

Proposal of RD50 common production of DJ-LGAD and adaptive gain layer

42° RD50 Workshop (2023, Montenegro)

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On behalf of the 13 institutes interested



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FOR PARTICLE PHYSICS
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RD50

LGAD arrays

- Granularity is a current limitation for LGADs
- Due to high fields in the multiplication layer the pads need electrical insulation
 - Protection structure: Junction Termination Extension (JTE)
 - Causes inter pad (IP) gap to 50-150 μm , also changes with applied bias voltage
 - Limits LGAD granularity to mm scale
- However 50 μm pitch (and lower) is required for next generation colliders and 4D tracking
 - At least same level as the ATLAS new inner tracker (ITk) needed
- Several possible solutions are being investigated by the community
 - AC-coupled (RSD) LGADs, Trench insulated LGADs, inverted LGADs...

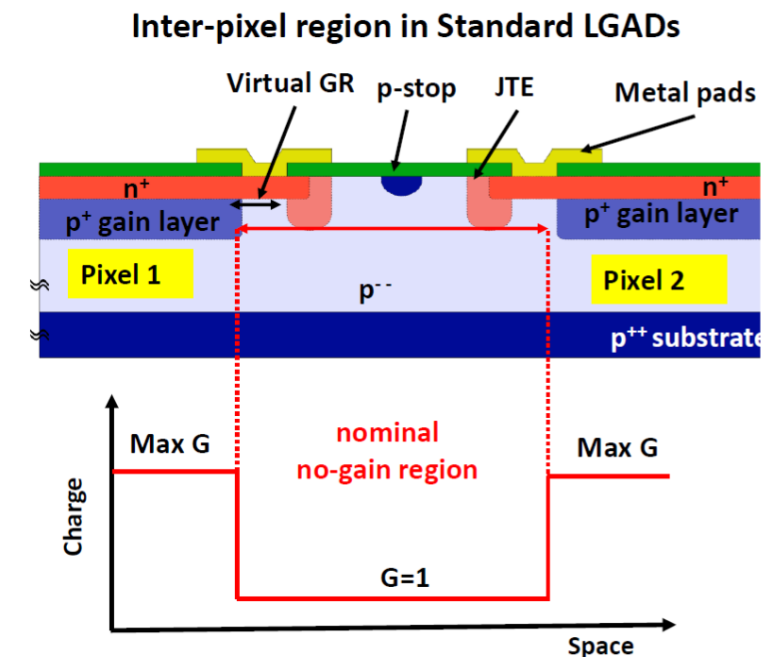
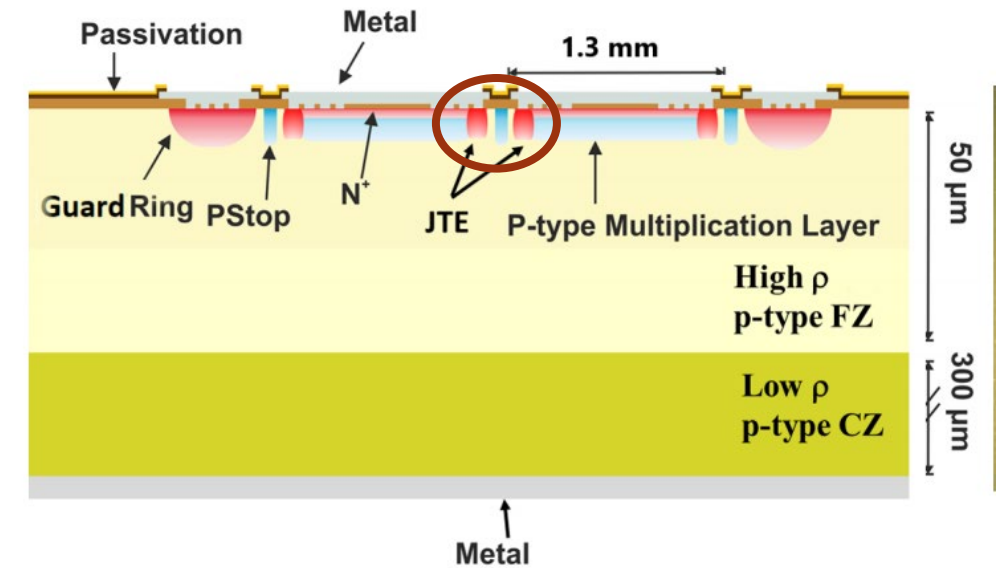
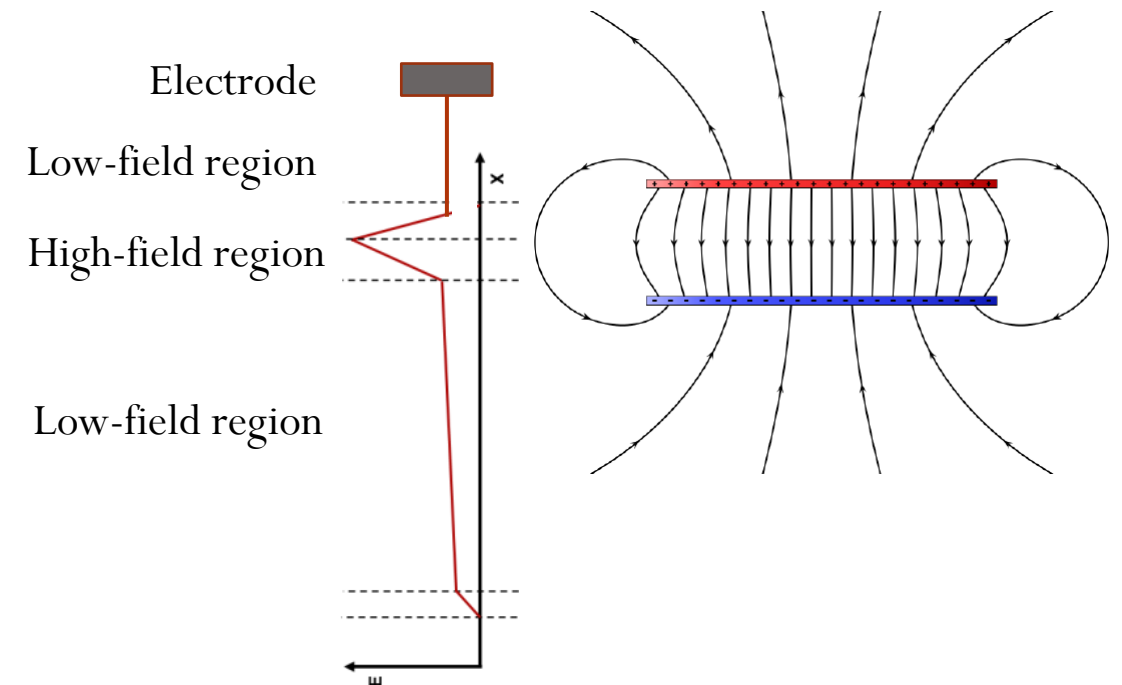
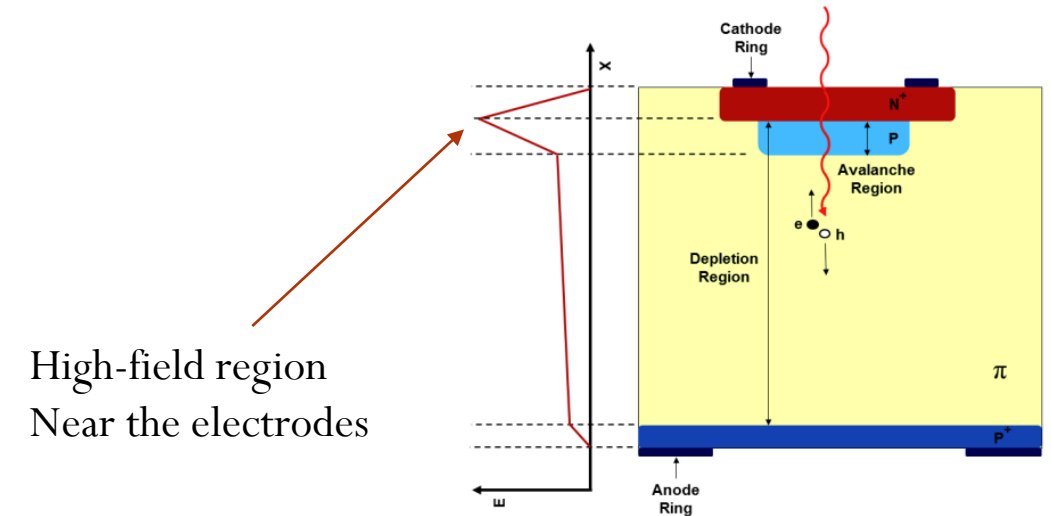


