High radiation resistance LGAD designs for future colliders

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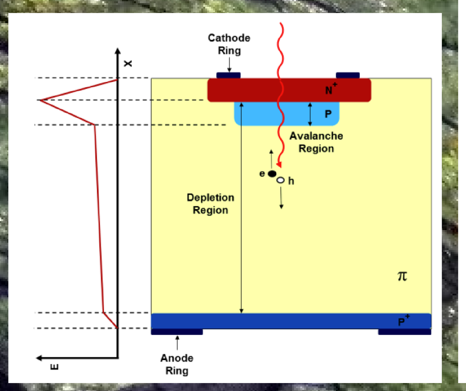
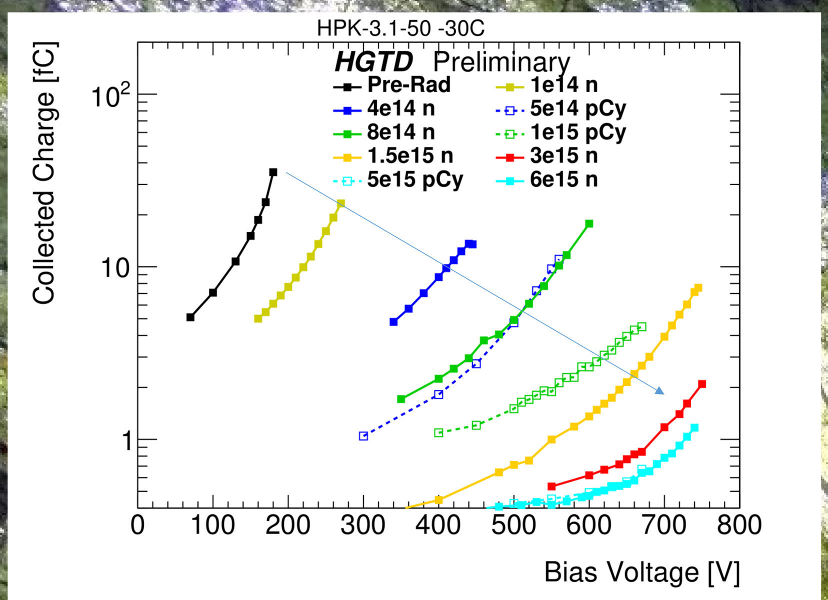
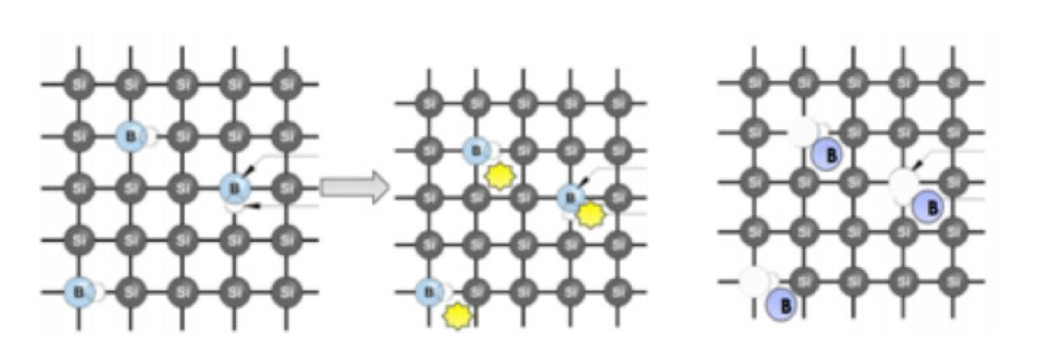




