DRD3 WG3/WP3:
Study of irradiation characteristics of carbon enriched LGAD for high radiation fluence application

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ON BEHALF OF THE PROJECT ORGANIZATION

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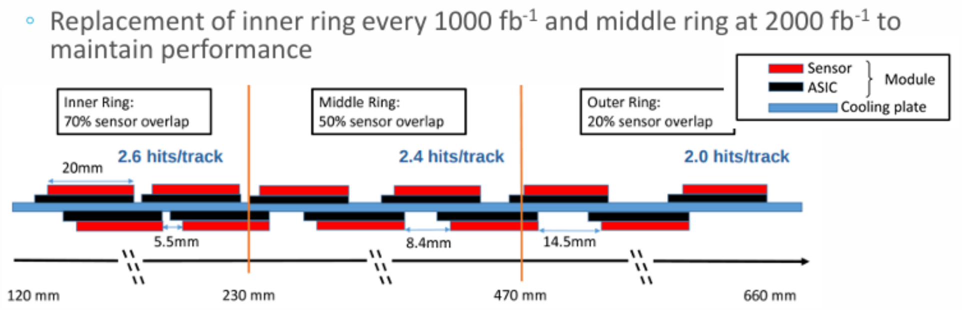
High radiation fluence application

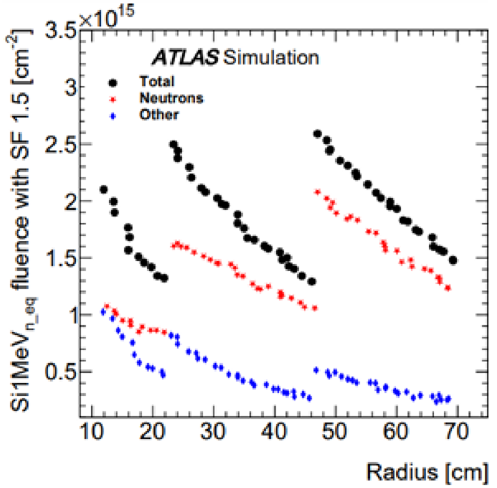
- Low Gain Avalanche Diode with 30ps timing resolution be chosen as sensors for solving the pile-up issues in the High Luminosity LHC.

- Radiation fluence/requirement for now and next:

HGTD: replacement of LGAD(inner ring and middle ring) during the whole operation life of the detector.

Now: $2.5e15 n_{eq}/cm^2$





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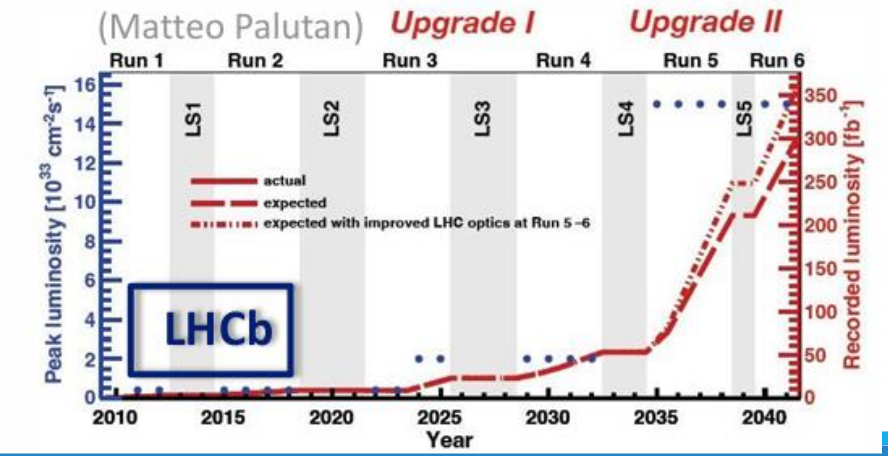


HL-LHC --> $10^{16} n_{eq}/cm^2$
FCC-hh → $10^{17}\ n_{eq}/cm^2$

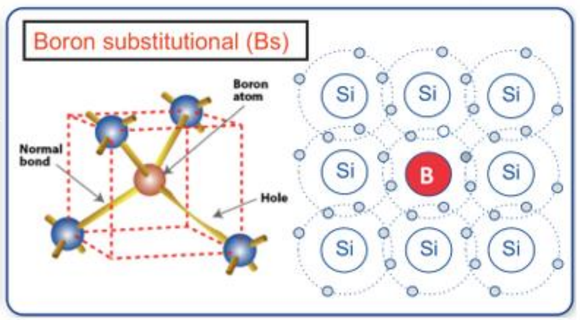
More radiation hardness
No need to replace
Good Hope! ☺

