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First results from thin silicon sensors irradiated to extreme fluence

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QUESTIONS

- **Is it possible to design a silicon sensor able to work in the fluence range $10^{16} – 10^{17}$ n_{eq}/cm^2?**

If so

- **Does such sensor generate enough charge to be used in a detector exposed to extreme fluences?**

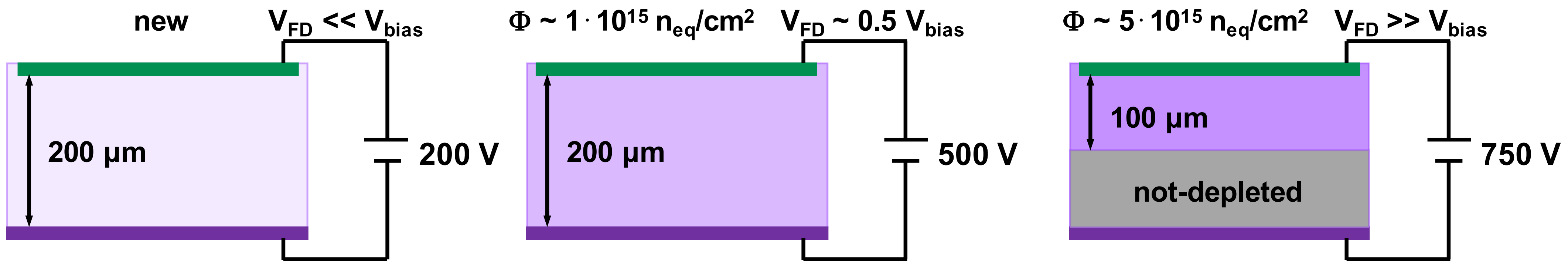
⇒ **The R&D to answer these questions is starting now**

EFFECTS OF RADIATION ON SILICON SENSORS

Irradiation results in 3 main effects:

- Decrease of the collected charge due to trapping effects
- Increase of the dark current
- Change in effective doping
  - → increase of the reverse bias to operate the sensor
  - → distortion of the electric field inside the sensor

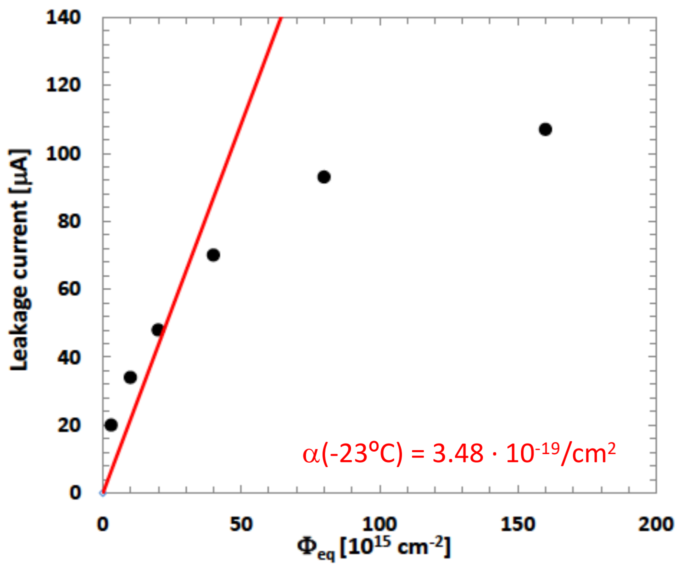
Irradiation models developed in the fluence range 10^{14} – 10^{15} n_{eq}/cm^2 predict standard silicon detectors (~ 200 μm) are almost impossible to operate



Fully depleted at low V_{bias} — Fully depleted at high V_{bias} — Partially depleted at very high V_{bias}

SOME OPTIMISM – SATURATION

At fluences above $5 \cdot 10^{15}$ n_{eq}/cm^2 → **Saturation of radiation effects observed**

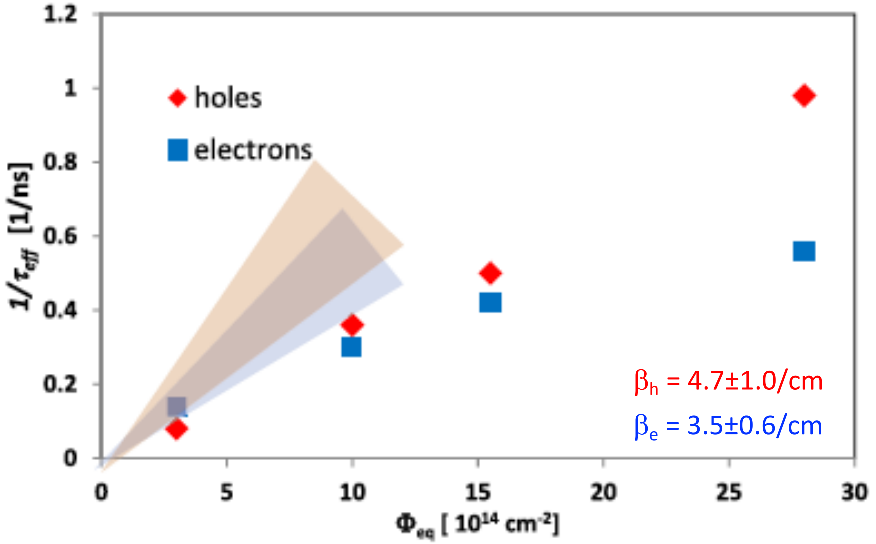


[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

Leakage current saturation

$I = \alpha V \Phi$

α from linear to logarithmic

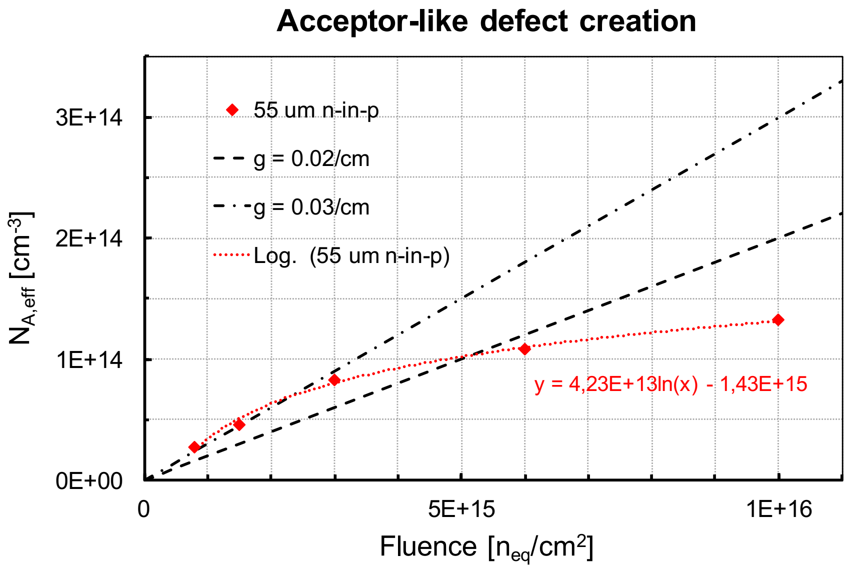


[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

Trapping probability saturation

$1/\tau_{eff} = \beta\Phi$

β from linear to logarithmic



[M. Ferrero et al., 34th RD50 Workshop, Lancaster, UK]

Acceptor creation saturation

$N_{A,eff} = g_c \Phi$

g_c from linear to logarithmic

Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

WHY SATURATION?

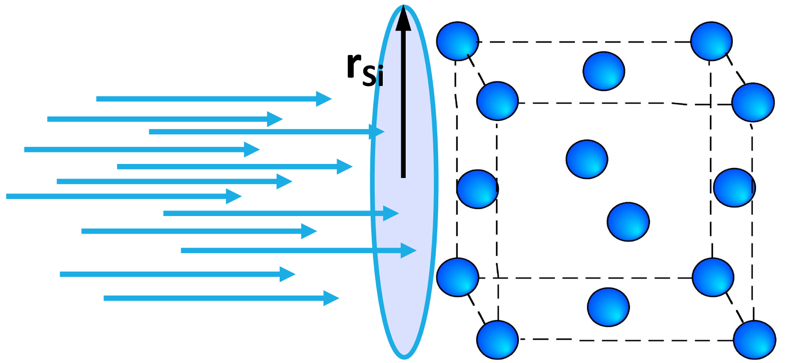
Possible explanation:

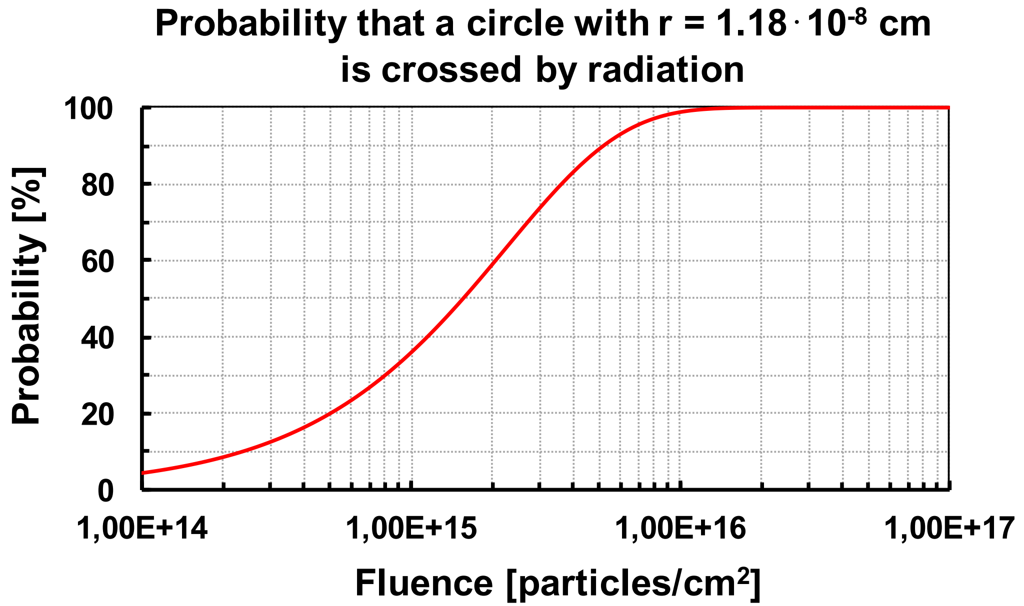
The distance between two atoms, the so-called Silicon radius, is

r_{Si} = 1.18 ·10^{-8} cm

The probability that a circle of radius r_{Si} has been crossed by a particle becomes 1 at 10^{16} particles/cm^2

Above 10^{16} particles/cm^2:
damage happening on already damaged Silicon might be different



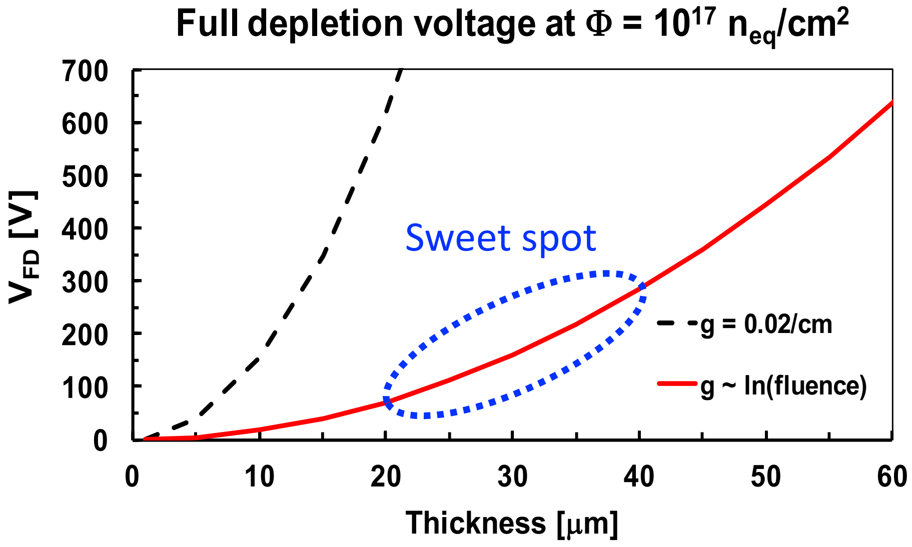


GO THIN

$$V_{FD} = e|N_{eff}|d^2/2\varepsilon$$

Saturation **Reduce thickness**

Thanks to saturation effects, thin sensors can still be depleted and operated at $V_{bias} \leq 500$ V



What does it happen to a 25 μm sensor after a fluence of $5\cdot10^{16}$ n_{eq}/cm^2?

