INFN TORINO

15th Trento Workshop on Advanced Silicon Radiation Detectors

eXFlu

Silicon Sensors for Extreme Fluences

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Fisica Torino Dipartimento di Eccellenza

FONDAZIONE BRUNO KESSLER

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?**

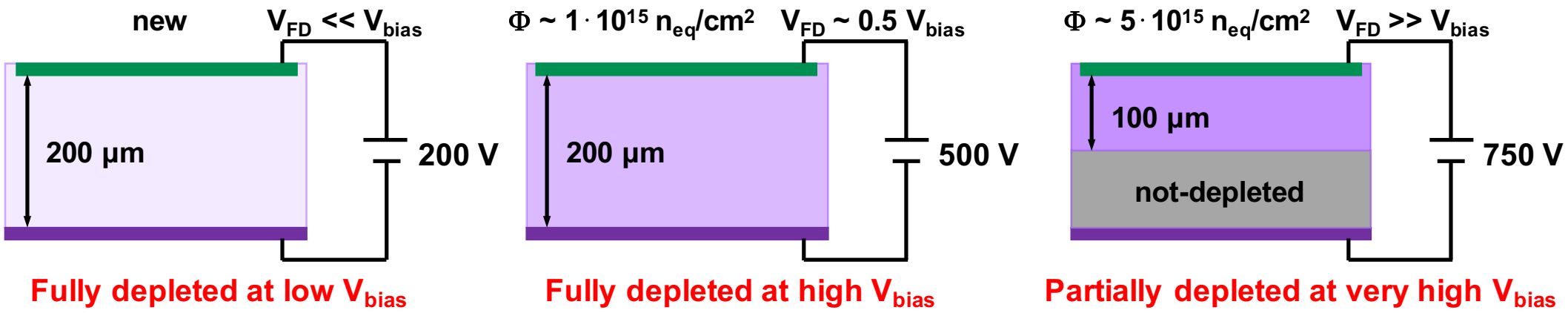
⇒ The R&D to answer these questions is starting now

EFFECTS OF RADIATION ON SILICON SENSORS

Irradiation results in 3 main effects:

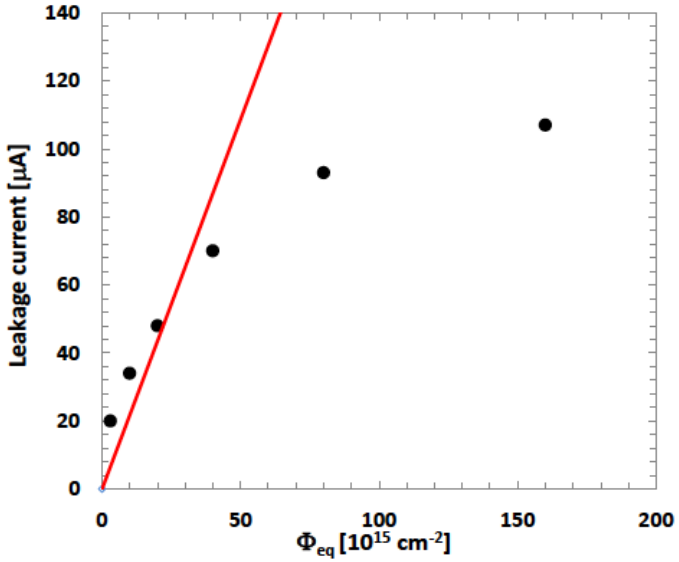
- Decrease of the collected charge due to trapping effects
- Increase of the dark current
- Change in effective doping
  - → increase of the reverse bias to operate the sensor
  - → distortion of the electric field inside the sensor

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



SOME OPTIMISM – SATURATION

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

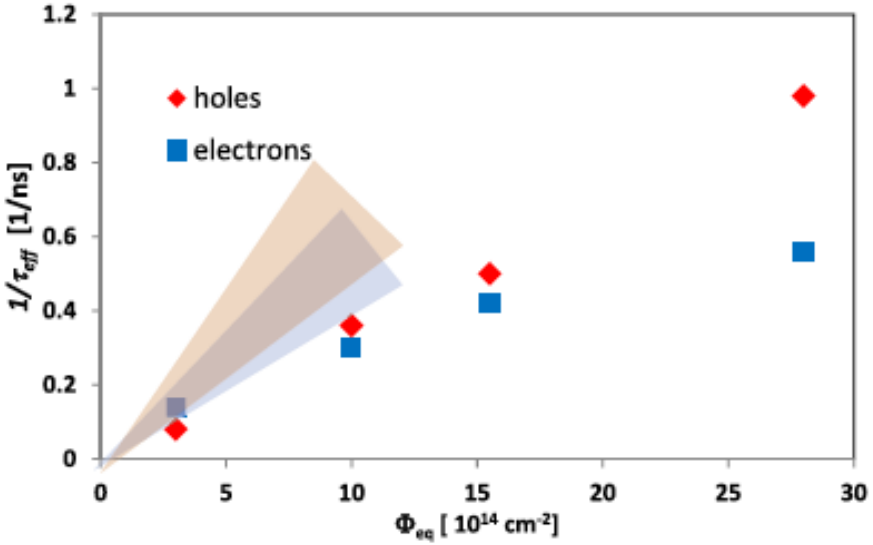


[G. Kramberger et al., doi:10.1088/1748-0221/8/08/P08004]

Leakage current saturation

$I = \alpha V \Phi$

α from linear to logarithmic

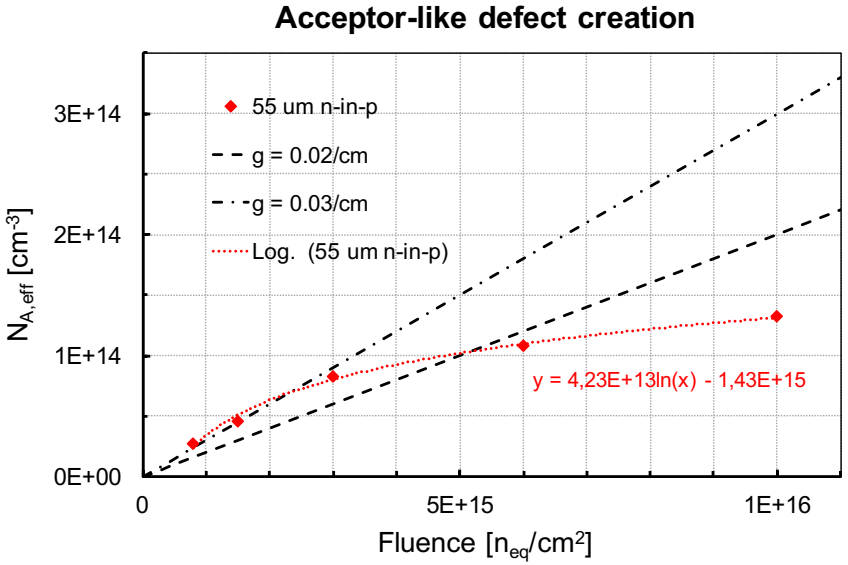


[G. Kramberger et al., doi:10.1016/j.nima.2018.08.034]

