Fast Timing and 4D Tracking with UFSD Detectors

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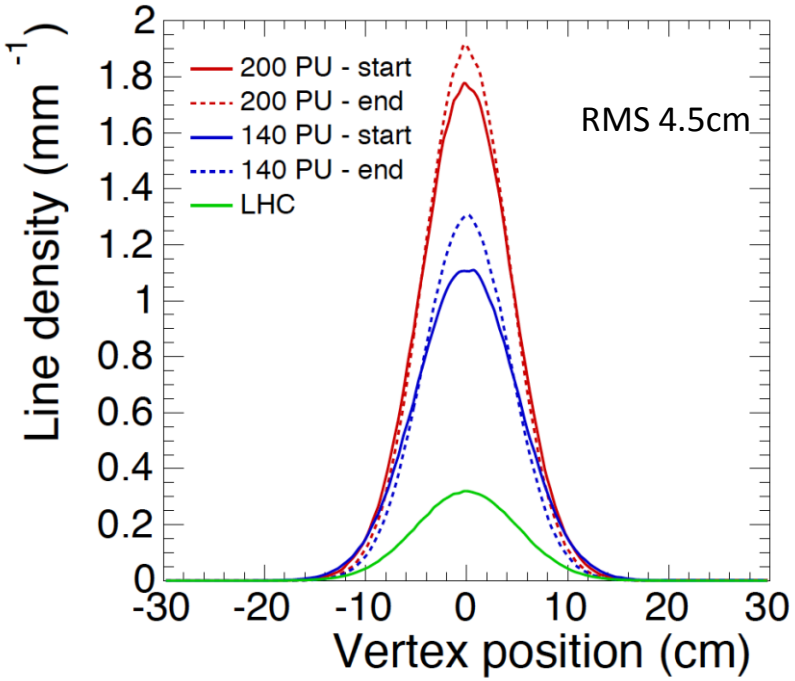
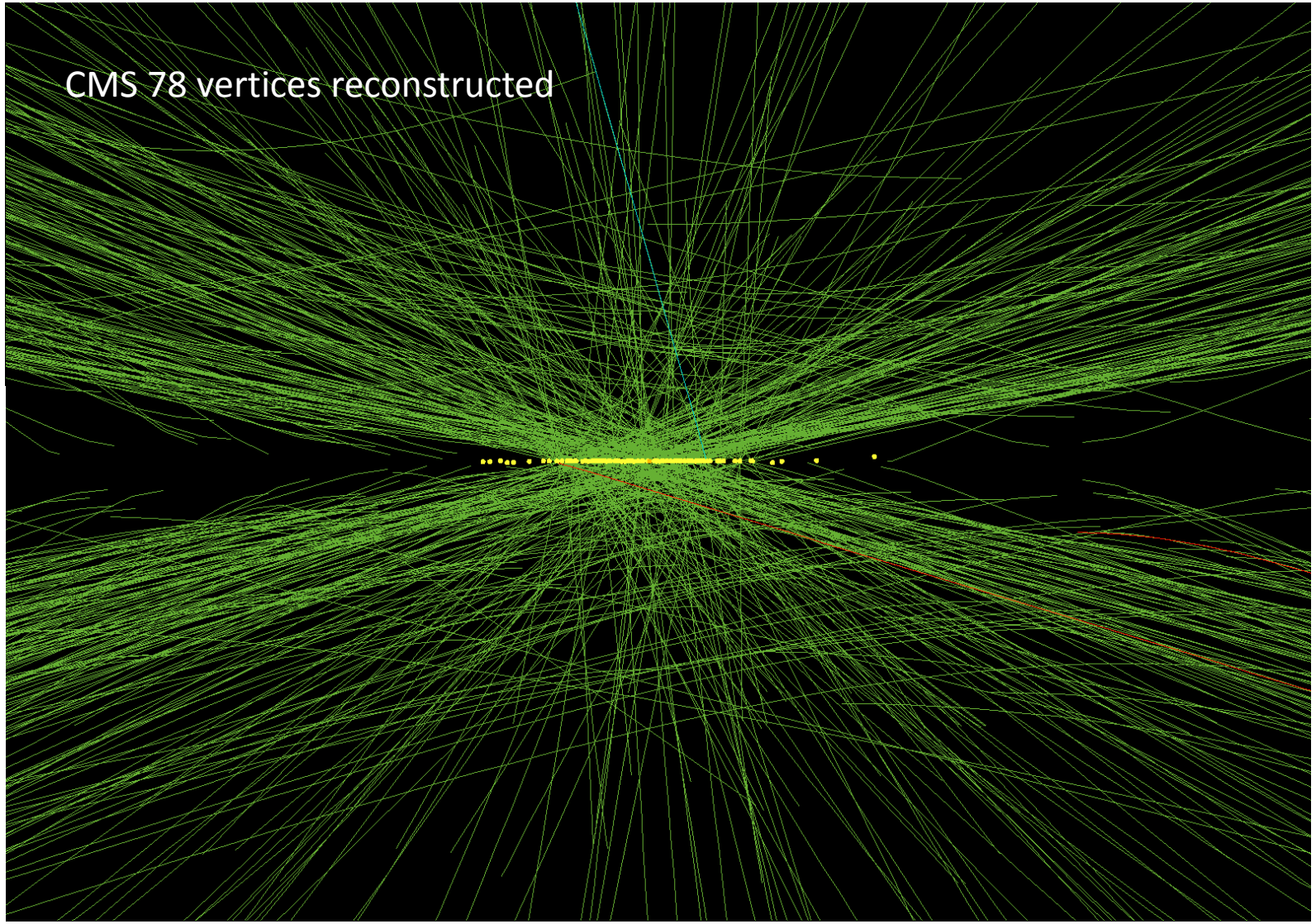
Outline

- 4D Tracking in HEP
- Timing in Silicon Detectors
- The UFSD Project
  - Front End Electronics
  - Detectors
  - Timing Performance
  - Radiation Hardness
- The CMS Endcap Timing Layer in HL-LHC
- Conclusions

Timing in High Luminosity HEP

The coming challenge:
High Luminosity = High Pile Up





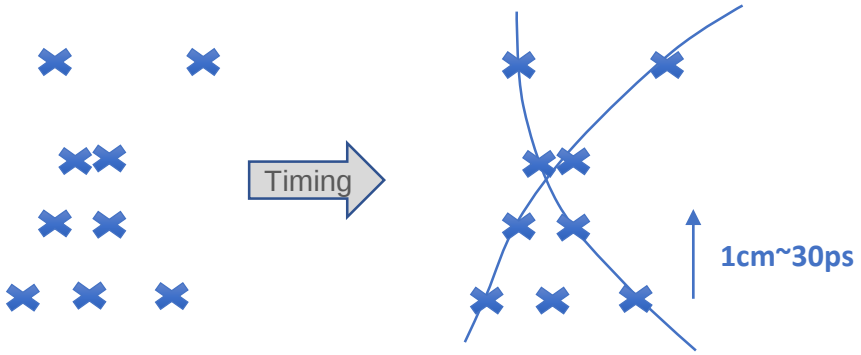
How to make use the timing information

1. Improve reconstruction by adding time information to each track point

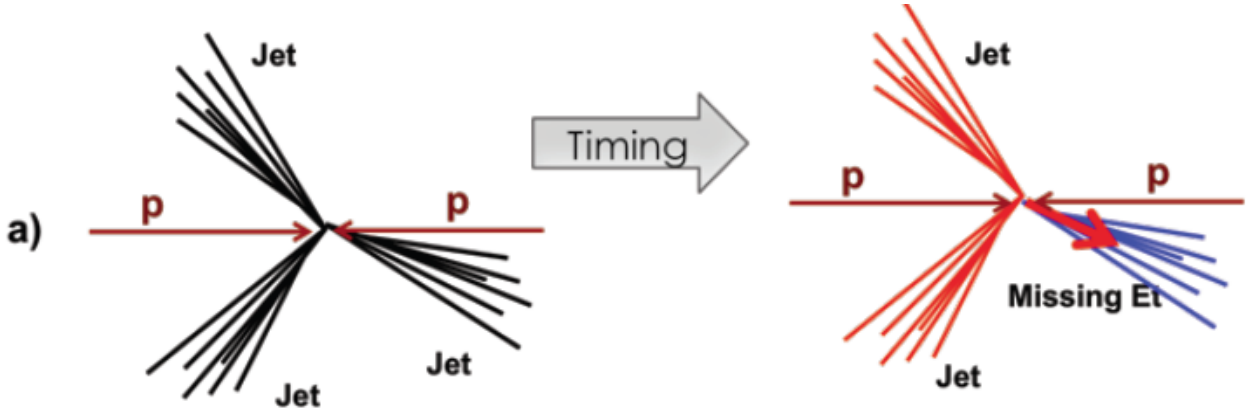
2. Determine the correct vertex track assignment

Correct **event reconstruction**

Correct **trigger assignment**



associate single hit timing to track reconstruction



3-Jet event?

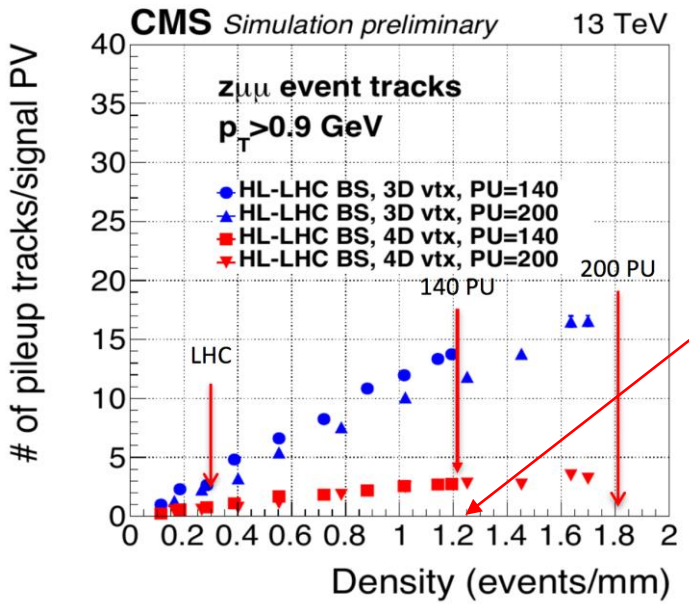
2-Jet and Missing Et event

How to make use the timing information

IN HL-LHC ($2x10^{35}cm^{-2}s^{-1}$)

- 150-200 vertices / beam crossing
- line density up to 1.8-2mm^{-1}
- $<t_{vertex}>_{RMS}$= ~**200ps**
- a vertex separation resolution of 250-300µm ➔ **10-15%** overlapping 2 events

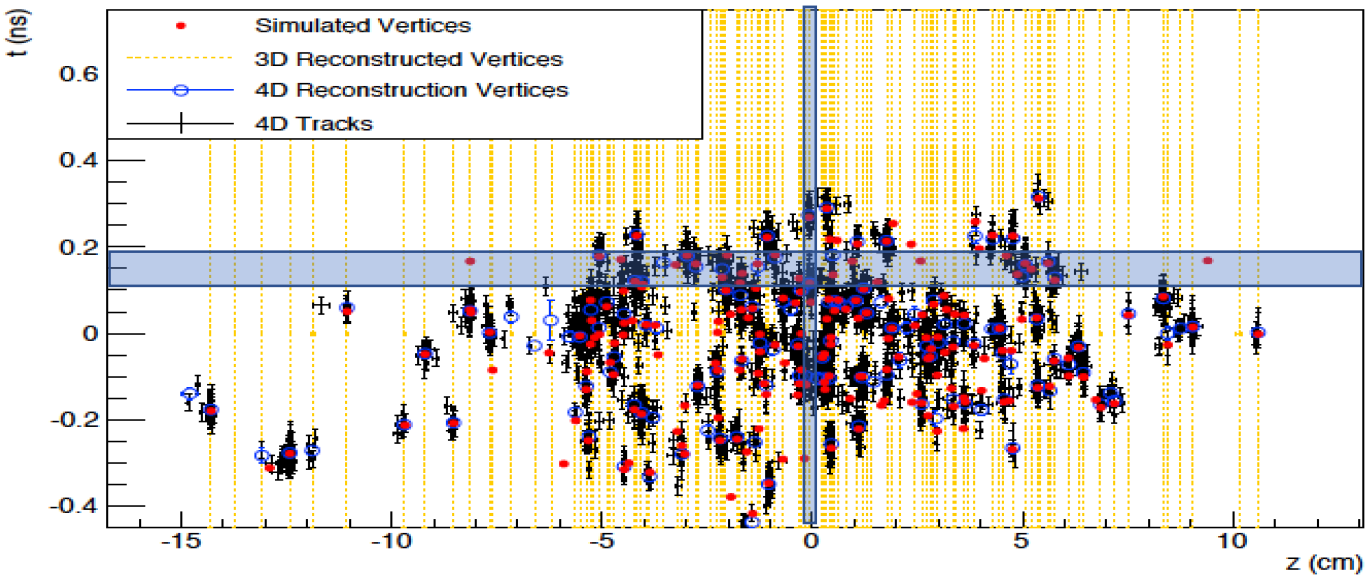
➡ Event loss = Luminosity loss



4D = add **30ps** timing information

~x5 pileup (@ PU=200) reduction in terms of associated tracks

on Linear Colliders 2017



With 30ps time resolution, instances of vertex merging are reduced from 15% in space to 1% in space-time

⬇

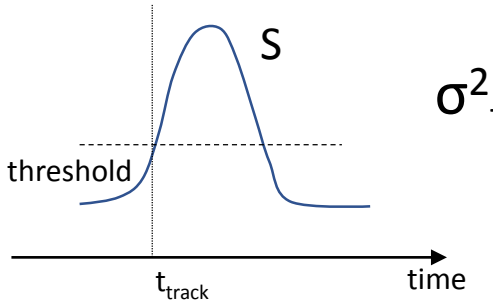
Mip **T**iming **L**ayer proposal at CMS to consolidate particle flow performance at 140PU events, and extend it to 200PU (and similar proposal in ATLAS)

4D Tracking

4D Tracking in HEP requires:

- High spatial resolution ⟶ Silicon Detectors
- High time resolution (~10ps)
- Fast FE electronics
- High radiation tolerance
- High fill factor (~1)
- High density ⟶ low power