- ▻ It can still be depleted
- ▻ Trapping is almost absent
- ▻ Dark current is low (small volume)

However: charge deposited by a MIP ~ 0.25 fC

→ **This charge is lower than the minimum charge requested by the electronics (~ 1 fC)**

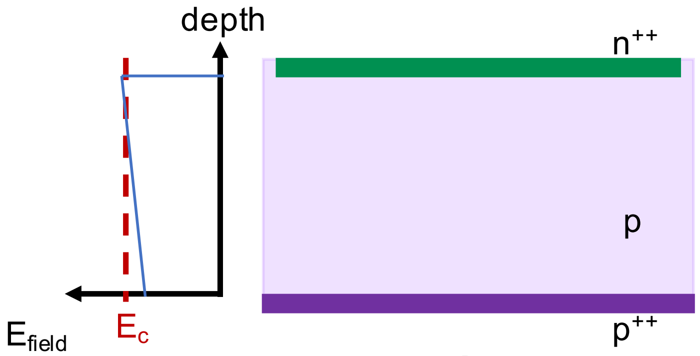
→ **Need for a gain of at least ~ 5 in order to provide enough charge**

SENSOR CHOICE

Impact ionisation occurs when $E_{field} > E_c = 250$ kV/cm

→ How to get internal multiplication of 5-10? Stable gain if:

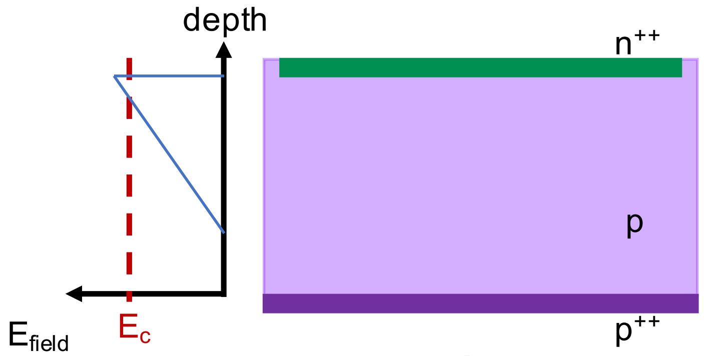
1) **$E_{field} > E_c$ for a short distance**
2) **This length is controlled by applied V_{bias}**



n-in-p
$p \sim 10^{12}$ cm^{-3}

E_{field} above E_c
over long distance

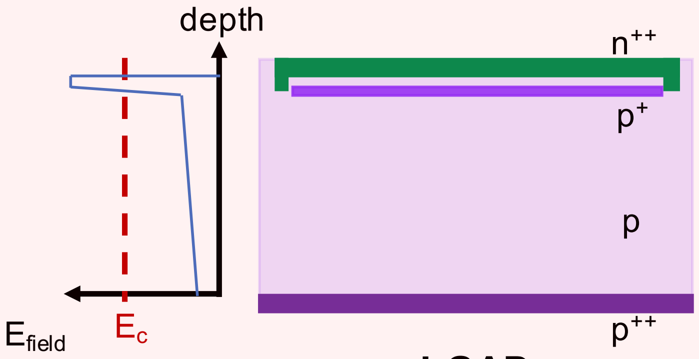
AVALANCHE



n-in-p
$p \sim 10^{14}$ cm^{-3}

Difficult to precisely
control E_{field}

RISK OF AVALANCHE

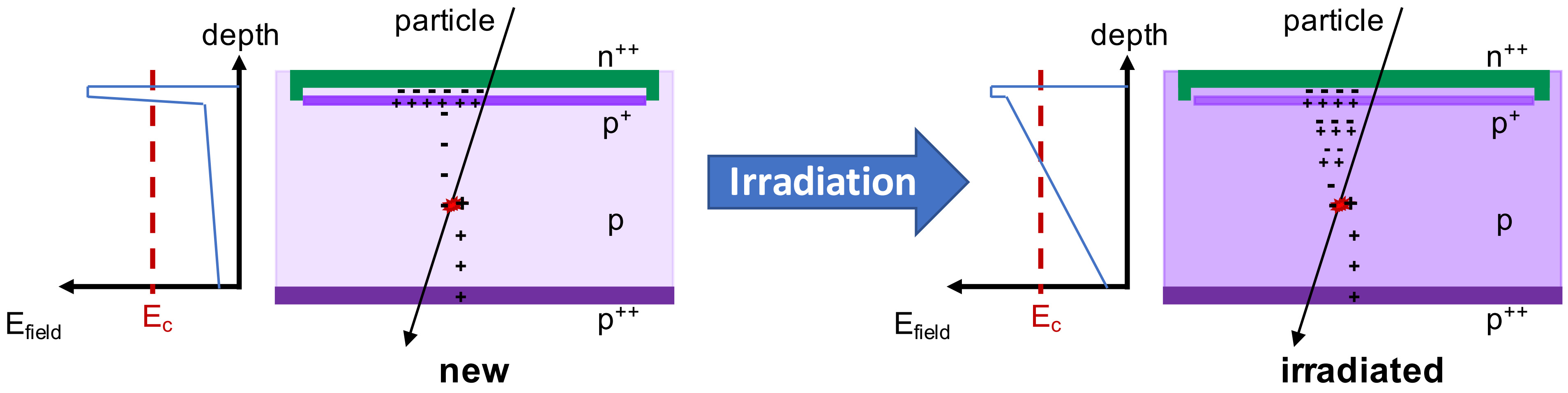


LGAD
$p \sim 10^{12}$ cm^{-3}, $p^{+} \sim 10^{16}$ cm^{-3}

E_{field} above E_c
for short distance
well controlled by V_{bias}

CONTROLLED GAIN

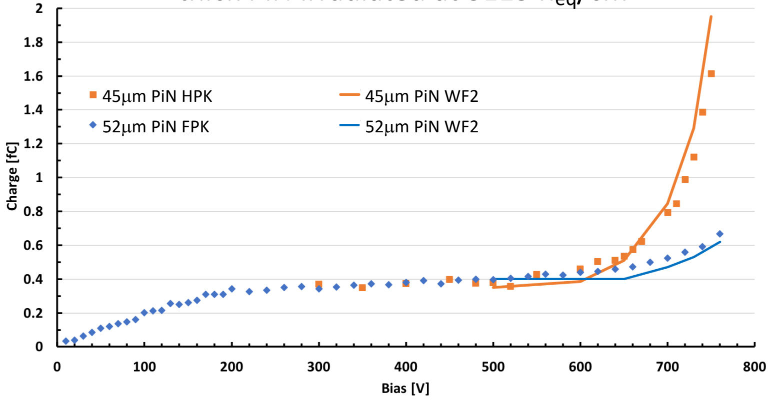
IRRADIATED LGAD



- Start with a thin LGAD, 20 – 40 μm thick (to be optimized)
- **$2\cdot10^{15}$ – $5\cdot10^{15}$ n_{eq}/cm^2**: with increasing fluence, the gain layer is deactivated
- **$5\cdot10^{15}$ – 10^{16} n_{eq}/cm^2**: compensate the decrease power of the gain layer by shifting the multiplication region to the bulk
- **10^{16} – 10^{17} n_{eq}/cm^2**: rely on bulk multiplication

→ **Does bulk multiplication exist at these fluences?**

Collected charge for 45μm and 52μm thick PiN irradiated at 3E15 n_{eq}/cm^2

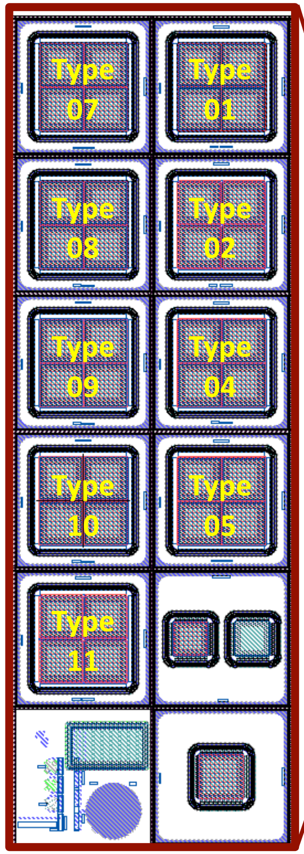


FIRST THIN WAFERS FROM FBK– EXFLU0

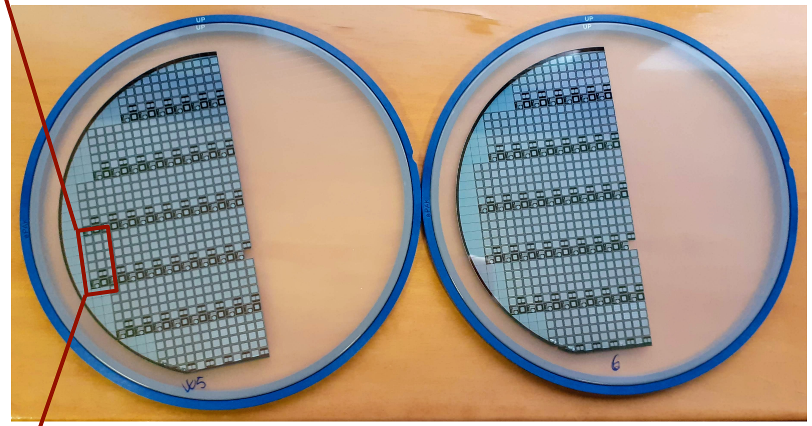
Wafer #	Thickness	Depth	Dose Pgain	Carbon	Diffusion
5	25	Standard	0.94	A	CHBL
6	35	Standard	0.94	A	CHBL

2 thin wafers have been produced at FBK
⟶ EXFLU0 production
(same layout as the UFSD3.2 production)

- ▻ epitaxial substrates
- ▻ 2 different wafer thickness: 25 and 35 μm
- ▻ 9 different inter-pad strategies (types)

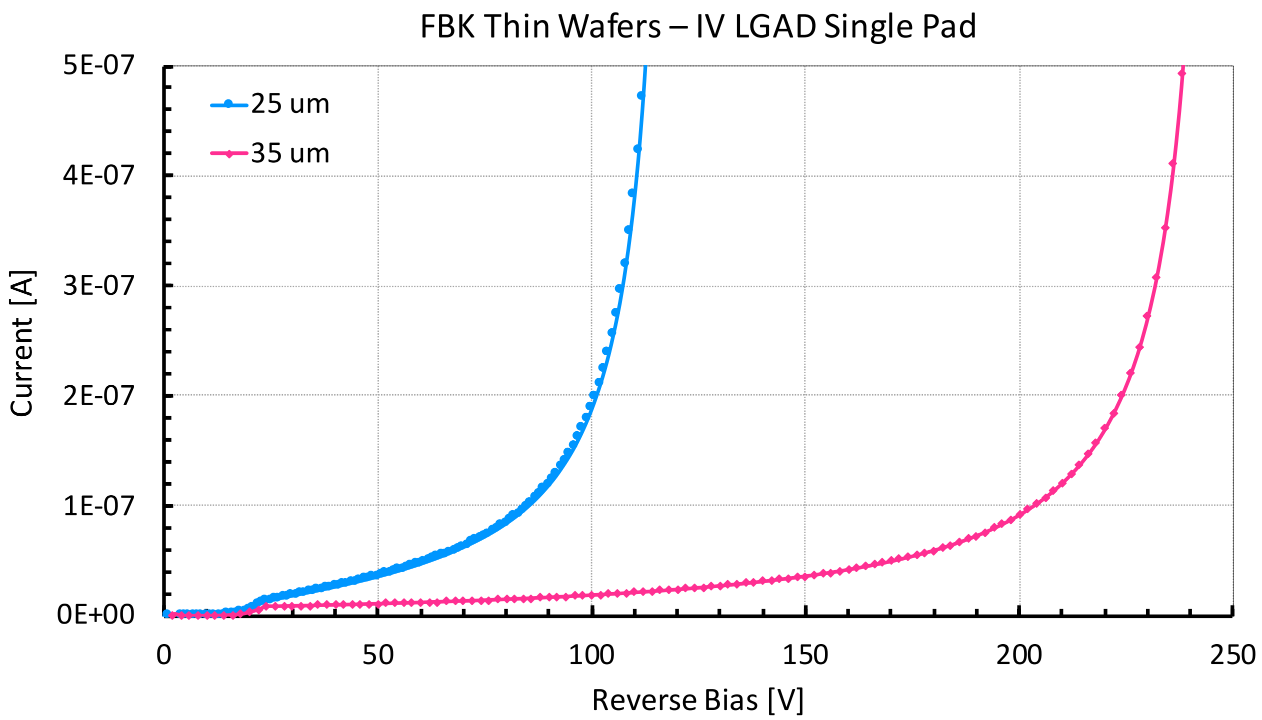


Arrived in Torino at the end of 2020

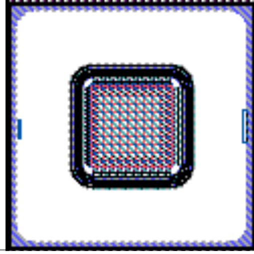


[Ref for types: https://indico.cern.ch/event/855994/contributions/3637004/]

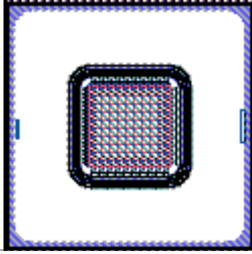
IV ON THIN LGAD – $\Phi = 0$

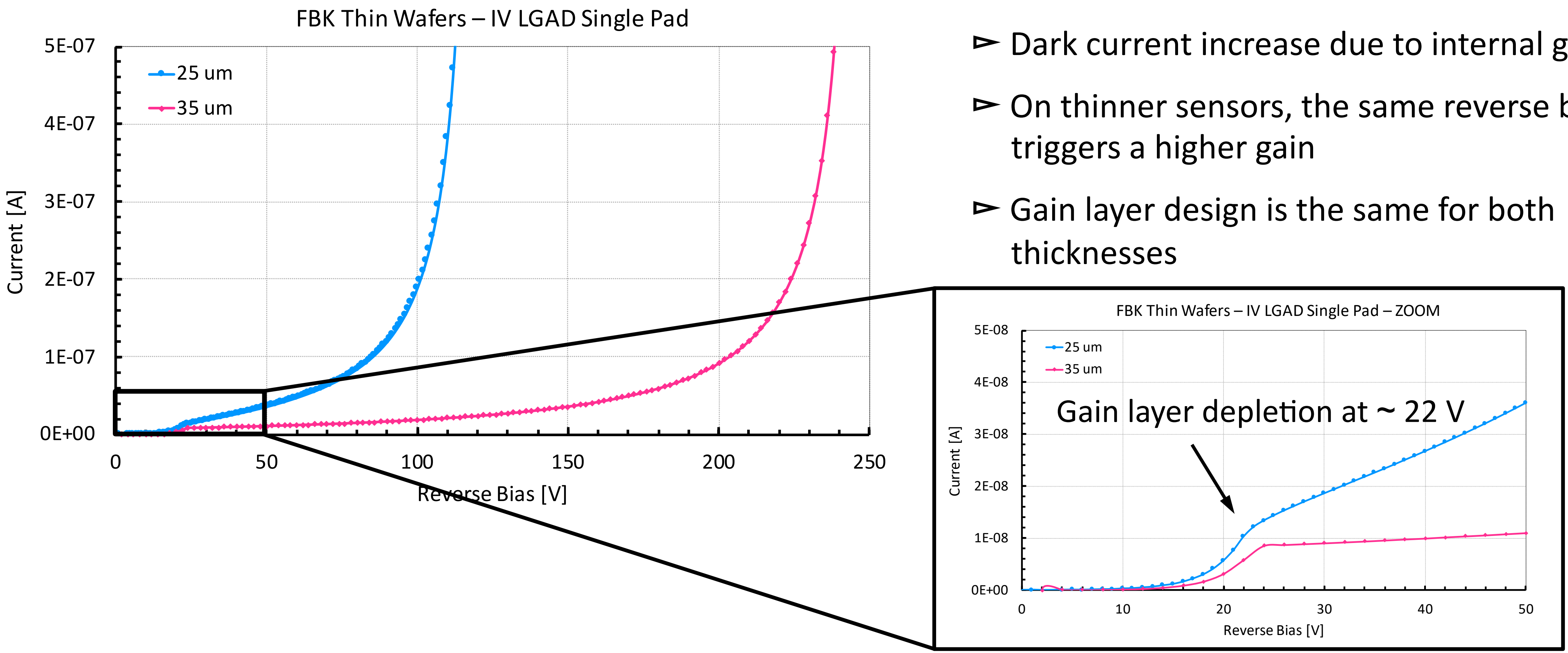


- Good electrical behaviour
- Dark current increase due to internal gain
- On thinner sensors, the same reverse bias triggers a higher gain
- Gain layer design is the same for both thicknesses