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

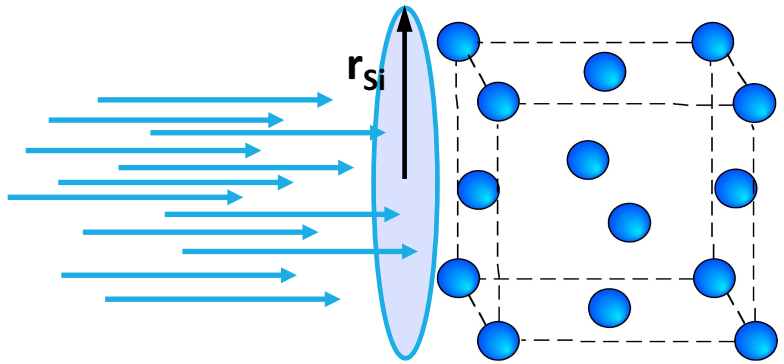
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

WHY SATURATION?

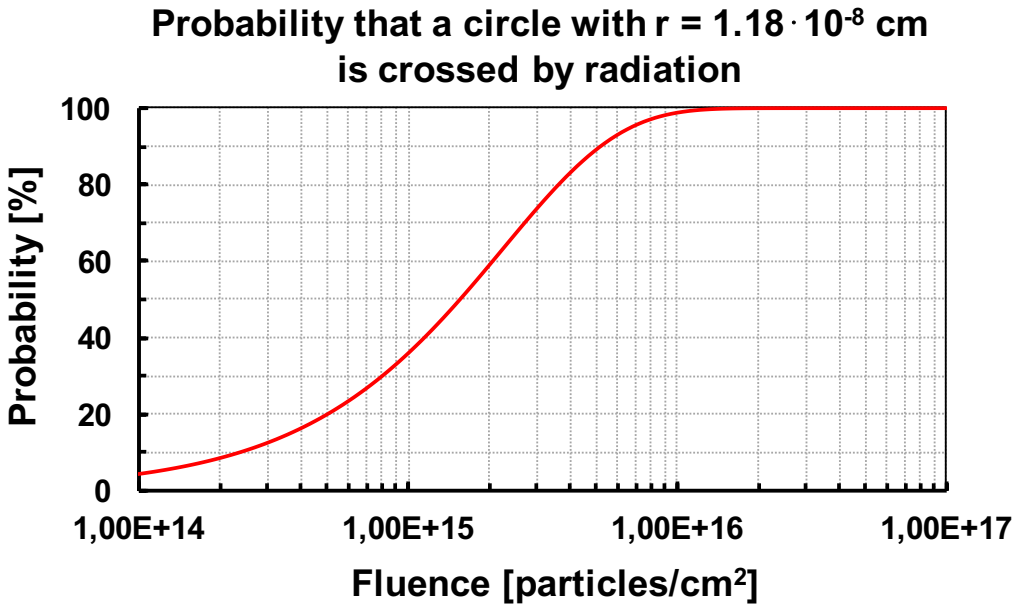
Possible explanation:

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

$r_{Si} = 1.18 \cdot 10^{-8}$ 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:

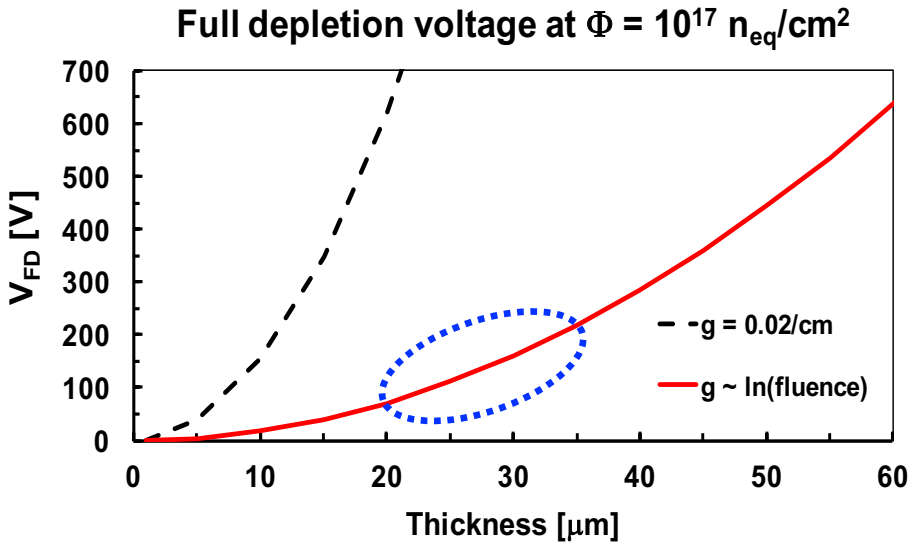
damage happening on already damaged Silicon might be different

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 happens to a 25 μm sensor after a fluence of $5 \cdot 10^{16}$ 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 a gain of at least ~ 5 in order to provide enough charge

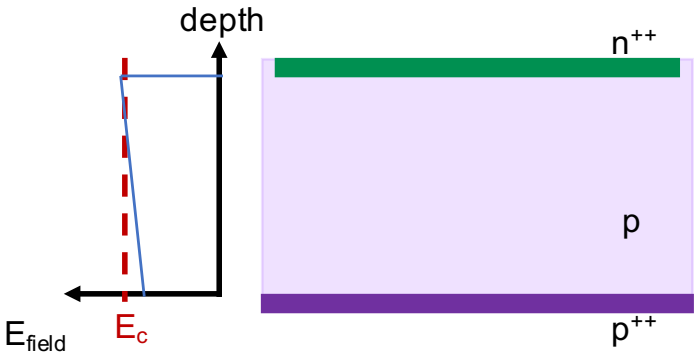
SENSOR CHOICE

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

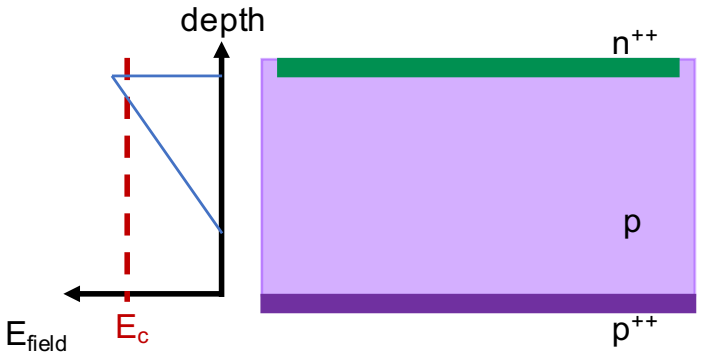
2) This length is controlled by applied V_{bias}