Silicon Detector Time Resolution

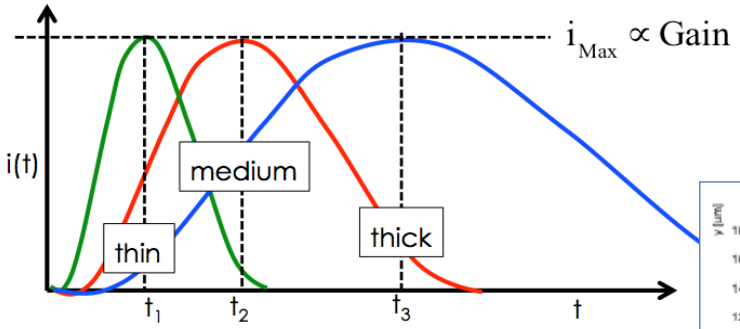


$$\sigma^2_t = \sigma^2_{Jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{Landau\ Noise} + \sigma^2_{Distortion} + \sigma^2_{TDC}$$

Negligible
Optimize FE electronics

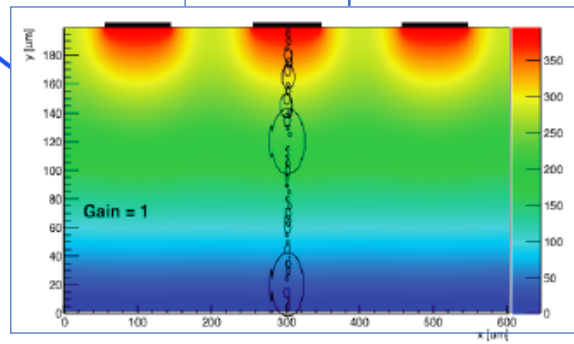
Negligible
Optimize RO electronics

$\sigma_{Jitter} \approx N/(dV/dt) \approx t_{rise}/(S/N)$
➔needs **Gain** to increase S/N
➔needs **thin detector** to decrease t_{rise}



NB: signal amplitude DOES NOT depend on detector thickness

$I_{Ramo} \approx q\ v_{drift}\ E_w$
Requires **uniform v_{drift} and E_w**
🡻
parallel plate geometry
strip implant ~ pitch

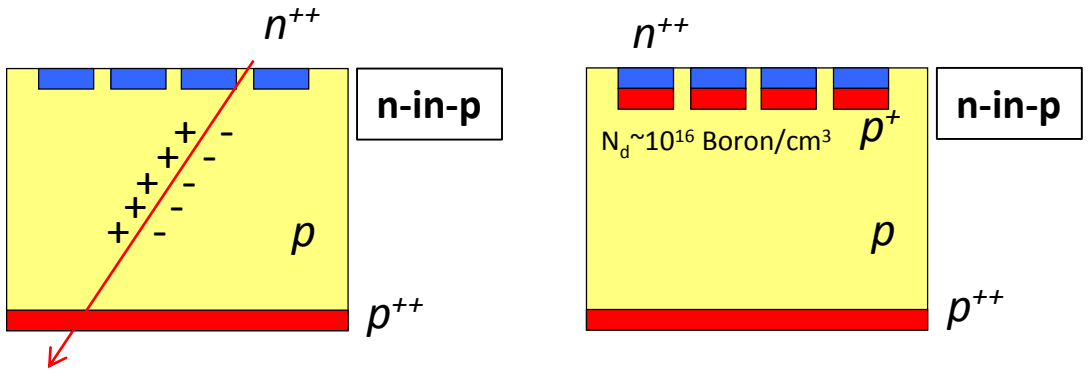


Decreases with detector thickness
Intrinsic Limit $\sigma_{Landau\ Noise} \approx 20ps$

Ultra Fast Silicon Detectors

use **Low Gain Avalanche Detectors layout** (Gain ~5-20 in p^+/n^{++} junction with E~300kV/cm) and optimize design in order to

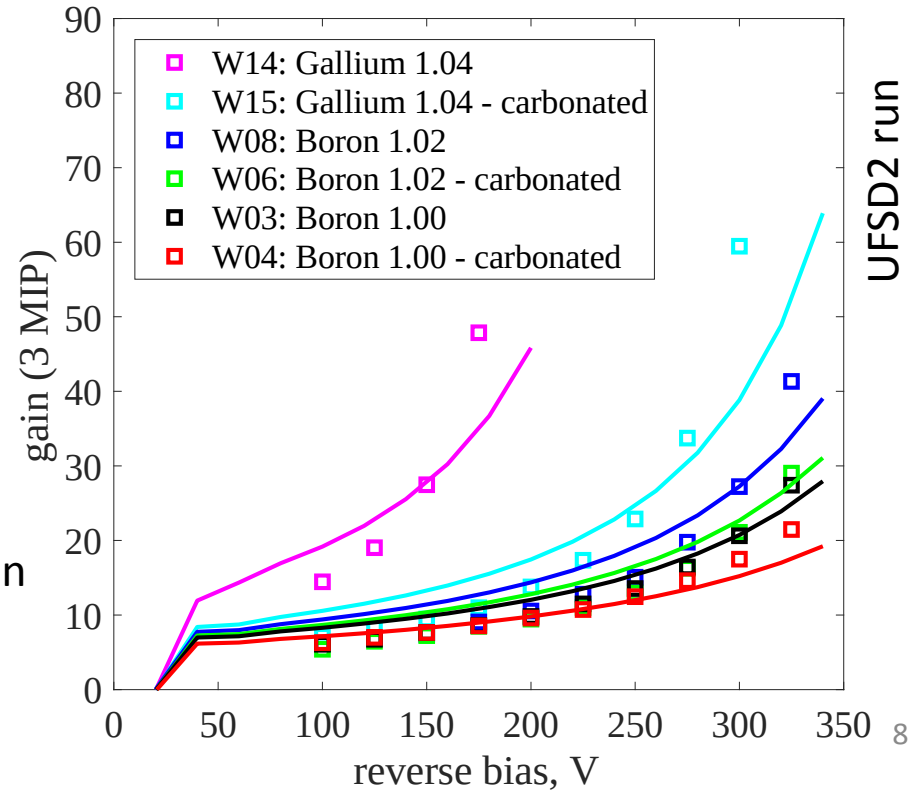
- optimize geometry for uniform E and v_{drift}
- optimize radiation hardness
- optimize doping profile for optimal gain
- optimize thickness, go to thin detectors (~50µm) to have small signal t_{rise}



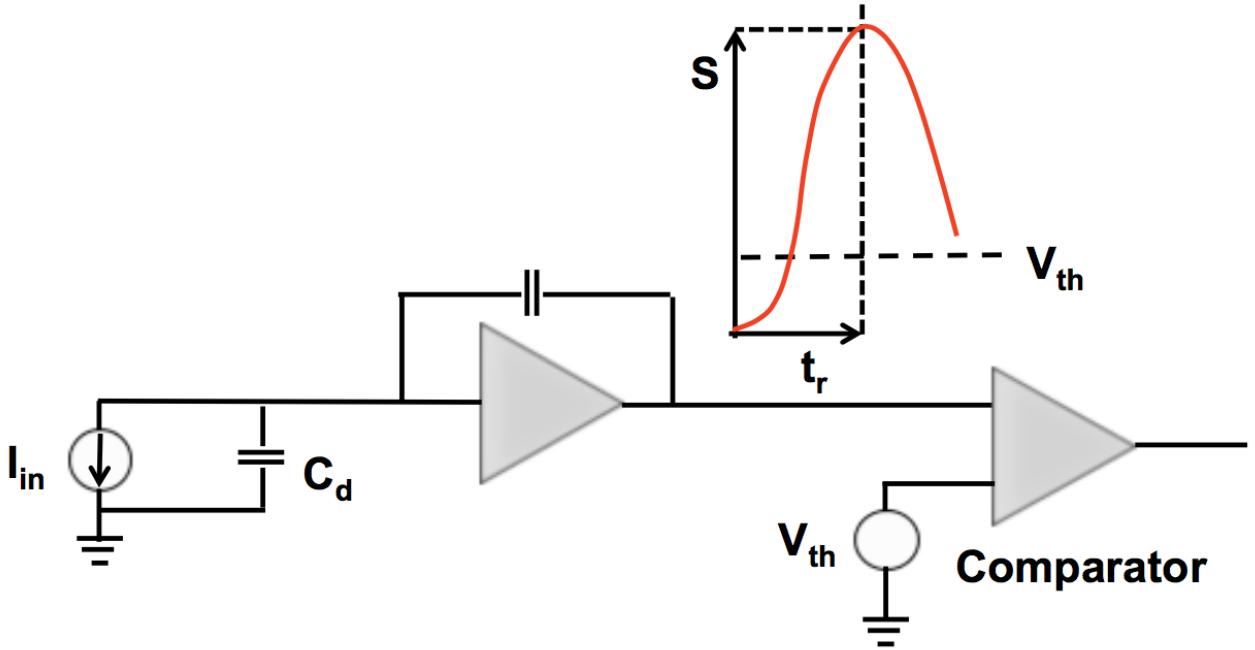
Traditional Si detectors **LGAD**

NB: Gain **very sensitive** to doping concentration (few %)

Excellent agreement with TCAD simulation (best fit van Overstraeten model)



Characteristics of FE Electronics

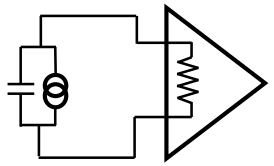


Sensor | **Pre-amplifier** | **Time measuring circuit**

Correct Time Walk by:

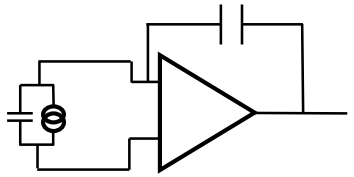
- Time over Threshold
- Constant Fraction Discriminator

Current Amplifier



- Fast slew rate
- Higher noise
- Sensitive to Landau bumps
- More power

Integrating Amplifier



- Slower slew rate
- Lower noise
- Signal smoothing
- Less power

Technology	CMOS 110 nm
Channels	8
Sensor capacitance	2-10 pF
Input dynamic range	3 fC – 60 fC
Analog gain	7 mV/fC
GBW	14 GHz
RMS noise (C=6pF)	800 µV
Discriminator output	2 – 14 ns
Power consumption	18 mW/ch
AVDD/DVDD	1.2 V/2.5 V

TOFFEE

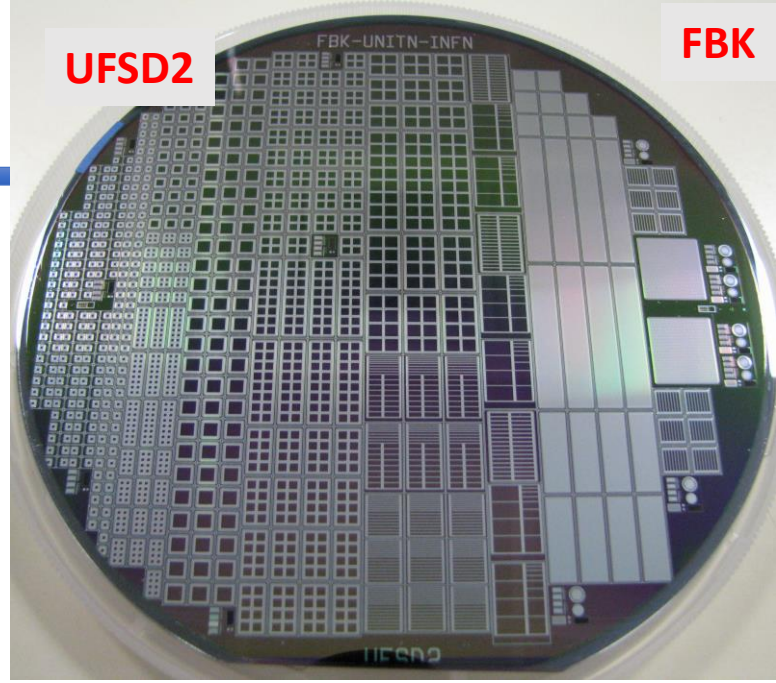
50ps time resolution achieved on test beam.

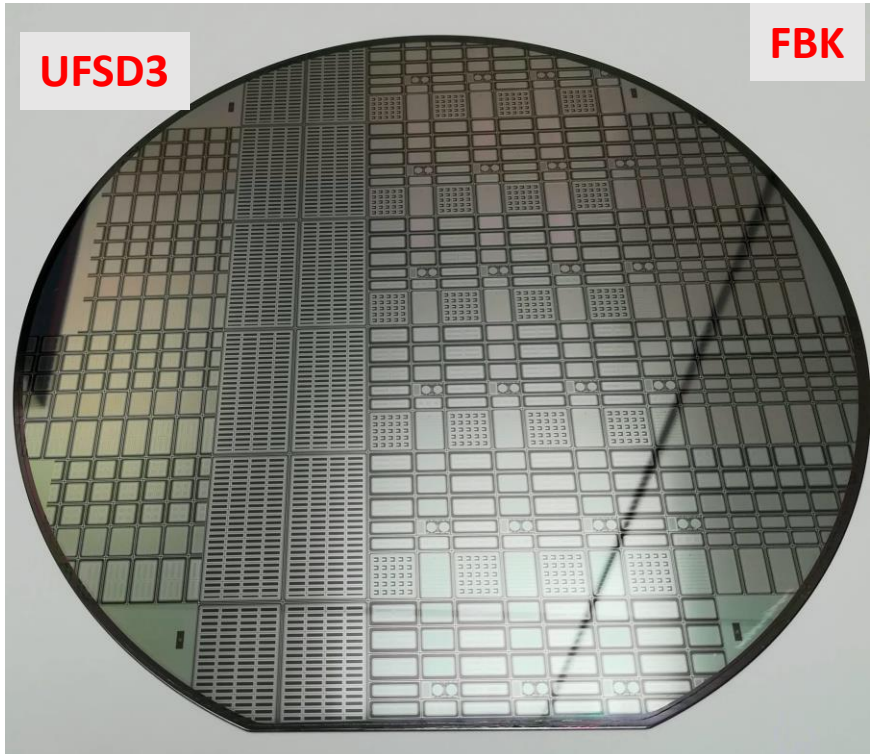
UFSD FBK Campaign

Close collaboration with FBK:

- **UFSD 1** FBK (300μm) various test structures to validate gain doping profiles, layout design, first irradiation tests — 2015
- **UFSD 2** FBK(55μm) focused to doping profiles validation, doping element validation for radiation hardness (B or Ga, and Carbon concetration splits) — 2017
- **UFSD 3** FBK (55μm), wafers for optimization of Carbon concentration fine splitting, layout design for fill factor optimization, pixel design and uniformity check for CMS ETL prototype — 2018