IV ON THIN LGAD – $\Phi = 0$





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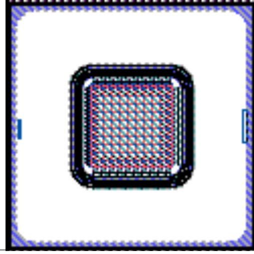
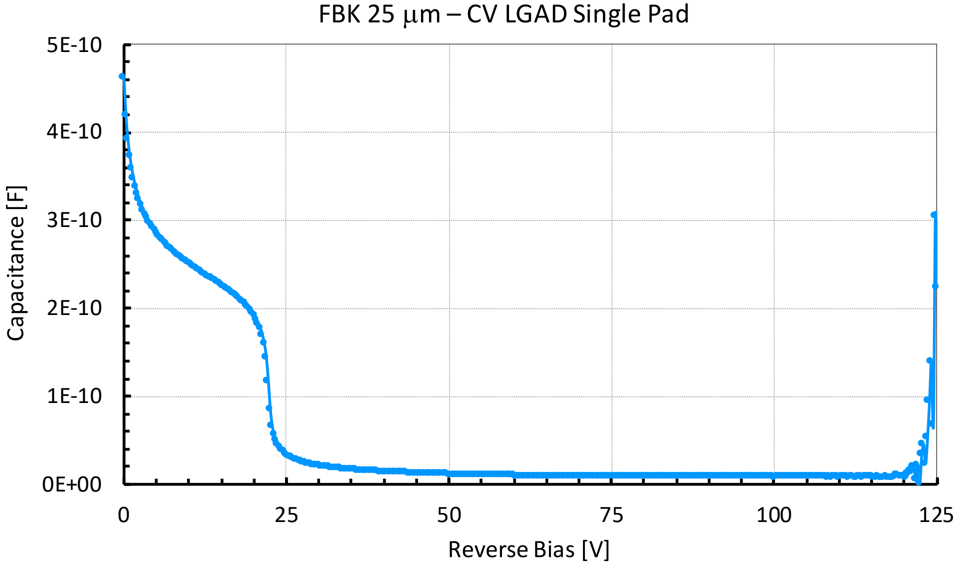
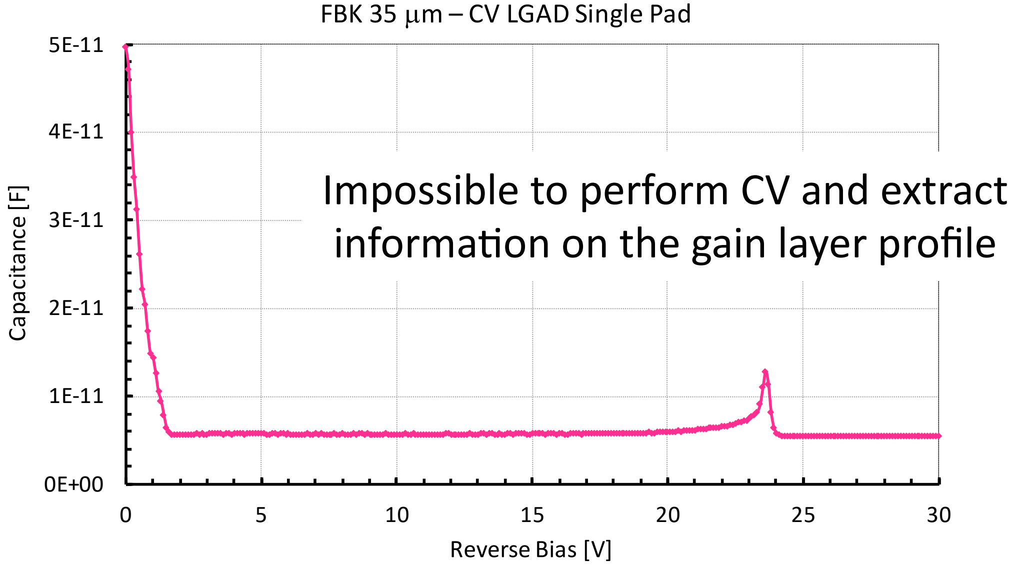
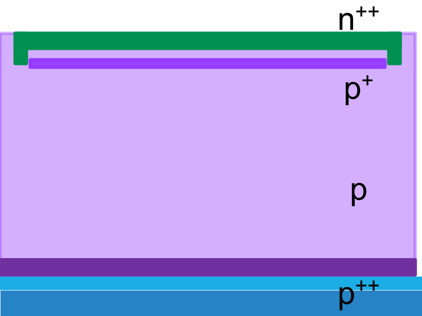
CV ON THIN LGAD – $\Phi = 0$



It is difficult to precisely control resistivity of thin epitaxial substrates







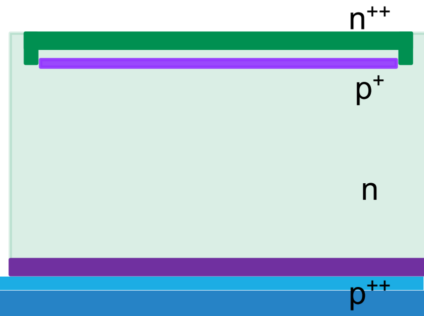
→ ρ_{W5} ~ 75 Ω·cm

Sensor depletion at about 100 V

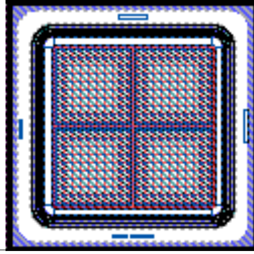
Thanks to saturation V_{FD} of bulk does not increase dramatically with radiation

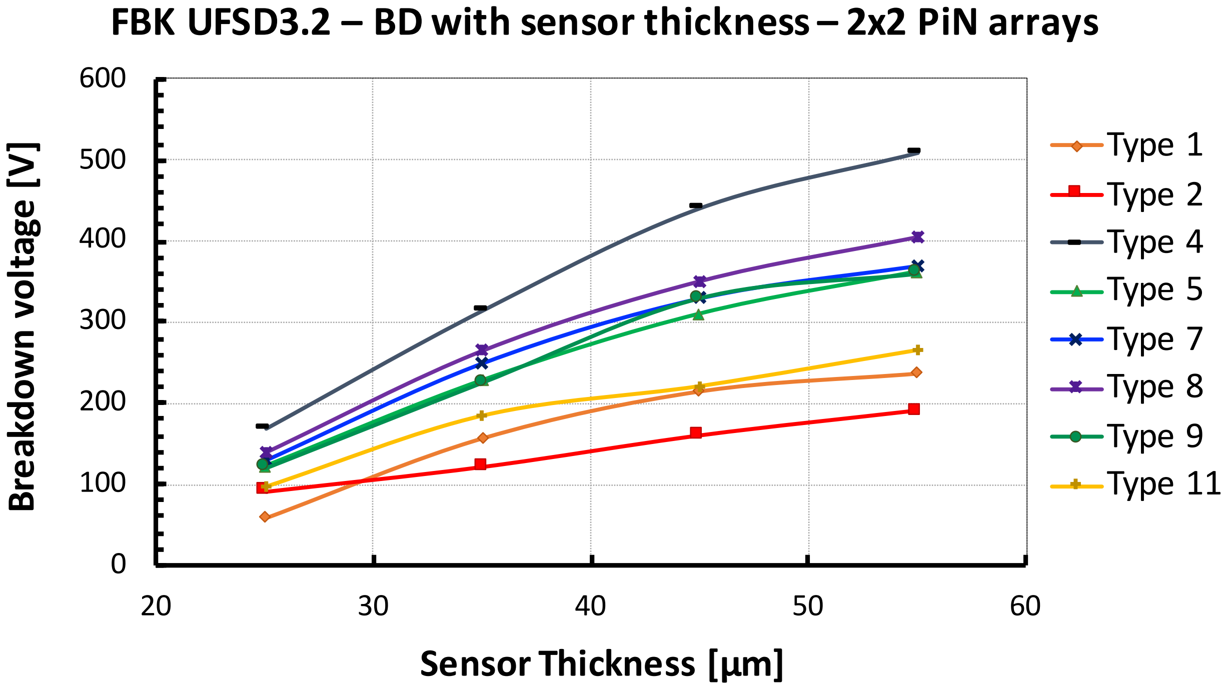
→ ρ_{W6} ~ 3,000 Ω·cm

Due to Oxygen diffusion from the support wafer, the active substrate undergo type inversion



BREAKDOWN ON THIN LGAD





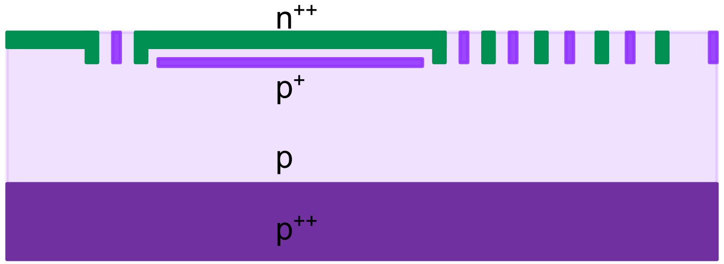
V_{BD} on sensors without gain shows a strong dependence on the sensor active thickness

When new, V_{BD} on PiN occurs at higher bias than V_{BD} due to gain, and do not limit sensor operation

But thin sensors have to sustain high bias up to very high fluences

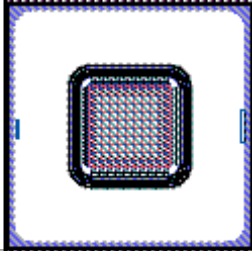
→ **Can we operate these sensors at 700 V once irradiated at $\Phi \geq 10^{16}$ n_{eq}/cm^2 ?**

Sketch not to scale

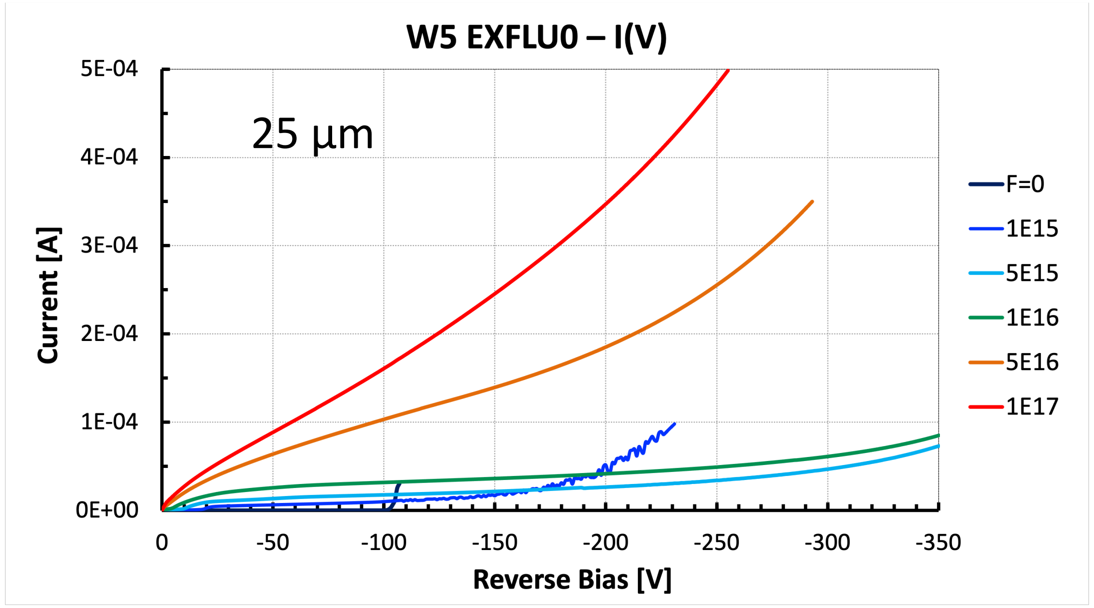


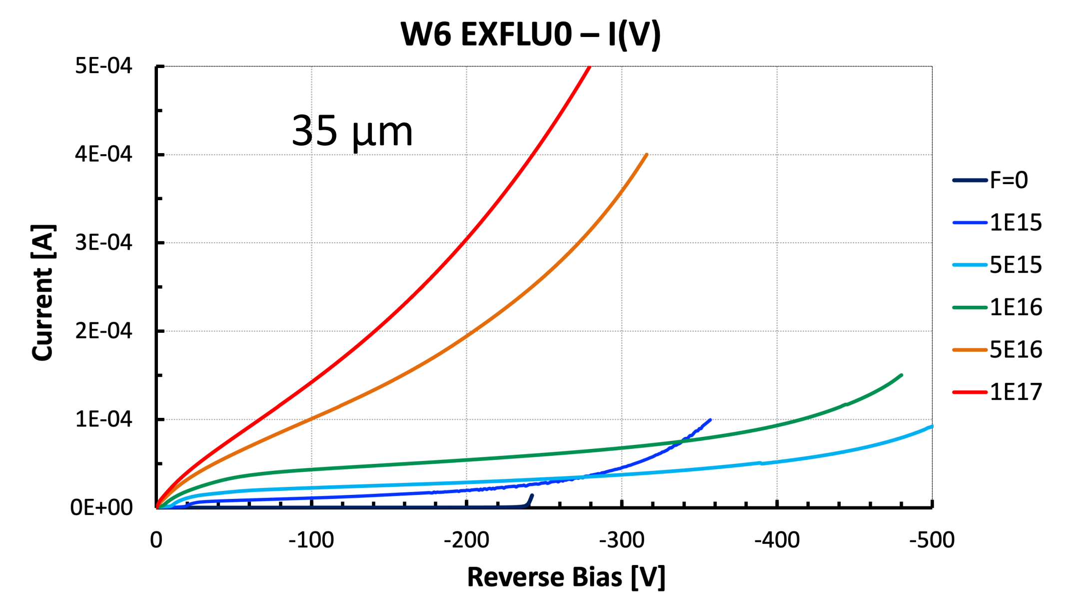
→ R&D on inter-pad and guard-ring structures is mandatory

