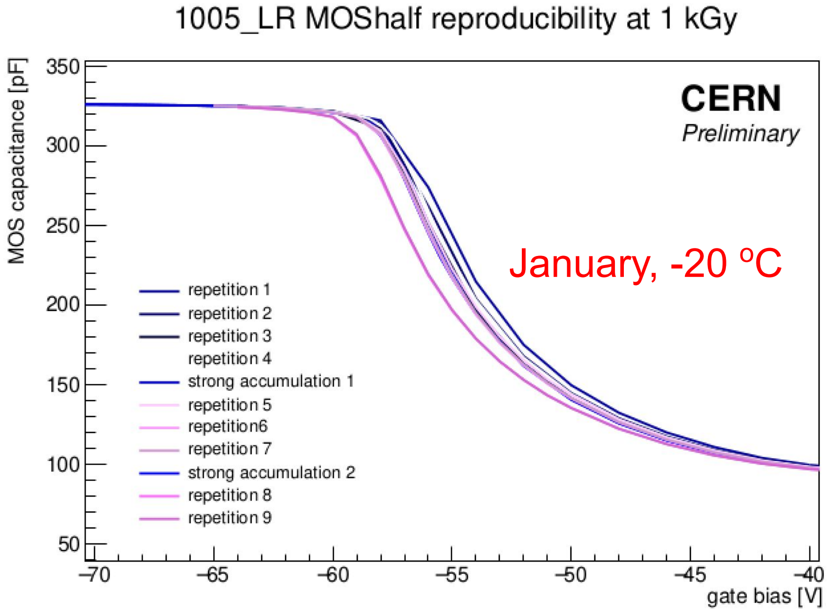




- Last second measurement at last dose step taken a few hours after the first one
- Significant decrease in accumulated oxide charge even at -20C

Reproducibility of MOS measurements





- Significant room-temperature annealing
- Charge injection in strong accumulation

- Good reproducibility of measurements
- Non-negligible annealing only observed on long time scales (e.g. overnight), even at lower temperatures (-28 °C)