Diagram credit: FBK, Trento, Italy

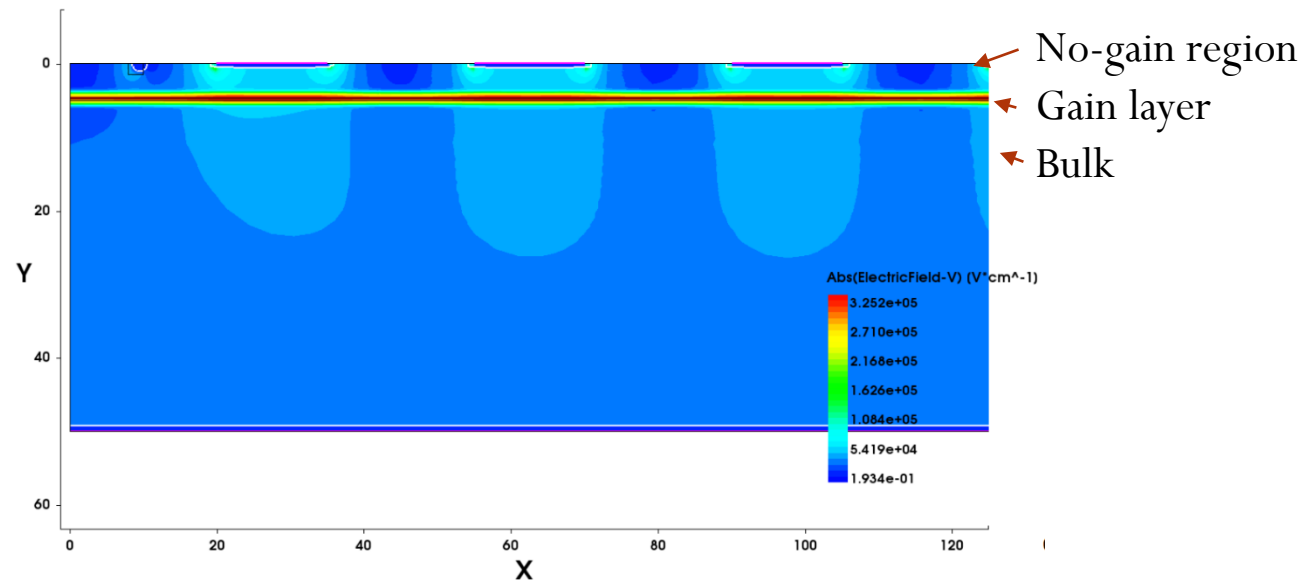
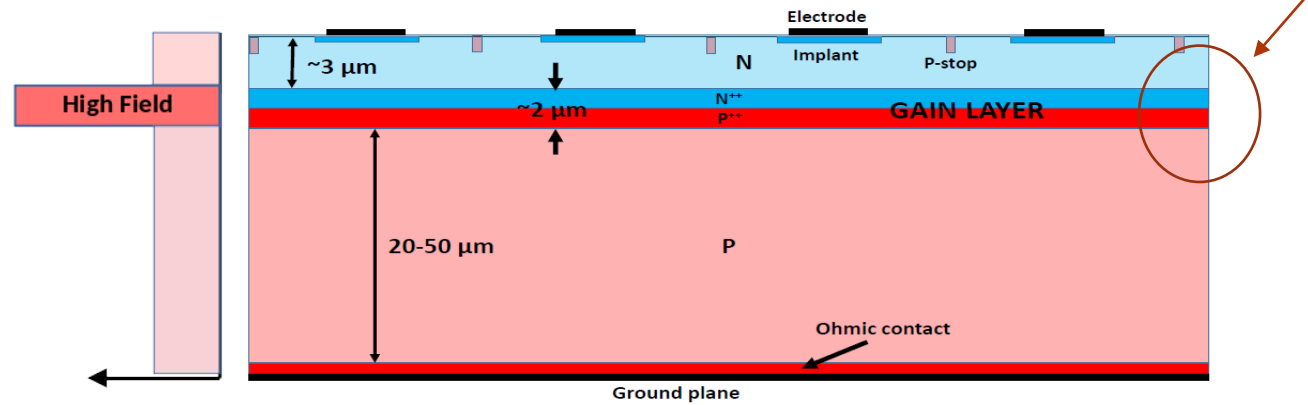
A new approach: deep junction

- Granularity limit is caused by high field near the electrodes
 - What if the field is kept low while maintaining gain?
- Basic inspiration is that of the capacitive field:
 - Large between plates, but surrounded by low-field region beyond the plates
- Use symmetric P-N junction to act as an effective capacitor
- Localized high field in junction region creates impact ionization
- Bury the P-N junction so that fields are low at the surface, allowing conventional granularity
- → “Deep Junction” LGAD (DJ-LGAD)
- Concept presented first at [TREDI 2020](#)
- Prototype results presented at previous [RD50 workshop](#)



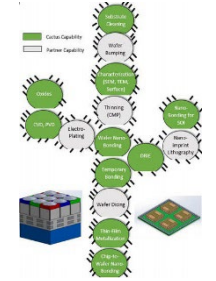
DJ-LGAD

Termination of the gain layer was studied in the first production



- **P++ gain layer is paired with a N++ layer that lowers the field**
 - Junction is buried $\sim 5 \mu\text{m}$ inside the detector
- Tuning of N+ and P+ parameters important
 - Low field outside of the electrodes while maintaining sufficient gain
 - No need for a JTE
 - Different termination of the gain layer designed
- DJ-LGAD design studied with TCAD Sentaurus
 - First production in collaboration with BNL and CACTUS completed and results presented
- **Patent WO2021087237A1**
 - C. Gee, S. M. Mazza, B. Schumm, Y. Zhao
 - <https://patents.google.com/patent/WO2021087237A1/en>

Fabrication process for first prototype run



Gain Layer Implantation on N and P type substrate



Wafer-wafer bonding



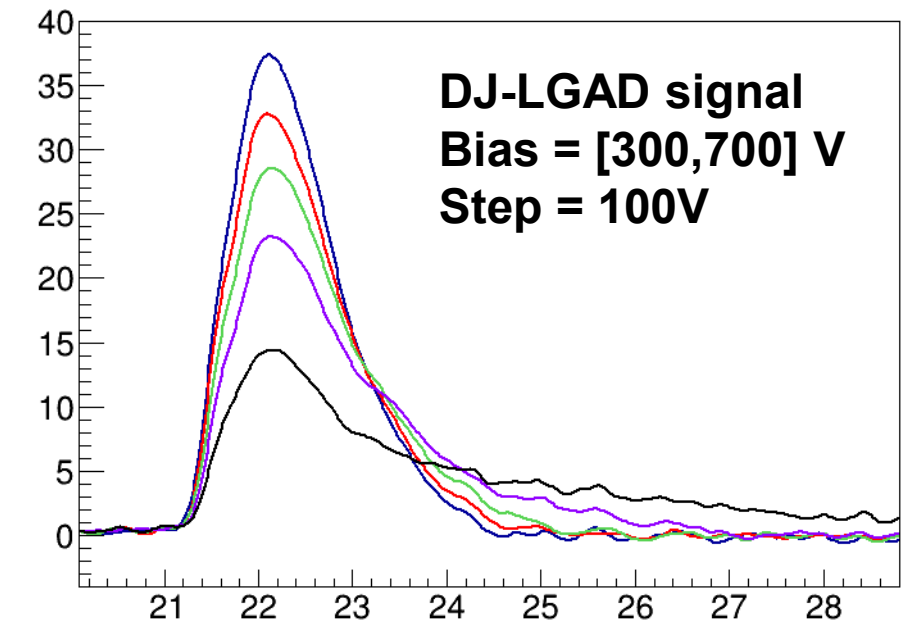
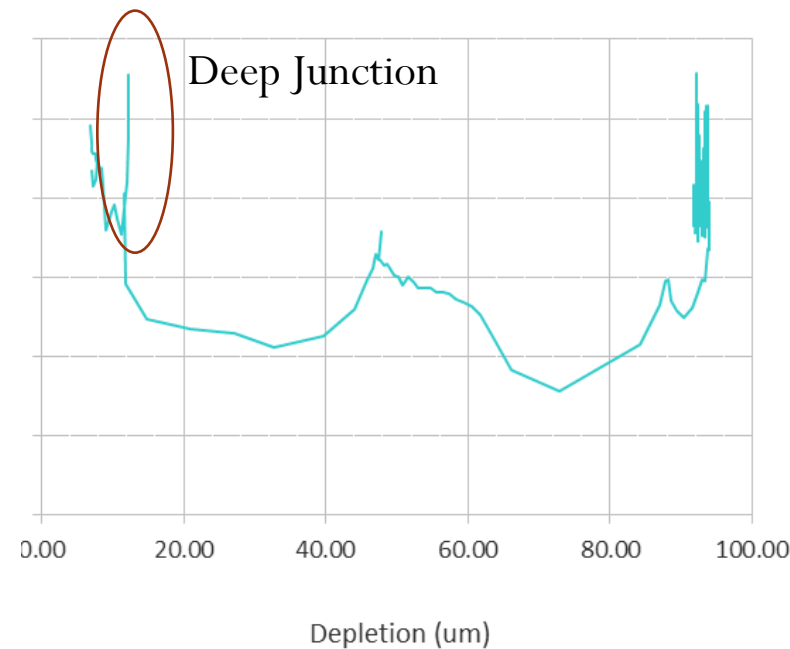
Production SCIPP, BNL, Cactus Materials, funded by SBIR

Prototypes work with moderate gain (~ 5)

2x1 arrays were also produced and show minimal IP gap

However the production had some issues

- Lengthy and complex
- Low yield (wafers easily break)
- High current in prototypes



Fabrication process for epitaxial prototype

Gain Layer Implantation
Similar to Conventional LGAD, but
with higher energy



Epitaxial growth of high
resistivity N type layer



Deposit electrodes and implants



- Proposed next fabrication using epitaxial growth
- Gain layer terminated with asymmetric N⁺ and P⁺ profiles
 - or terminated with deep trenches
- **Demonstration of the process and production of finely pixelated arrays**