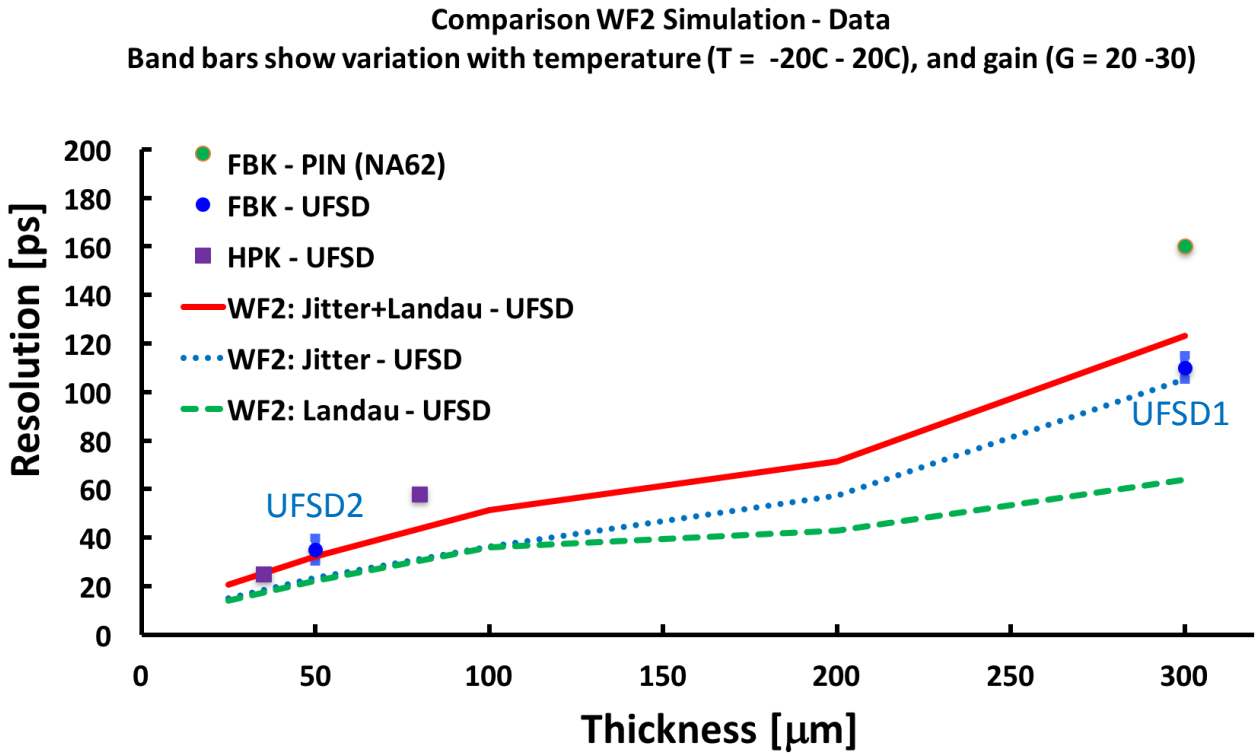
UFSD 2 and UFSD 3 parallel productions with **CNM** and **HPK**

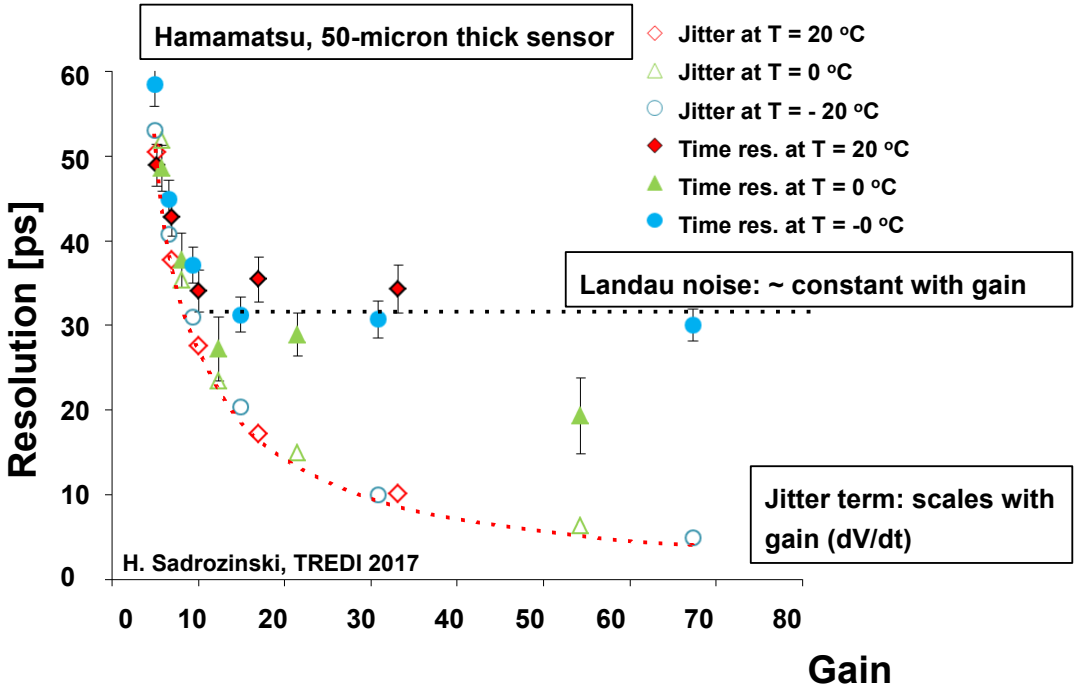




UFSD Time resolution

UFSD best resolution achieved so far **30ps**





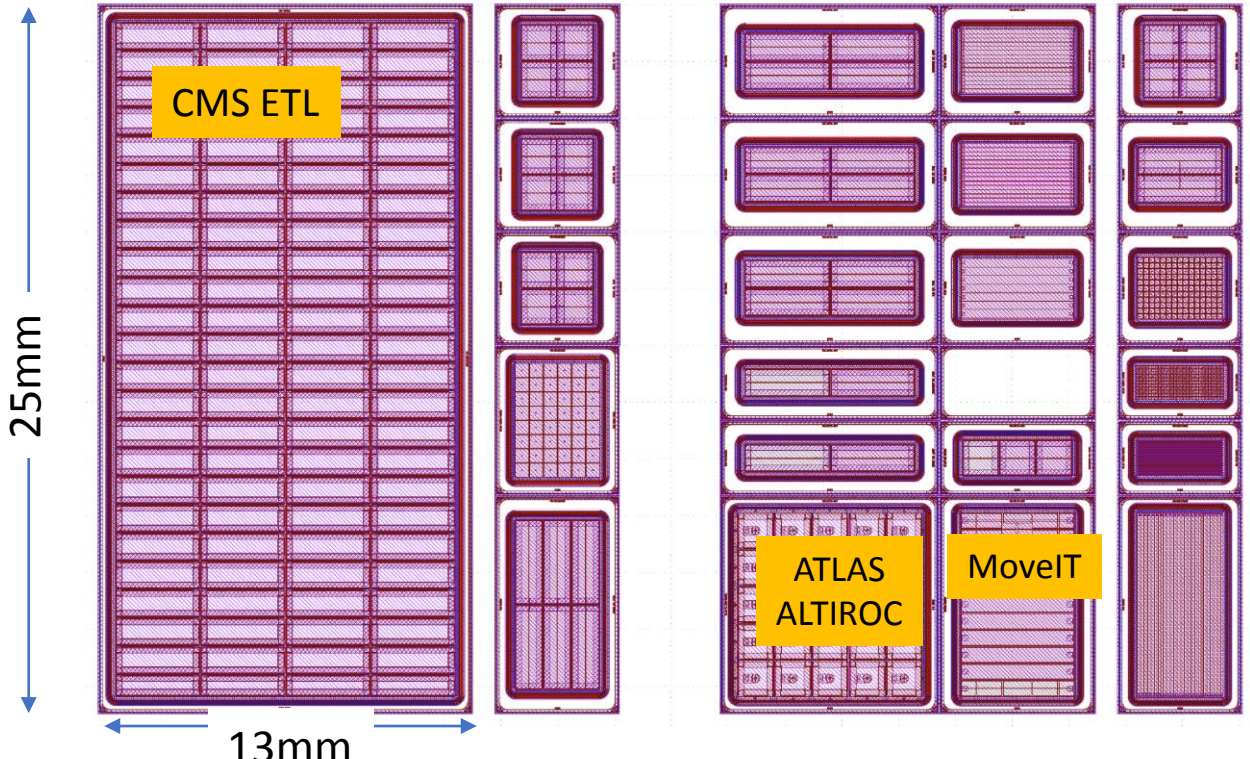
UFSD3 splits (stepper production)

Wafer #	Dose Pgain	Carbon	Diffusion
1	0.98		L
2	0.96		L
3	0.96	A	L
4	0.96	A	L
5	0.98	A	L
6	0.96	B	L
7	0.98	B	L
8	0.98	B	L
9	0.98	C	L
10	1.00	C	L
11	1.00	D	L
12	1.02		H
13	1.00		H
14	1.02	A	H
15	1.00	A	H
16	1.02	B	H
17	1.02	B	H
18	1.04	B	H
19	1.02	C	H
20	1.04	C	H

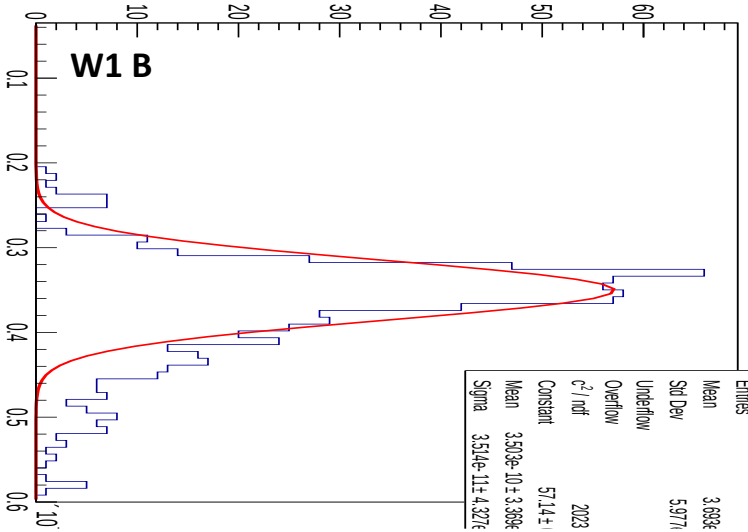
20 wafers with combinations of

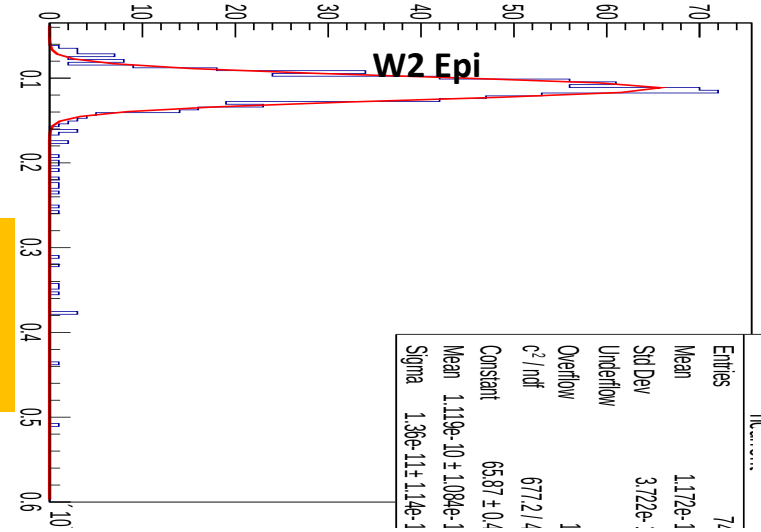
- Low and High gain layer diffusion profiles
- 5 splits of Carbon doses (A,B,C,D, no Carbon)
- 5 splits of gain layer doses
- Epi vs FZ

Wafers delivered in summer 2018



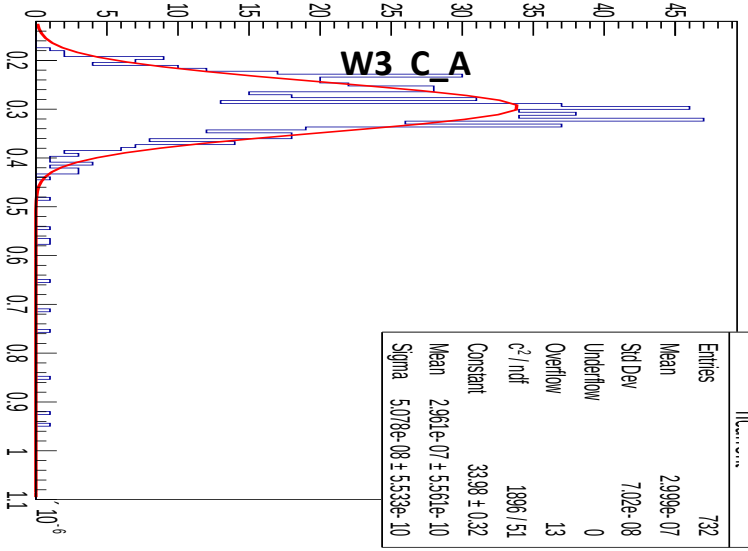
UFSD3 I-V and C-V curves, uniformity check