n-in-p
p ~ 10^{12} cm^{-3}

E_{field} above E_c
over long distance

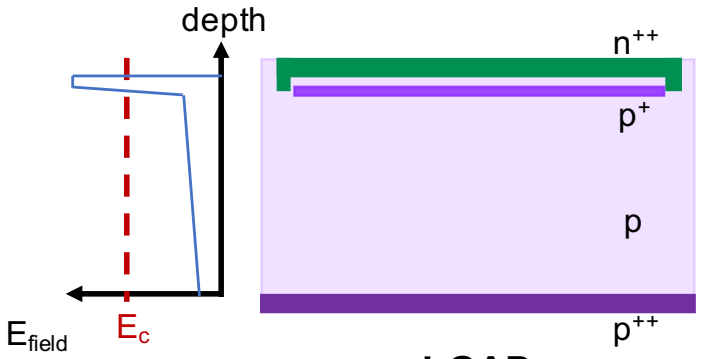
AVALANCHE



n-in-p
p ~ 10^{14} cm^{-3}

Difficult to precisely
control E_{field}

RISK OF AVALANCHE



LGAD
p ~ 10^{12} cm^{-3}, p^+ ~ 10^{16} cm^{-3}

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

CONTROLLED GAIN

SENSOR CHOICE

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

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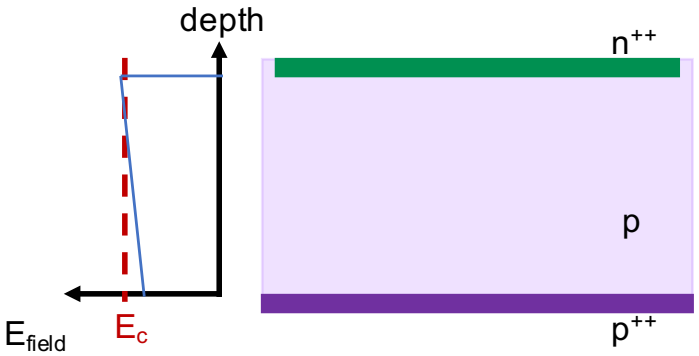

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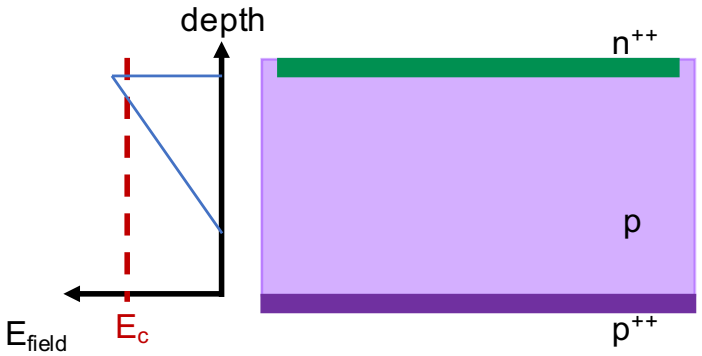

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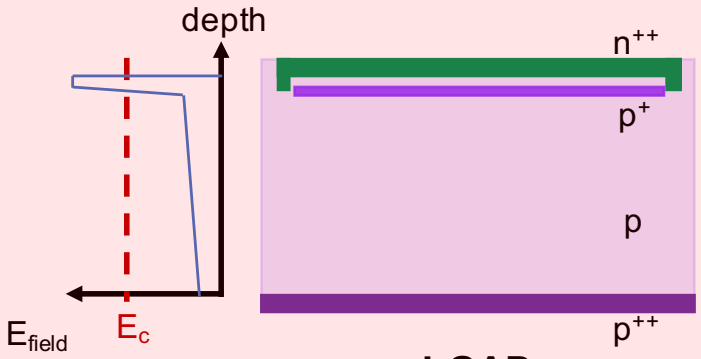
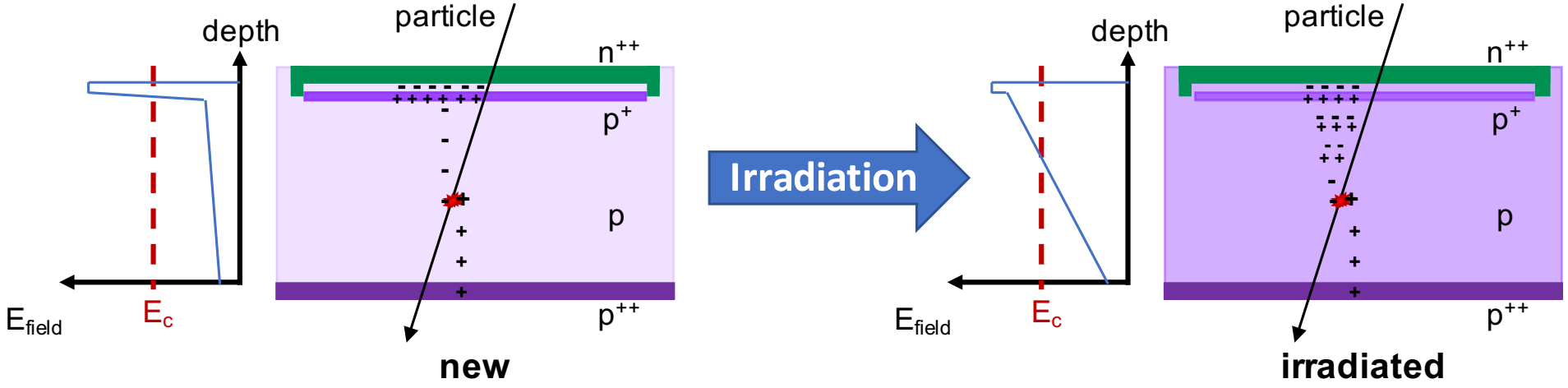


LGAD
p ~ 10^{12} cm^{-3}, p^+ ~ 10^{16} cm^{-3}

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

CONTROLLED GAIN

IRRADIATED LGAD



- Start with a thin LGAD, 20 – 35 μm thick (to be optimized)
- **$2 \cdot 10^{15} – 5 \cdot 10^{15}$ n_{eq}/cm^2**: with increasing fluence, the gain layer is deactivated
- **$5 \cdot 10^{15} – 10^{16}$ 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 solely on bulk multiplication