Deep trenches for gain layer termination

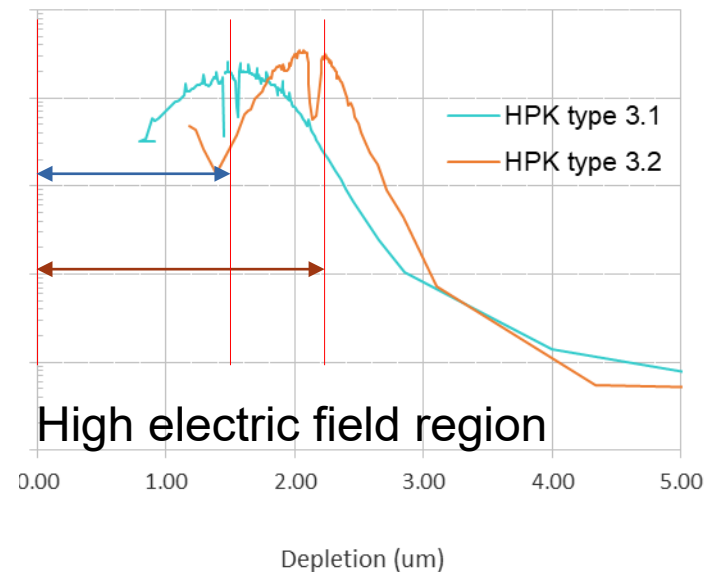
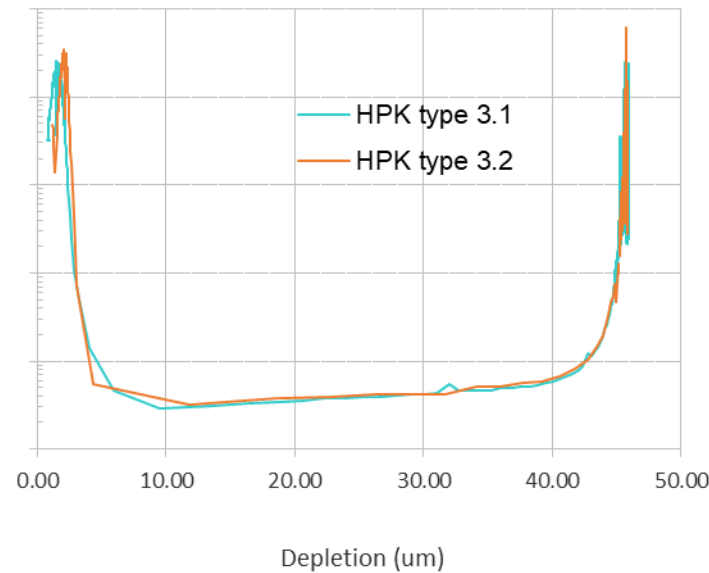


P/N junction at the edge, needs
very sharp dicing or trenches as well

“Adaptive” gain layer

Using the deep Junction to push radiation hardness

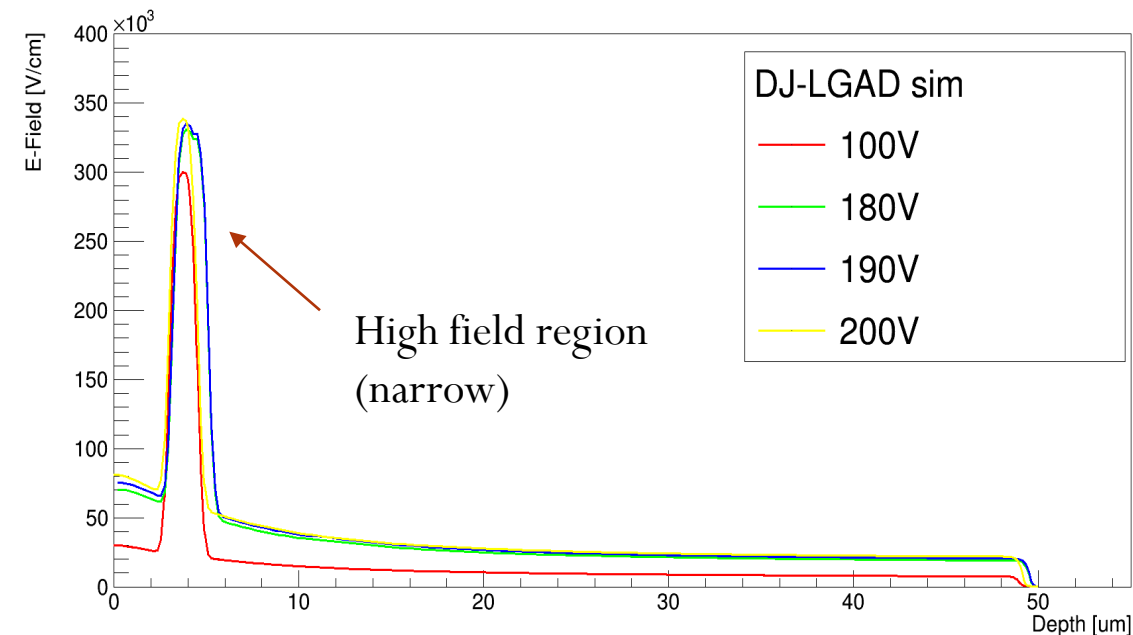
Deep gain layer LGAD effect (HPK sensor examples)



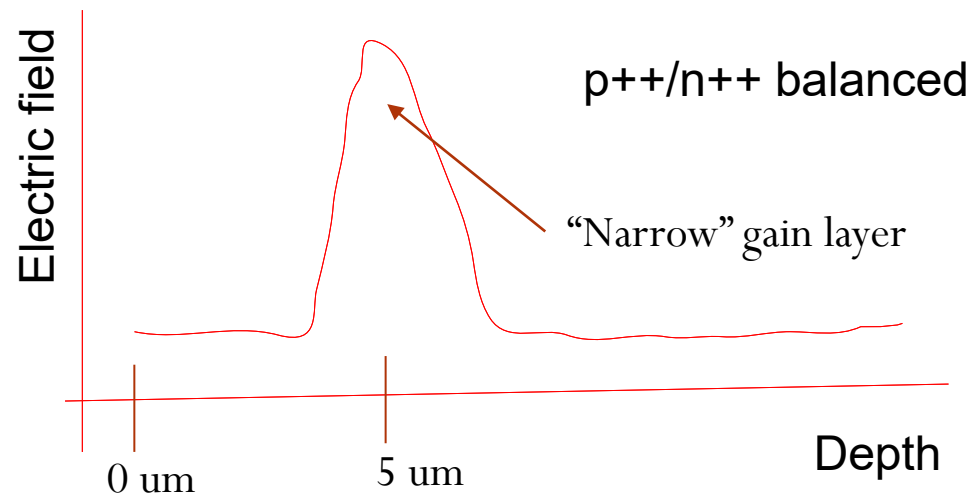
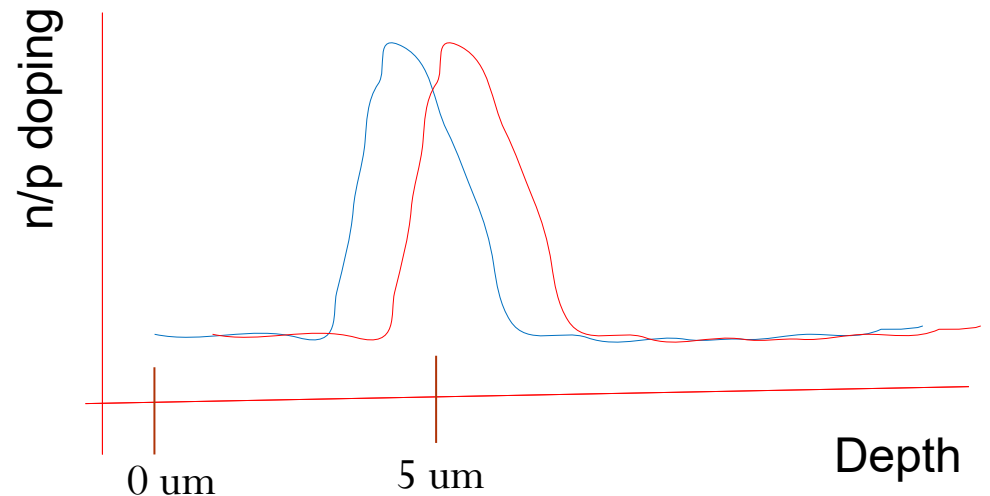
Deep gain layer increases electric field region, makes bias voltage increase after irradiation more effective in recuperating the gain

However doping concentration can't be too high or it would cause early breakdown and bad time resolution

With DJ-LGAD the junction is inside the device, but the field is high only for a narrow region