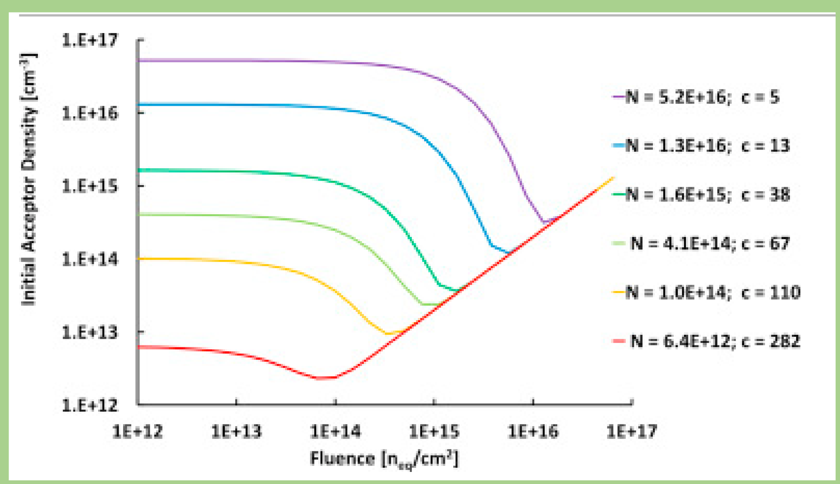


LGADs and radiation damage

- **LGADs** are thin (20-50um) silicon detectors with moderate (10-50) internal gain that can have exceptional time resolution (down to 20ps)
- However, while operating in high energy physics experiments LGADs will sustain radiation damage (both fluence and ionization dose)
- The change in performance is caused by reduced doping concentration in the gain layer by the initial acceptor removal mechanism, removal speed depends on the "c" factor
  - Other coefficient (g_{eff}) is acceptor defects creating by deep traps, not relevant for thin detectors such as LGADs
- Performance can be partly recovered by increasing the bias Voltage applied to the diode
- **Reduction of gain and collected charge**
  - Charge collected up to 30fC (Gain ~50) before irradiation to 1fC (gain 2-3) after a fluence of 6E15 Neq/cm^2 (Neq: equivalent 1 MeV neutrons on cm^2)
- **Increased time resolution**
  - Time res. of 25ps to 60ps after a fluence of 6E15 Neq/cm^2 due to reduced S/N