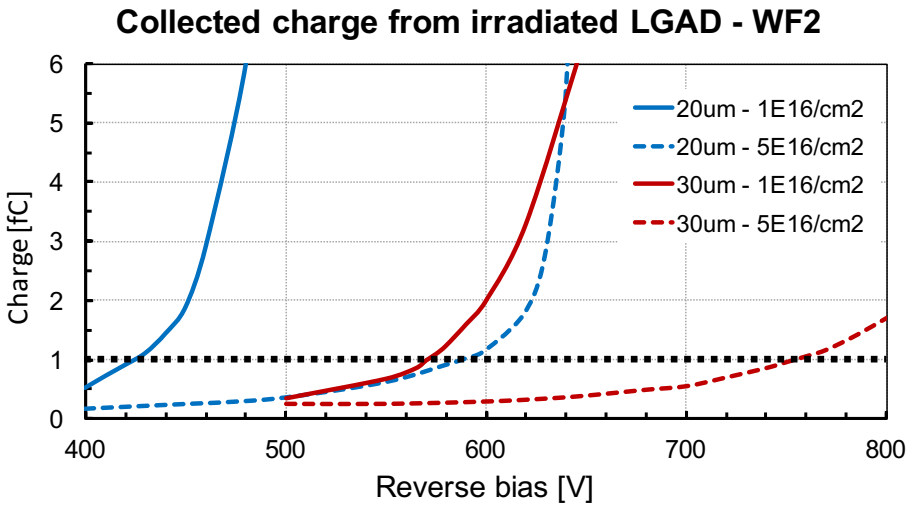
  → **Does bulk multiplication exist at these fluences?**

SENSOR R&D

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

Predictions from Weightfield2 using van Overstraeten – de Man model for 20 and 30 µm thick sensors**, providing 5 fC of charge at 120 V when new**

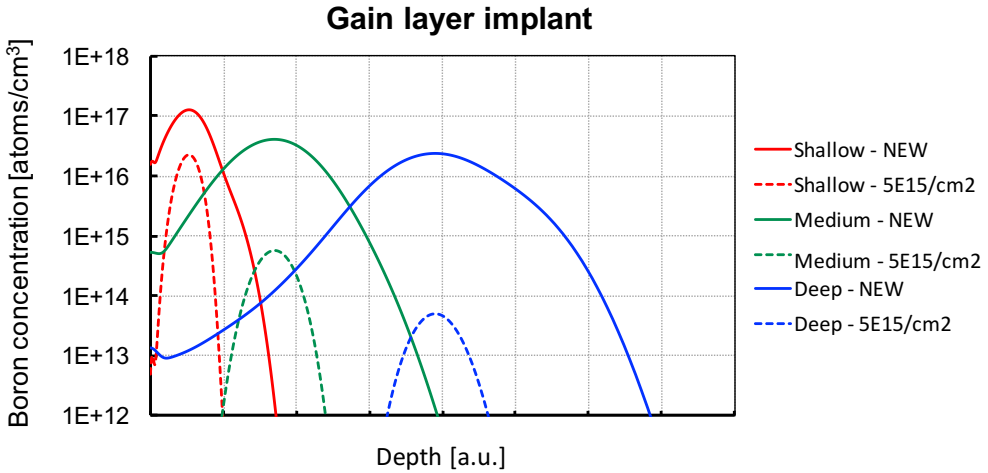
[personalpages.to.infnf.it/~cartigli/Weightfield2/Mail.html]



→ **R&D on the gain layer to retard multiplication shift from the gain layer to the bulk region**

Defect engineering and different gain layer implantation strategies will be investigated

R&D efforts with the FBK foundry



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

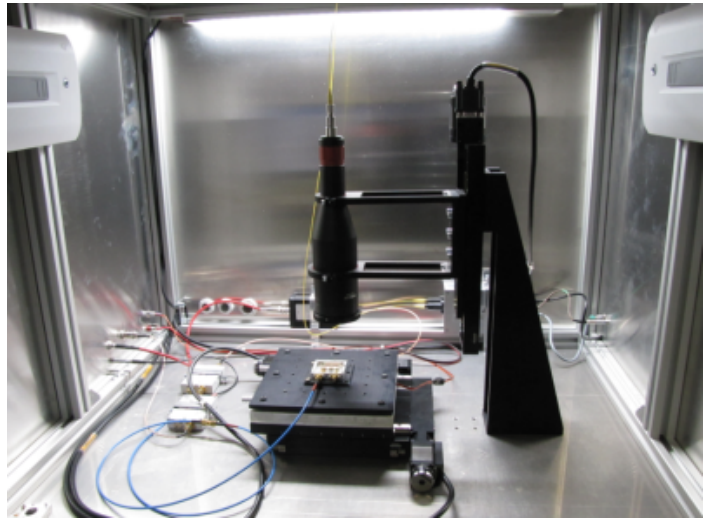
eXFlu SETUP – COOL SYSTEMS

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

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

ACKNOWLEDGEMENTS

We kindly acknowledge the following funding agencies, collaborations:

- Horizon 2020, grant INFRAIA
- Horizon 2020, grant UFSD669529
- AIDA-2020, grant agreement no. 654168
- U.S. Department of Energy, grant DE-SC0010107
- Ministero degli Affari Esteri, Italy, MAE, “Progetti di Grande Rilevanza Scientifica”
- 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, Gruppo V
- RD50, CERN

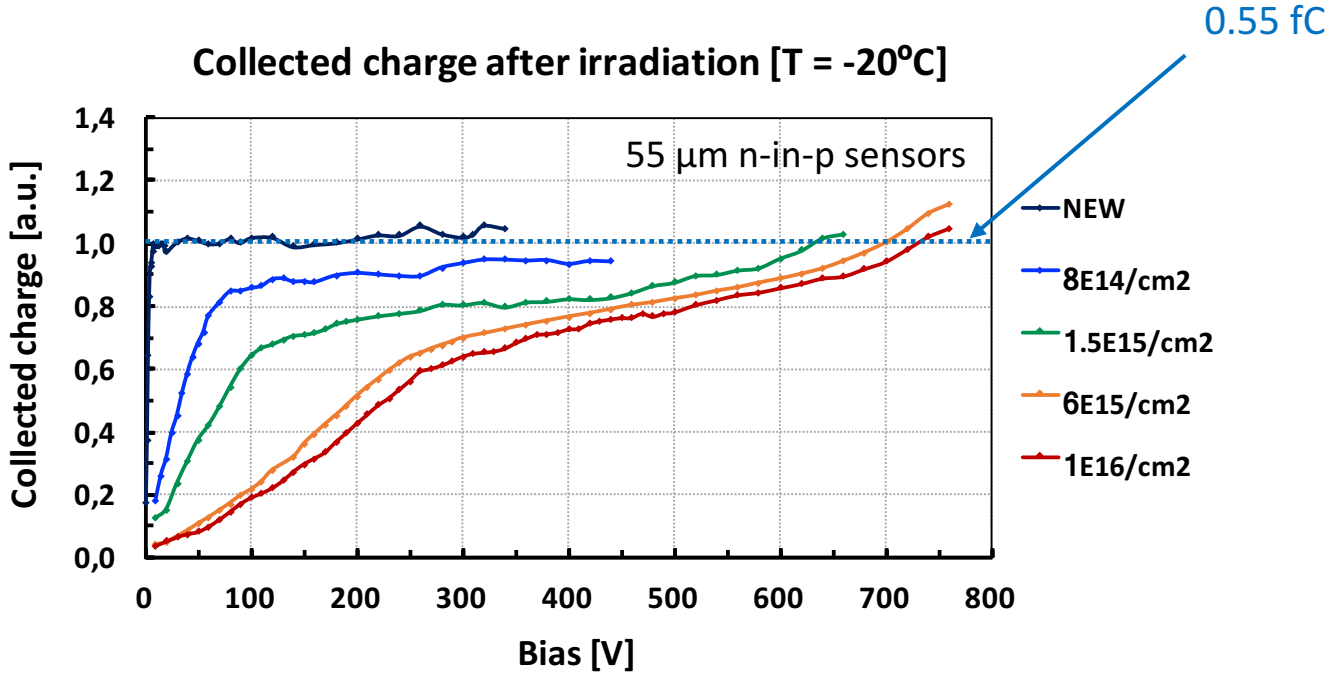
BACKUP

HOW THIN?