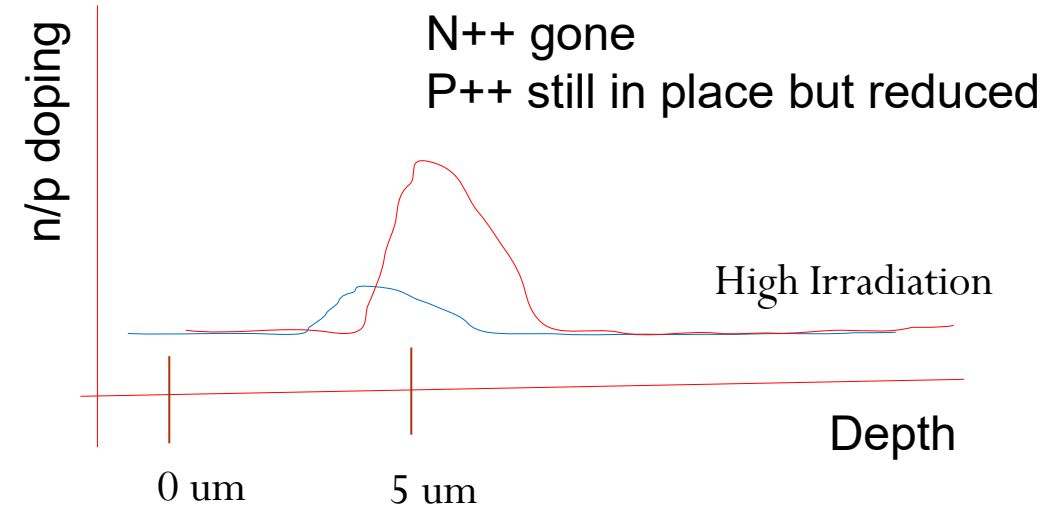
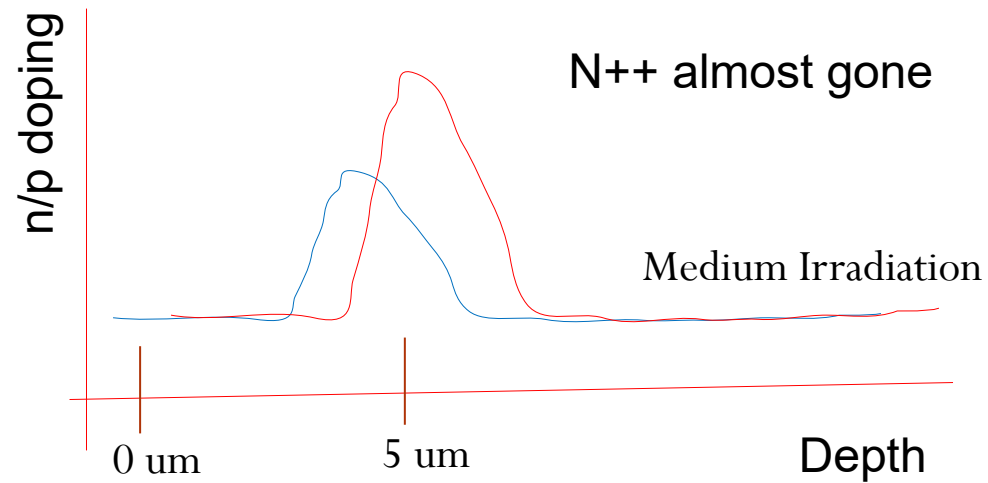
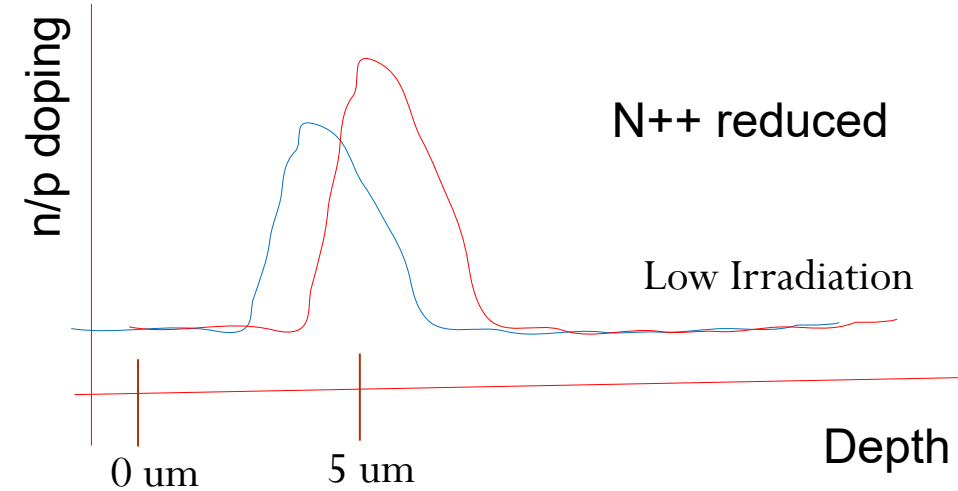
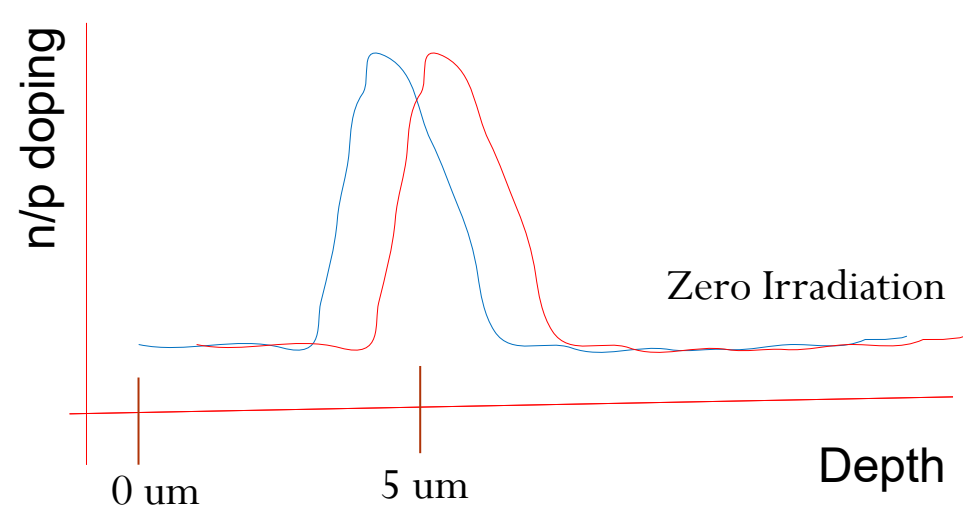


Adaptive gain layer

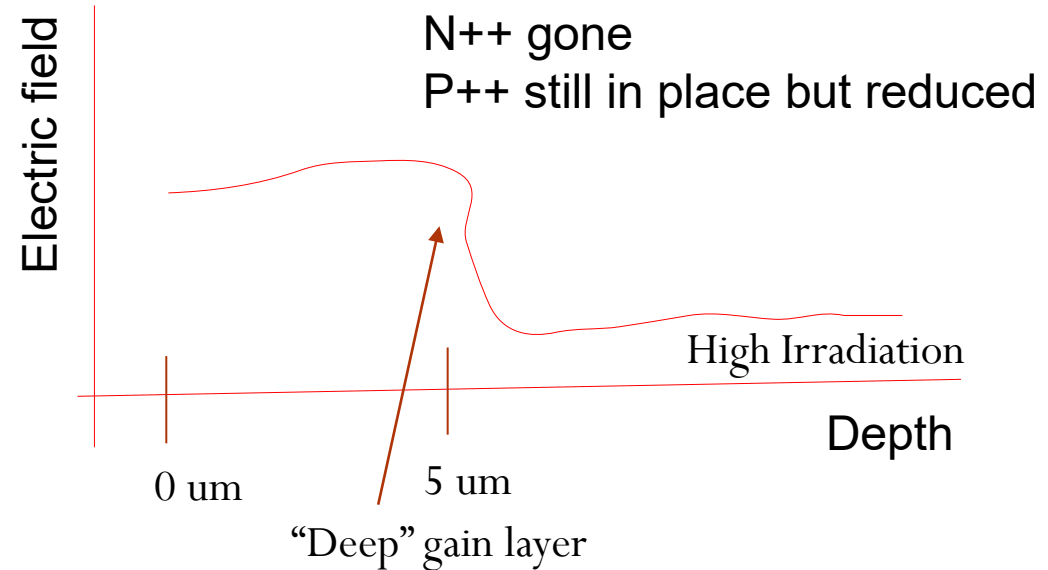
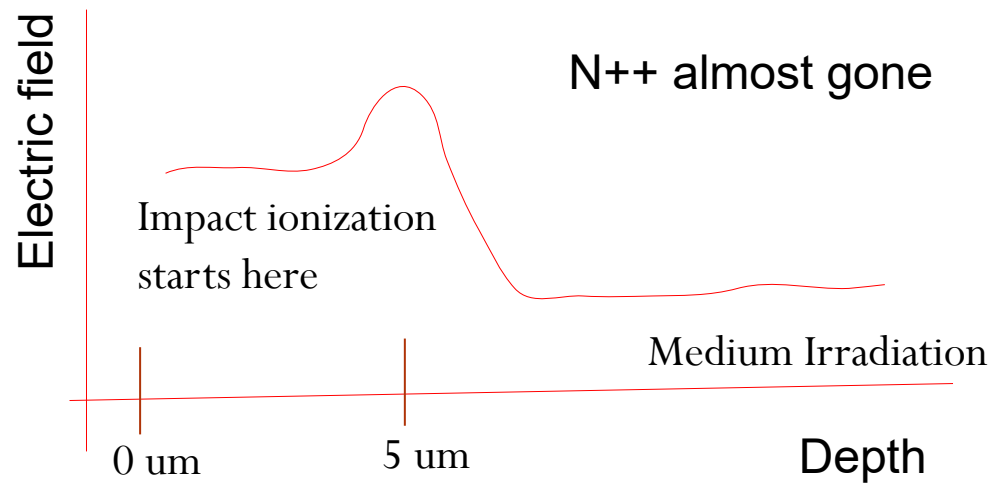
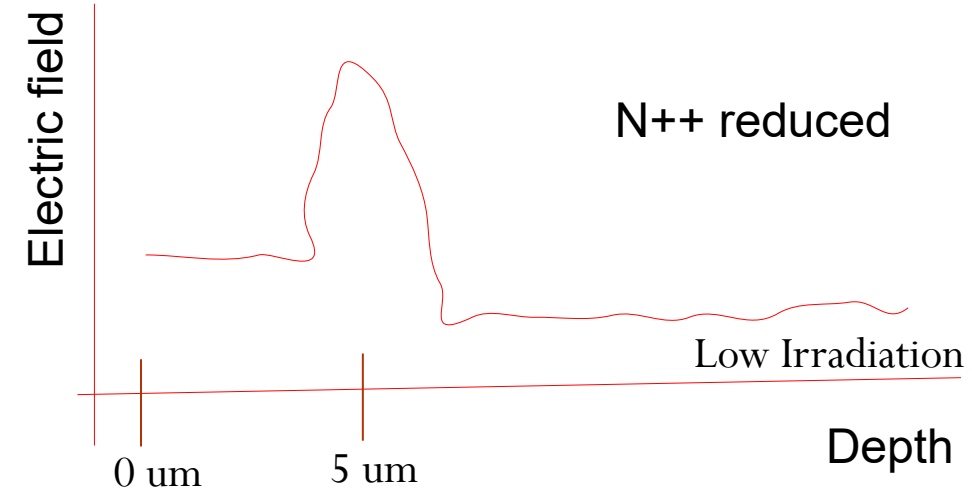
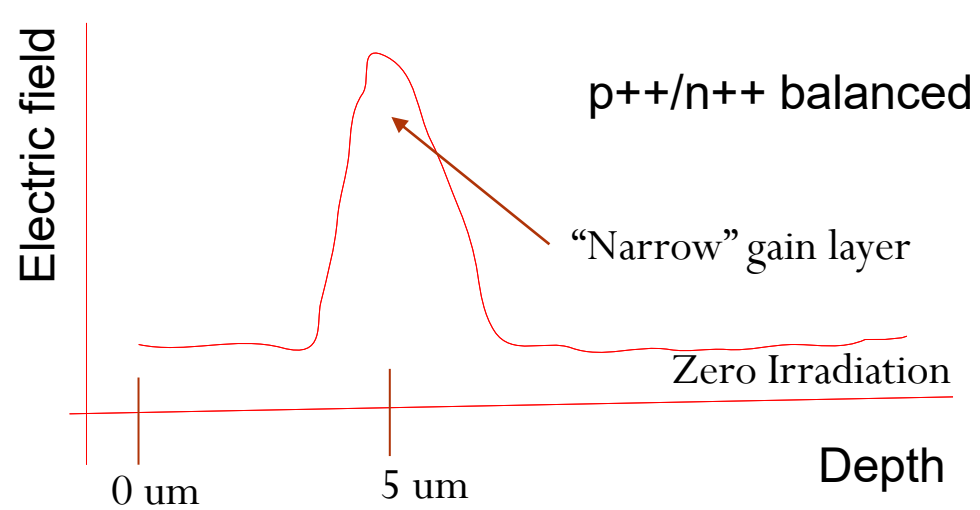