Acceptor removal

$$\rho_A(\phi) = g_{eff}\phi + \rho_A(0)\, e^{-c\phi},$$

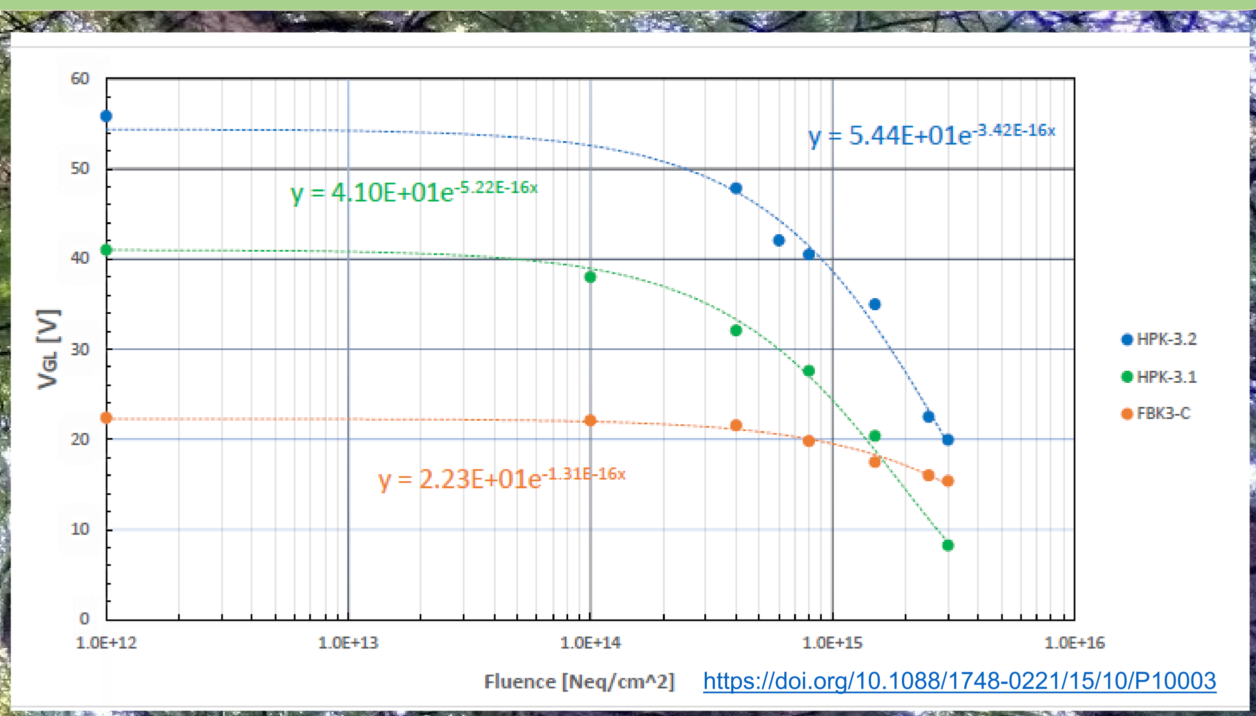


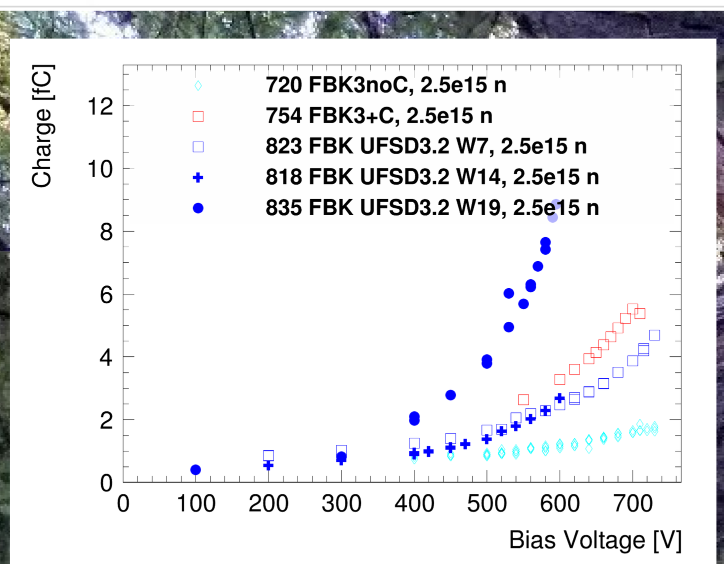
https://doi.org/10.1016/j.nima.2018.11.121

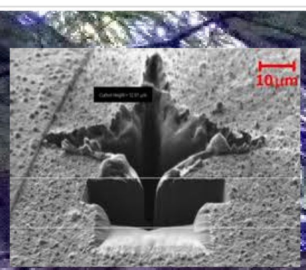
Successful radiation hard LGAD designs

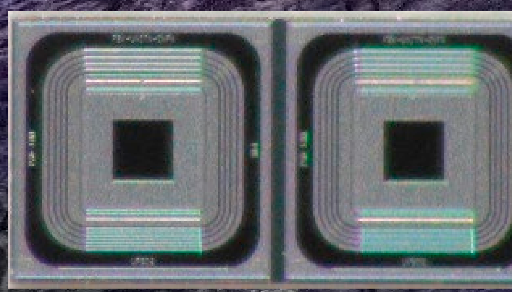
- Radiation hard LGADs developed for the ATLAS and CMS timing layers for HL-LHC
- **Thin but highly doped gain layer**
- **Addition of Carbon**
  - Carbon is electrically inactive (no effect pre-irradiation), catches interstitials instead of Boron, reduces acceptor removal after irradiation
- **Deeper gain layer**: high field for larger volume
  - Allows for better recovery of the gain from increased bias voltage after radiation damage
- The combination of all these techniques (by FBK) allowed to produce a sensor with gain ~20 at 2.5E15 Neq/cm^2 (maximum requirement for ATLAS timing layer)
  - An increased maximum fluence reach of a factor 10 than first LGADs in ~5-6 years!
- However, since this breakthrough the community has been struggling to develop a design that can push the boundaries further
- Another issue is **Singe Event Burnout (SEB):** device breaking after irradiation caused by a single, high ionization event

