Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Developments of LGAD sensors

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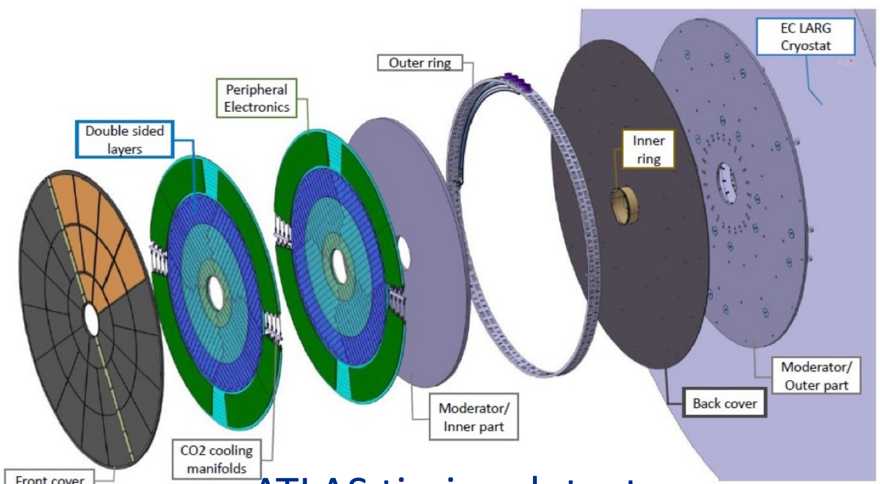
4D-Tracking workshop

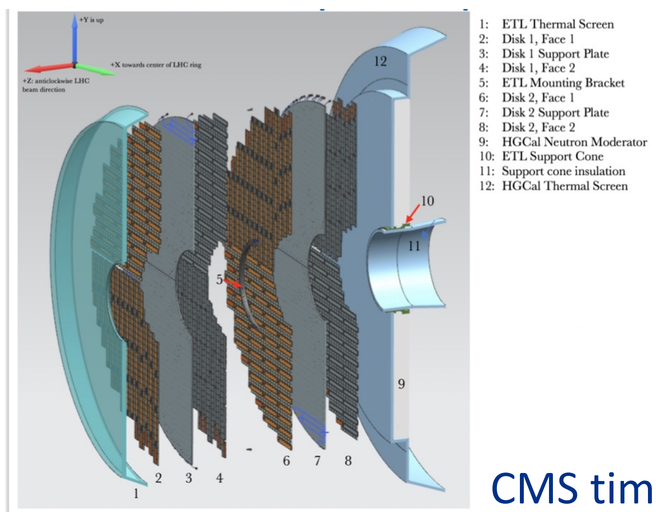
7 November 2024

Precision timing

- Traditionally in collider experiments we measure very well
  - Position, charge and energy of particles
- CMS and ATLAS are building first-generation of 4D-detectors
  - Next-gen detectors will have high granularity also in **time domain**
  - At the tracker, calorimeter, muon detectors, and L1 trigger
- Future detectors moving towards full **5D Particle Flow**
  - Active R&D to achieve required performance for future experiments
  - Sensors, ASIC, front-end electronics developments