- P++ and N++ regions ramp up and down the E field
 - When new the layers are balanced so the electric field in the n region is low
- **Before irradiation n++ and p++ can be very high since the gain layer can be narrow**
 - The breakdown is under control because they balance out
- But after irradiation **if N++ goes down faster than P++** the electric field in the region is increased
 - From literature N is more affected by acceptor removal
 - Ratio of acceptor removal can be adjusted with Carbon (P) and Oxygen (N) co-implantation
- After irradiation the n++ “shielding” goes away and the gain layer adapts to a “deep” one in a controlled way
- **Good performance before and after irradiation!**

Adaptive gain layer - doping

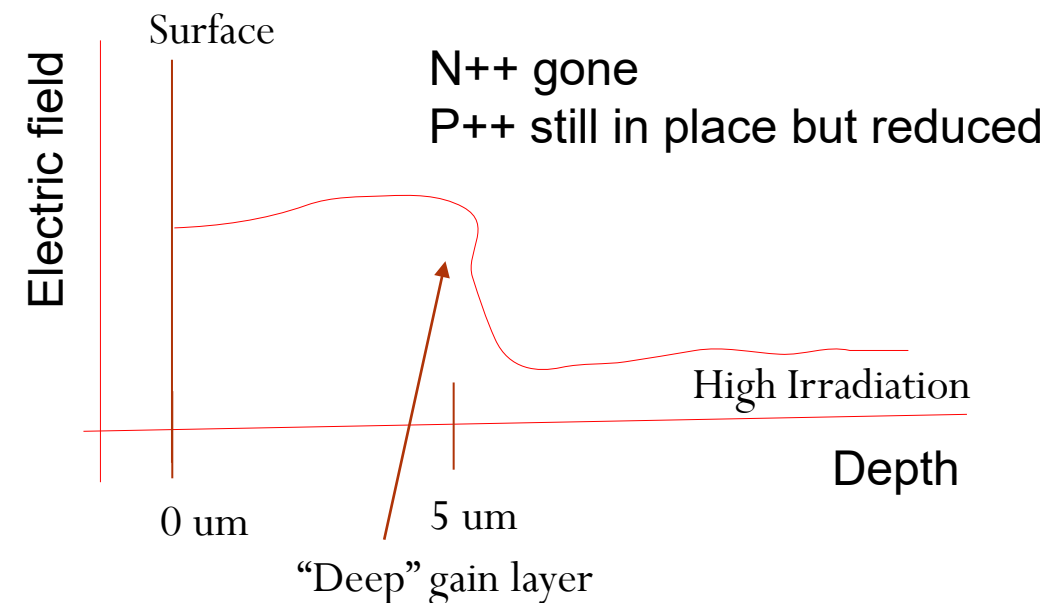


Adaptive gain layer – Electric field



Adaptive gain layer – Top surface field

- After irradiation the high electric field “leaks” to the surface
- The fine pixelation advantage of DJ-LGAD is gone
- Need either AC-coupling or trenches for arrays
 - But that’s an issue for another day...



RD50 fabrication

Proposed fabrication of DJ-LGAD in RD50

- Proposed Fabrication within RD50 of DJ-LGAD at FBK
 - First estimate of the project cost $\sim 100k$
- **14 institutes showed interest in the production**
- Preliminary financial numbers
 - Sum of institutions tentative financial contribution $\sim 60k$
 - FBK might provide in-kind contribution
 - **Asking for $<40k$ contribution from RD50 funds**

Institute	People
SCIPP (UCSC)	Simone Mazza, Bruce Schumm, Hartmut Sadrozinski, Abe Seiden
HEPHY Vienna	Thomas Bergauer, Albert Hirtl, Marko Dragicevic
CERN	Michael Moll, Veronika Kraus, Moritz Wiehe, (Marcos Fernandez Garcia), Niels Sorgenfrei
UNM	Sally Seidel, Jiahe Si, Radek Novotny, Josef Sorenson, Hijas Farook, Andrew Gentry
KIT	Michele Caselle, Alexander Dierlamm
PSI	Jiaguo Zhang, Anna Bergamaschi, Mar Carulla
FBK	Maurizio Boscardin, Matteo Centis Vignali, Giovanni Paternoster
UCG	Gordana Lastovicka-Medin, Vanja Backovic, Ivona Bozovic, Jovana Doknic
Nikhef	Martin van Beuzekom, Frank Filthaut, Mengqing Wu, Hella Snoek
UZH	Ben Kilminster, Anna Macchiolo, Matias Senger
IHEP Beijing	Zhijun Liang, Mei Zhao, Yunyun Fan
Manchester	Oscar Augusto De Aguiar Francisco, Enoch Ejopu, Marco Gersabeck, Alex Oh
CIS	Kevin Lauer, Stephanie Reiss
U. New Delhi	Ashutosh Bhardwaj, Kirti Ranjan

Proposed fabrication of DJ-LGAD in RD50

- Purpose: develop further the DJ-LGAD technology
 - Increase LGAD technology granularity
 - Solve high current issue (trench termination and careful dicing)
 - Fabricate a device that is possibly very rad-hard
- Why FBK?
 - Long-standing expertise in LGADs
 - Can do epitaxial growth (outsourced)
 - Expertise in Carbon co-implantation
 - Trench technology (might be necessary for gain layer termination)

Patent considerations

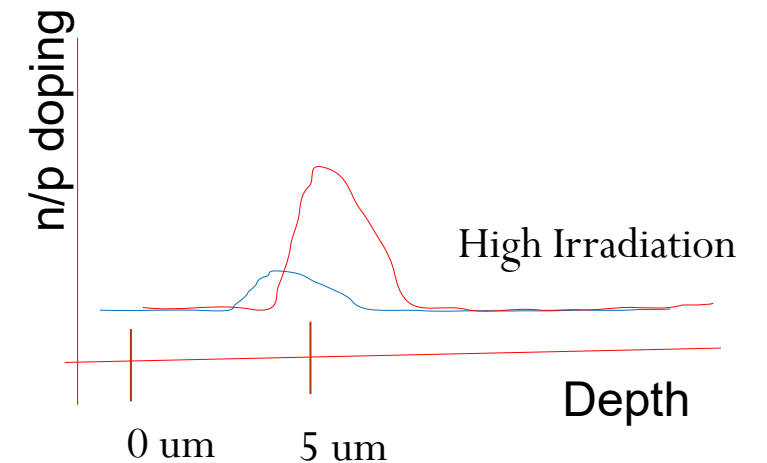
- DJ-LGAD is a IP pending of UC (US and EU): **Patent WO2021087237A1**
 - <https://patents.google.com/patent/WO2021087237A1/en>
 - Per RD50 MOU the patent can be 'foreground' or 'background'
 - Might be worth to have it documented, especially since RD50 will terminate at the end of the year and DRD3 will have a slightly different group of institutions
- DJ LGAD would be "background IP" under 7.1 of Article 7 of the MOU
 - The DJ LGAD won't appear in Article 8 because it hadn't yet been invented when the MOU was executed, but it was developed outside the RD 50 consortium, so it fulfills the spirit of Article 8.
 - Can be discussed during the collaboration Board meeting
- Discussion ongoing with FBK for license terms