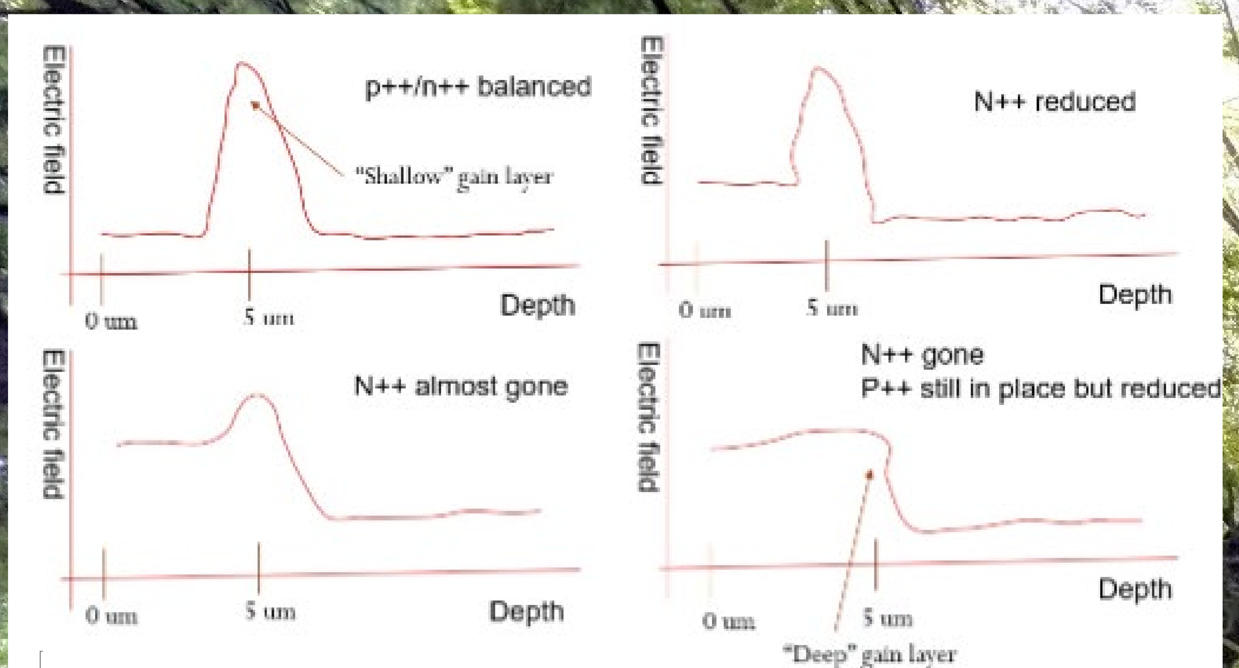
https://indico.cern.ch/event/1029124/contributions/4411270/
https://iopscience.iop.org/article/10.1088/1742-6596/2374/1/012173