IV ON IRRADIATED THIN LGAD



EXFLU0 sensors have been irradiated up to 10^{17} n_{eq}/cm^2 at the JSI neutron reactor in Ljubljana
Extremely irradiated sensors arrived in Torino in April 2021



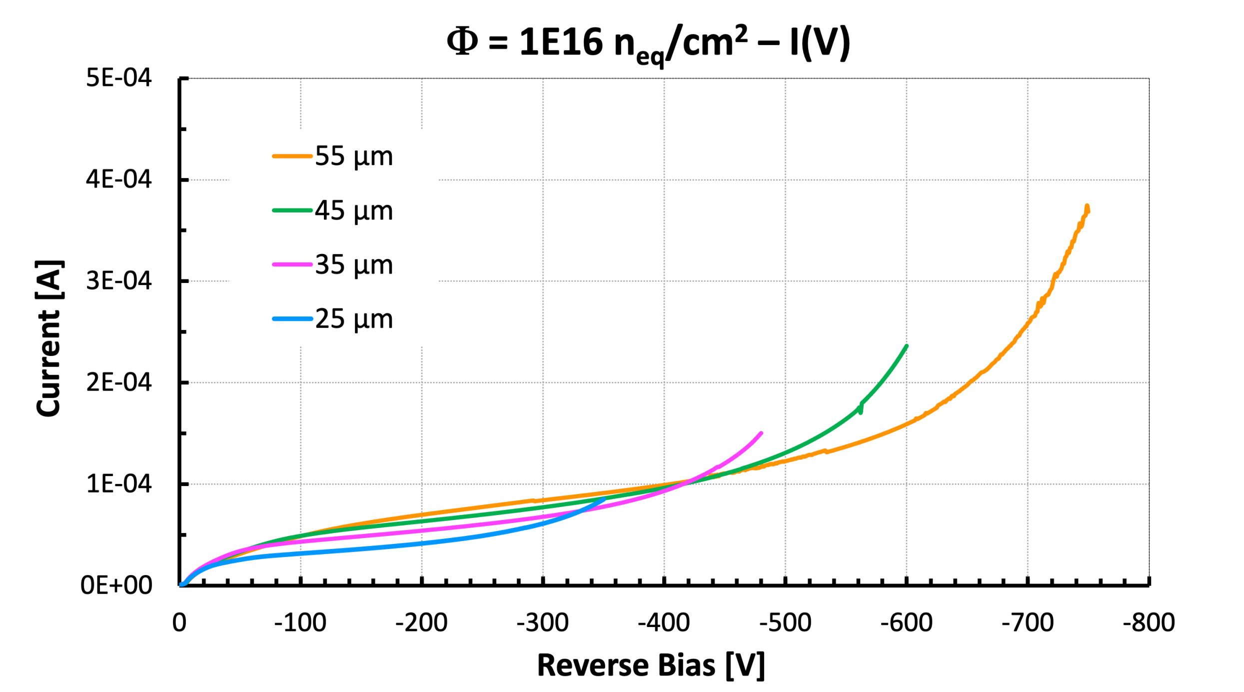


Measurements have been performed at room temperature
→ A rapid increase of the dark current is observed at fluences above 10^{16} n_{eq}/cm^2

⟹ Measurements in reverse and forward bias will be repeated at –30°C

IV AND THICKNESS – Φ = 1E16 n_{eq}/cm^2

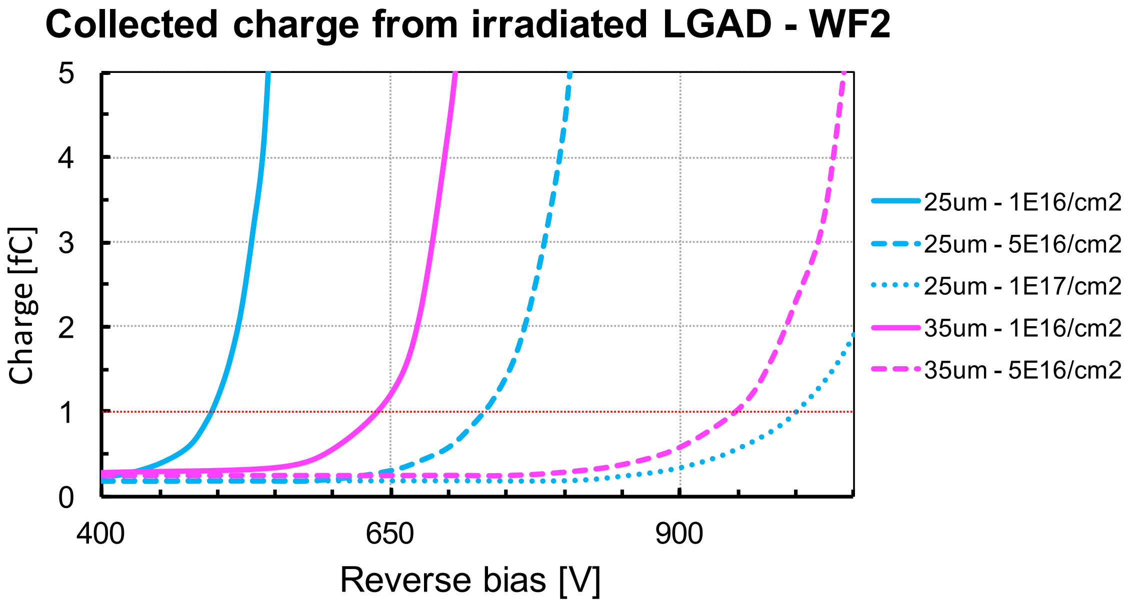
Measurements on irradiated sensors with different active thickness are compared



An increase of the dark current with thickness is observed, as expected

Breakdown voltage due to internal multiplication shifts to higher values for thicker sensors

PREDICTIONS



→ **Thinner sensors provide higher gain after irradiation**

Predictions from Weightfield2 using Massey model for 25 and 35 µm thick sensors**, designed as W5 & W6 UFSD3.2**

[l.infn.it/wf2]

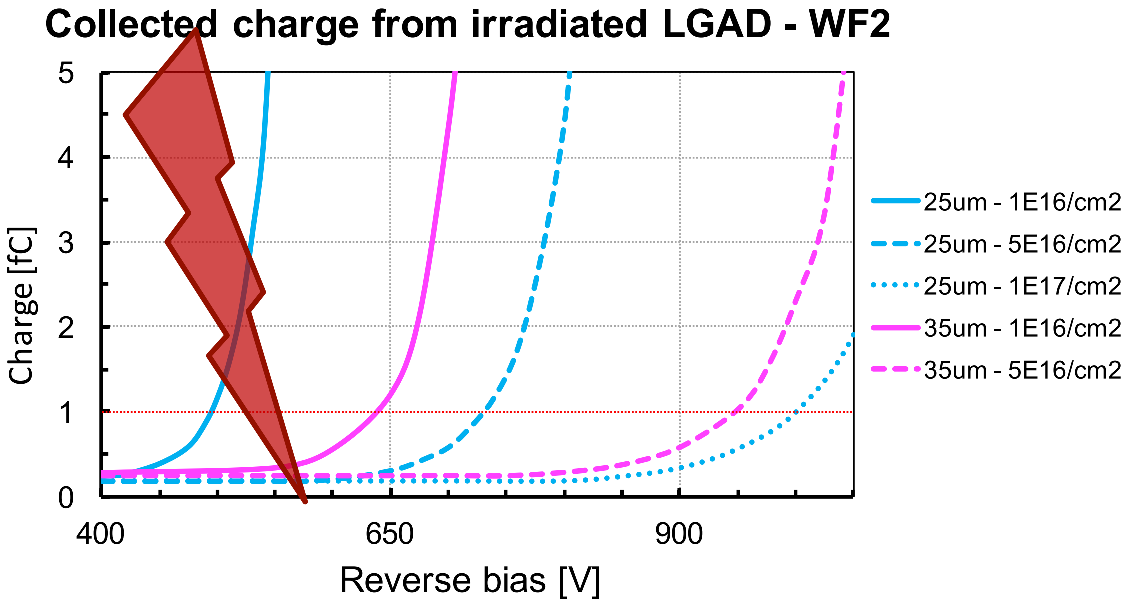
Simulation in progress with the Perugia group [T. Croci, A. Morozzi, F. Moscatelli, D. Passeri] to find the optimal gain layer design for the next production on thin wafers

Perugia model precisely describes behaviour of thin n-in-p sensors up to 1E16 n_{eq}/cm^2

[A. Morozzi et al., doi:10.22323/1.373.0050]

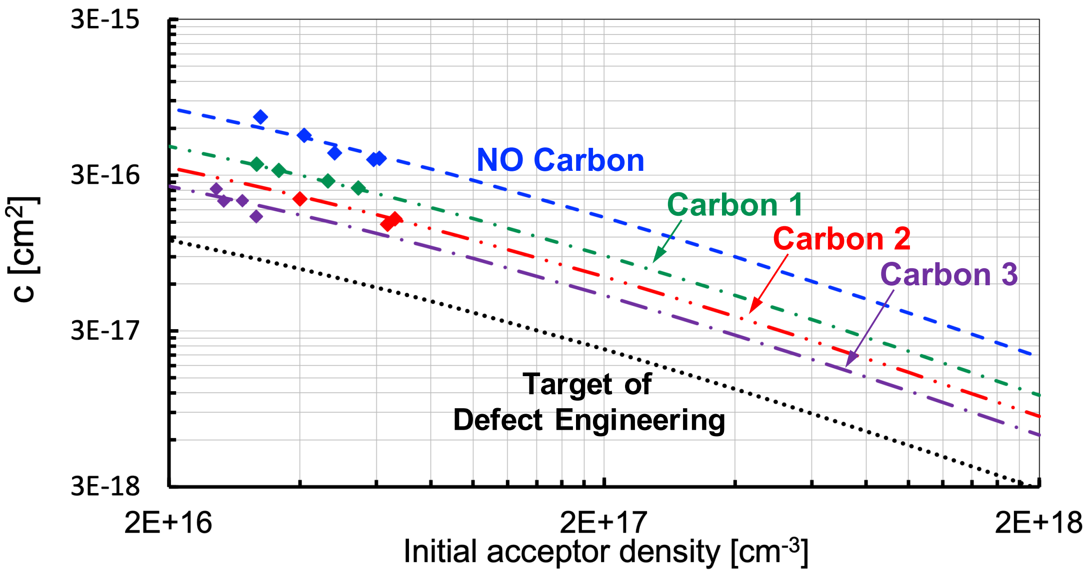
→ **Does it predict thin LGAD performances up to 1E17 n_{eq}/cm^2 ?**

IMPROVE THE GAIN LAYER DESIGN



What happens if the sensor experience breakdown at a bias lower than the one needed to collect 1 fC of charge?