ATLAS timing detector

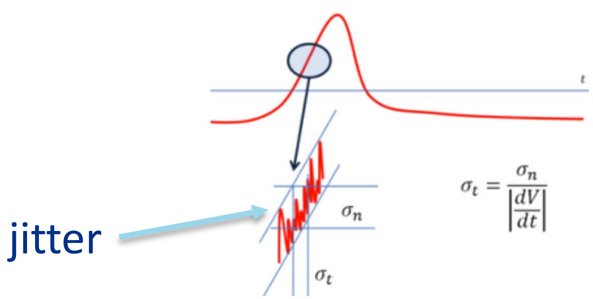


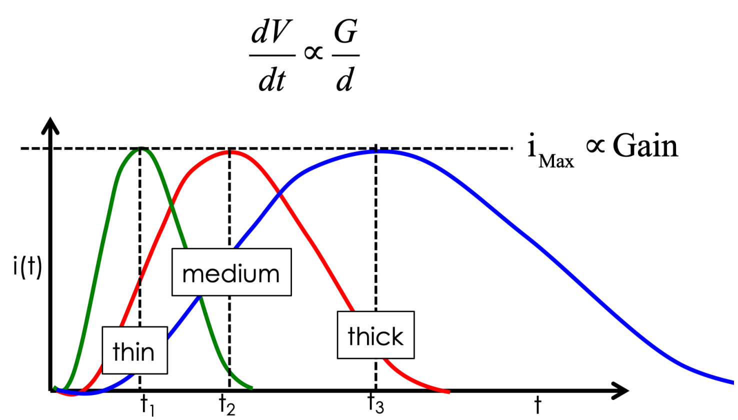
CMS timing detector

Time resolution components

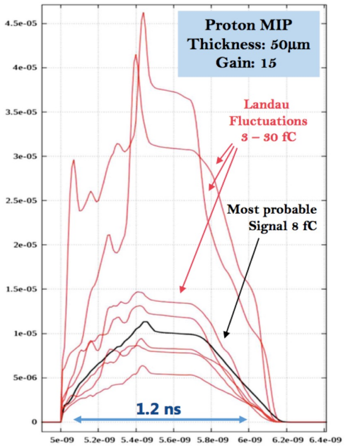
- Optimize detector timing resolution
  - Increase Signal/Noise to minimize jitter
  - Fast rise time to reduce impact of electronic noise: thinner sensor
- Non uniform charge deposition:
  - Landau fluctuations: cause fluctuations in signal shape and amplitude
  - Effect is reduced in thinner sensors
- Thinner sensor means small signal: can we add Gain?

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} = \frac{N}{\frac{S}{t_r}} = \frac{t_r}{S/N}$$





Rise time dependance on Si thickness



Landau fluctuations

Timing resolution

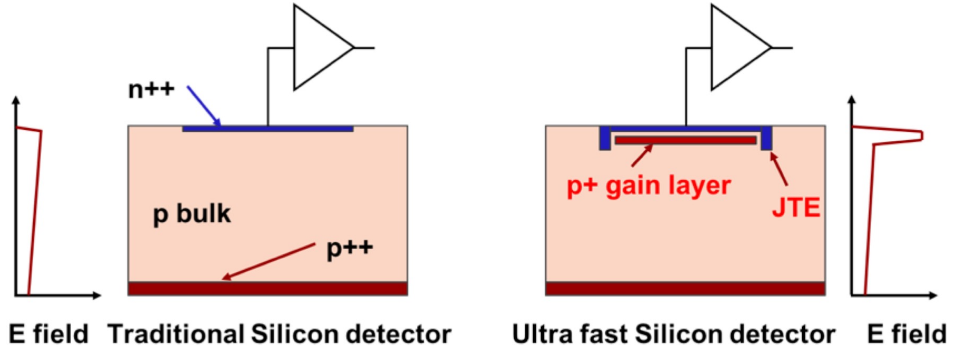
- Putting together various components

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{timewalk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

- Ideal detector components
  - Fast signals with large S/N ($\sigma_{jitter} = t_{rise}/(S/N)$)
  - Thin sensors to minimize σ_{Landau}
  - Stable and uniform signals across sensor area
  - Optimized electronics to reduce time-walk and clock jitter
  - Electronics with low power consumption
- Radiation damage complicates things, so all these need to be also resilient to high fluences in hadron colliders

Low Gain Avalanche Diode (LGAD) detectors

- Increase the initial signal : Ramo's theorem: increase the E_{field}
- Could increase by doing:
  - Increase bias voltage
  - Gain everywhere in the bulk
  - ***Add a specific gain layer***
- Turns out only the solution with gain layer provides a stable sensor
  - Key breakthrough in sensor design in the past decade!
  - High field in the gain region around 300 kV/cm, causes avalanche
  - High gain → high signal → faster rise → smaller "jitter"