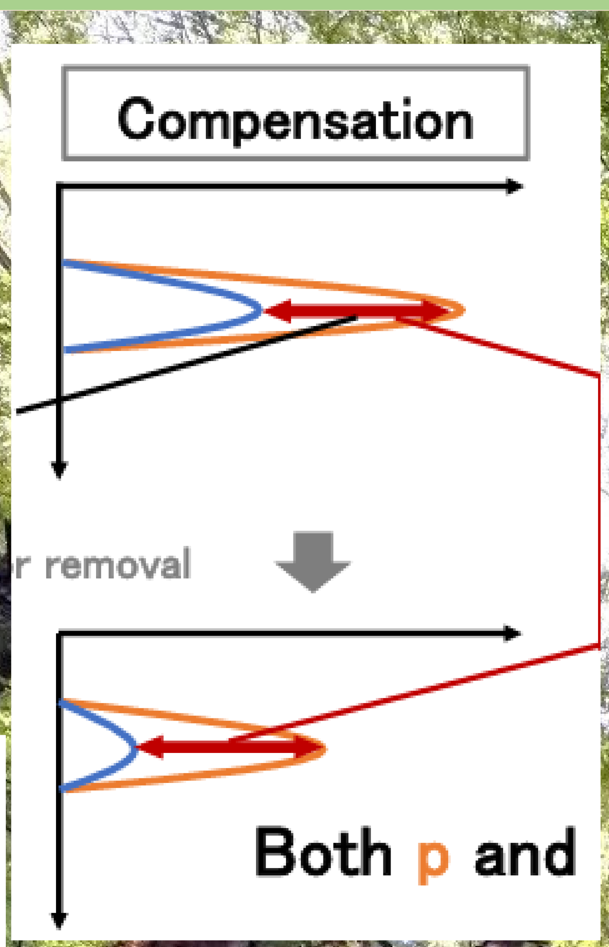


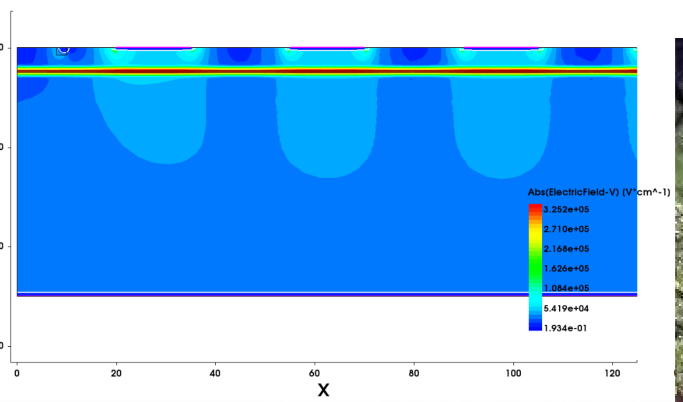


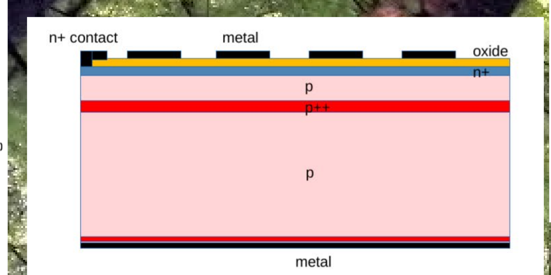


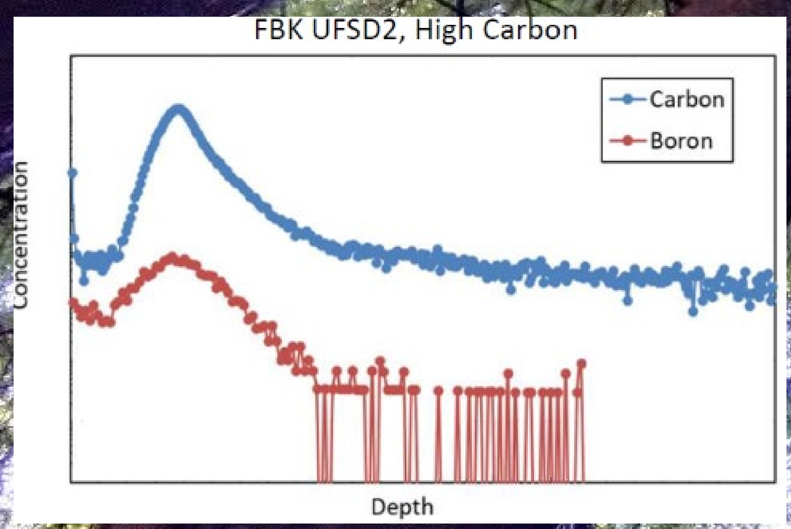


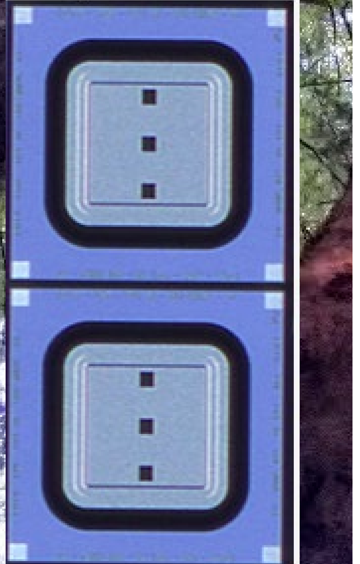


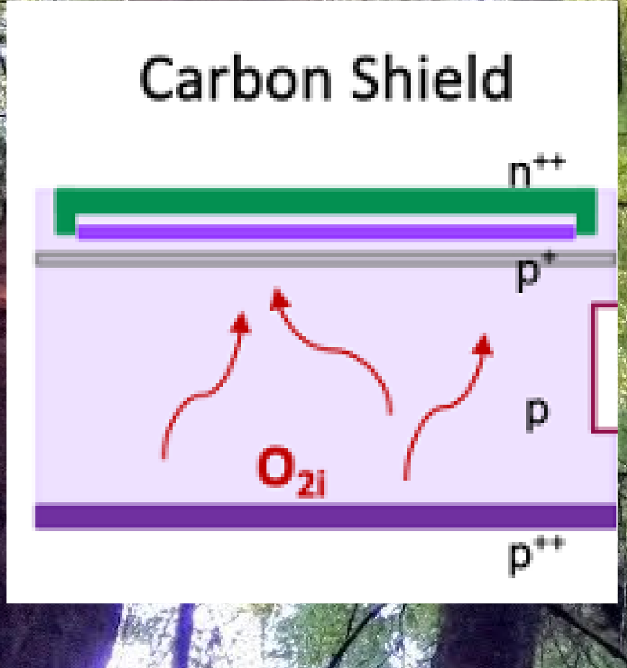












What's needed for FCC-ee/hh

- At FCCee the environment will be low fluence and low occupancy, but high hit precision is needed
  - 'standard' AC-LGADs can make the trick, see contribution on Tuesday https://indico.cern.ch/event/1298458/contributions/5977771/
  - Effect of radiation damage on AC-LGADs have to be verified
- For FCChh need for order of magnitude increase in radiation hardness ($10^{16\text{-}17}$ Neq/cm^2)!
  - Many parallel efforts are ongoing to push the radiation hardness of LGADs
- **Compensated Boron (exFLUO, FBK)**
  - Both P and N doping in the gain layer, offset generates electric field. If P and N go down in the same way gain is preserved.
- **Carbon shielding (exFLUO, FBK)**
  - Carbon layer under gain layer to shield the Boron from O defects from the bulk
- **Partially activated Boron (KEK, HPK)**
  - Implant more Boron but leave a portion non-activated to intercept and remove the O defects
- **Very deep gain layer (FNAL)**
  - Place the gain layer very deep in the device to have a large gain area
- **Adaptive gain layer (UCSC, FBK)**
  - Use the Deep-Junction (DJ-LGAD) technology to have an initial 'shallow' gain layer that becomes 'deep' after radiation damage

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https://indico.cern.ch/event/1334364/contributions/5672078/ https://indico.cern.ch/event/1334364/contributions/5672083/
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