Conclusions

- DJ-LGAD: a device with deep gain layer
 - Avoid high field near the electrodes while maintaining gain
 - Fine pixelation of the top surface
- **Adaptive gain layer can increase greatly the radiation hardness capabilities of LGADs**
 - Adaptive gain layer can be combined with compensated gain layer and Carbon co-implantation
- First working DJ-LGAD prototype demonstrated but with some issues
- **Proposed RD50 production with FBK using Epitaxial growth**
 - Cost $\sim 100k$, more than half might be financed through participating institutions funds
 - First draft of the project attached in the agenda
- This work was supported by the United States Department of Energy, grant DE-FG02-04ER41286 and SBIR DE-FOA-0002145



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Backup

N and p removal

Acceptor and donor removal happens at different rates, donor removal seems to happen faster

Only direct comparison source I could find:
[https://doi.org/10.1016/0168-9002\(96\)00217-3](https://doi.org/10.1016/0168-9002(96)00217-3)

The rate of acceptor and donor removal can also be modified by co-implantation of Carbon (acceptor) and Oxygen (donor)

→ we can fine tune how highly doped p and n layers can change with radiation damage

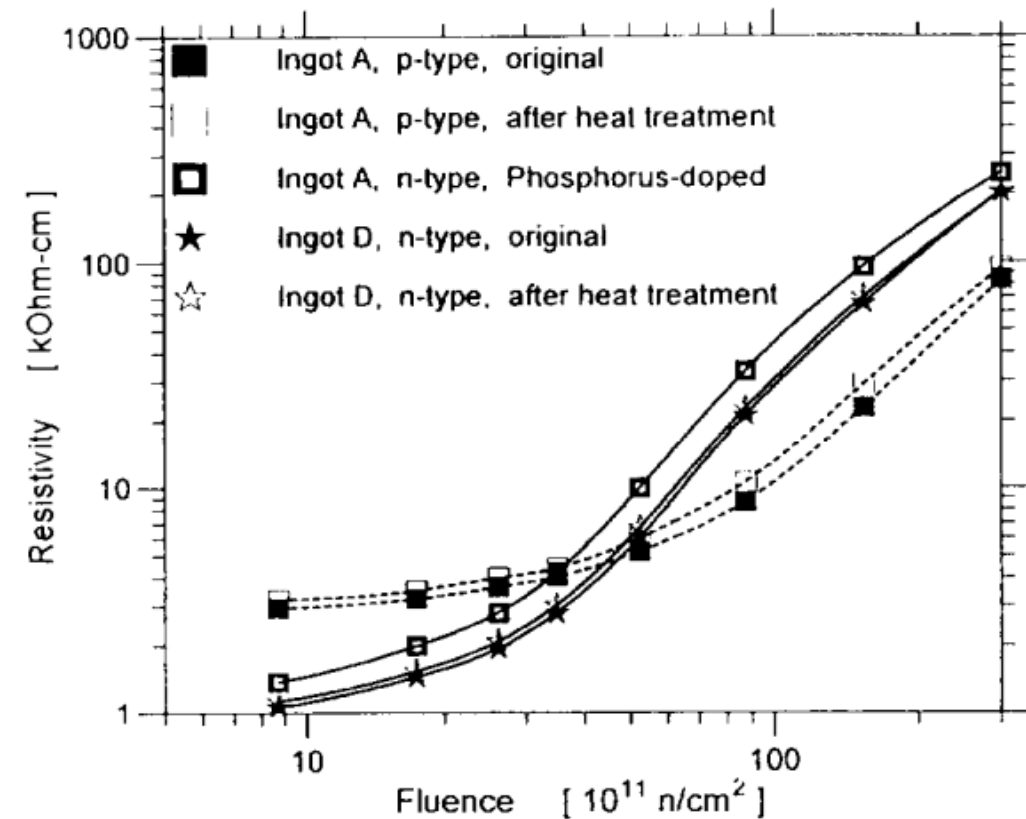
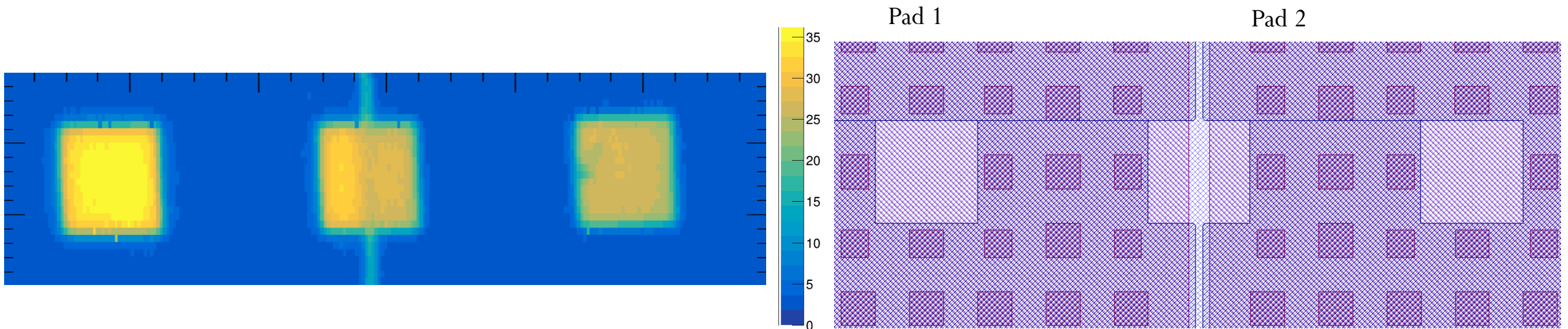


Fig. 1. Typical fluence dependence of the resistivity of different silicon wafers.

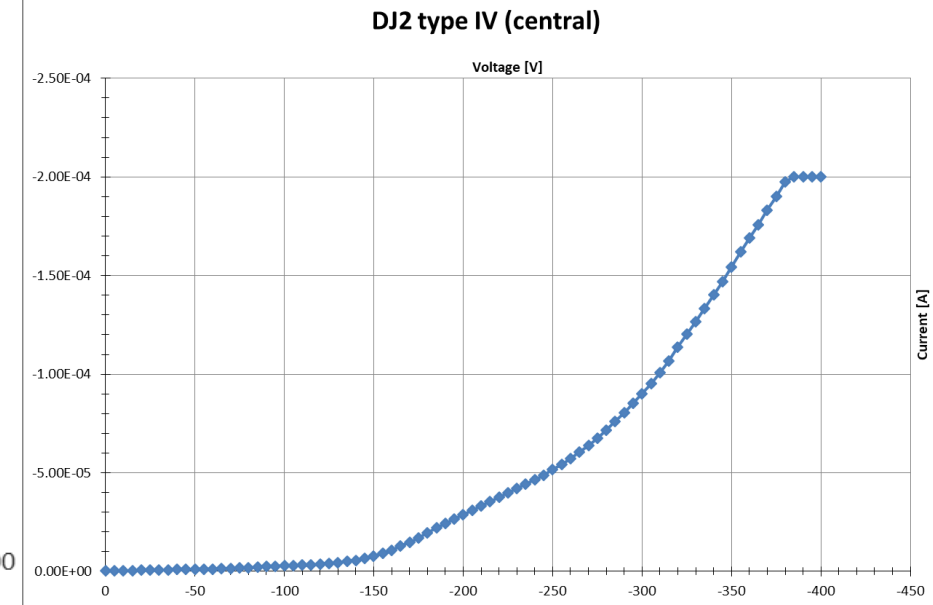
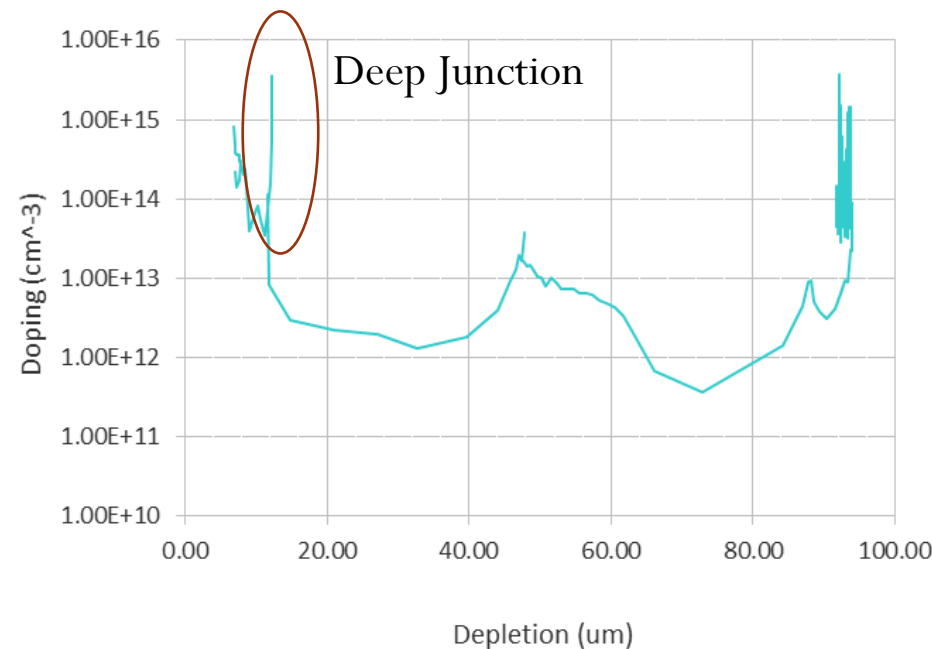
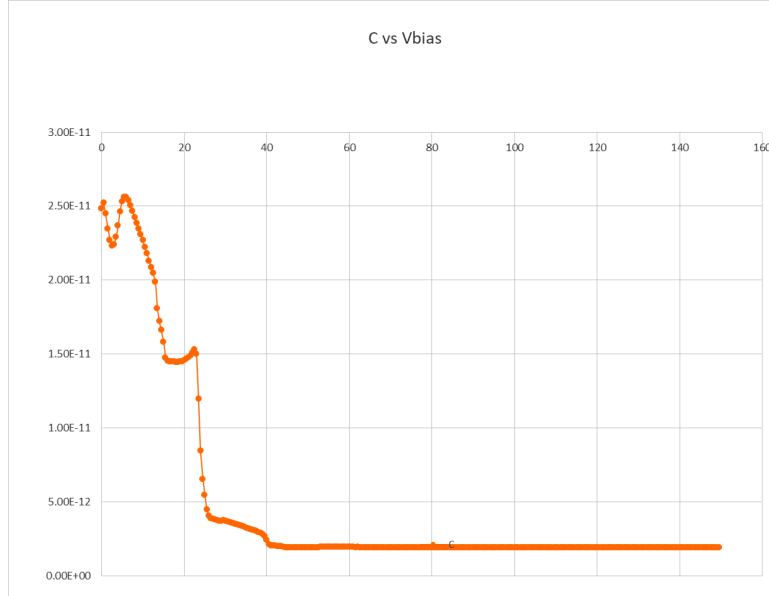
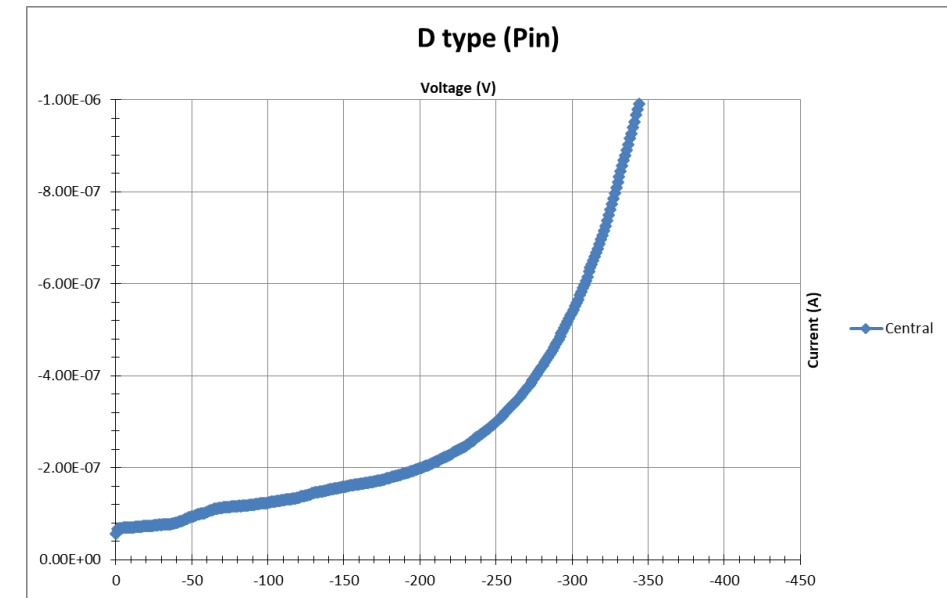
Laser studies