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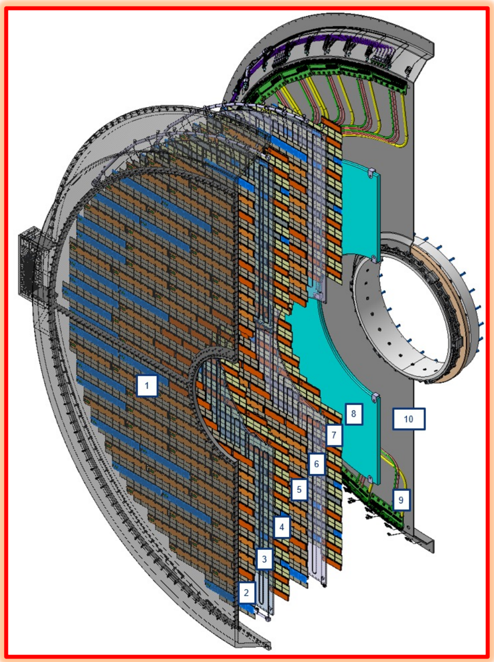
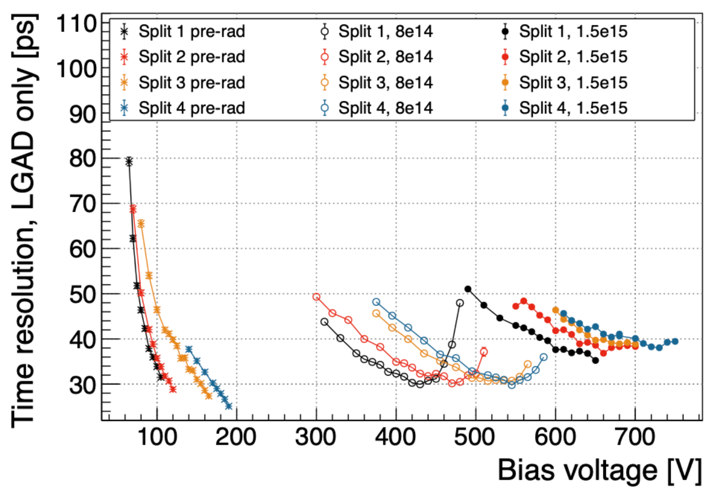
CMS Endcap Timing Layer (ETL)

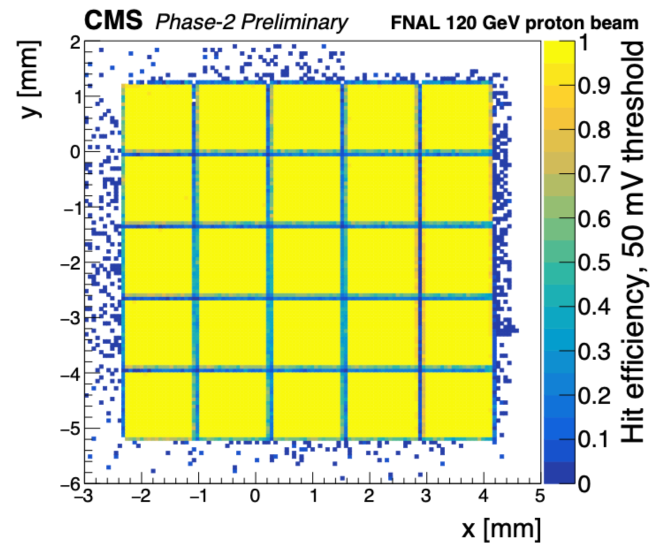
- Sensitive element are LGAD sensors
- Time resolution 30 ps at the beginning of life, 40 ps by the end
- Total silicon surface area of ~14 m^2 for the two Z-sides
  - Two hits for most tracks to improve per track efficiency and resolution