A dedicated program of defect engineering will be pursued, to enhance the radiation tolerance of the gain layer implant, to reduce the minimum bias necessary to collect 1fC



[See M.Ferrero contribution at this conference]

TOWARDS THE EXFLU1 PRODUCTION

The design of the EXFLU1 production is in progress

The production will include

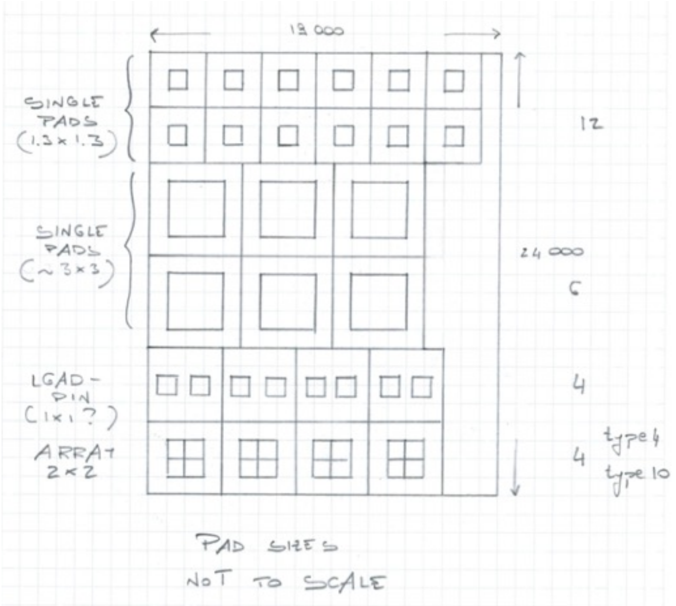
→ different substrate active thicknesses, ranging from 15 µm to 55 µm

→ different design of the gain layer implant, to improve the radiation tolerance

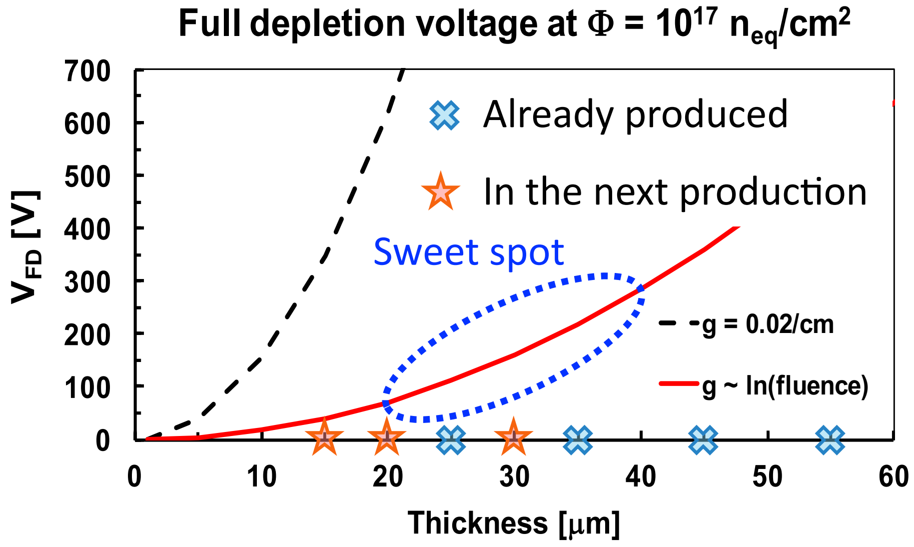
→ defect engineering on the bulk and the gain layer regions

→ optimisation of the guard ring design for thin substrates

⇒ The production is expected by the end of the year



Summary & Outlook



- **R&D of thin silicon sensors for extreme fluences has started**
- **First thin LGAD have been produced at FBK and a new production on thinner substrates will follow soon**
- **Simulation of thin LGAD behaviour under irradiation is ongoing and a comparison with data will be available soon**

⇒ The ultimate goal is to pave the way for the design of silicon sensors able to efficiently record charged particles up to 10^{17} n_{eq}/cm^2 and beyond

ACKNOWLEDGEMENTS

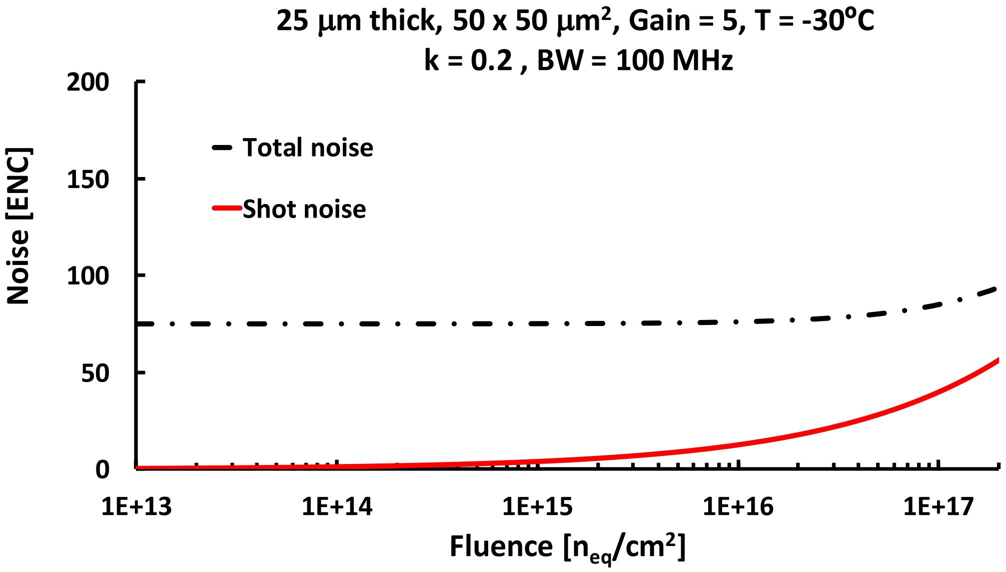
We kindly acknowledge the following funding agencies, collaborations:

- RD50, CERN
- Horizon 2020, grant UFSD669529
- AIDA-2020, grant agreement no. 654168
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare
- INFN CSN5

BACKUP

SHOT NOISE

It is crucial to study the interplay between irradiated thin sensors and the electronics



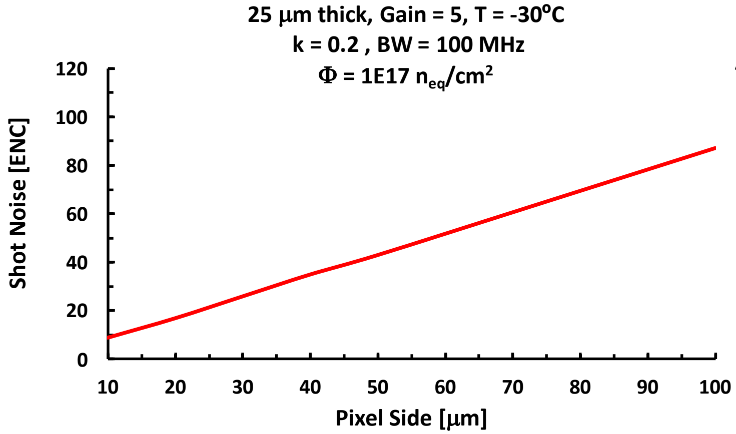
For LGAD sensors, shot noise is given by

$$\sigma_{shot} = \sqrt{2q\left(I_{surface} + I_{bulk}G^2F\right)\Delta f}$$

G = gain

F ~ G^x = excess noise factor (0 < x < 1)

Δf = bandwidth interval



Assuming squared pixels

Shot noise is compared to RD53 chip performances [https://rd53.web.cern.ch/]

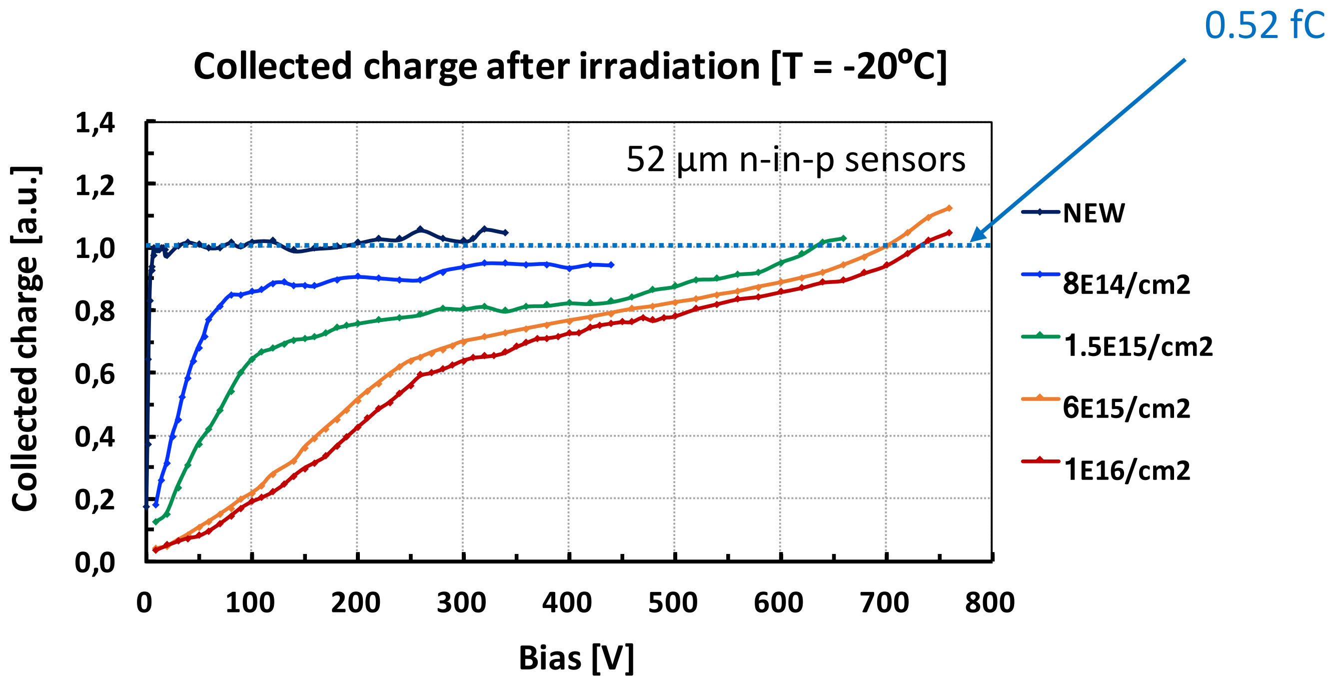
→ To further reduce the shot noise it is possible to decrease the detector operating temperature and the pixel size

HOW THIN?

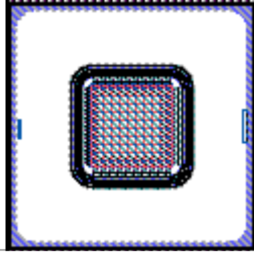
To efficiently record a hit, electronics require al least **1 fC**

MPV charge from a MIP crossing silicon ~ 75 e-h/μm
52 μm thick ⟶ 0.52 fC
25 μm thick ⟶ 0.25 fC

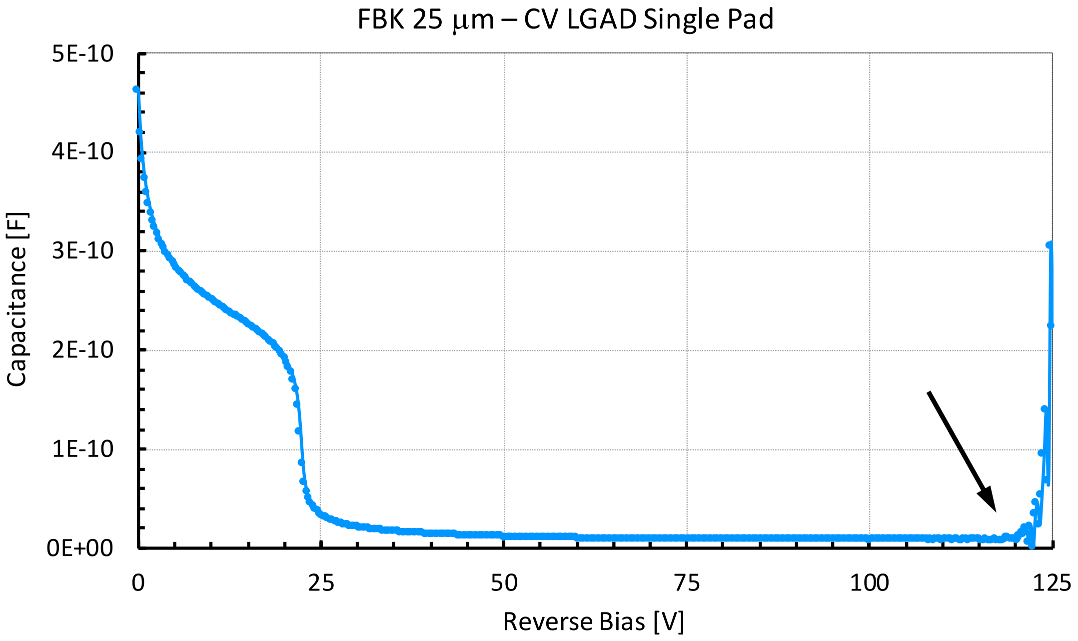
Signal multiplication by a factor of 5-10 is needed

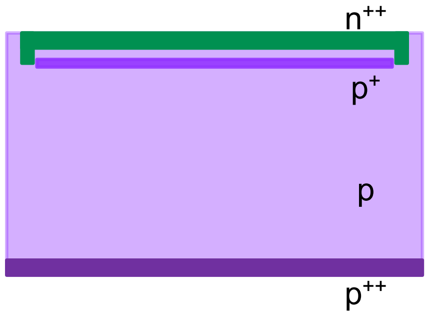


CV ON 25 μm WAFER – Low ρ



It is difficult to precisely control resistivity of thin epitaxial substrates
→ ρ_{W5} ~ 75 Ω·cm