- **DJ-LGAD 2x1 array prototype is studied with IR Laser scan**
 - Digitized by fast scope, laser spot size is 10-20 μm
- Pmax values in terms of the laser beam location are shown for sum of channels
 - Sensors have 3 open areas in the metal, one in each pad and in between pads
 - In the scan the blue low signal region corresponds to the metal
 - The sum of the two signals is more or less constant on the sensor (no gain loss in between pads)



DJ-LGAD 2nd prototype run

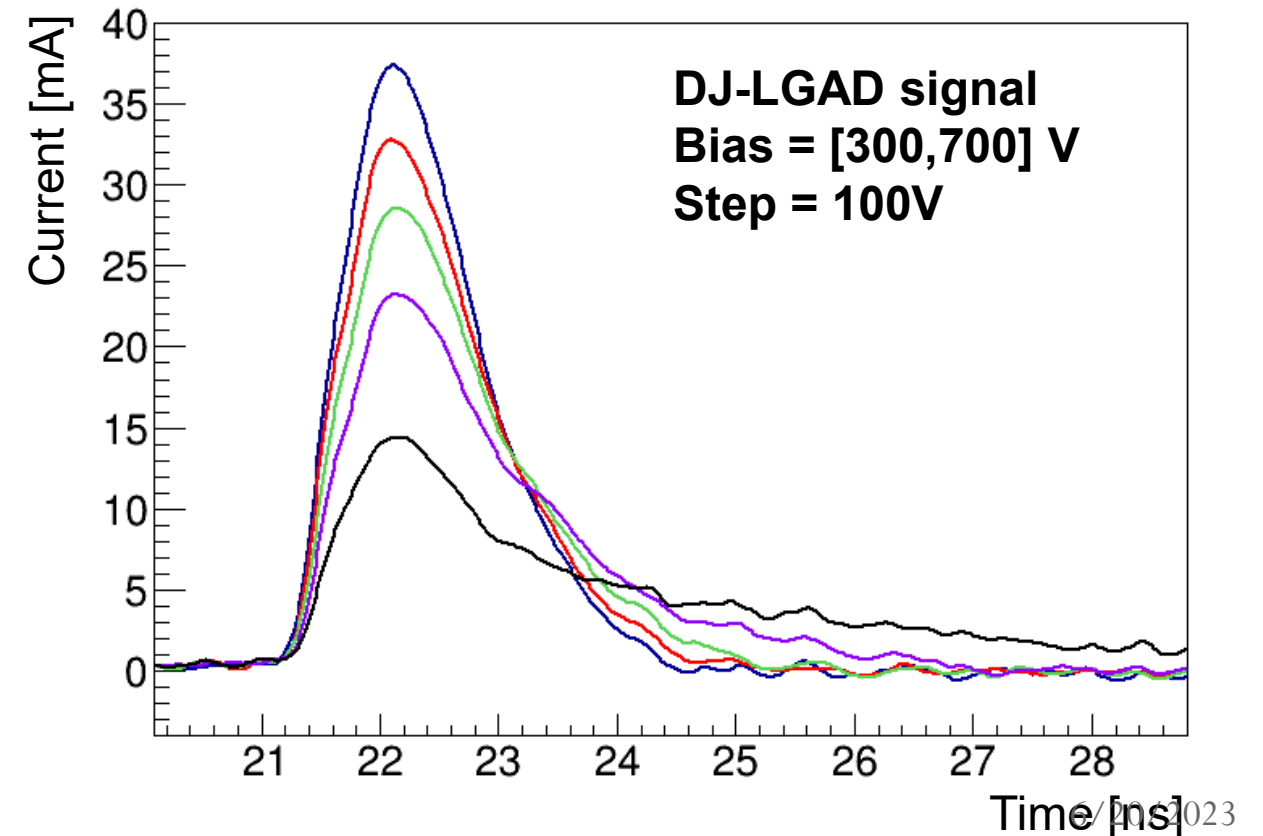
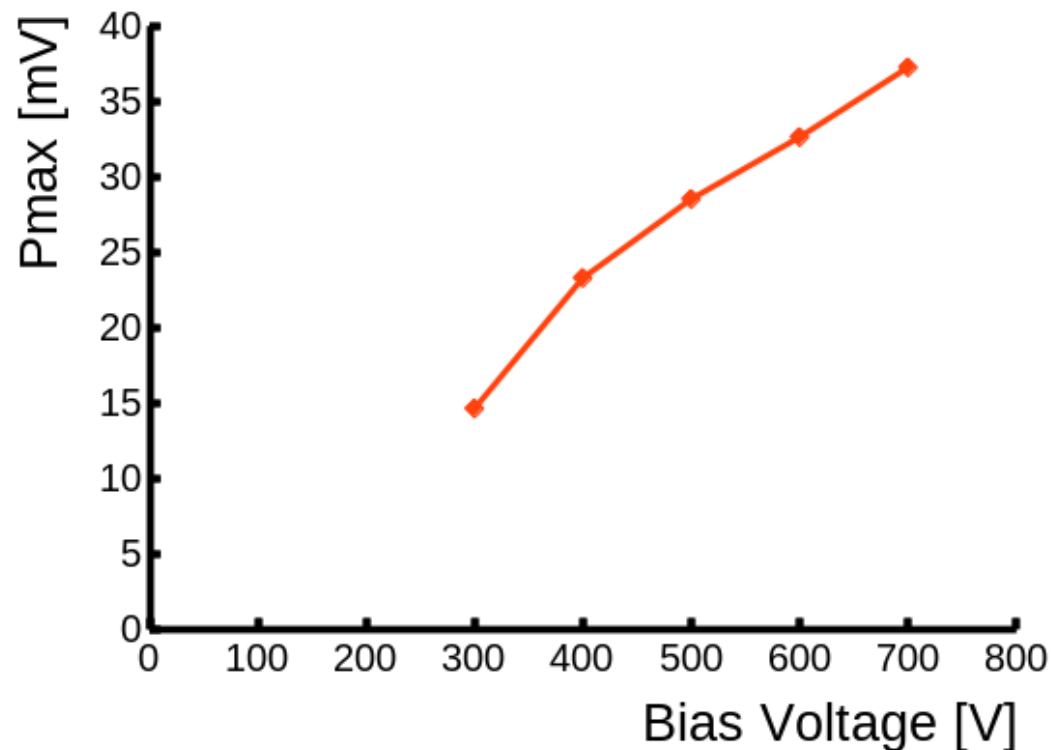
- D-type, standard PiN with deep junction, Current <1uA
- DJ-type, deep junction ending below the active area, High current (100s uA)
 - The sensor is also very noisy, not usable
- DJ2-type, deep junction ending under the Guard ring
 - Manageable current (10s uA), BV seems to be very high
 - CV shows deep junction structure, thickness seems higher than expected
- DJ3-type, 2x1 array, termination as DJ2, Manageable current (10s uA)