CMS Endcap Timing Layer



Time resolution for different fluences



Hit efficiency across sensor area

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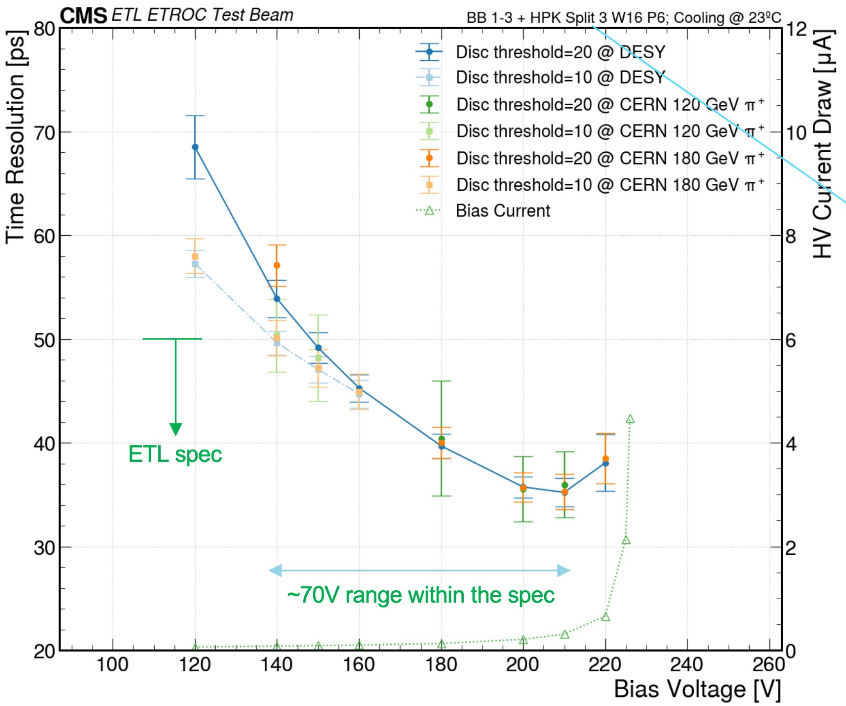
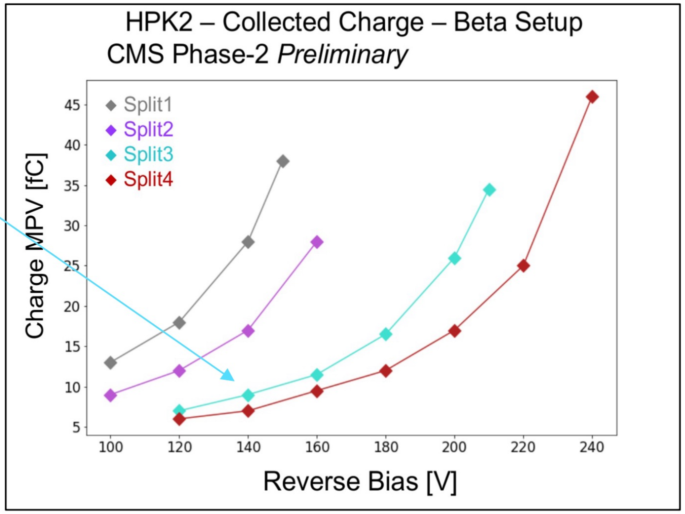
DC-LGAD sensors and performance in systems

- Developments for the LHC applications are now frozen
  - Current activities focused to scale up the production with high yields and QA/QC
- Excellent performance achieved for CMS/ATLAS applications





From T. Liu @ TWEPP24

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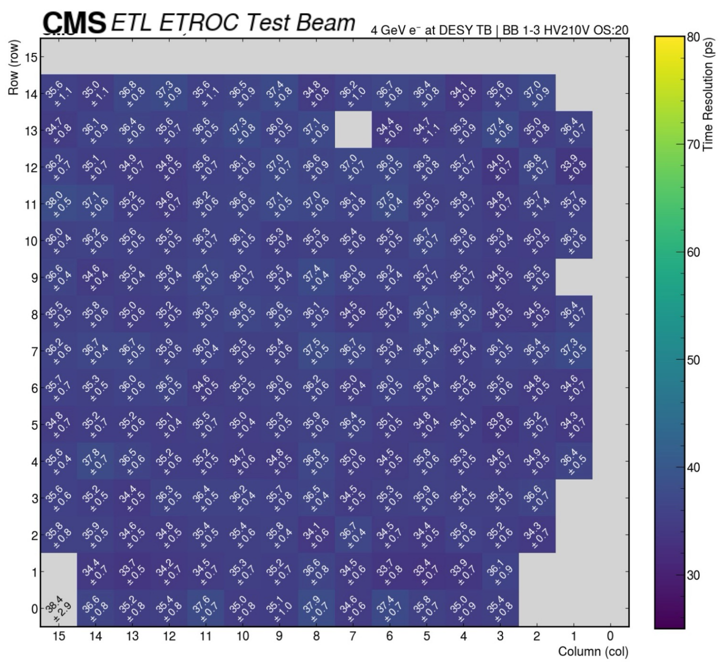
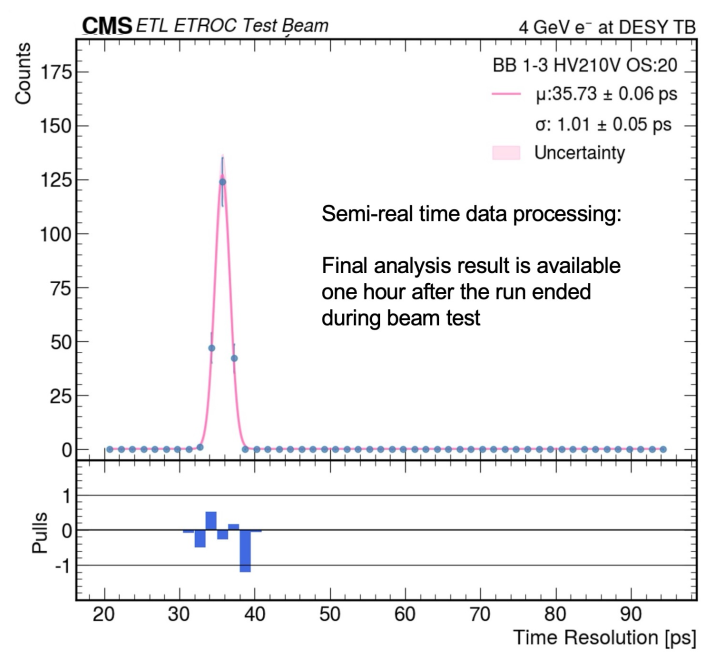