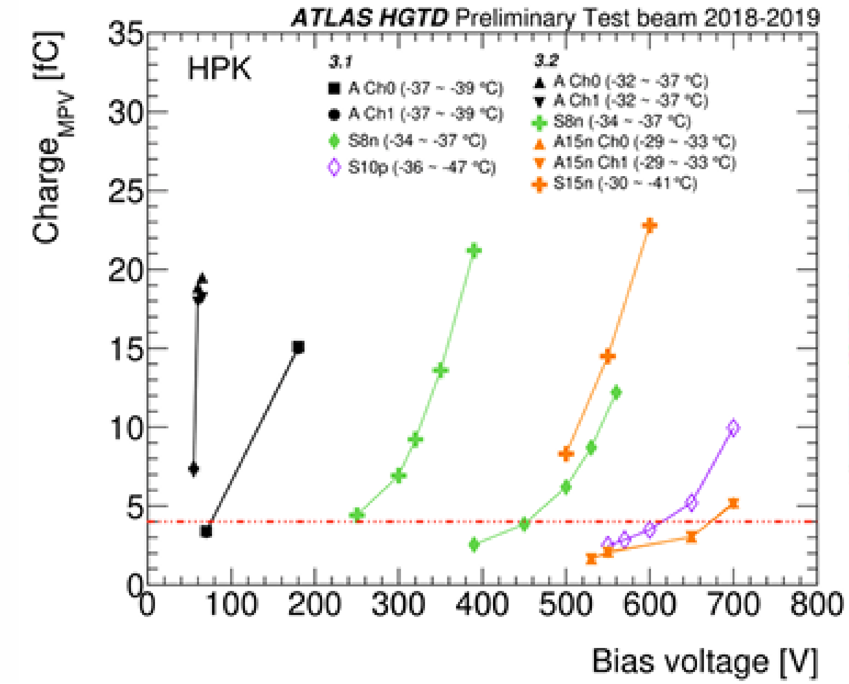
Radiation challenge

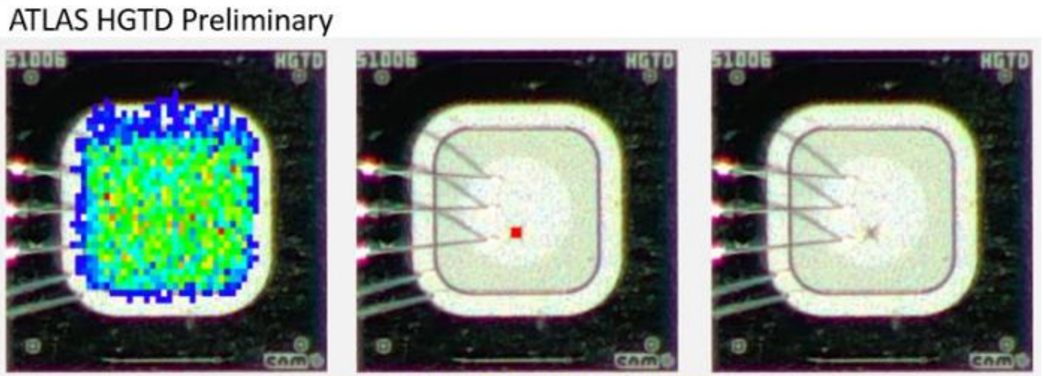
- Boron doping in gain layer became less active after irradiation.

- LGAD performance degrades due to loss of the gain layer after irradiation. And irradiated sensors require higher bias voltage to maintain performances.

- Single event burnout issues show up(E>12V/um). For 50um active thickness, the voltage should be <600V.







Beresford et al, 2023 JINST 18 P07030

V. Gkougkousis, "LGAD Safety and Stability Concerns " – HGTD Sensor Meeting April 2018, CERN-OPEN-2023-017
https://cds.cern.ch/record/2870268 <https://cds.cern.ch/record/2870268>