Charge collection studies

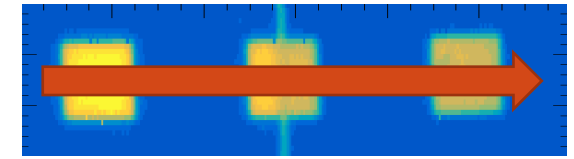
Data taken by Miguel Godoy

- Sensor mounted on UCSC 1ch and 4ch board, test with Sr90 source with know trigger sensor to study MiP response
 - Read out by fast oscilloscope, trigger on the trigger sensor
- **Rise time ~ 580 ps, similar to a typical 50-60 μ m LGAD, Breakdown >700 V**
- **Measured gain of ~ 3 to 5**
 - Lower than conventional LGAD
 - Optimization of the gain layer doping is required for future prototype



Laser studies

Data taken by Yuzhan Zhao

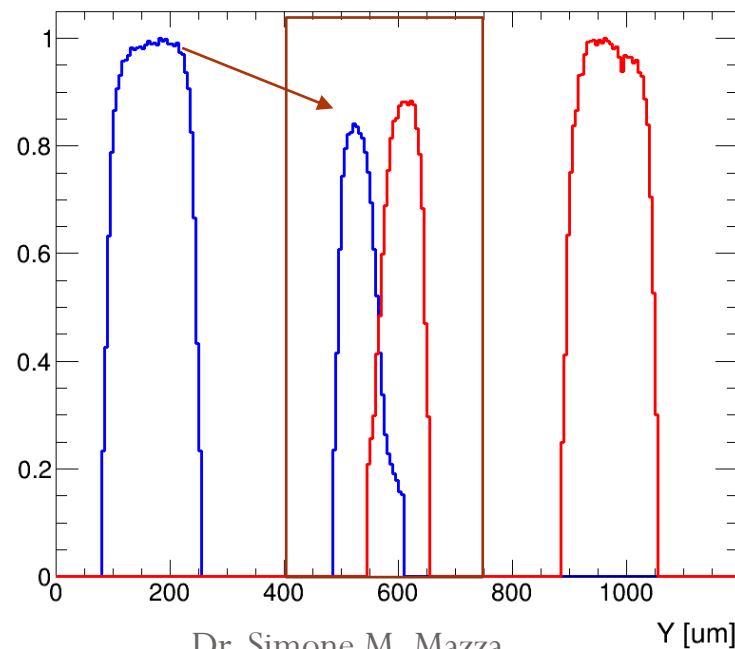


- **1D profile fractions shows a slightly lower signal next to the gap**
 - 2D simulation shows the field in the gain layer is reduced in the inter pad region
- Zoom in the inter pad region (nominal electrode gap is 30um)
 - Sum of signal show almost no reduction in the gain
 - Minor cross talk in a 50 um region between pads

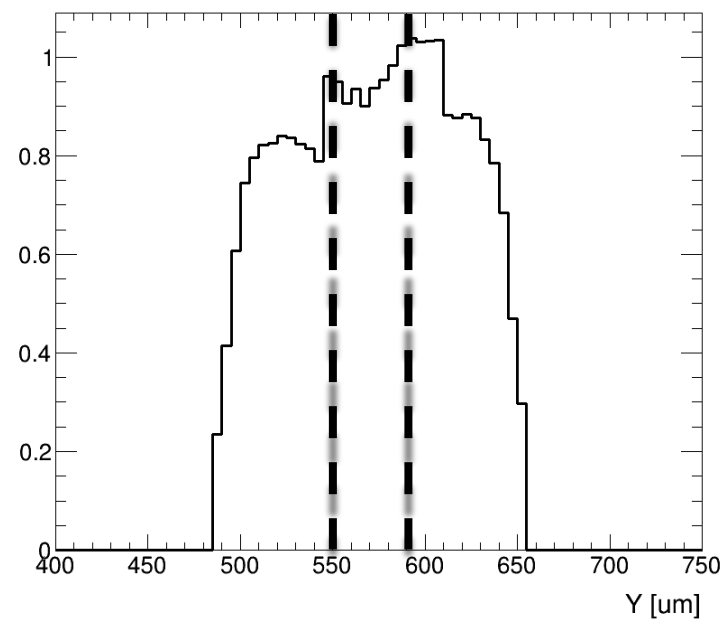
The pmax fraction of an individual strip is defined as:

$$pmax\ fraction\ (channel) = \frac{pmax\ (channel)}{\sum pmax}$$

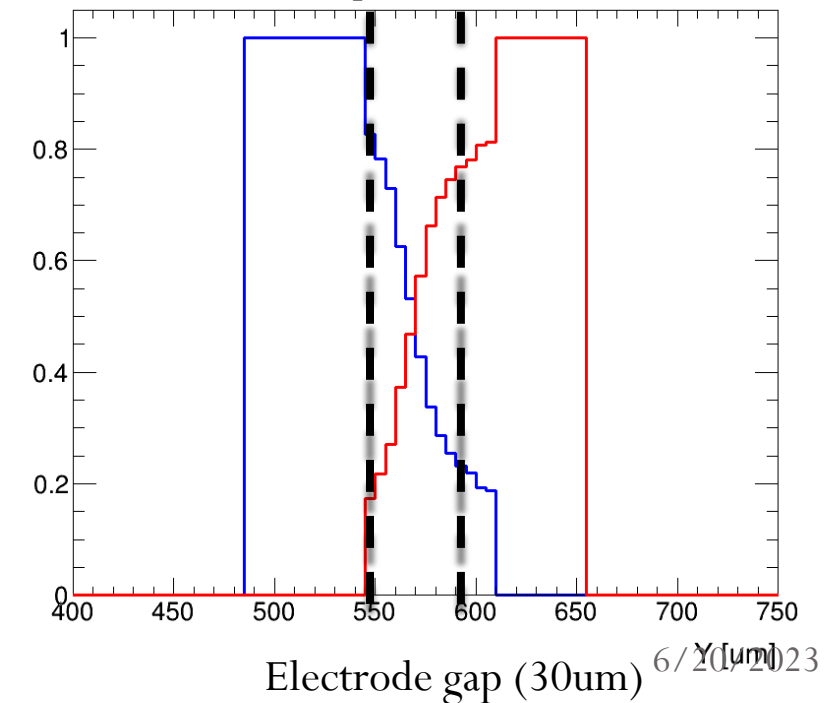
Normalized profile for Pad 1 and 2



Normalized sum of Pad 1 and 2



Fractional Pmax profile between Pad 1 and 2



Article 7. Intellectual Property

In addition to Article 7 of the General Conditions, the following clauses apply:

- 7.1 Each Party shall, prior to entering into this MoU, identify to the best of its knowledge at the time, the protected intellectual property ("IP") it owns and contributes to the Collaboration for the execution of the RD-50 programme, and list such IP in **Annex 8** together with any applicable restrictions ("Included Background IP"). A Party wishing to transfer its Included Background IP listed in **Annex 8** to a third party shall notify the other Parties of such transfer and ensure that the rights of the Parties under this MoU are adequately safeguarded.
- 7.2 For the avoidance of doubt, it is hereby clarified that all Background IP (as such term is defined below) not listed in **Annex 8**, is hereby explicitly excluded from the definition of "Included Background IP" under this MoU and from any rights that otherwise would have been granted under this MoU to the Parties.
- 7.3 For the purpose of this MoU, "Background IP" shall mean any information and scientific and/or technical knowledge i.e. know-how, secret processes, trade secrets, data, software in its source code version or in its object code version, files, plans, diagrams and figures, designs, formulae and/or any other type of information, in any form, whether it is patentable or not and/or whether it is patented or not, as well as copy rights and other intellectual property rights pertaining to

such information, which belongs to or is held by a Party prior to the entry into force of this MoU and/or which is developed outside the scope of the Collaboration.

- 7.4 Any IP developed in the execution of the RD-50 programme ("Foreground IP") shall belong to the Party having generated such Foreground IP. Such Party shall be free to decide whether to protect and/or exploit the same at its own cost and risk, subject always to the provisions of this MoU.
- 7.5 In case Foreground IP has been generated by more than one Party, and either their respective share of the Foreground IP cannot be distinguished, or cannot be dissociated for the purpose of its protection, such Foreground IP shall be owned jointly by the Parties having generated it, unless agreed otherwise in writing by such Parties. In such case, the Parties concerned shall jointly apply to obtain and/or maintain the relevant intellectual property rights and shall strive to set up amongst themselves, in good faith, through the representative of the offices of technology transfer or their equivalent, a co-ownership agreement in order to do so. These co-ownership agreements shall specify the allocation of expenses and royalties in connection with the jointly owned Foreground IP, and the share of each of the Parties in its development, all subject to the provisions of this MoU.
- 7.6 The conditions of access to IP of a Party for the purpose of executing the RD-50 programme are set out in the General Conditions. Access for all other users, including but not limited to commercial exploitation, shall be the subject of a separate written agreement involving the Parties concerned and shall be at the sole discretion of the Party/Parties owning the IP.
- 7.7 For avoidance of doubt, the Parties have no obligation to spend any amount in order to protect their IP; however, a Party that did not participate in the costs of an enforcement action of IP which is jointly owned shall not be entitled to any reward collected therein.
- 7.8 Any publication by a Party relating to the execution and results of the RD-50 programme shall acknowledge the contribution of the other Parties.