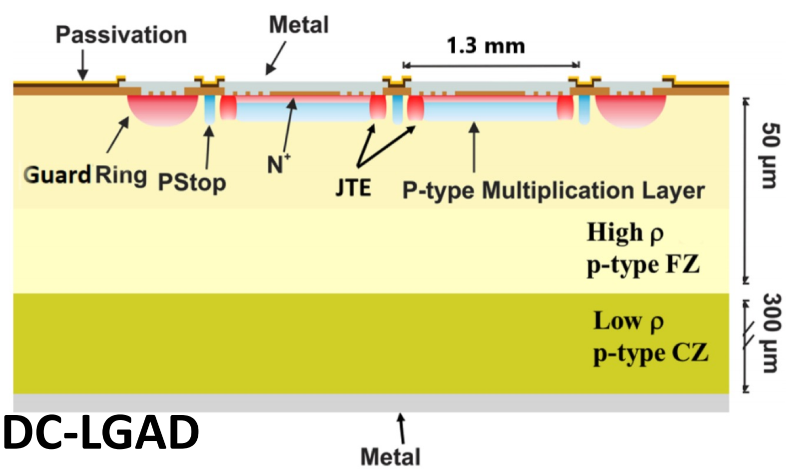
From T. Liu @ TWEPP24

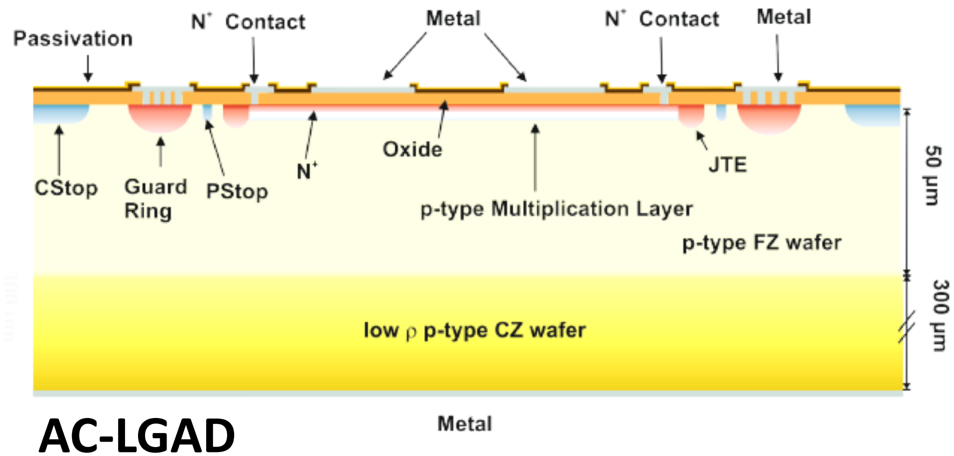
Uniform performance over the surface of 16x16 matrix of 1.3x1.3 mm2 sensors

AC-coupled LGADs

- **Improve 4D-trackers to achieve 100% fill factor, and high position resolution**
- Active R&D, many applications in colliders and beyond
  - 100% fill factor, and fast timing information at a per-pixel level
  - Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric