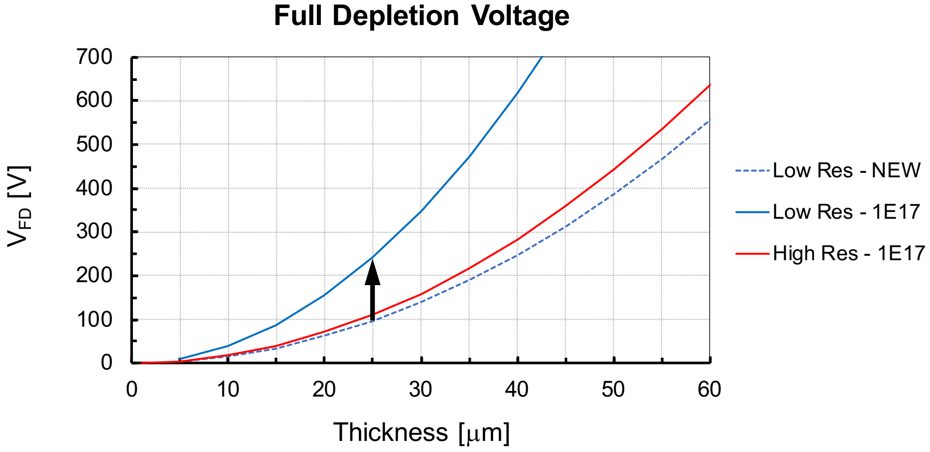




V_{GL} depletion ~ 22 V
V_{bulk} depletion ~ 95 V
Sensor depletion ~ 120 V

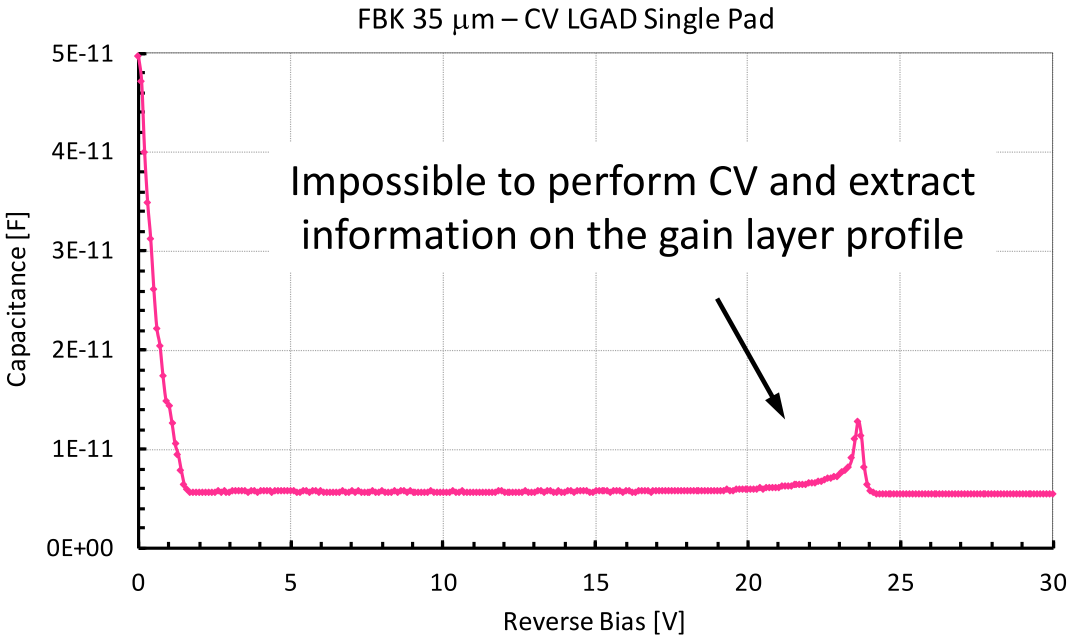
Gain at 120 V ~ 25
Gain at 130 V ~ 40

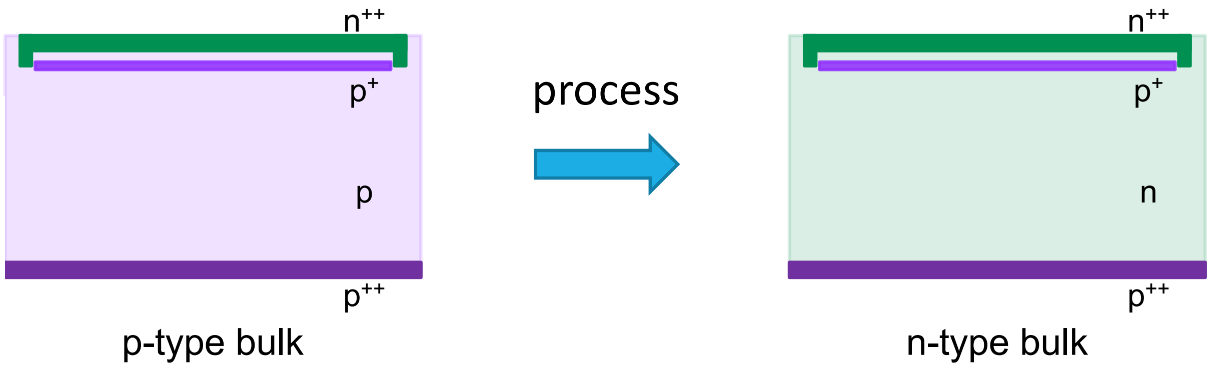
→ **Thanks to saturation V_{FD} of bulk does not increase dramatically with radiation**

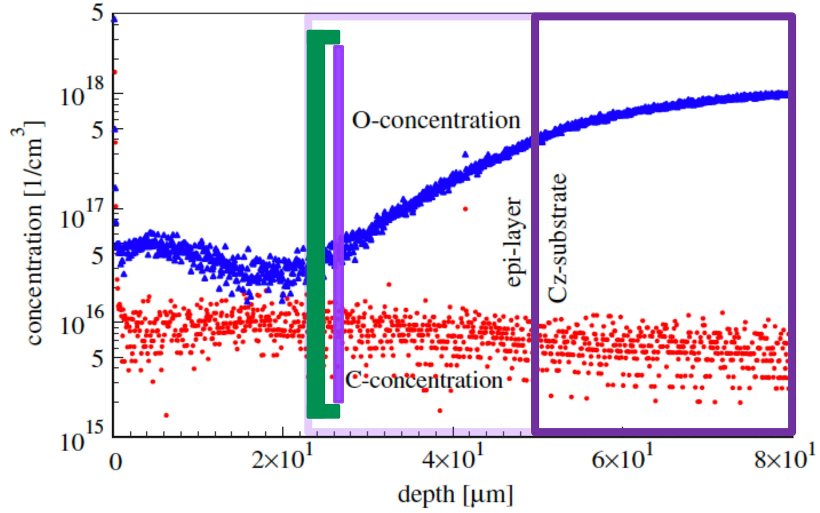


CV ON 35 μm WAFER – High ρ

It is difficult to precisely control resistivity of thin epitaxial substrates
→ ρ_{W6} ~ 3,000 Ω·cm





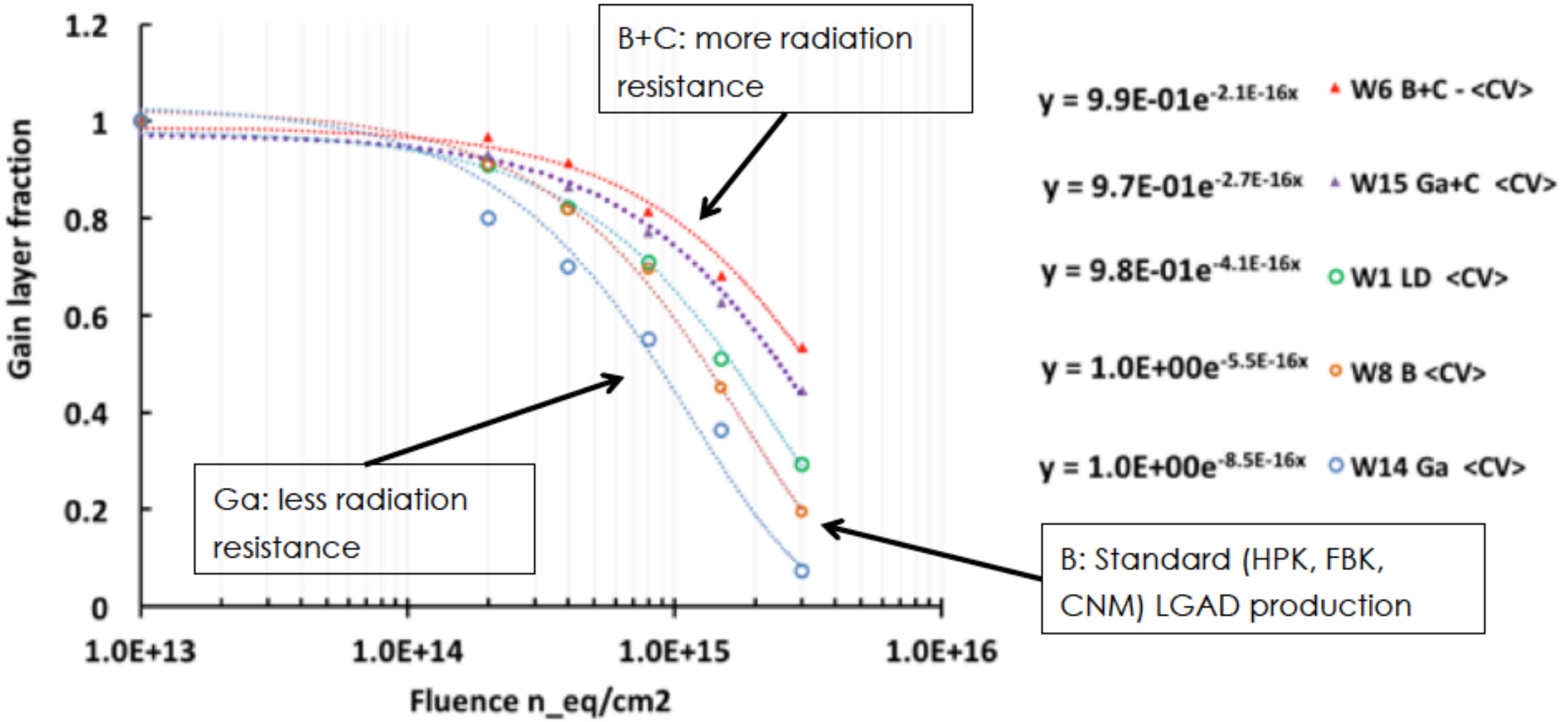


[I. Pintilie 2005 et al., doi:10.1016/j.nima.2005.10.013]

→ **Due to Oxygen diffusion from the support wafer, the active substrate undergo type inversion**

GAIN LAYER RADIATION TOLERANCE

UFSD suffer for gain reduction due to irradiation
FBK used both Boron and Gallium as gain layer dopant, and added Carbon in the gain layer volume



⇒ **The usage of Carbon double the radiation hardness of UFSD**

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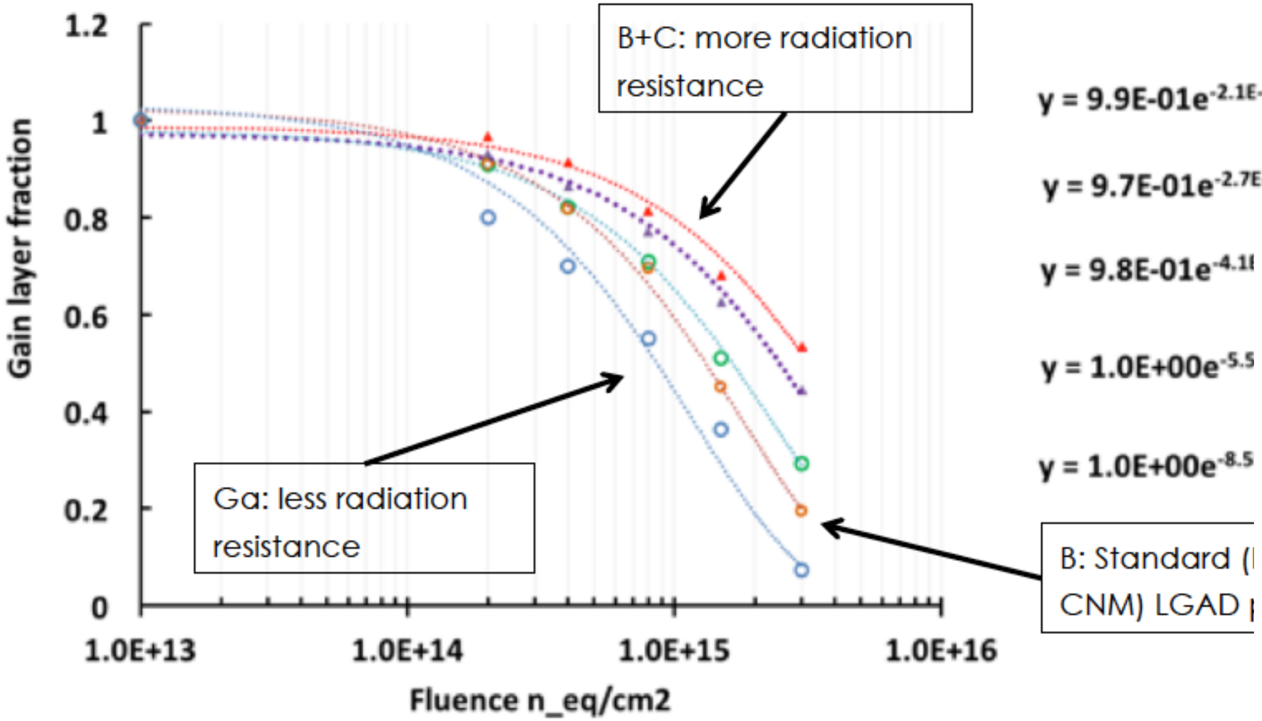
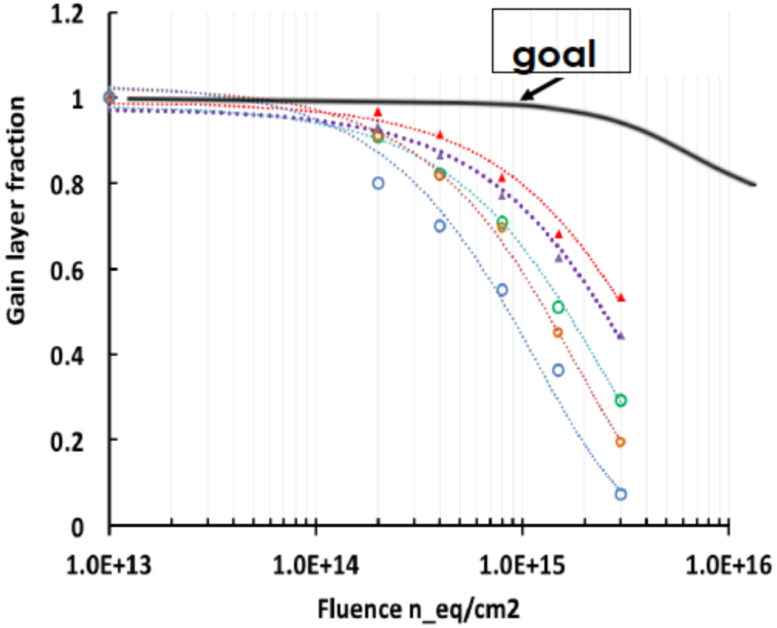
UFSD suffer for gain reduction due to irradiation