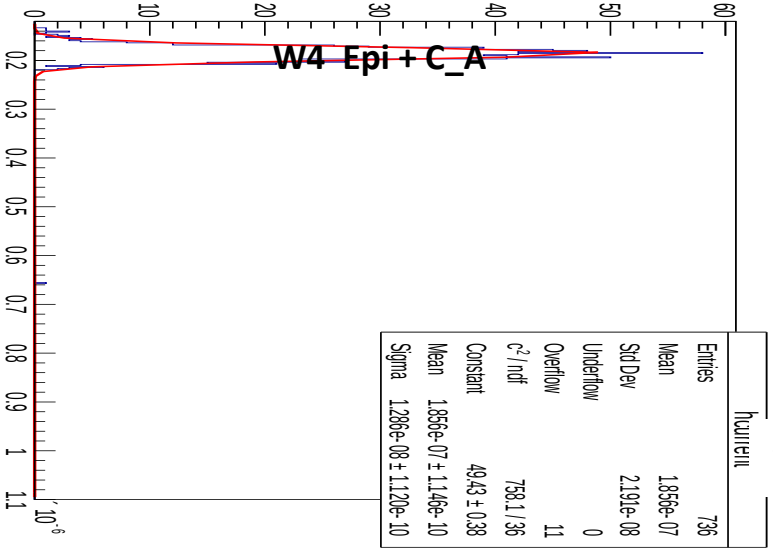




56 CMS ROC

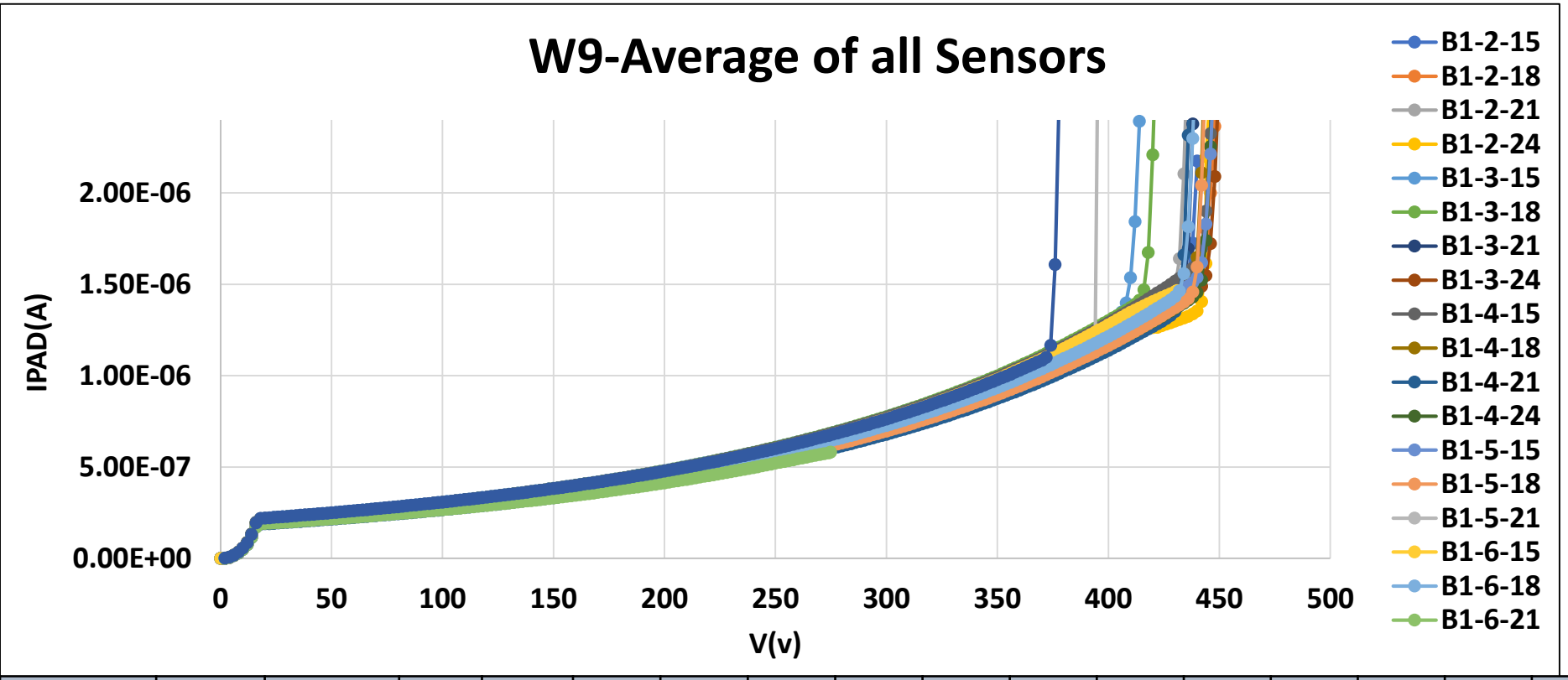
10 bad channels out of 5600 in 7 gain splits <0.2%





Same results On ALTIROC and MoveIT structures

UFSD3 MoveIT Strips (11strips, pitch 500μm)



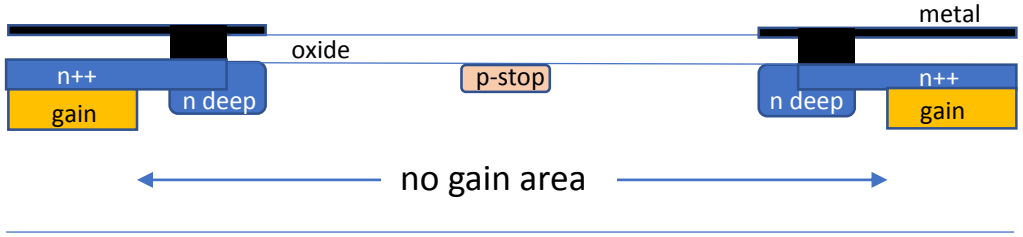
76 detectors tested from 16 Wafers (**836 strips**), 7 bad Channels

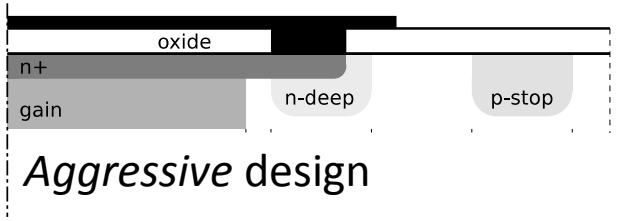
Breakdown voltages and CV curves as expected

Wafer/ Max Voltage	Dose Pgain	Carbon	c2-15	2-18	2-21	2-24	3-15	3-18	3-21	3-24	4-15	4-18	4-21	4-24	5-15	5-18	5-21	5-24	6-15	6-18	6-21	6-24
W1	1.00												300		335						300	
W4	0.98	A	415	410	430	288	411	389	412	411	360	348	400	364	382	405	408	385	376	410	409	275
W5	1.00	A		300		333	300	331	300	237		323			342					331		
W7	1.00	B	440	303	453	450	457	442	281	460	449	450	380	449	403	460	408	450	420	214	450	375
W9	1.00	C	455	458	450	465	430	445	454	460	460	460	450	459	460	460	430	445	430	454	290	390
W11	1.02	D					171	466			474			300					450			

UFSD3 fill factor test structures

Dedicated test structures to study and minimize interstrip dead region



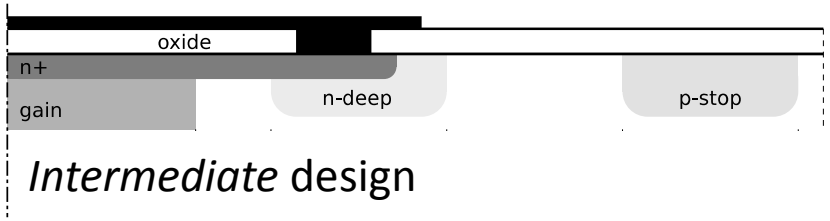


Aggressive design

Currently no gain area

CNM 70µm
HPK 100µm
FBK 70µm

30µm gap corresponds to 96% fill factor, target!
p-stop could be replaced by tranches, 1µm wide



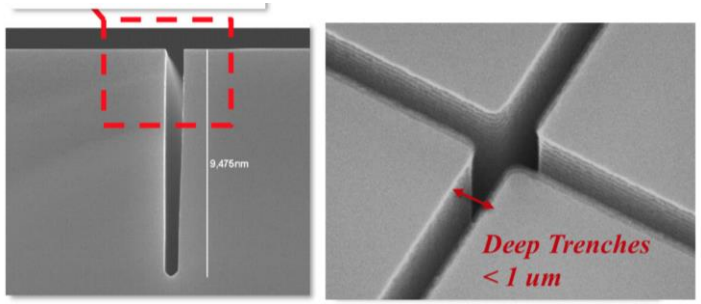
Intermediate design

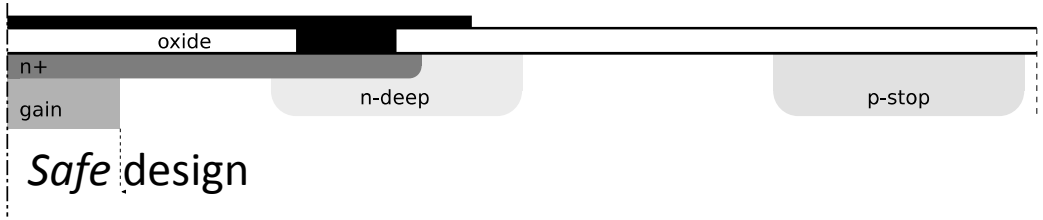
How to further increase fill factor

Trench isolation technology

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi

CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS

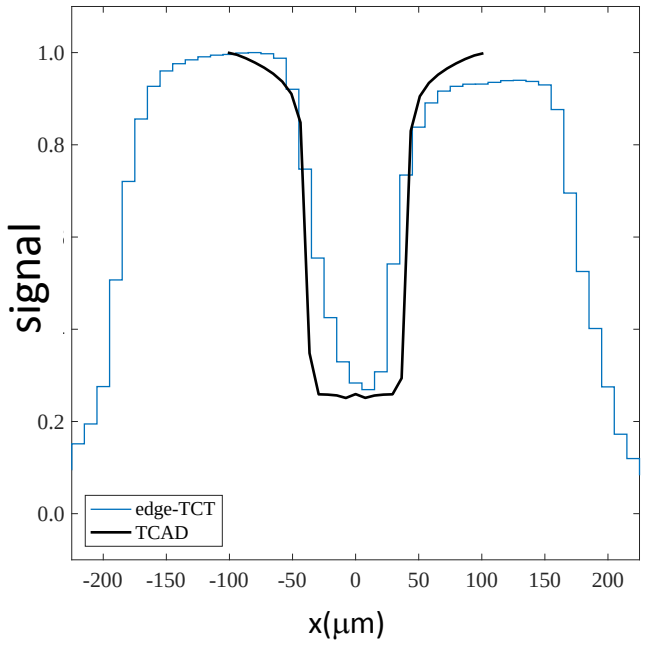




Safe design

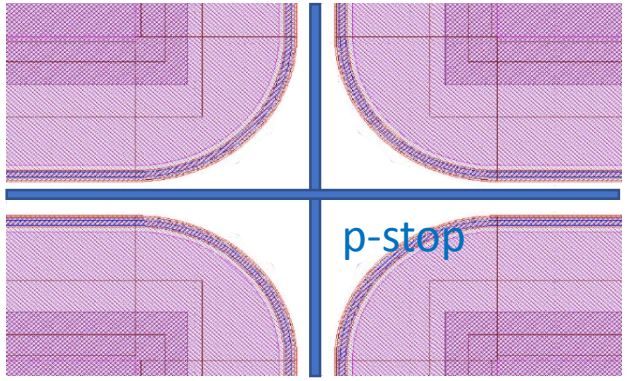
UFSD2 - UFSD3 test structures fill factor studies

Good agreement with TCAD simulation

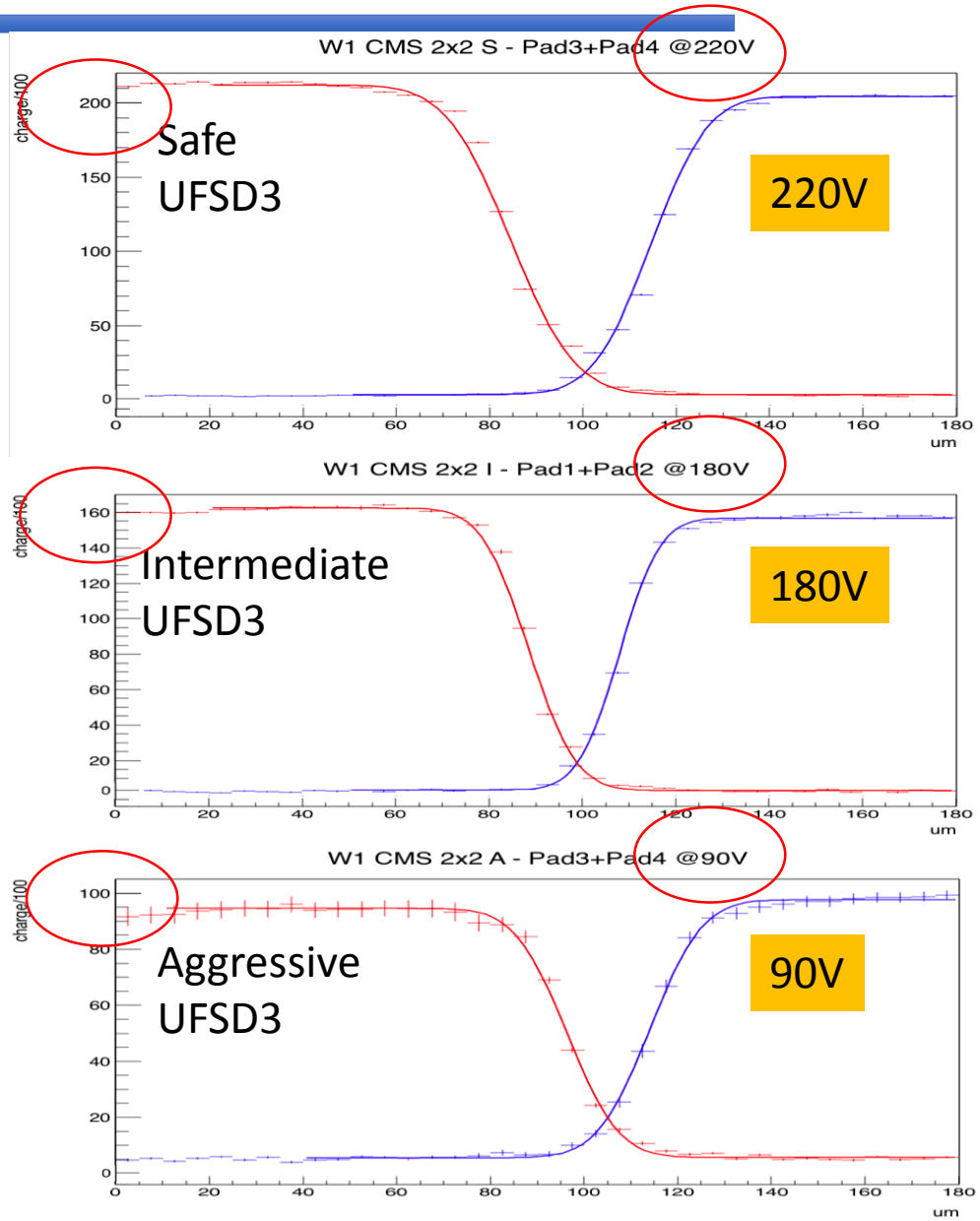


UFSD2 MoveIT strips

UFSD3 test structures: moving from «safe» to «aggressive» design, the V_{BD} decreases strongly. «aggressive» design V_{BD} is so low that the structure is not fully depleted and the interpixel dead region increases wrt «intermidiate» ts.