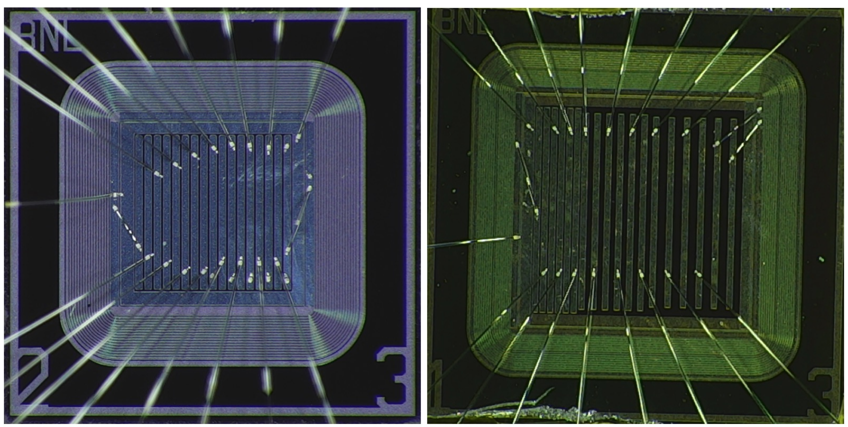
Diagram credit: CNM



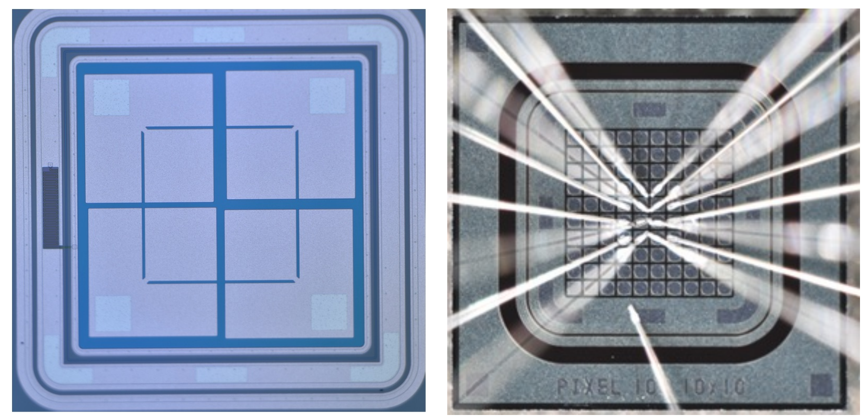


AC-LGAD sensors prototypes

- Several rounds manufactured over the last few years
  - R&D from developments for HL-LHC, synergies between HEP and NP
  - Optimize position resolution, timing resolution, fill-factor, …
- Extensive characterization and design studies
  - Optimize the geometry of readout, and sensor design for performance