Research goals

- The goal of this project is to study the damage characterization of the carboned LGAD sensors and improve its radiation hardness to at least 7e15 n_{eq}/cm^2.
  - Studies of irradiated carbon enriched sensors by IV, CV, TCT method

    carbon doping profile using SMIS

    irradiated damage by DLTS and other method

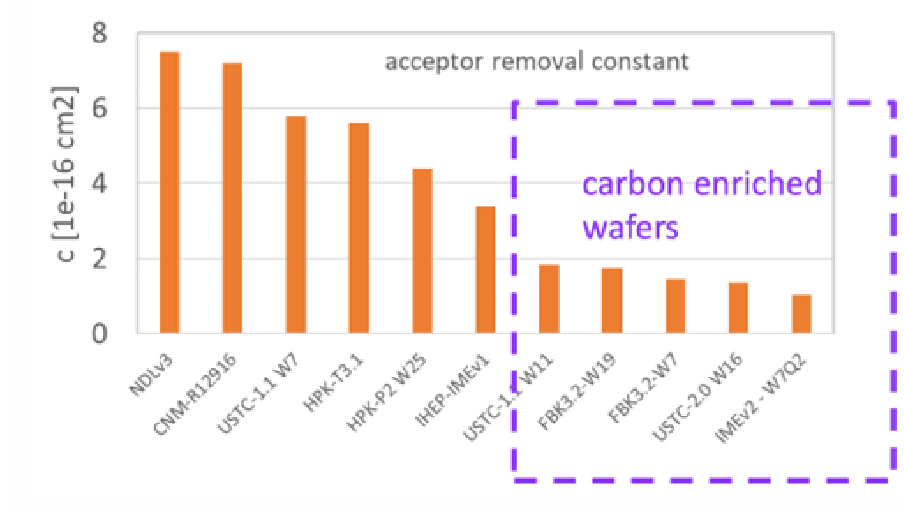
  to identify the damage caused by radiation(neutron and proton), how carbon can improve, the doping parameters of carbon for better radiation hardness.

  - improve the radiation performance of LGAD by optimizing the carbon enrichment process and gain layer implantation, such as high energy boron and carbon implantation, and aim to increase the radiation fluence to 7e15n_{eq}/cm^2 and more.

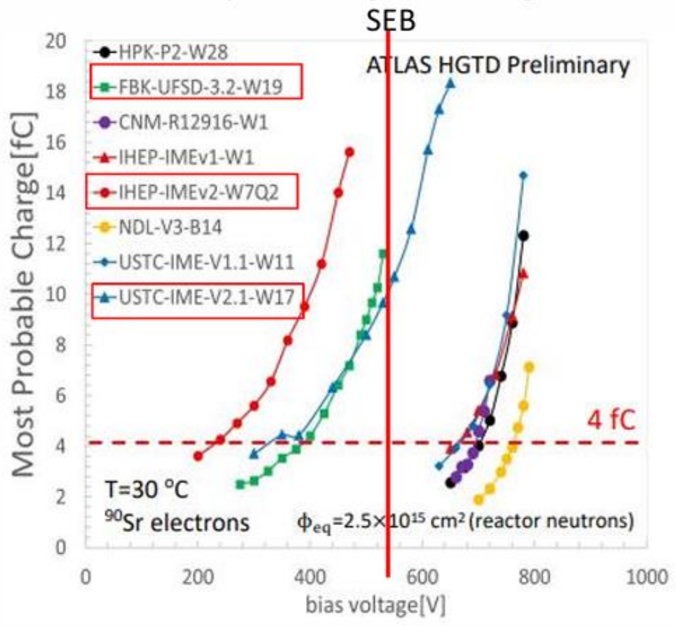
  - for usage of LGAD replacement in HGTD project and future collider.

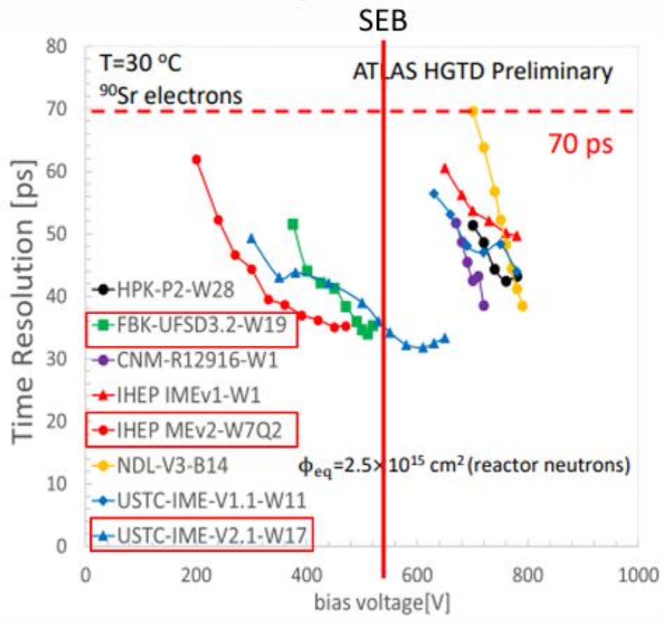
Carbon enriched LGAD

- Sensors from carbon enriched wafers show very low acceptor removal constant(1-2 $\times 10^{16}$ cm^2), which would reduce the required voltage for enough charge collection and avoid the SEB.
- LGAD with carbon implantation be demonstrated to have good radiation hardness as compared to the one without carbon.