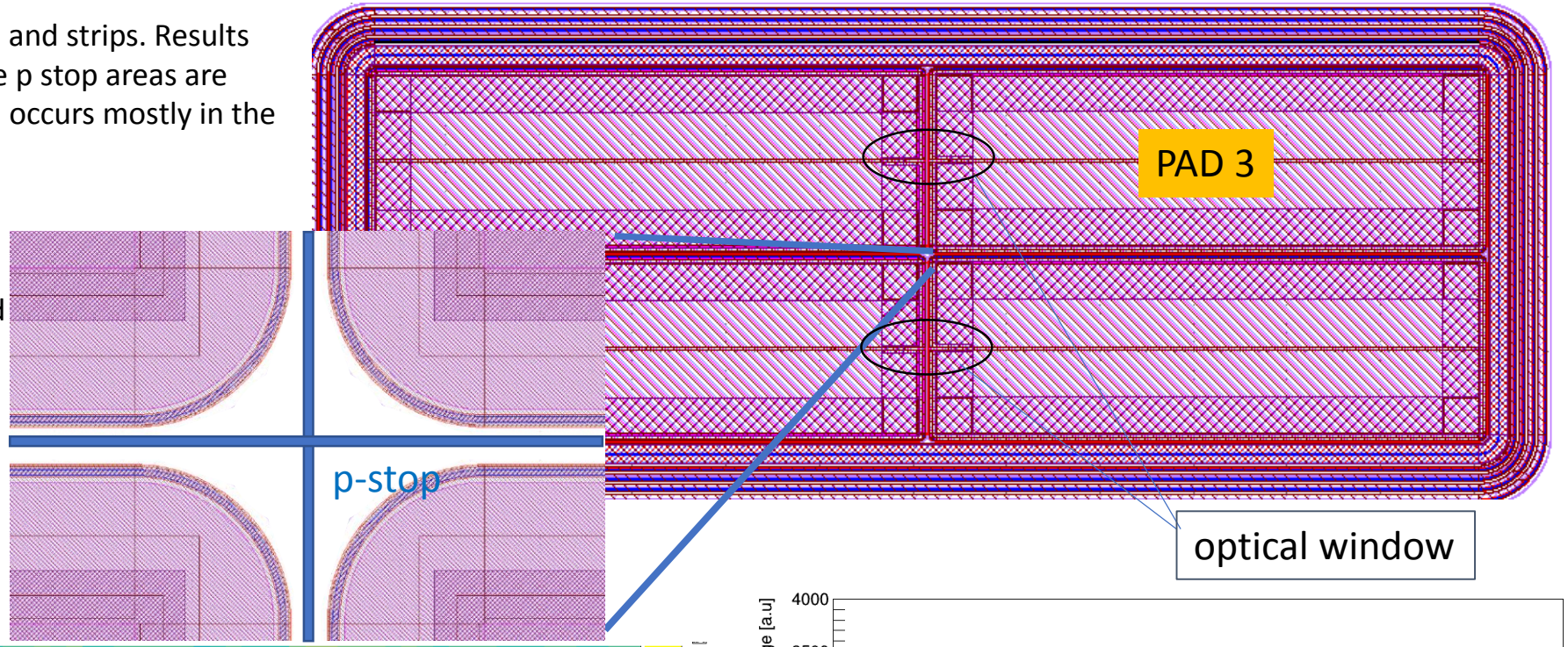
A long uniform p-stop might be causing early brakdown by shifting its potential away from the n++ pixel via punch-through

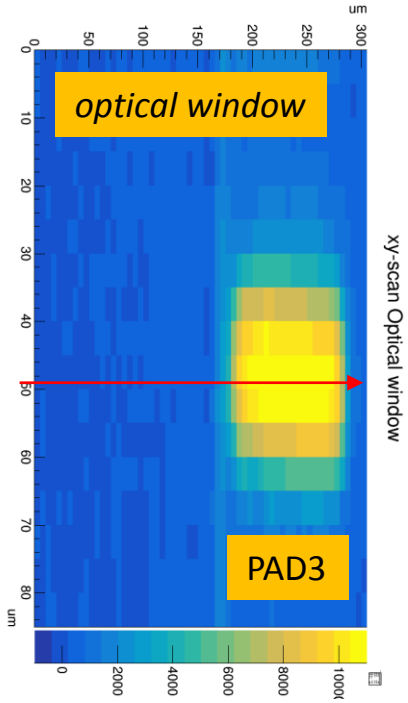


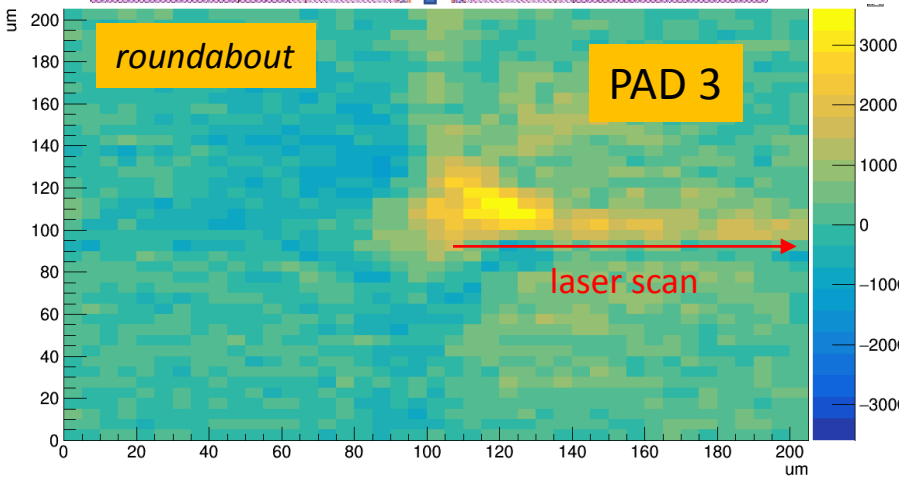
UFSD3 test structures fill factor studies

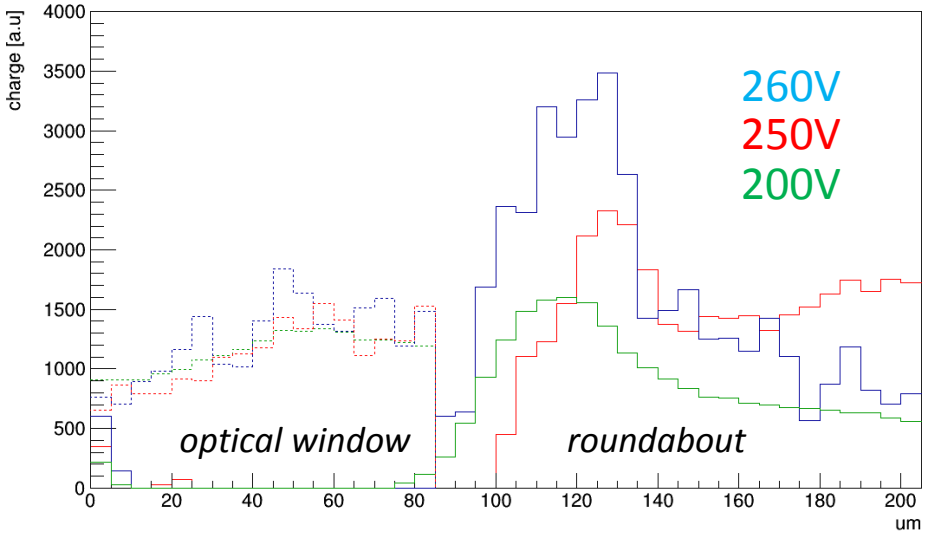
TCT laser scan on a 2x2 test structures and strips. Results indicate that V_{BD} decreases when large p stop areas are present, and that charge amplification occurs mostly in the corners.

The effect is not present for UFSD3 structures for the experiments (CMS, ATLAS, MoveIT) where each pad is surrounded by a a single p-stop.





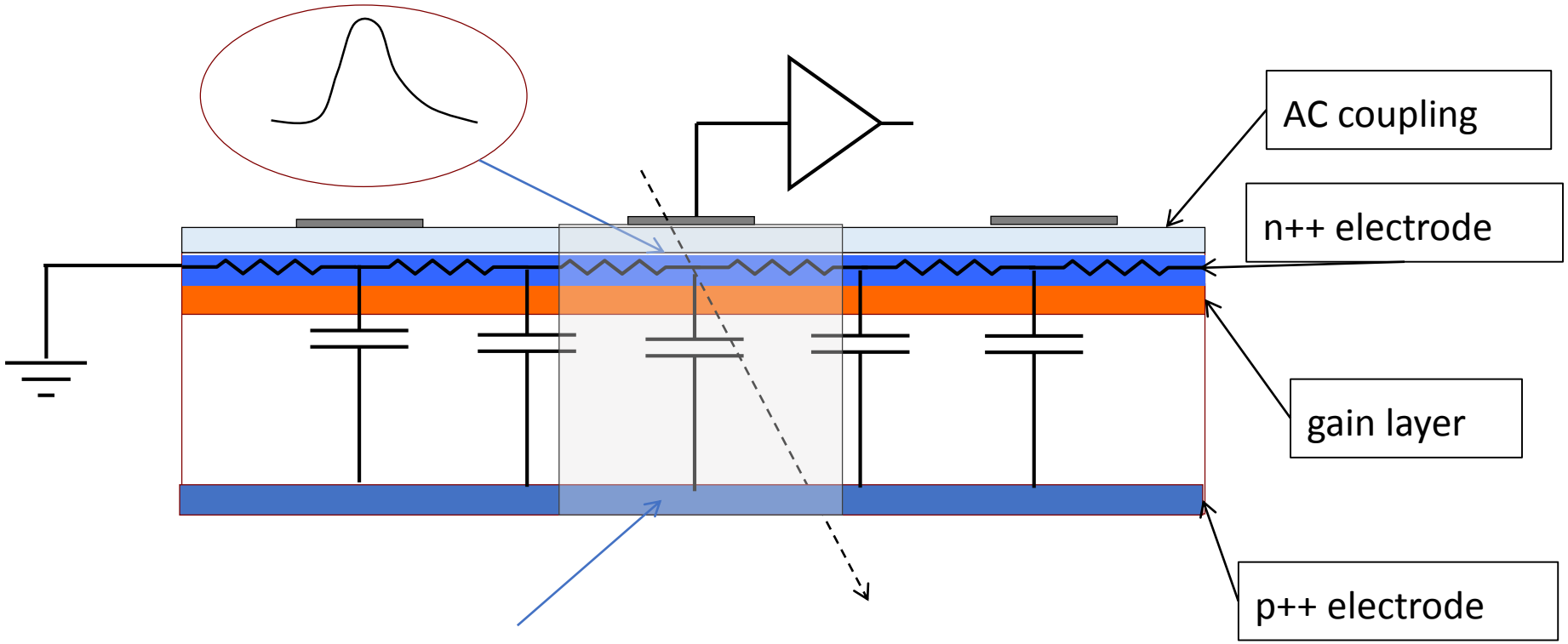




Fill factor: a possible alternative under study

➔ 100% fill factor

➔ Segmentation is achieved via AC coupling



The AC read-out sees only a small part of the sensor:

small capacitance and small leakage current.

N.Cartiglia TREDI 2015, M.Mandurrino (INFN grant **R**esistive AC coupled **S**ilicon **D**etectors, 2018)

UFSD Radiation tolerance

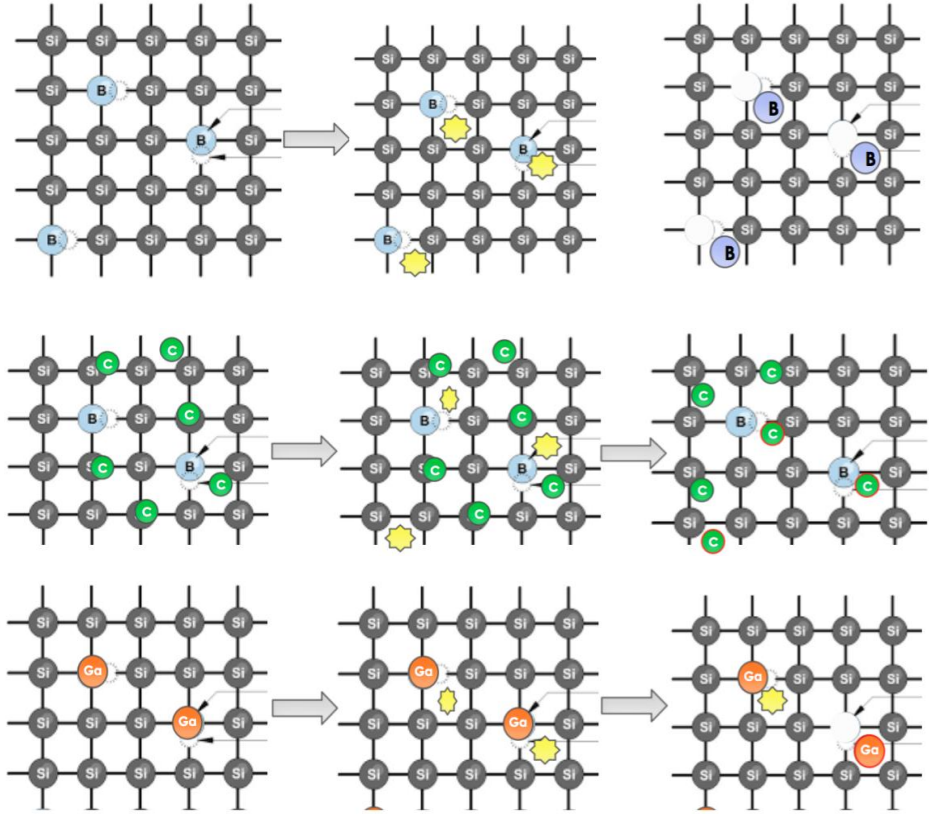
LGAD radiation tolerance studied within the CERN RD50 collaboration
Radiation fluences requested to operate at HL-LHC ~5 10^{15} particles/cm^2 , radiation doses of 150Mrad (primarily due to **N**on-**I**onizing **E**nergy **L**oss)