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

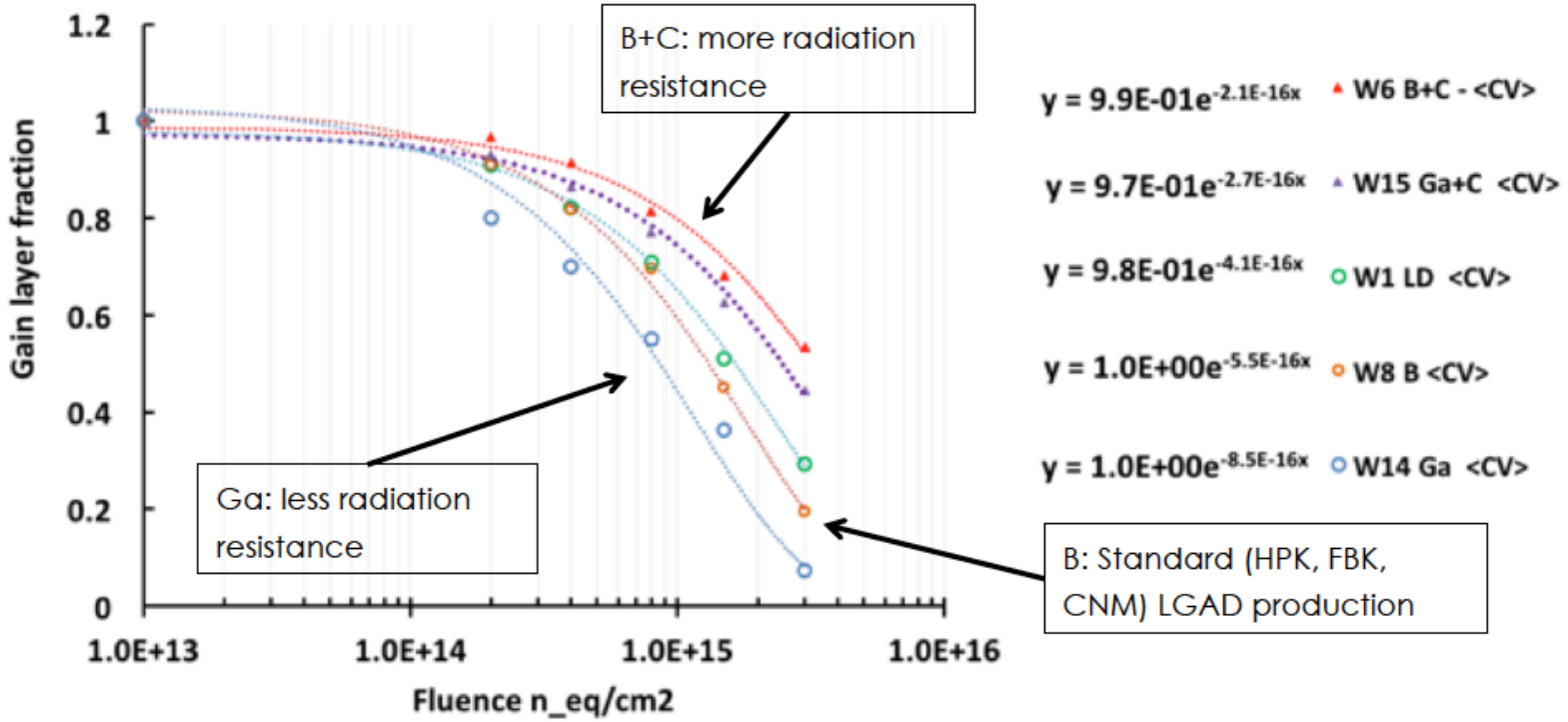
MPV charge from a MIP crossing silicon ~ 75 e-h/µm
50 µm thick ⟶ 0.5 fC
20 µm thick ⟶ 0.2 fC