The c factor is extracted from the behavior of the gain layer active fraction represented as a function of fluence. The gain layer active fraction is calculated using the gain layer depletion voltage at each fluence, obtained from CV measurements.





Carbon enriched LGAD performance

- Carbon doping profile affect the radiation performance of LGAD.

(position and concentration)

IHEP-IME, FBK sensors all show such results.

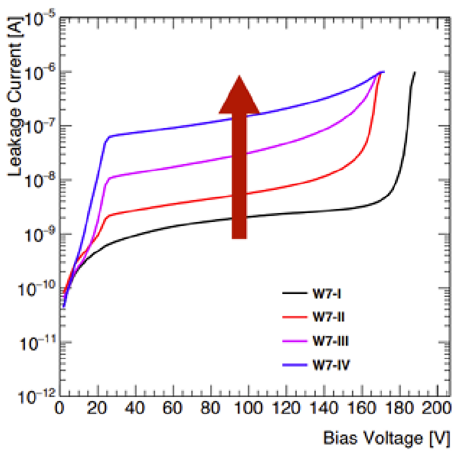
- Doping profile is determined by carbon doping parameters: implantation dose and energy, thermal treatment(CLBL, CHBL).

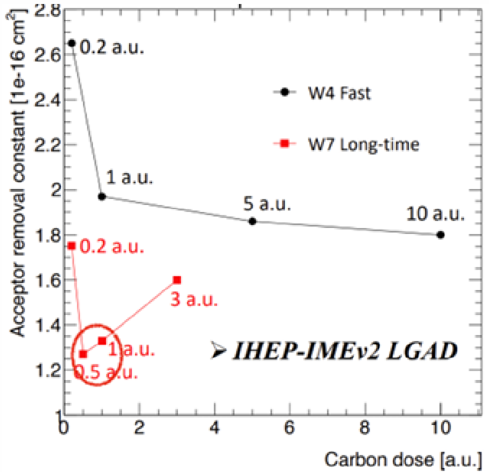
- More IHEP-IME LGAD with different carbon doping profile be fabricated. Show good radiation hardness.

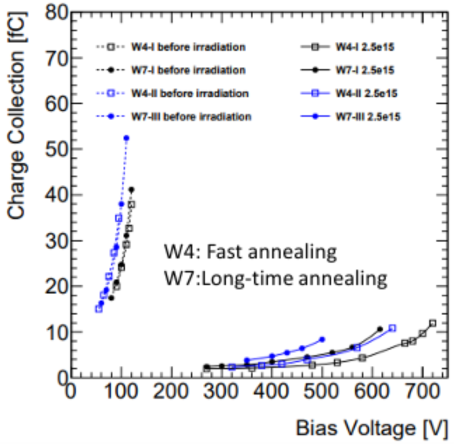
Results be shown by Yuan Feng.

Sensor		Diffuse*	C dose(a.u.)	C factor (x10^16 cm2)
W4	Q1	CLBL	0.2	2.57
	Q2	CLBL	1	1.77
	Q3	CLBL	5	1.60
	Q4	CLBL	10	1.50
W7	Q1	CHBL	0.2	1.62
	Q2	CHBL	0.5	1.14
	Q3	CHBL	1	1.18
	Q4	CHBL	3	1.34
W8	Q1	CHBL	6	1.30 1.32
	Q2	CHBL	8	1.32
	Q3	CHBL	10	1.23
	Q4	CHBL	20	1.29