$$N(\emptyset) = N(0) * e^{-c\emptyset}$$

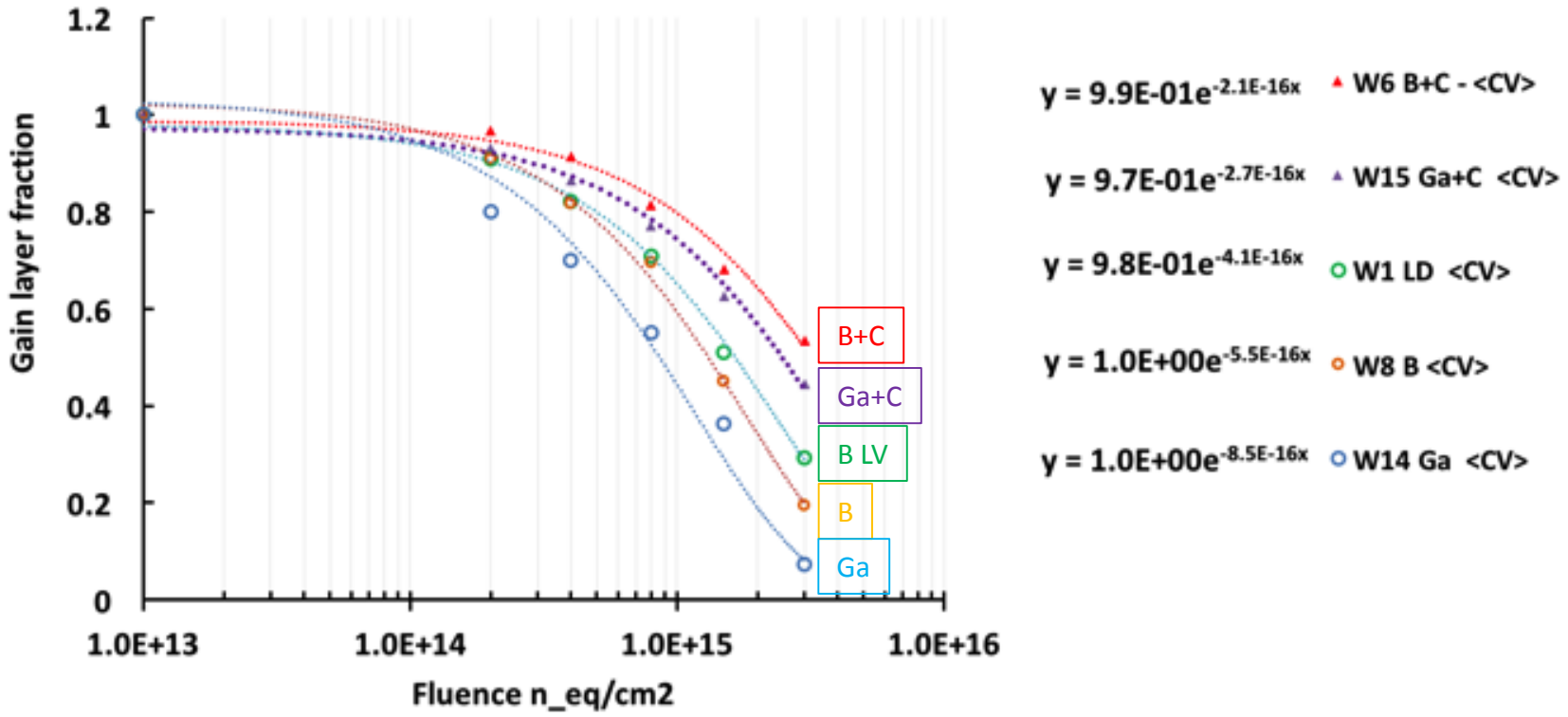
gain layer radiation depletion

Effects:

1. same effects of standard n-p Si detectors: increase of Leakage Current (decrease T), increase of V_{BD} and $V_{FD,}$ due to increase of doping concentration. Creation of trapping centers (minimize the effect going to **thin sensors (!)**)
2. peculiar on **LGAD**:
    1. Further increase of leakage current (and power) due to gain layer: **go thin, keep gain low**
    2. UFSD2: <u>Gain loss due to gain layer acceptor removal</u>. Boron atoms are displaced and become interstitial, thus not contributing to the doping profile: **increase V_{bias}, change acceptor (<u>add Carbon to decrease interstitial phase space</u>, and test <u>replacing Boron with Gallium</u>)**

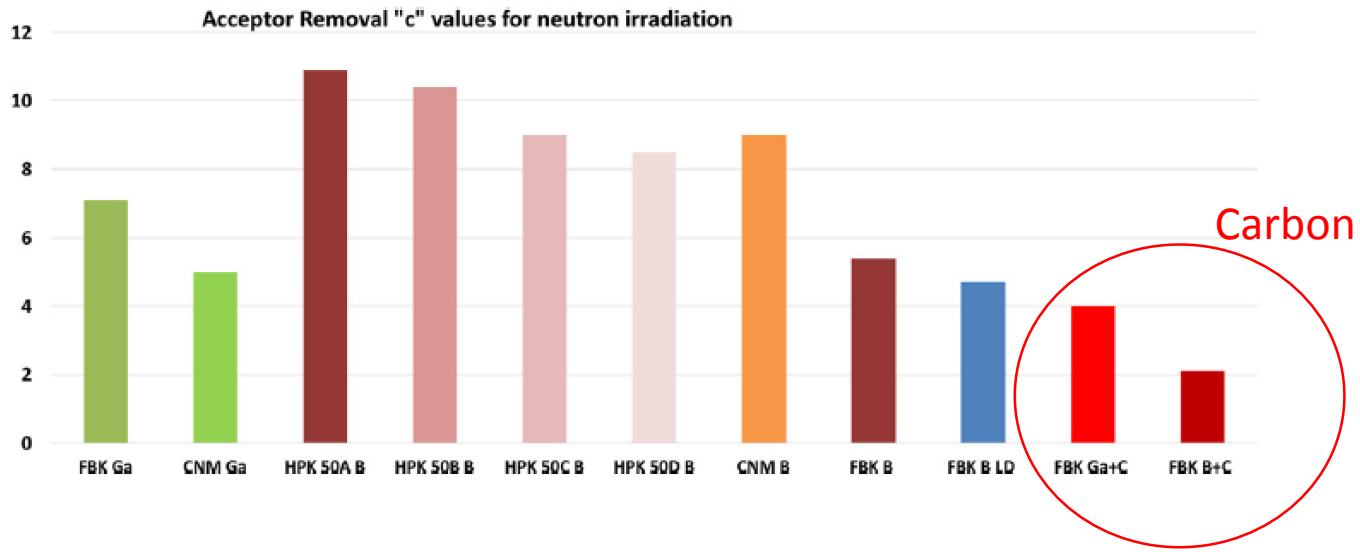


UFSD2 irradiation tests



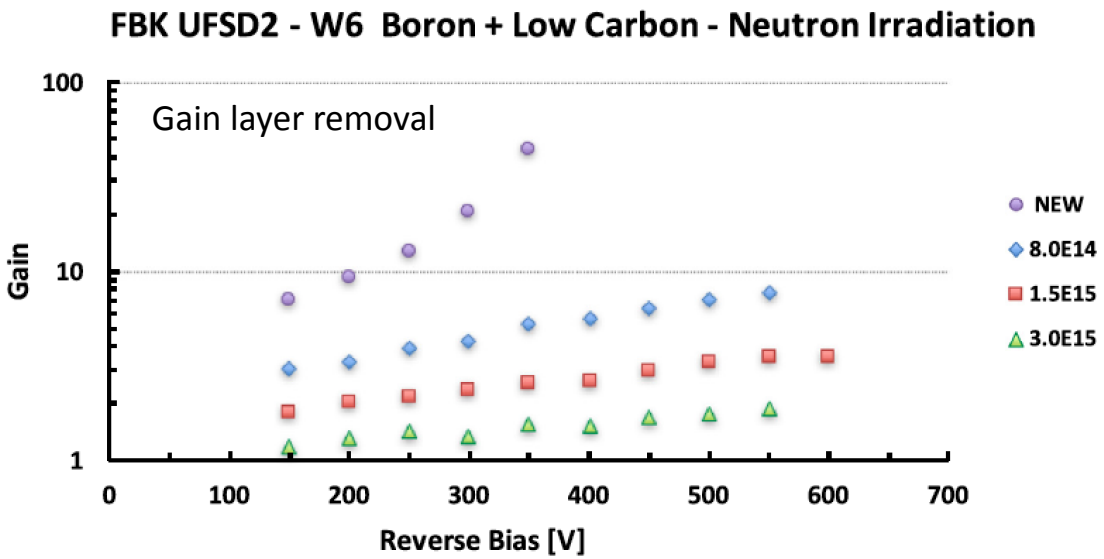
Results from UFSD irradiation test campaign: Gallium doped gain layer is the most radiation sensitive. Carbon is very effective, both with Gallium and Boron. Boron+Carbon wins!

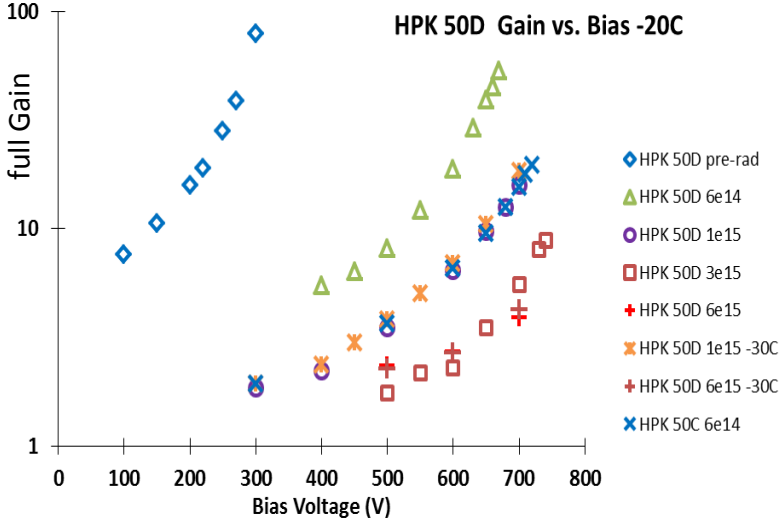
UFSD2 irradiation tests (cont.)

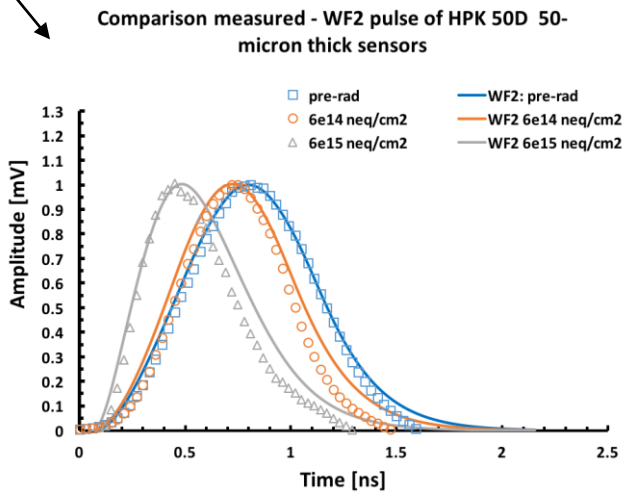


24 GeV/c protons produce the same amount of initial acceptor removal as a function of the fluence (particles/cm^2) as neutrons

Gain recovery is well described by simulation (WF2). At higher doses high V_{bias} gain layer disappear but gain starts occurring in the bulk