Signal multiplication by a factor of 5-10 is needed



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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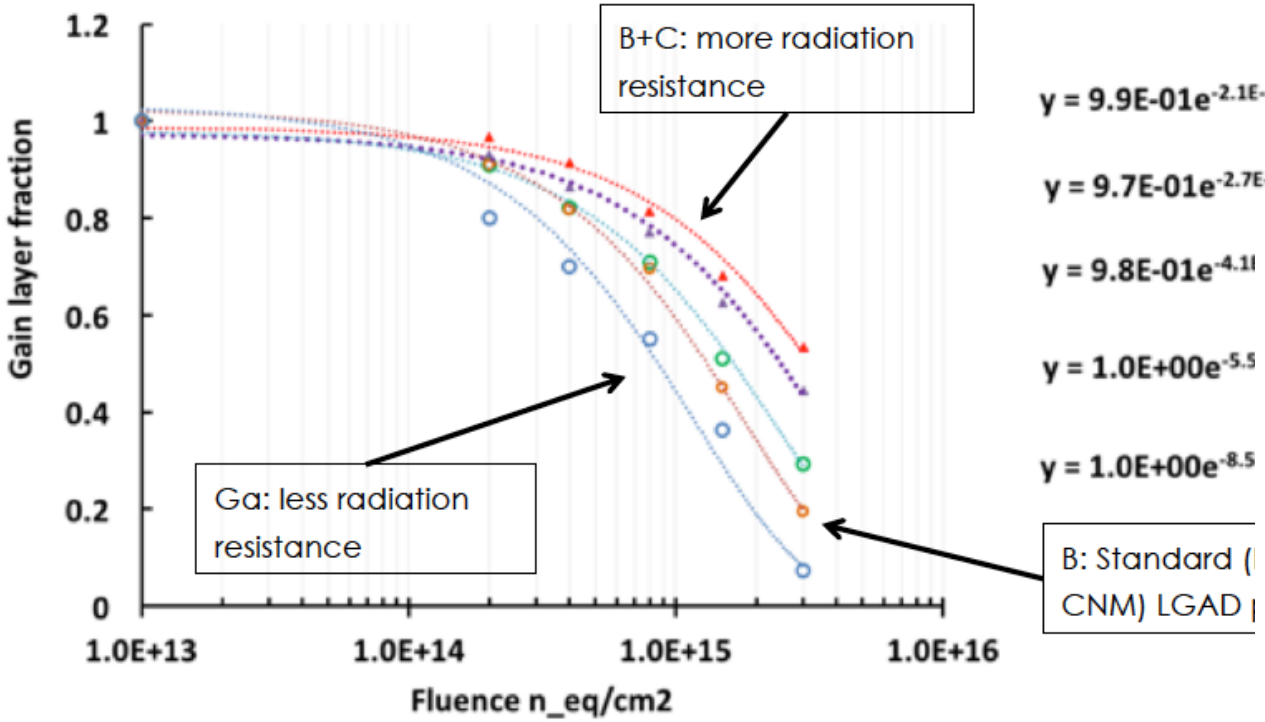
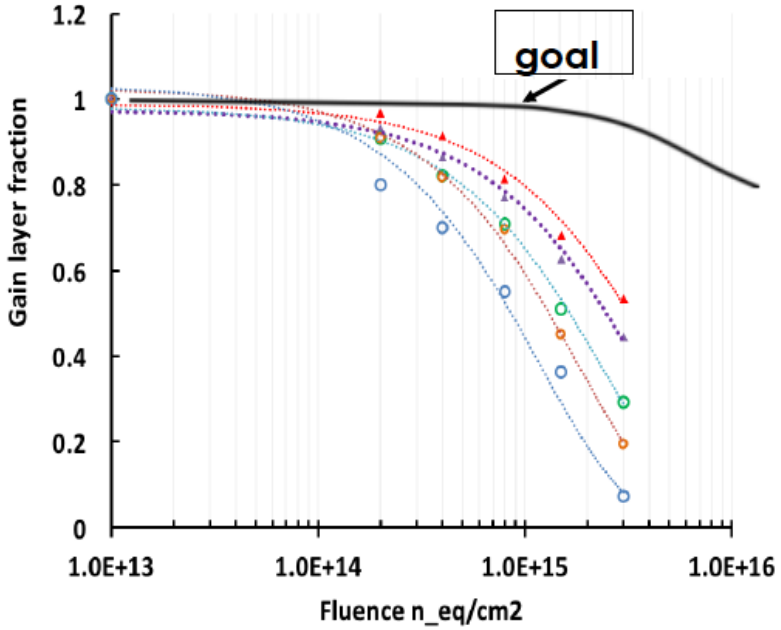


Future R&D



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

GAIN LAYER RADIATION TOLERANCE

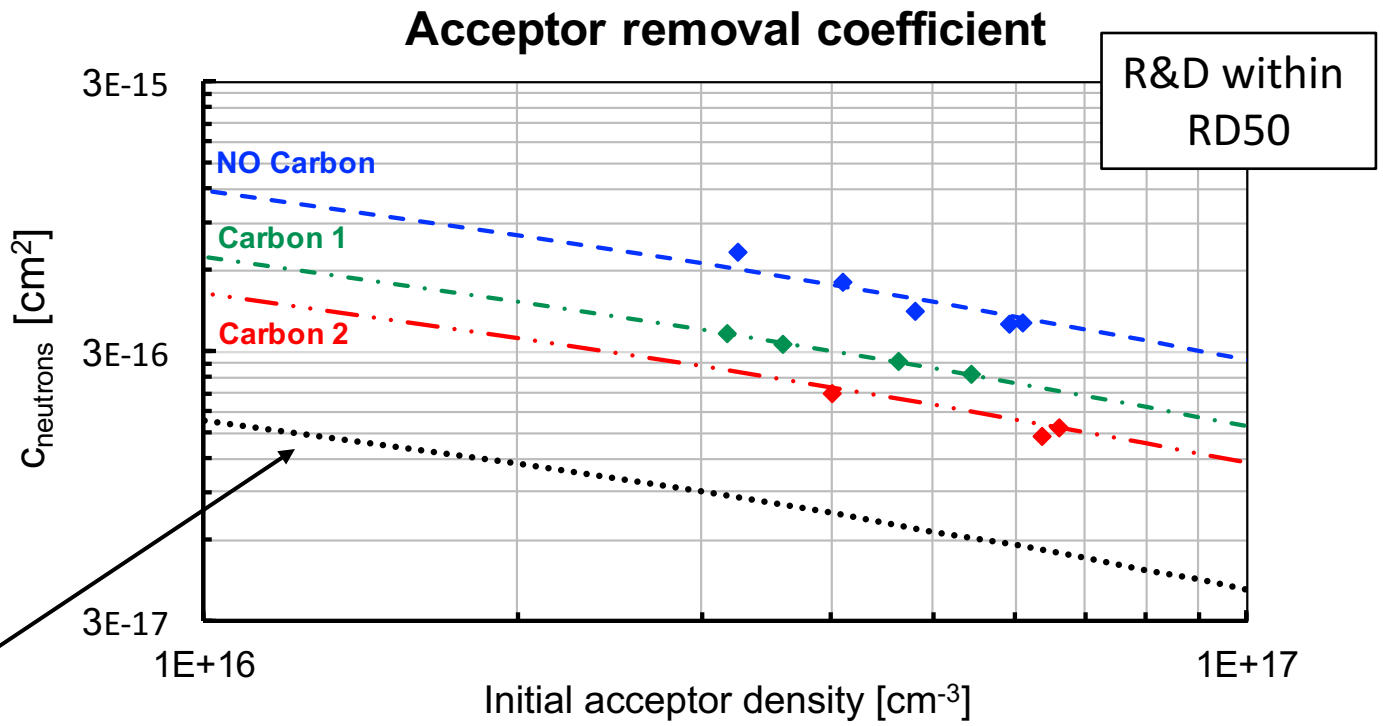
Goal: retard multiplication transition from the gain layer to the bulk region

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**



Possible?