FBK used both Boron and Gallium as gain layer dopant, and added Carbon in the gain layer volume



Future R&D



⇒ The usage of Carbon double the radiation hardness

GAIN LAYER RADIATION TOLERANCE

Goal: retard multiplication transition from the gain layer to the bulk region

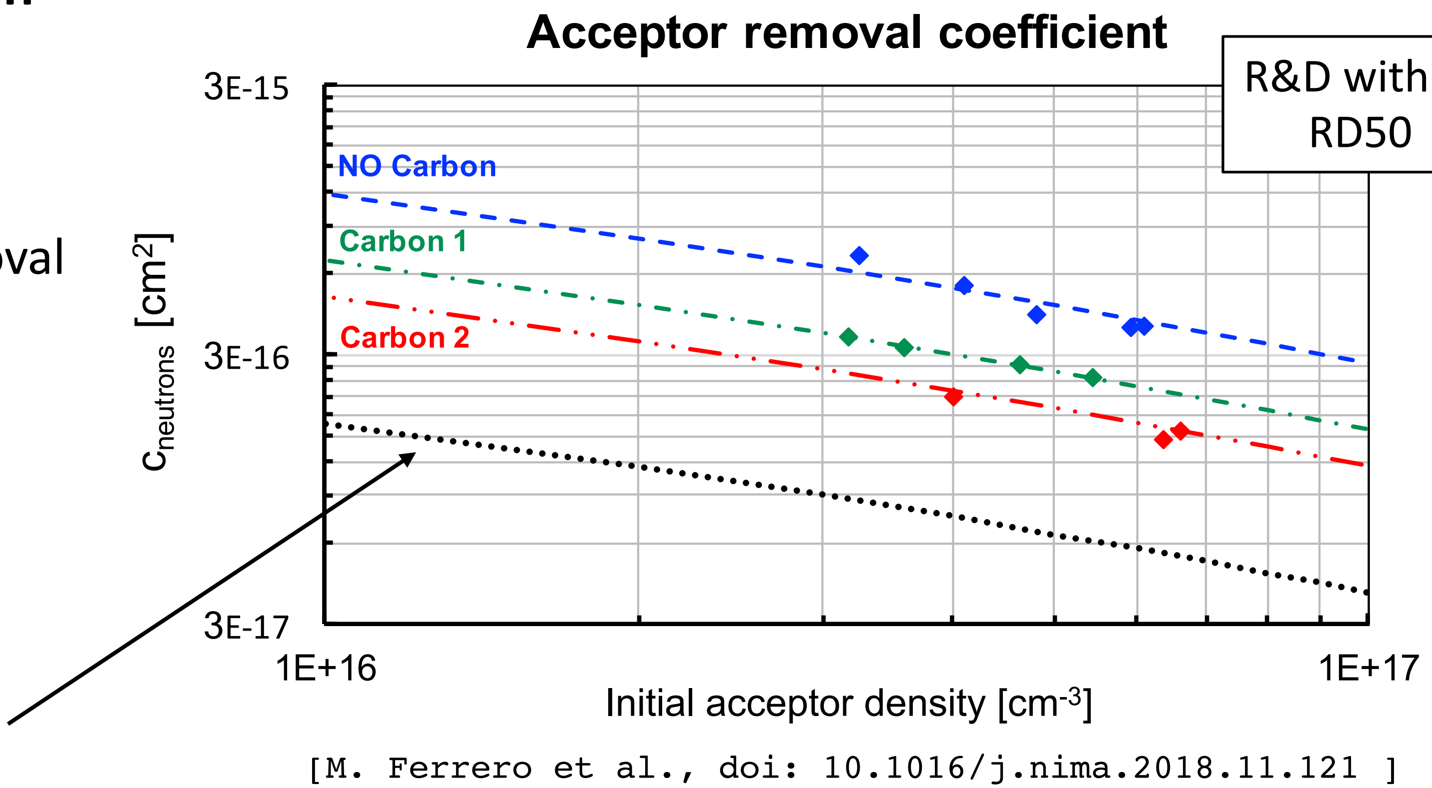
Acceptor removal:

$$N_{A,eff} = N_{A,0} \cdot e^{c\Phi}$$

Adding carbon protects boron from removal
Different carbon concentrations have different impact on boron protection

→ **Gain layer engineering to extend its contribution to $5 \cdot 10^{16}$ n_{eq}/cm^2**

R&D within RD50



[M. Ferrero et al., doi: 10.1016/j.nima.2018.11.121]

GAIN LAYER RADIATION TOLERANCE

Goal: retard multiplication transition from the gain layer to the bulk region

Acceptor removal:

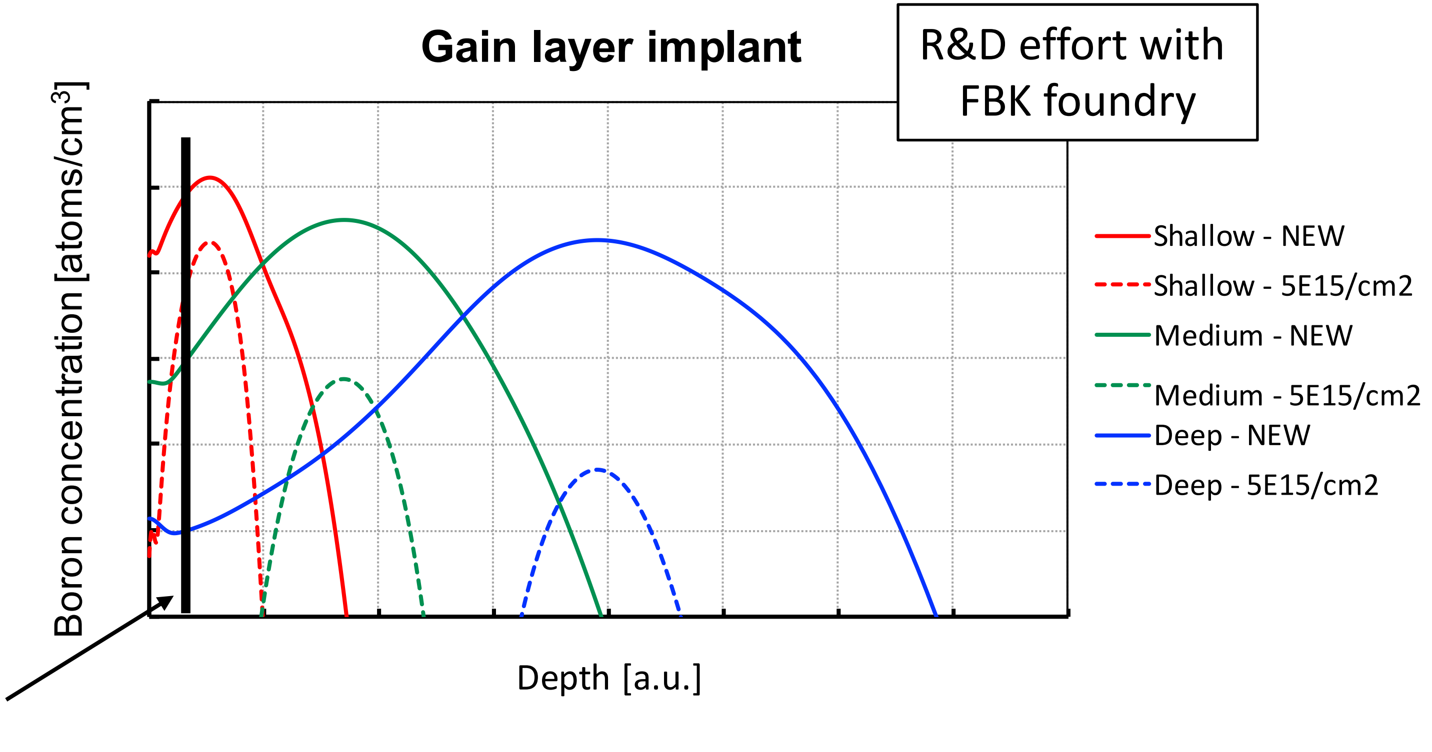
$$N_{A,eff} = N_{A,0} \cdot e^{c\Phi}$$

Defect engineering and different gain layer implantation strategies will be investigated

$$\mathbf{c \cdot N_{A,0} = 60\ cm^{-1} \rightarrow\ < 10\ cm^{-1}}$$

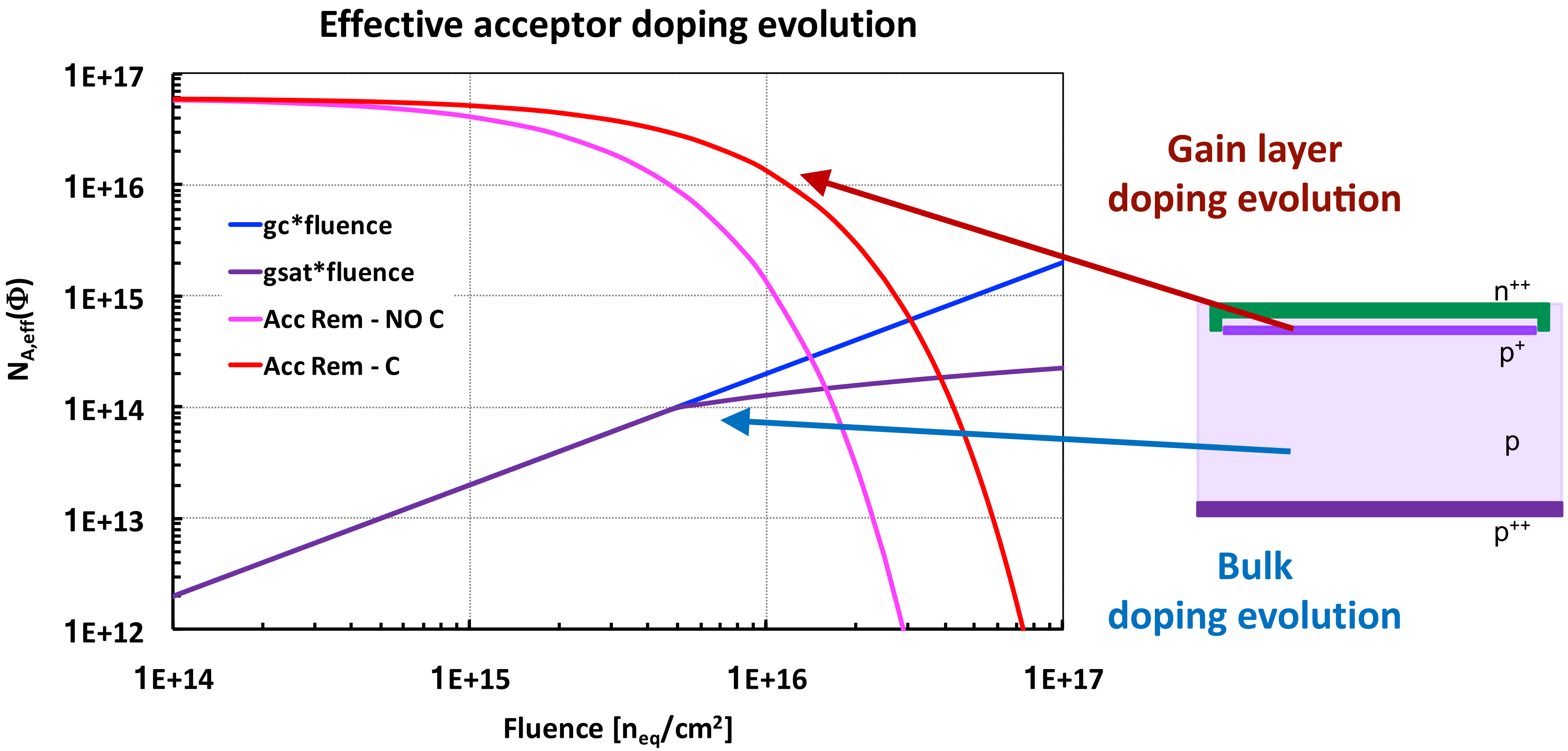
for $N_{A,0} = 10^{17}$ atoms/cm^3

R&D effort with FBK foundry



ACCEPTOR DOPING EVOLUTION WITH Φ

$$N_{A,eff}(\Phi) = g_c \cdot \Phi + N_A(0) \cdot e^{-c \cdot \Phi}$$



GAIN SIMULATION ON THIN PiN

To nicely reproduce data, a quenching factor on bulk gain need to be introduced (Massey model is used)