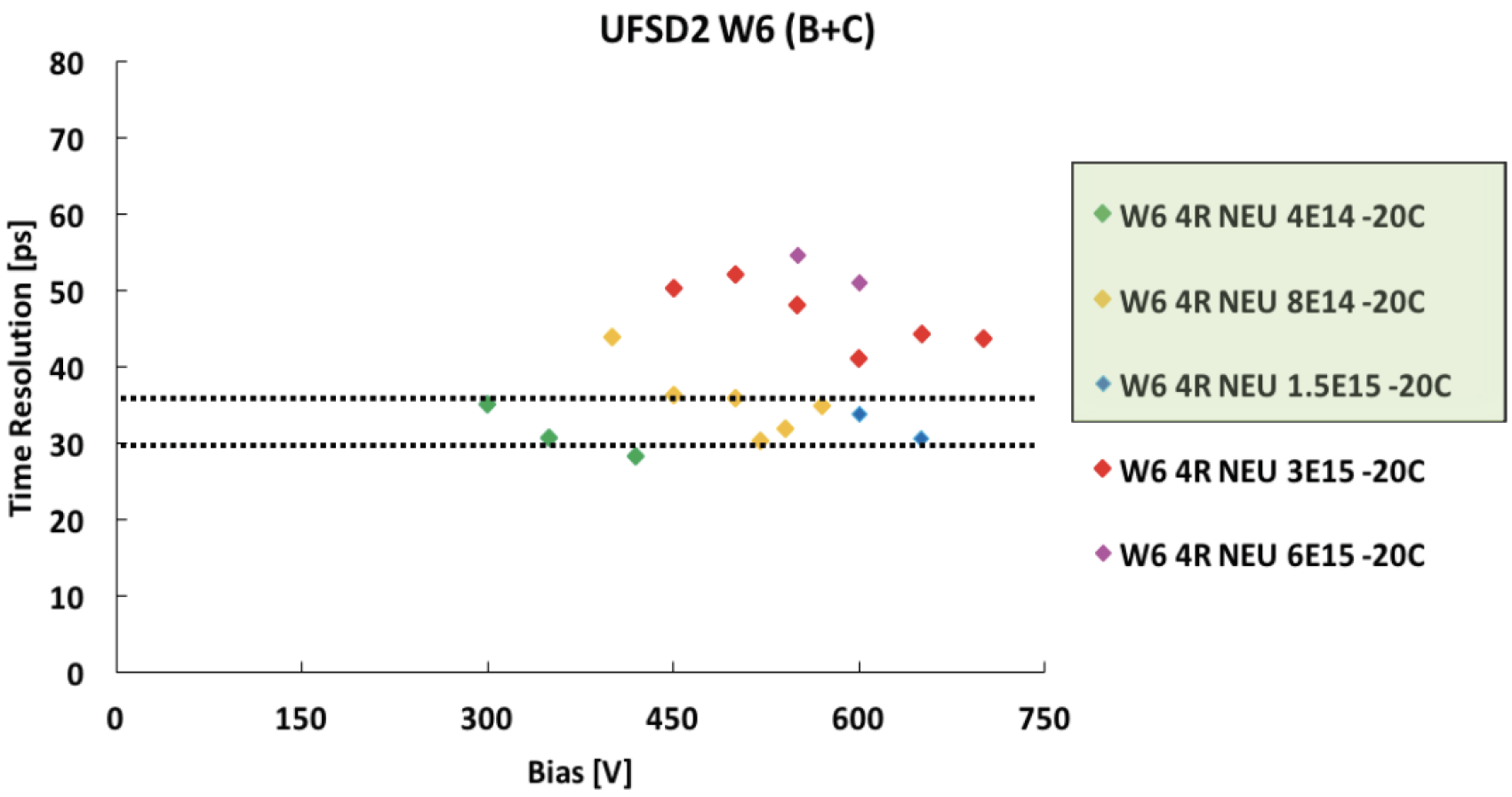




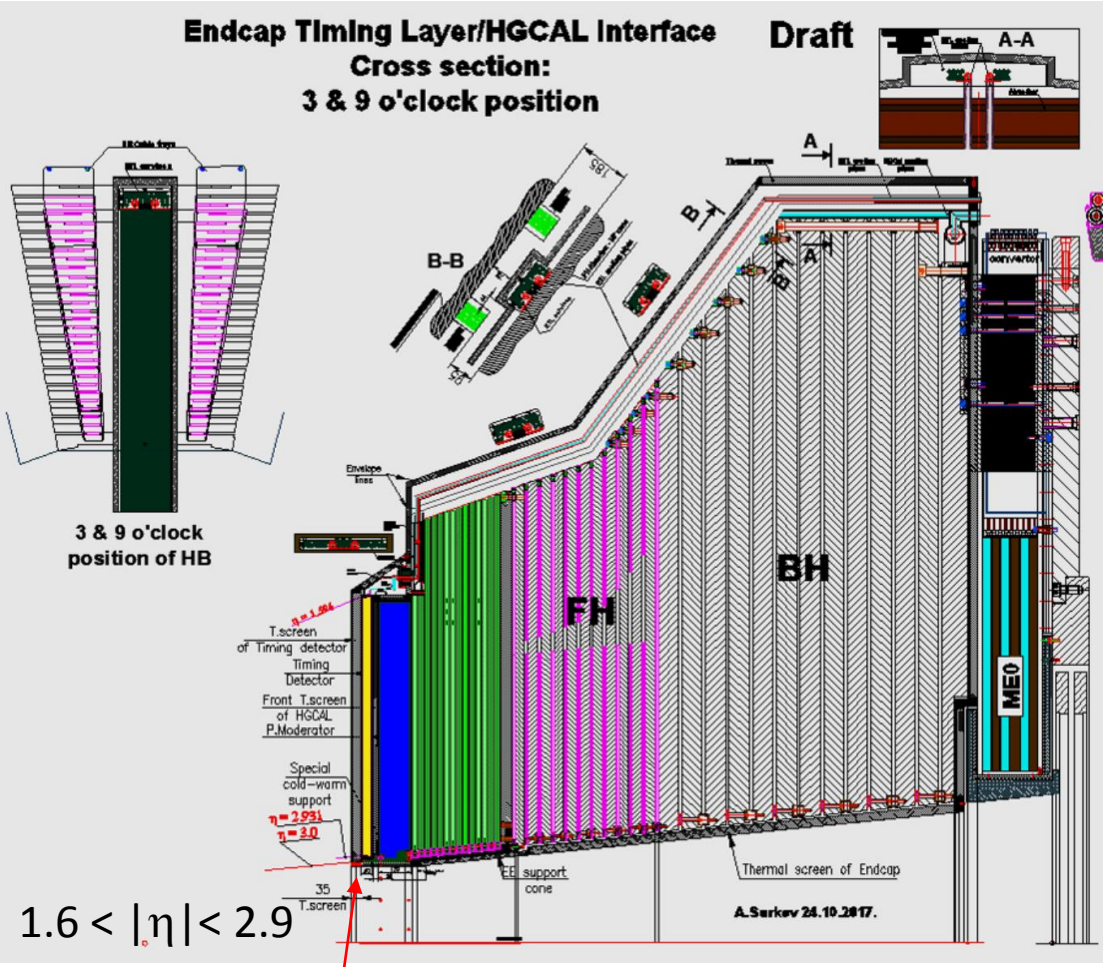


UFSD2 irradiation tests, time resolution

30-35ps resolution @ 1.5e15 n_{eq}/cm^2, which corresponds to HL-LHC ETL CMS lifetime of $4000fb^{-1}$

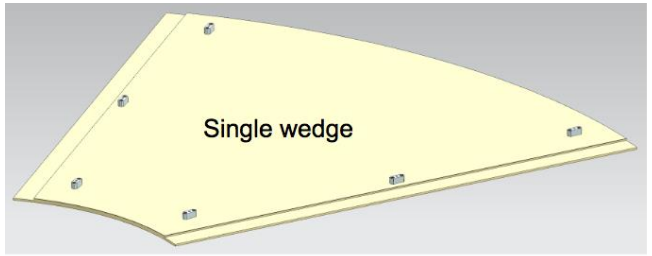


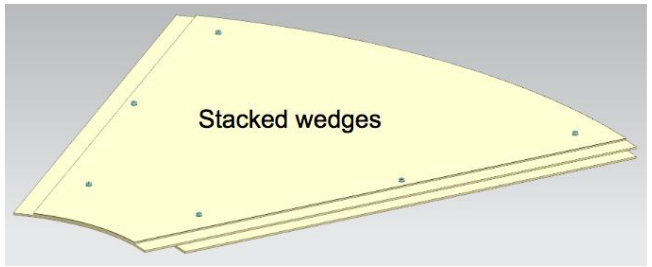
The Endcap Timing Layer for CMS at HL-LHC

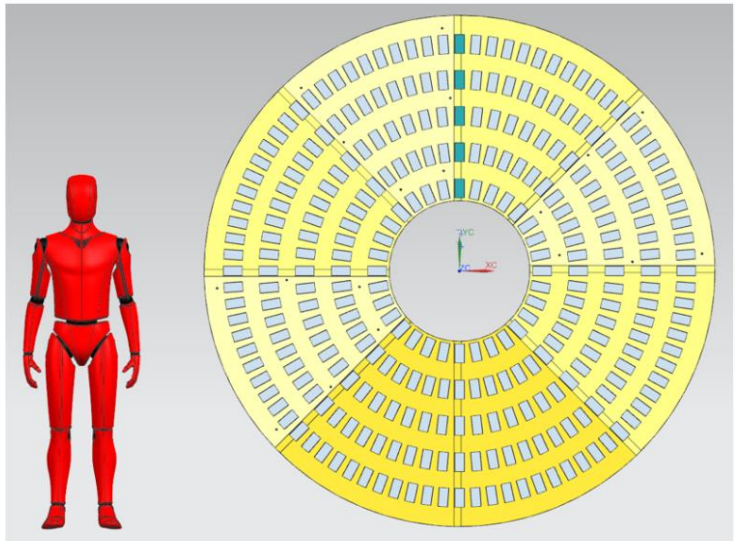


$1.6 < |\eta| < 2.9$

CMS Endcap Timing Layer

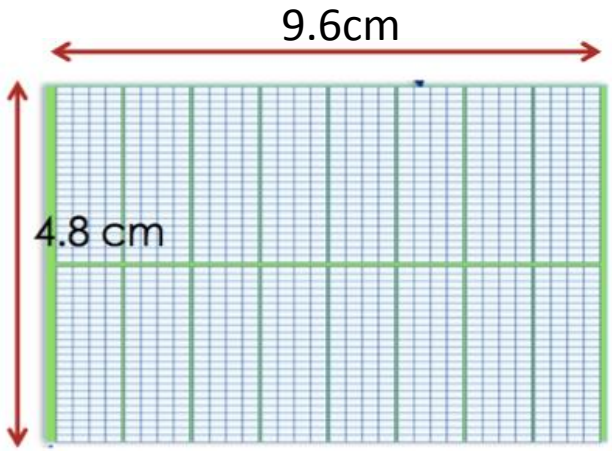






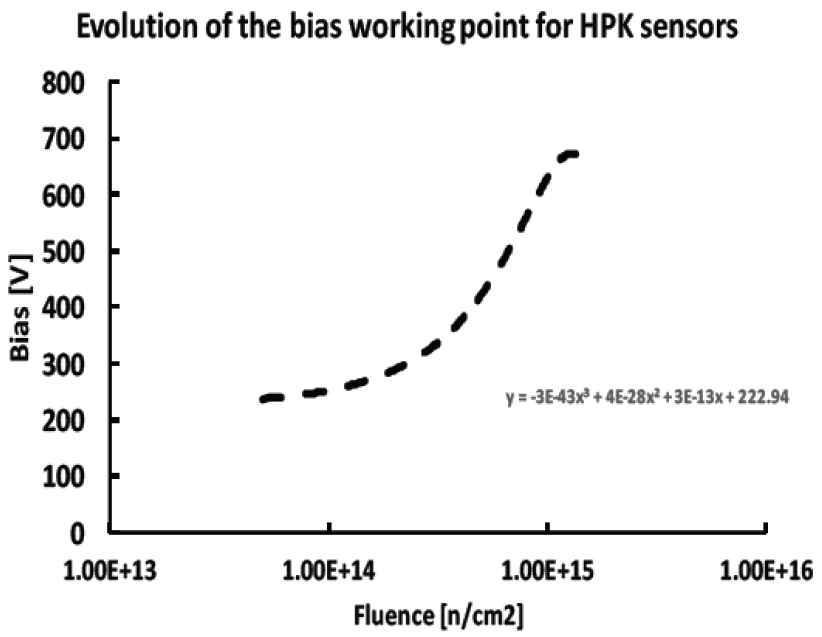
~1800 sensors =

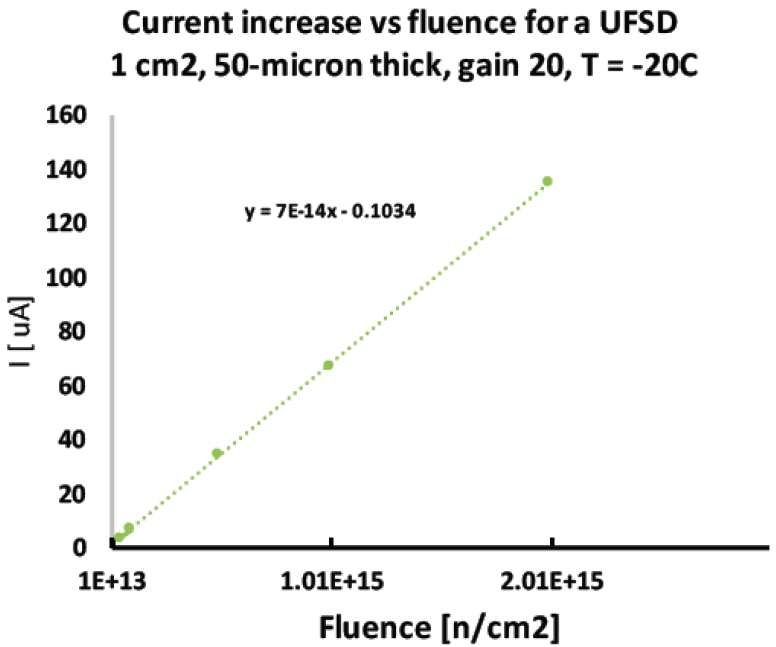
~15m²

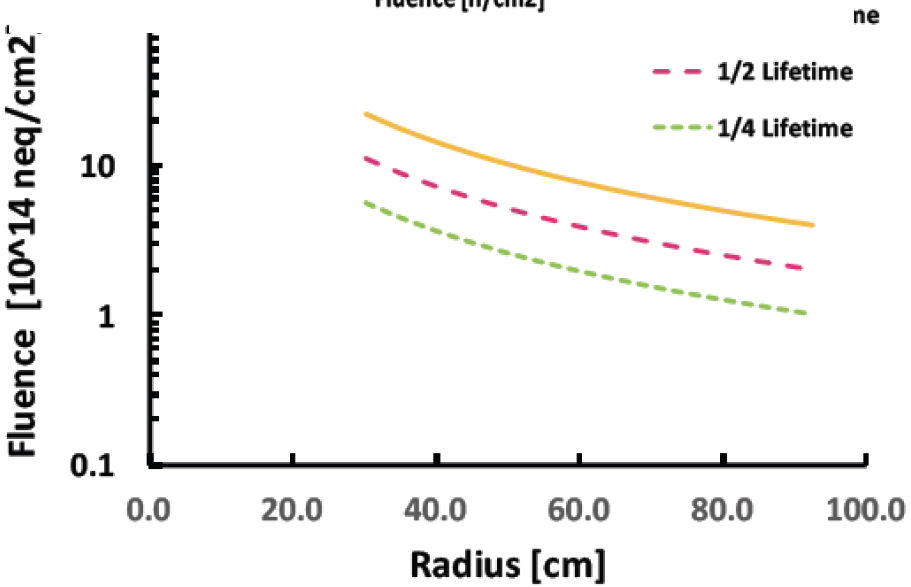


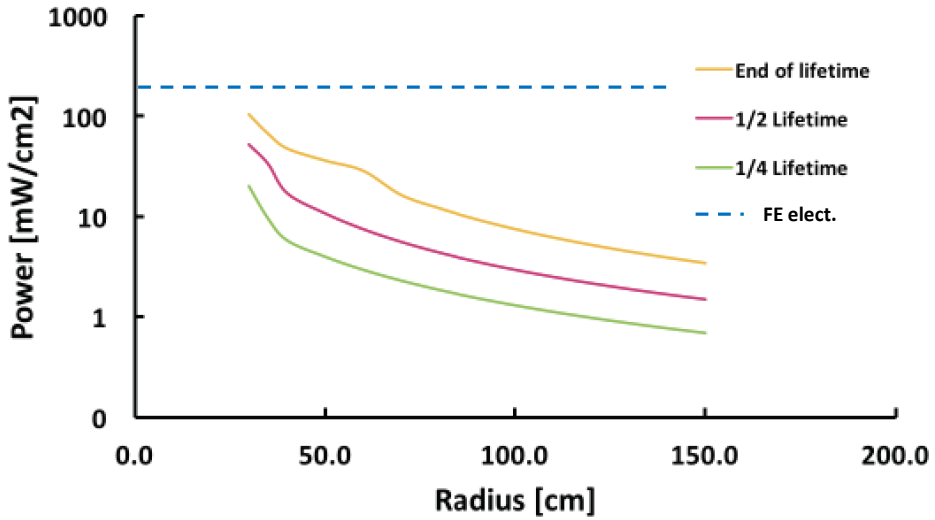
Single pad **1x3mm²**
In the current TP, recently proposed to move to ALTIROC geometry (**1.3x1.3mm²**)

ETL detector power consumption









Large fluctuations at small radii, requires specific R&D (increase V_{bias} fragmentation by reducing sensor dimensions requires better fill factor performances).

Outlook and conclusions

- irradiation campaign on UFSD3, detectors irradiated and ready for testing (currently being done in Torino)
- fill factor: probably needed a new dedicated UFSD3.x run on interstrip geometry optimization. Improve TCAD simulation
- 2 postdocs studying and designing optimized FE electronics for UFSD fast timing applications in Torino
- collaboration ongoing on side projects
  - MoveIT (development of fast beam monitor for Hadrontherapy treatments)
  - PSI R&D plan for enhancement of soft (1-5keV) x-ray detection
  - **R**esistive AC coupled **S**ilicon **D**etectors (TCAD simulation and first run in preparation)
- growing involvement in ETL activities (deadline for ETL TDR march 2019)
- more UFSD**n** to come….
- **LGAD is a fast developing but mature technology (4 manufacturers on the market)**
- **4D tracking is an HEP experimental need. UFSD are being proposed for large area detectors in HL-LHC (~30m^2 in CMS and ATLAS)**

Acknowledgments

Thank you for your attention !