[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

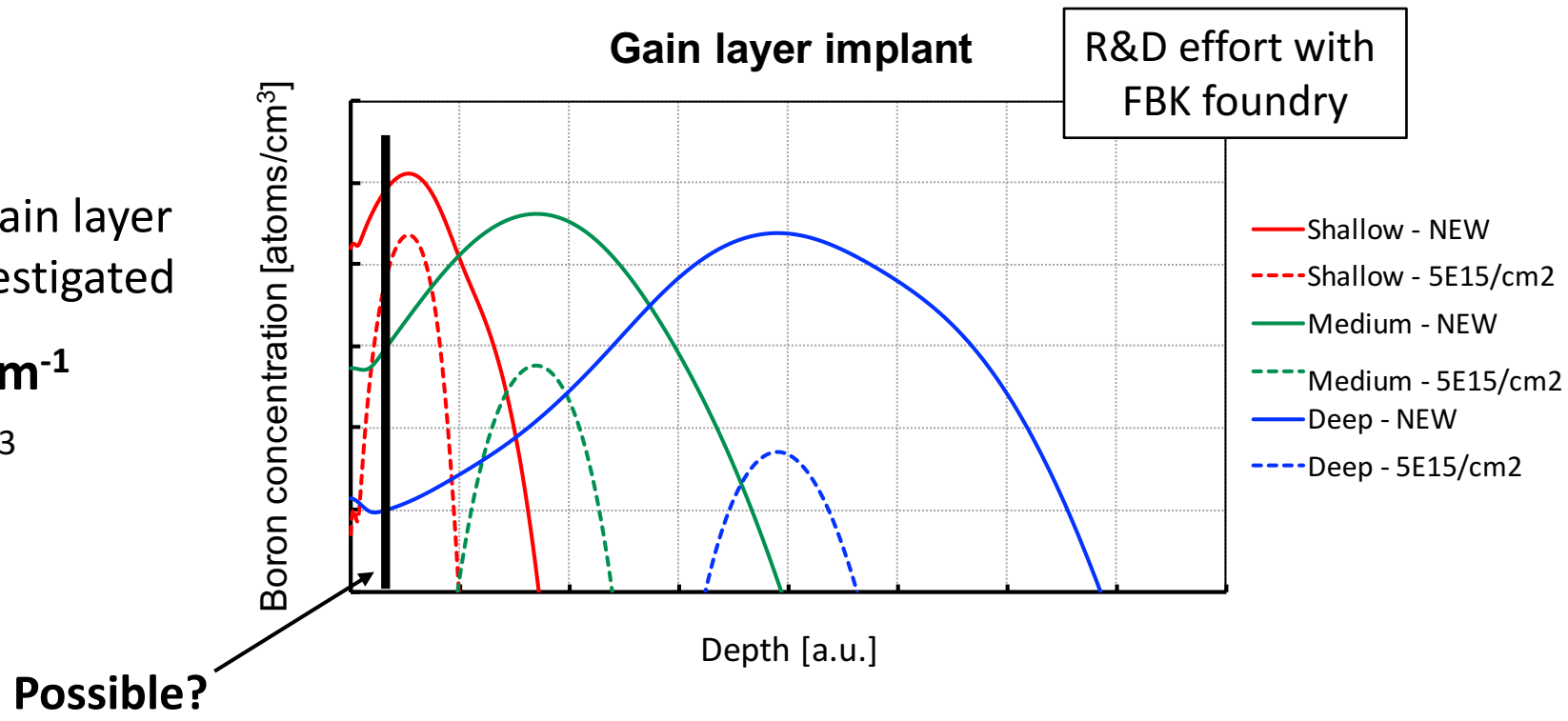
Acceptor removal:

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

Defect engineering and different gain layer implantation strategies will be investigated

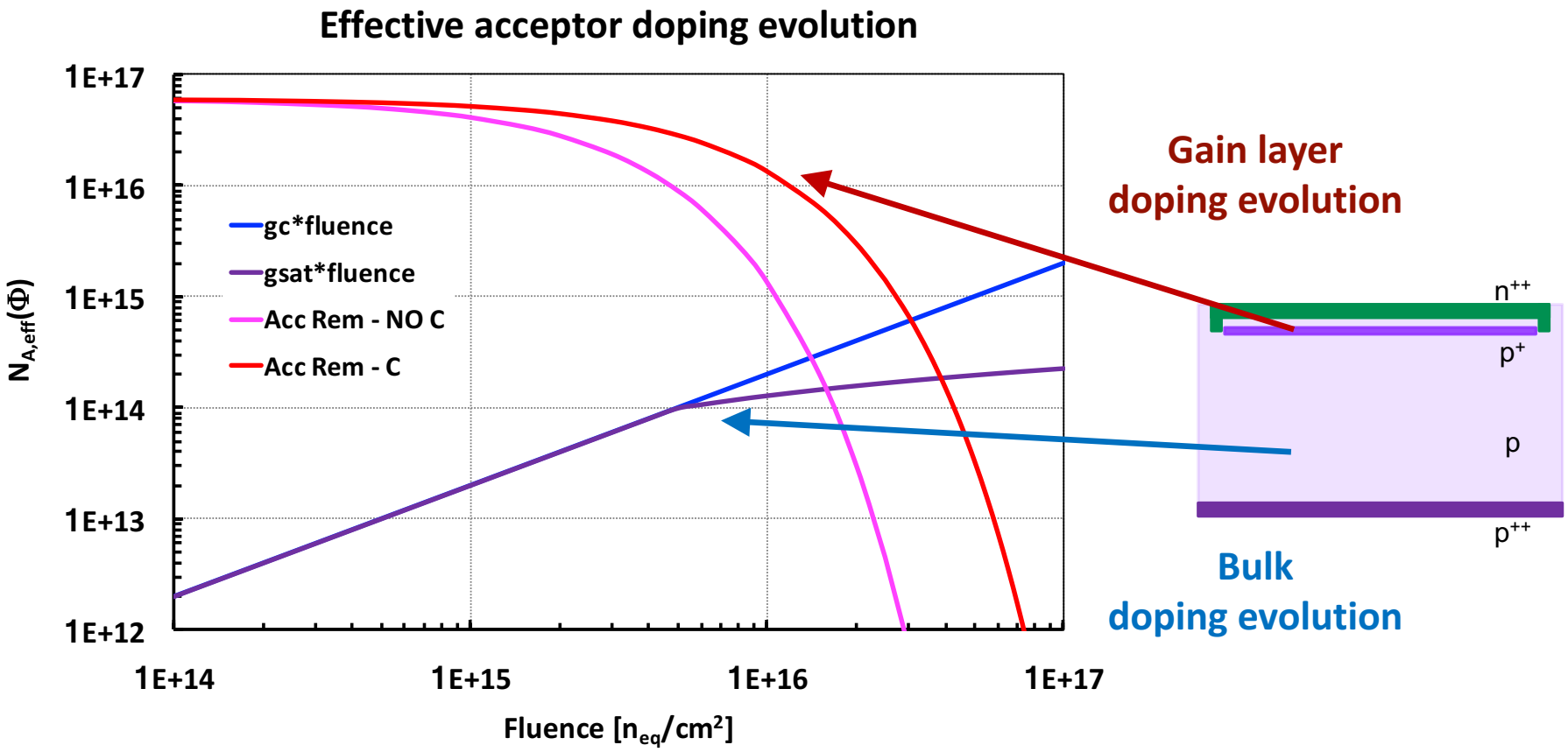
$$\mathbf{c \cdot N_{A,0} = 60\ cm^{-1} \longrightarrow\ < 10\ cm^{-1}}$$

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



ACCEPTOR DOPING EVOLUTION WITH Φ

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



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)