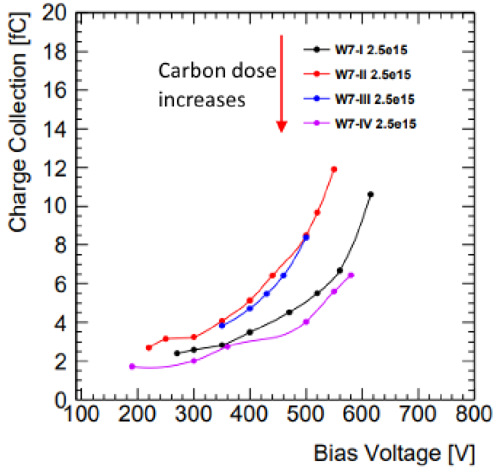
BEST

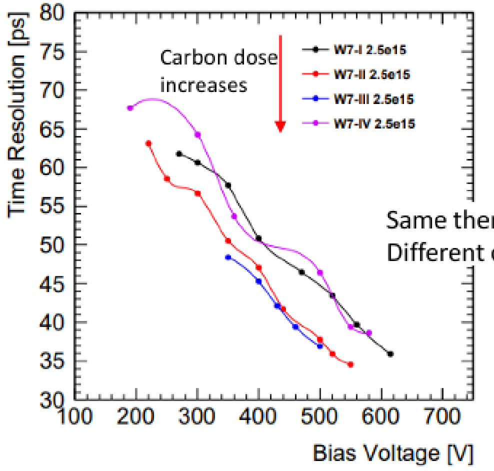






Same carbon dose
Different thermal treatment





Same thermal treatment
Different carbon dose

https://doi.org/10.1016/j.nima.2022.167697

Carbon enriched LGAD

- Why can carbon implantation improve the radiation hardness of LGAD?

Radiation induced interstitials react with boron atoms by Bs + I → Bi.

carbon implantation is utilized to suppress transient enhanced diffusion, since substitutional carbon acts as a trap for excess Si self-interstitials in crystalline: Cs + I → Ci.

Owing to this property, carbon in LGAD acts as a competitor for I generated by high-energy particles; thus, carbon implantation helps suppress the boron acceptor removal.

- Which is the best doping profile of carbon for C-factor and LGAD radiation performance?

Preliminary results

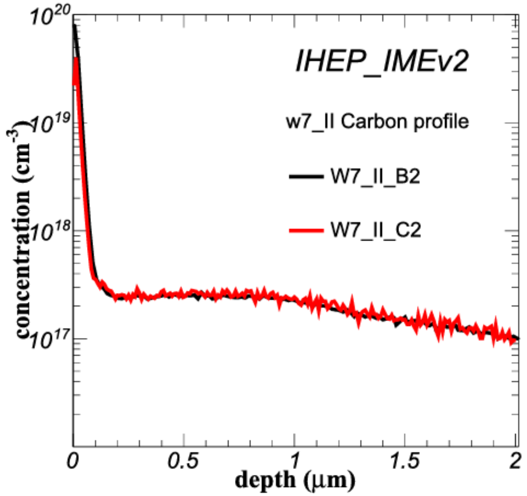
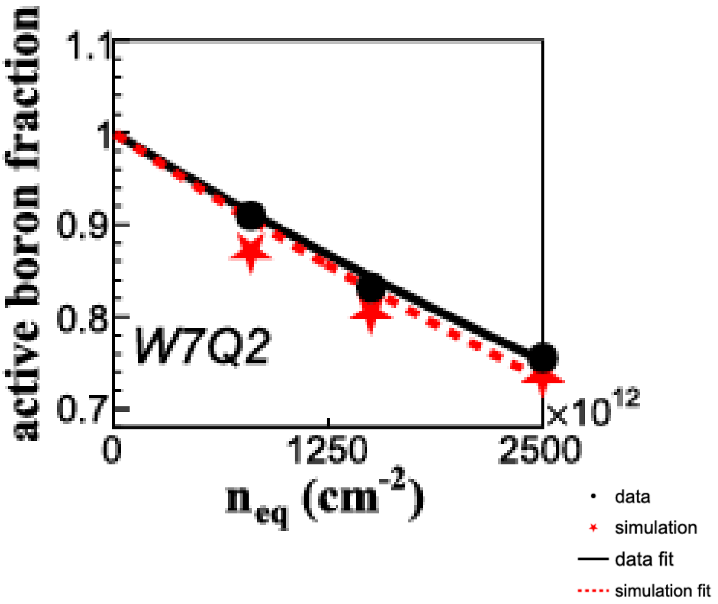
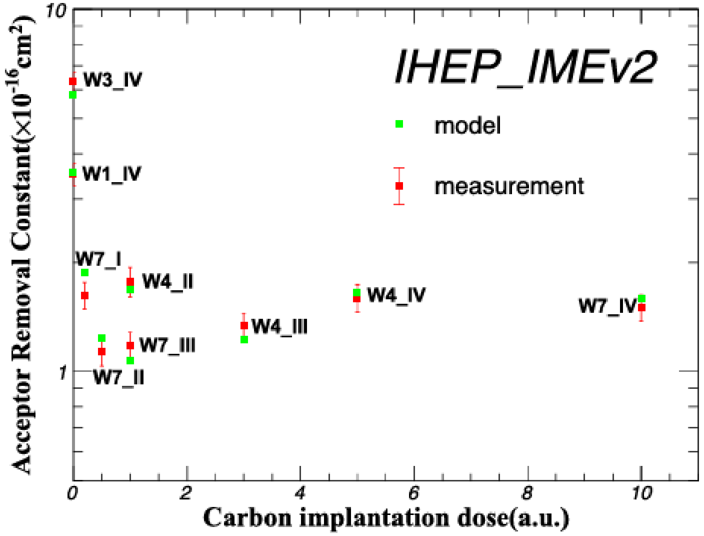