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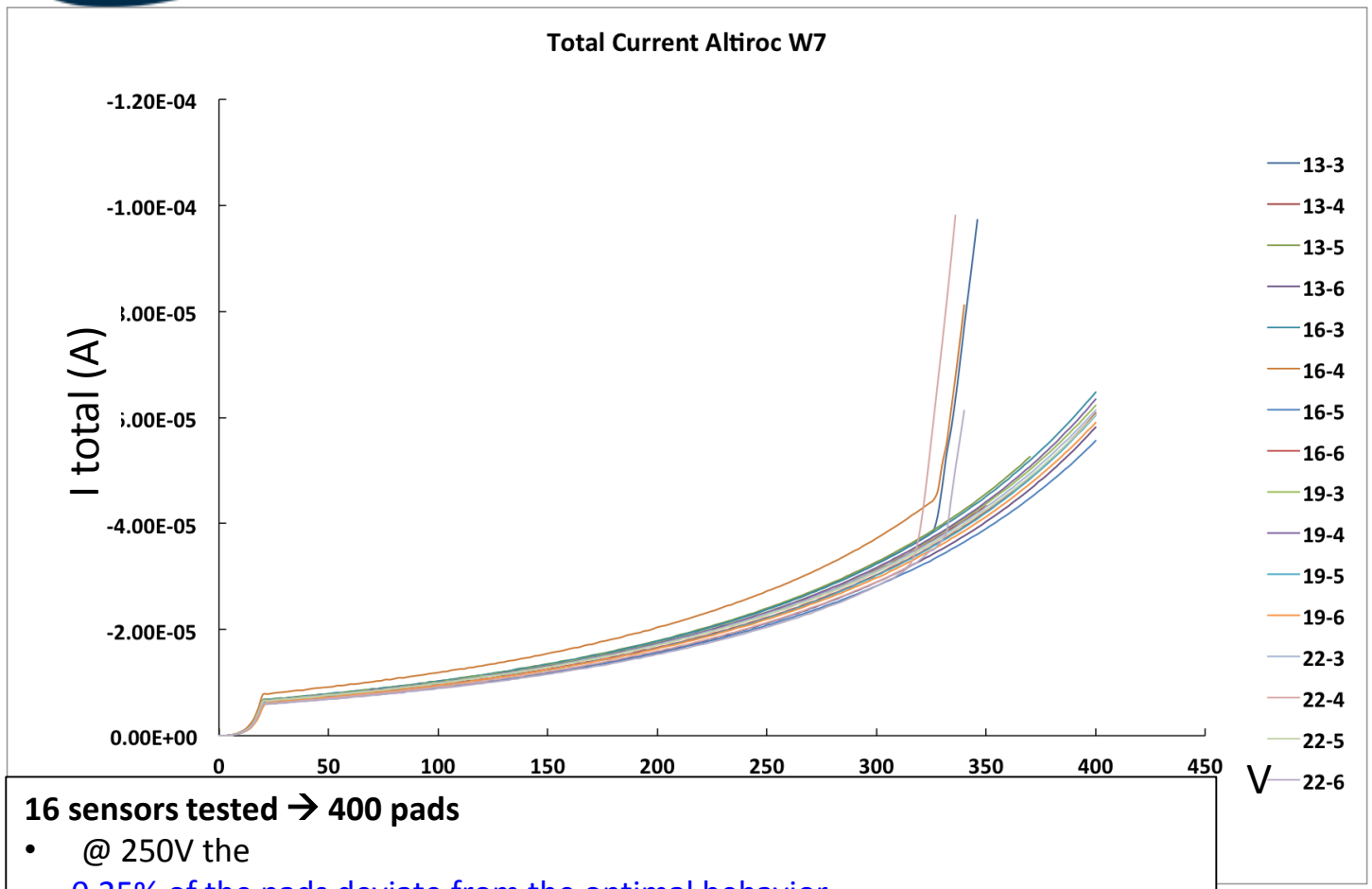
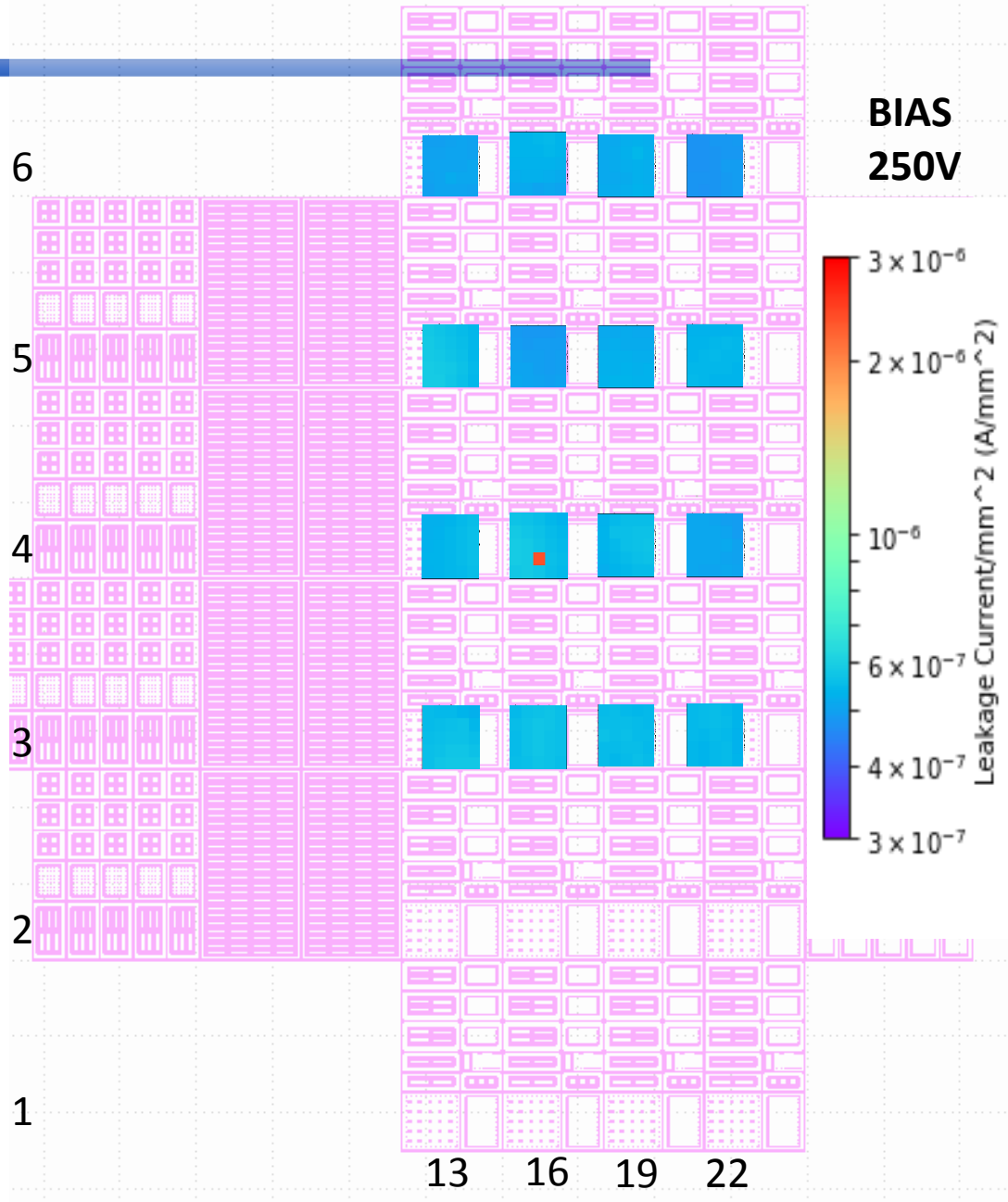
Backup Slides

UFSD3 I-V and C-V curves, uniformity check



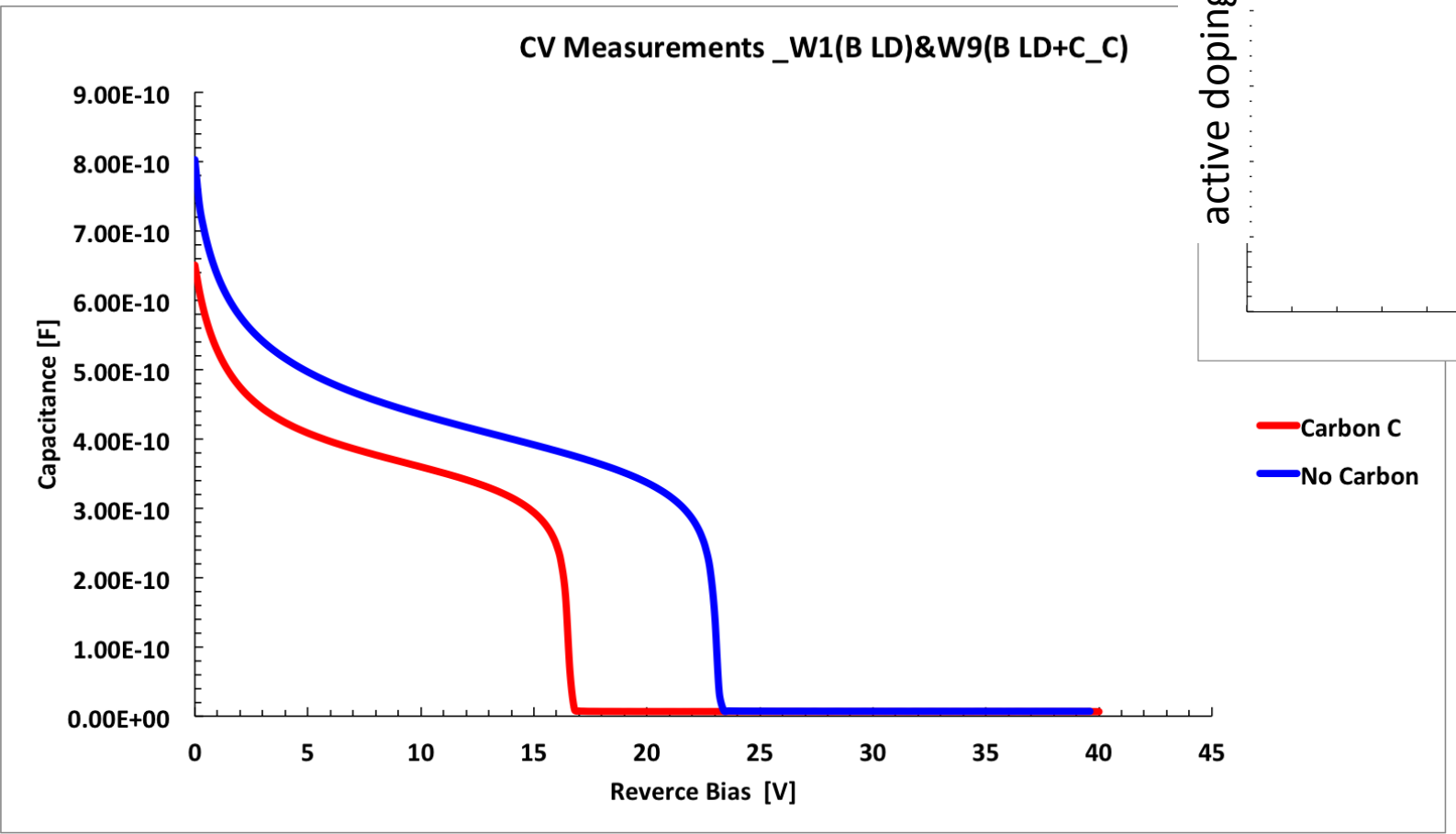


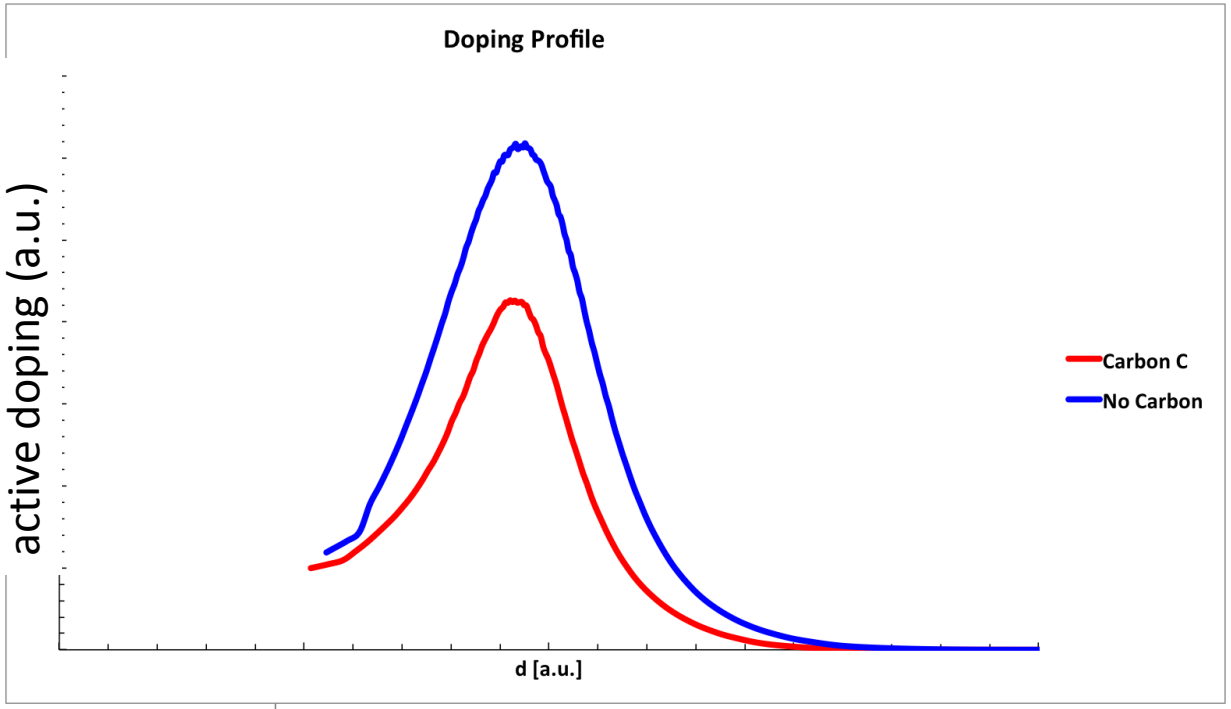
16 sensors tested → 400 pads

- @ 250V the
  0,25% of the pads deviate from the optimal behavior
- @ 300V the
  0,5% of the pads deviate from the optimal behavior
  the 0,25% of the pads is in BD
- @ 350V
  12,5% of the sensors in BD before 350V
  2,6% of the pad in BD (on sensors not in BD)

UFSD3 CV curves

Carbon depletes the gain layer





$d = [2\varepsilon V_{bias}/(qN)]^{1/2}$