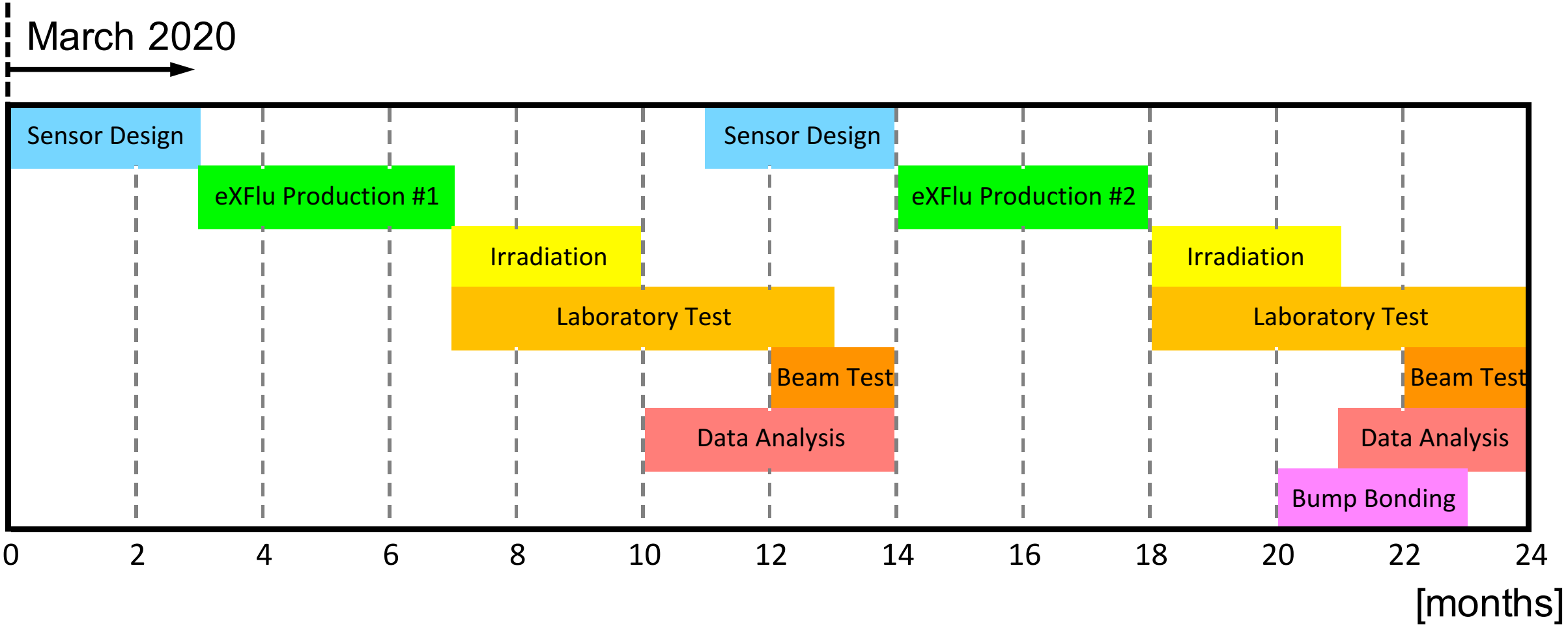
- **INFN, Torino**
  - **Valentina Sola** (PI), particle physicist expert both in data analysis and detector R&D, involved in the development and characterisation of Ultra-Fast Silicon Detectors, actively participating to laboratory and beam tests, organisation of irradiation campaign, and supervision 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**

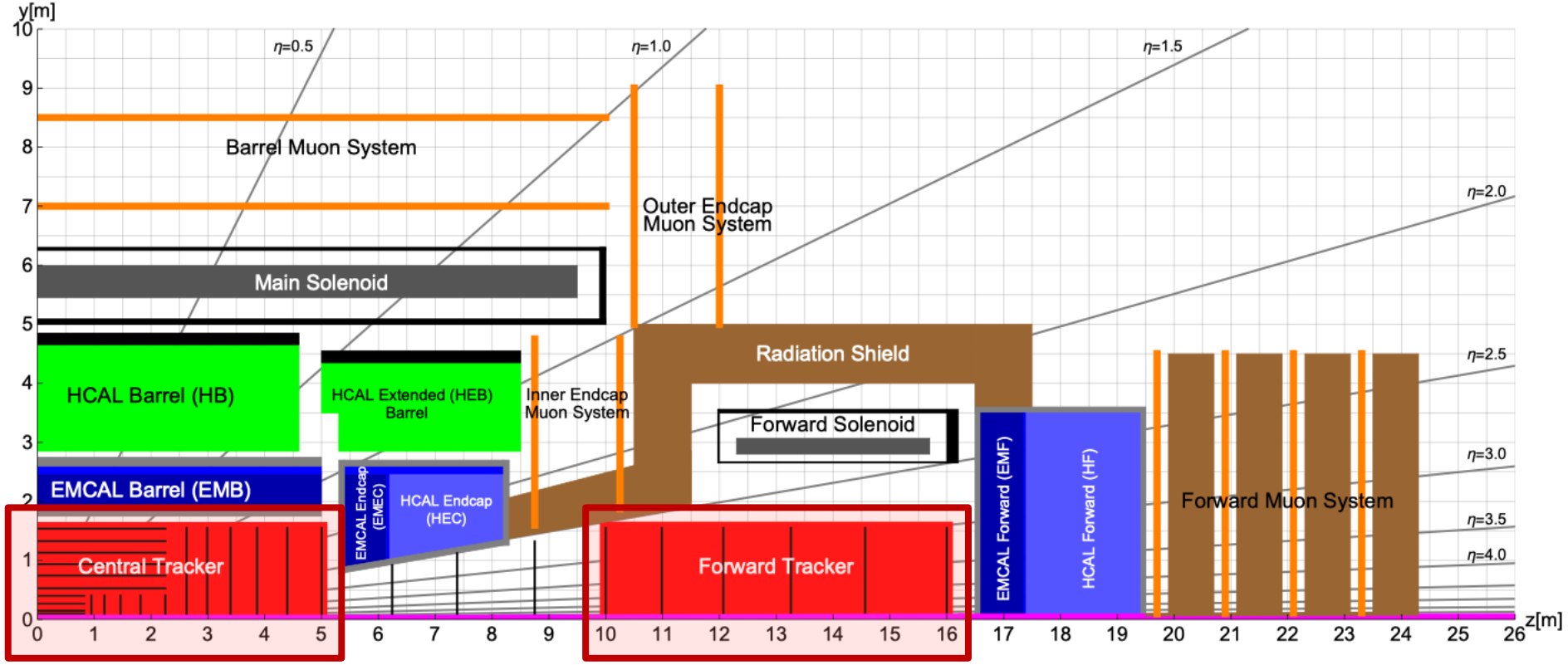
eXFlu TIMELINE



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