Fig. 1. SIMS measurements of the density of implanted carbon atoms as a function of the depth, for unirradiated (W7_II_B2) and irradiated (W7_II_C2, fluence about 2.5×10^{15} n_{eq}/cm^2) LGADs. The two doping profiles are identical, and the fluctuations of the curves are noises of the test.



10.1109/TNS.2022.3221482



modeling the acceptor removal constant based on SIMS spectra of IHEP_IMEv2 sensors with several reasonable assumptions.

Carbon enriched LGAD: radiation damage

- Radiation damage(Defect) characterization:

  Trap level and density?

  for LGAD with different carbon profile? What is the difference of defect concentration?

  Still not clear

- Method:

  Capacitance Deep-Level Transient Spectroscopy (C-DLTS)

  Current Deep-Level Transient Spectroscopy (I-DLTS)

  Thermally Stimulated Current (TSC) techniques

Milestones & Deliverables

Number	Deliverable/Milestone Title	WP project #	Lead	Type	Dissemination Level	Due Date
D-Project#-1	Irradiation testing of LGAD sensors with Carbon implantation Testing of irradiated sensors	3	JSI	Report	DRD3 report	2024.12
M-Project#-1	Model of accept removal constant be built Damage characterization	3	IHEP	Report	Publication	2025.6
M-Project#-2	New sensors fabrication with optimized carbon implantation process	3	IHEP, IME	Prototype	DRD3 report	2025.12
D-Project#-2	Sensor testing including radiation damage testing and TB	3,5	JSI	Report	Publication	2026.6
M-Project#-3	Sensor radiation hardness to 5e15 n_{eq}/cm^2	3	IHEP	Prototype	DRD3 report Publication	2026.12
M-Project#-4	New sensors fabrication with new method	3	IHEP	Prototype	DRD3 report Publication	2028.6
M-Project#-5	Sensor radiation hardness to 7e15 n_{eq}/cm^2	3	IHEP	Prototype	DRD3 report Publication	2029.6

Collaborative work

TCAD simulation, sensor fabrication

WG3 / WP3 : radiation to the sensors

characterization of LGAD sensors after irradiation

radiation damage model

WG5 / WP5 : beam test of sensors after irradiation to check the SEB and sensors' performance

Participating Institutes

Institute	People	Contribution
IHEP (contact person: Mei Zhao)	Mei Zhao, Zhijun Liang, Mengzhao Li, Yuan Feng, Weiyi Sun, Yunyun Fan Tianyuan Zhang, Xuan Yang	TCAD simulation, Carbon enriched LGAD sensor design, Testing of irradiated sensors, C-factor model, Proton radiation with China Spallation Neutron Source (CSNS) 80MeV beam
IME	Gaobo Xu, Yupeng Lu, Mingzheng Ding, Jiahan Yu	LGAD sensor fabrication
JSI	Gregor Kramberger	Sensor irradiation with neutron equipment, testing of irradiated sensors by probe station and TCT method
Missing, call for collaboration	**We need you!**	DLTS or other testing, characterization of radiation damage

The project is open to new collaborators who are willing to contribute to any of the areas.

Summary

- Proposing project for study of irradiation characteristics of carbon enriched LGAD for high radiation fluence application
- Including TCAD simulation, radiation damage characterization, model of c-factor and gain as radiation fluence for LGAD, carboned LGAD sensor design and fabrication, beam test of irradiated sensors
- LGAD with different carbon implantation process be fabricated, preliminary model of C-factor be built.
- More analysis especially radiation damage characterization need to be done next.
- Now 3 institutes(IHEP, IME, JSI) participating.
- Welcome you to join! Please contact us!