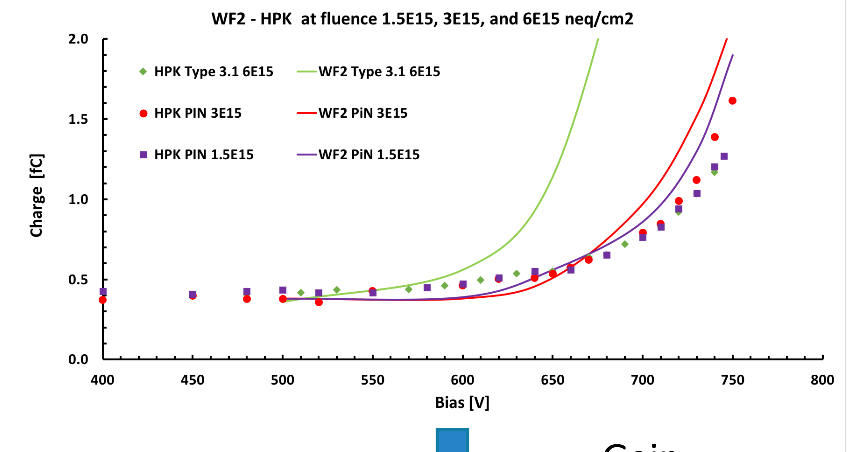
$$G \propto e^{\alpha(E,T)*d}$$

$$\alpha \propto e^{-(a+b*T+c*\emptyset)/E}$$

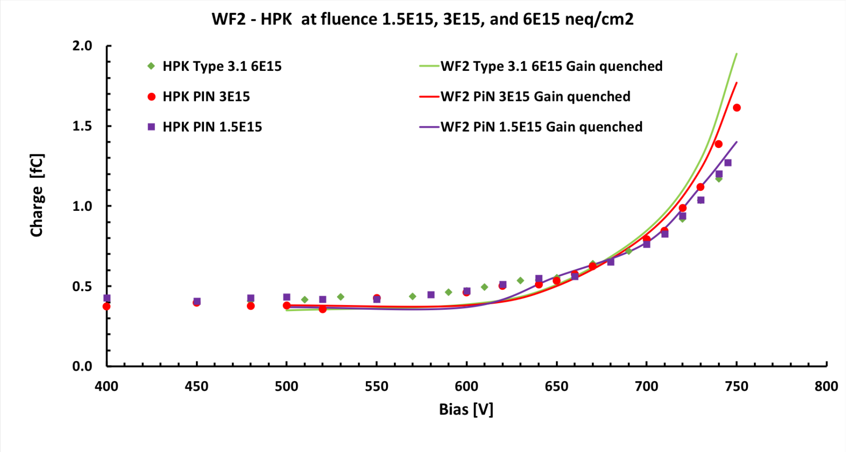
Using data on charge multiplication in PiN and the measured bulk doping, a value of c can be determined

$$\mathbf{c = 2 * 10^{-11}\ V/\emptyset}$$

[N. Cartiglia, https://indico.cern.ch/event/812761/contributions/3459057]



Gain quenching



eXFlu PROJECT

INFN awarded for funding the *Silicon Sensor for Extreme Fluences (eXFlu)* project[*]
to develop, produce, irradiate and study thin silicon sensors (V. Sola as PI)

The eXFlu project aims to

→ Optimise the design of thin silicon sensors

→ Measure the onset and the magnitude of saturation effects in thin sensors

→ Map the shift of multiplication from the gain layer to the bulk

→ Study the signal multiplication mechanism in highly irradiated sensors – does it disappear at very high fluences?

→ Collaborate with colleagues to extend radiation damage models (RD50, Perugia, ...)

[*] Award funding for one over six projects presented by young researchers in the fields of research and technological development carried out by the Institute (Announcement No.21188)

eXFlu IN A GLANCE

- **Involved institutes:**
  INFN Torino and FBK

- **Work Packages:**
  WP1: sensor simulation and design
  WP2: sensor production
  WP3: irradiation (n, p, π ...)
  WP4: laboratory characterisation and signal analysis
  WP5: beam test

- **Total budget:**
  ~ 130k euro

eXFlu EXPECTED OUTCOMES

- Measure silicon properties in an unexplored region of radiation fluences
- Study of saturation of radiation effects in thin silicon sensors
- Understanding of impact ionisation mechanism in highly irradiated sensors
- Contribute to building models for very irradiates silicon detectors

⇒ The ultimate goal is to pave the way for the design of silicon sensors able to efficiently record charged particles up to 10^{17} n_{eq}/cm^2 and beyond

eXFlu TEAM

The eXFlu project consists of 2 Research Units: one centered on the sensor design, irradiation and test (INFN – Torino) while the other on the sensor fabrication (FBK)

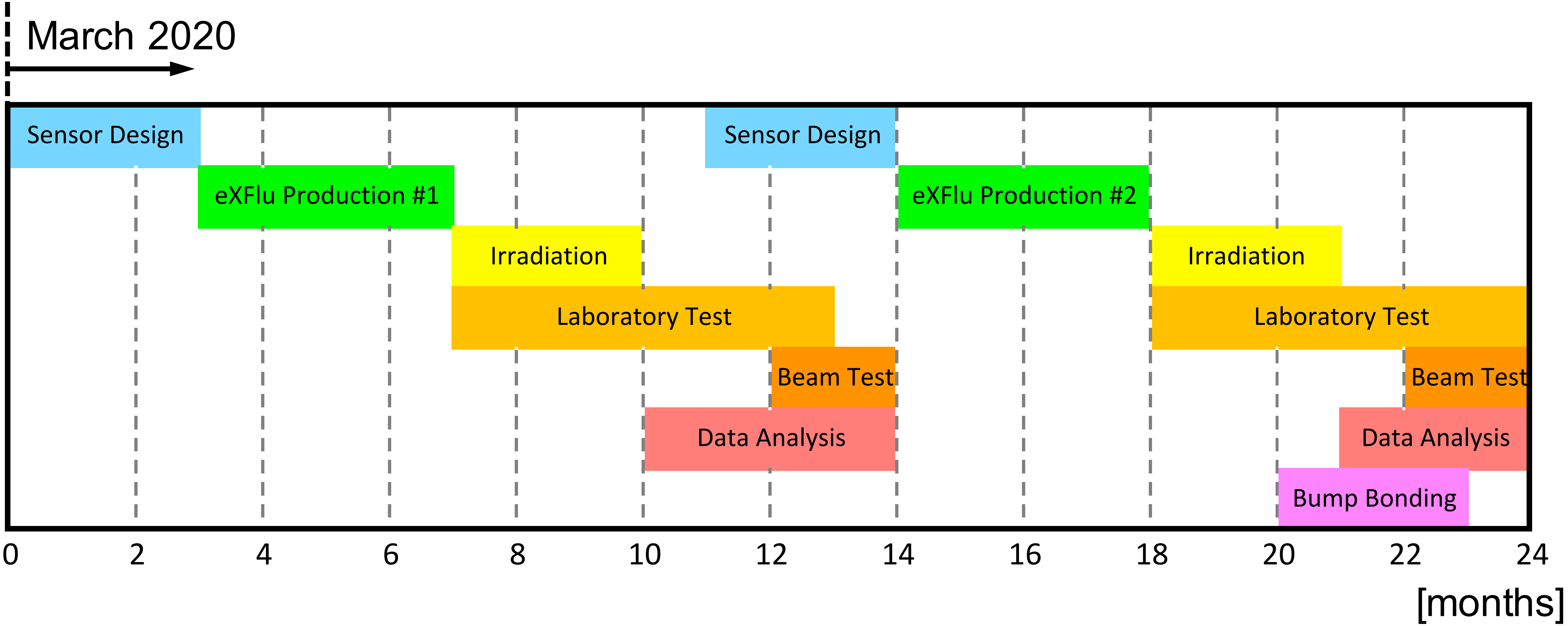
- **INFN, Torino**
  - **Valentina Sola** (PI), particle physicist expert both in data analysis and detector R&D, involved in the development and characterisation of Ultra-Fast Silicon Detectors, actively participating to laboratory and beam tests, organisation of irradiation campaign, and supervision of students
  - **Simona Giordanengo**, researcher at INFN Torino; **Ennio Monteil**, technician at the Physics Department of the University of Torino; **Marta Tornago**, Ph.D. student at Torino University
- **FBK, Trento**
  - **Maurizio Boscardin**, senior researcher at Fondazione Bruno Kessler in Trento; **Giacomo Borghi**, researcher at Fondazione Bruno Kessler in Trento

→ **The team includes a diverse composition of expertise, well fitted to the project**
→ **The project can rely on a fully functional laboratory**

eXFlu BUDGET TABLE

Item	First year		Second year		Total (Euros)
	Cost per unit (Euros)	Units	Cost per unit (Euros)	Units	
Wafers (Epitaxial)	80	25			2.000
Wafers (Si-Si DWB FZ)	300	20			6.000
LGAD Production	30.000	1	30.000	1	60.000
Chiller	30.000	1			30.000
Irradiation	3.000		3.000		6.000
Bump-bonding			10.000		10.000
Read-out boards			400	10	4.000
Travel	3.000		10.000		13.000
Total	**74.000**		**57.000**		**131.000**

eXFlu TIMELINE



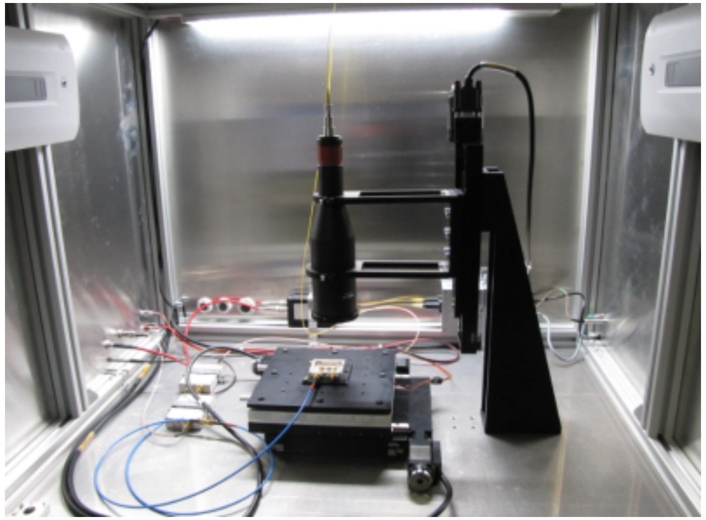
COOL SYSTEMS

A key aspect of eXFlu project is to be able to perform measurement on irradiated sensors at low temperatures

→ Preparation of cold setups in progress

MPI TS200-SE Manual Probe Station
with temperature range from -40 to +300°C
will arrive soon in Torino Laboratory

Vötsch VCL4010 Test Chamber
with temperature range from -40 to +180°C
available in Torino Laboratory

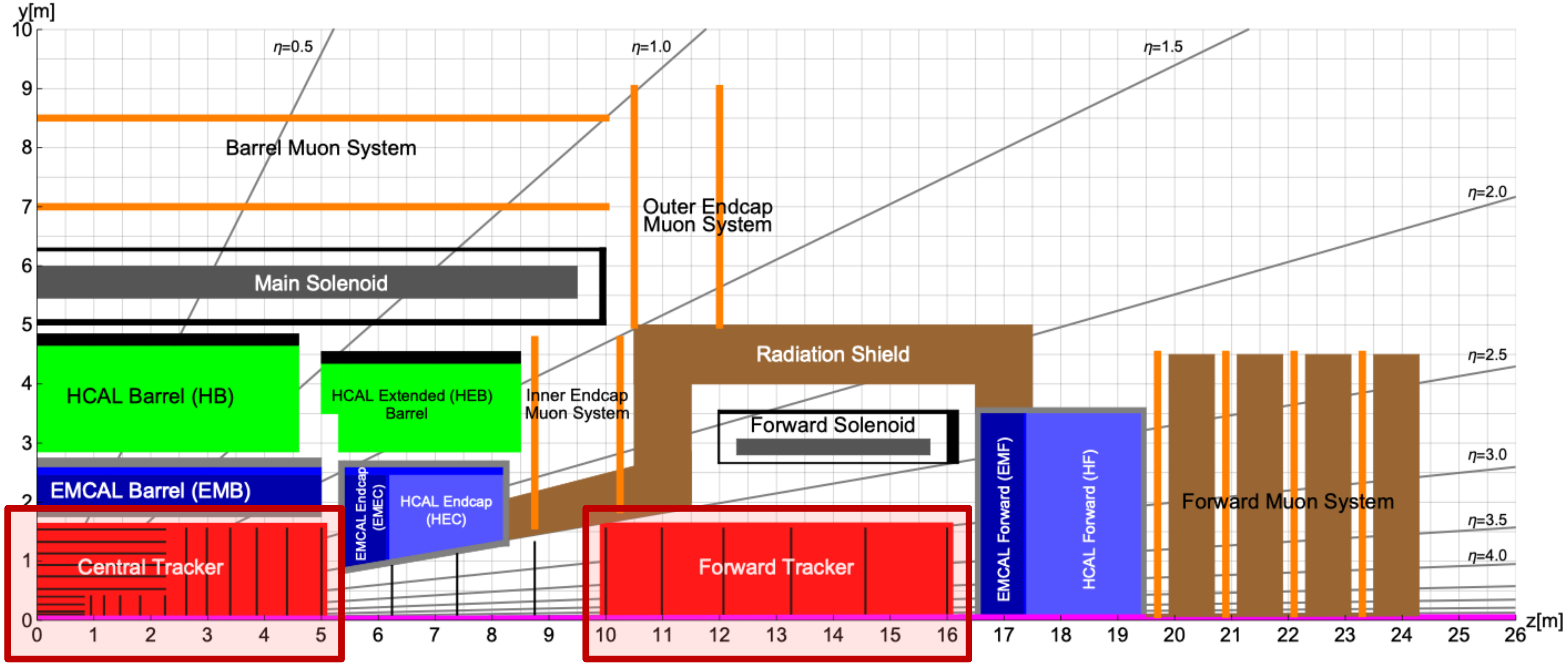


Particulars Large Scanning TCT setup
connected to Lauda chiller down to -20°C
available in Torino Laboratory

TRACKING AT FUTURE HADRON COLLIDER

Next generation high-energy and high-intensity hadronic collider ⟶ FCC-hh

FCC-hh reference detector



The tracker

[http://cds.cern.ch/record/2651300]

Running conditions:

- Pile-up per bunch crossing ~ 1000
- Vertex region σ_z ~ 44 mm, σ_t ~ 165 ps
- Average distance between vertices at z = 0 is 125 μm

Tracker requirements:

- $\sigma_{r\phi}$ = 7.5 - 9.5 μm
- Low material budget N_{layers} = 12
- Effective pile-up = 1 σ_t = 5 ps

RADIATION BUDGET - TRACKER VOLUME

Fluence foreseen at L_{int} = 30 ab^{-1}

Courtesy of M.I. Besana