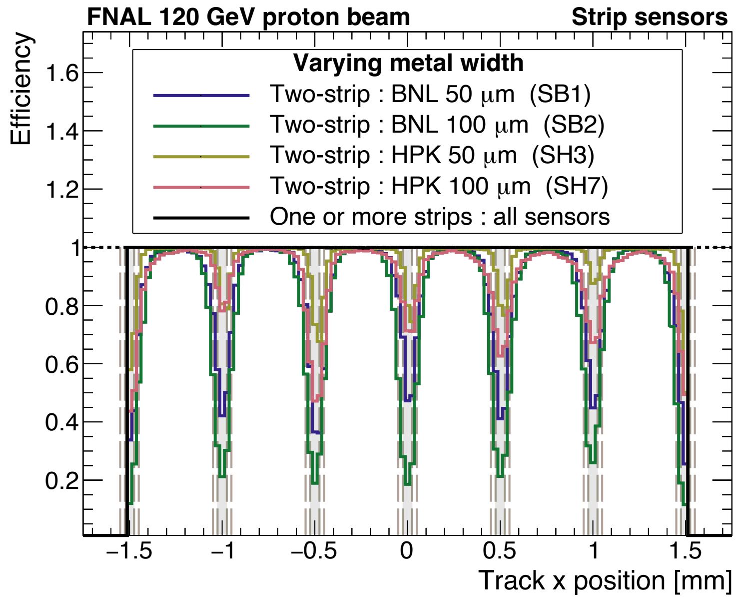
BNL strip AC-LGAD

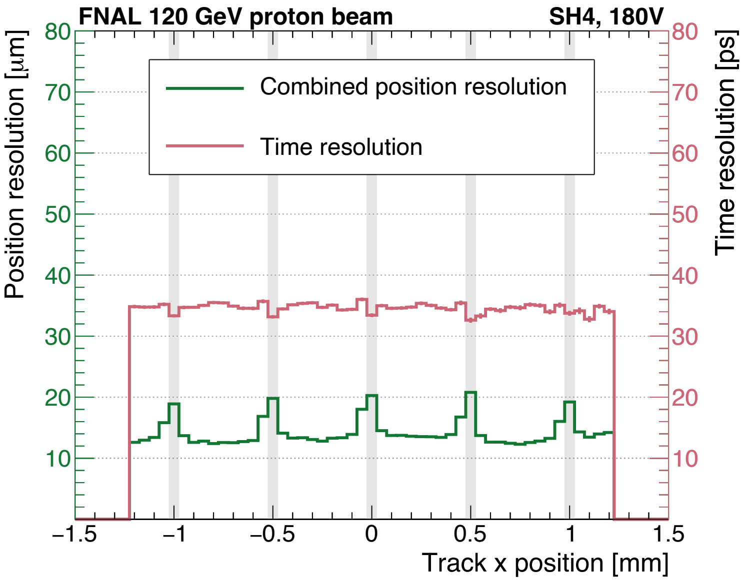


HPK pads AC-LGAD

Long AC-LGAD strip sensors performance

- Position reconstruction
  - Achieve 15-20 µm resolution in 10mm strips, 500 µm pitch
- Excellent time resolution
  - Achieve 30-35 ps for 10 mm strips





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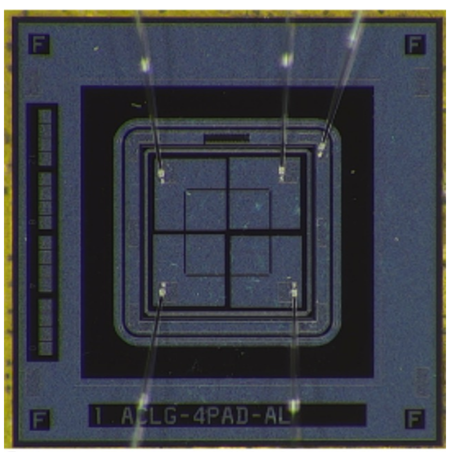
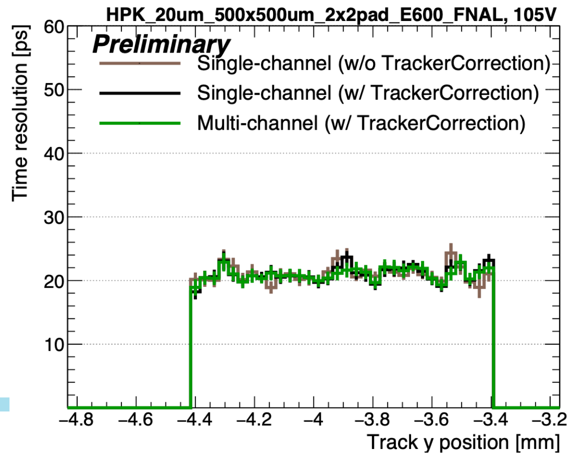
arXiv:2407.09928

Towards better time resolution

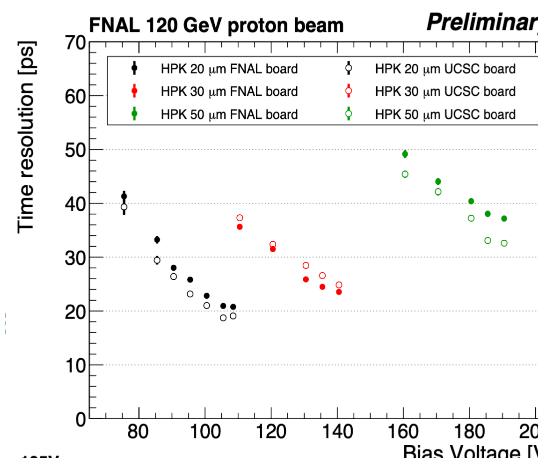
- How do you get better time resolution?
  - Thinner sensors to decrease Landau contribution
- AC-LGAD from HPK with 20, 30, 50 µm thickness
  - Almost fully metallized, optimized for timing performance
- Uniform time resolution across full sensor area
  - 25 ps for 30 µm thick sensor, 20 ps for 20 µm thick sensor



HPK 2x2, 500x500 µm^2 pixel size



20 ps across full sensor surface



Time resolution for **20**, **30** and **50** µm-thick sensors

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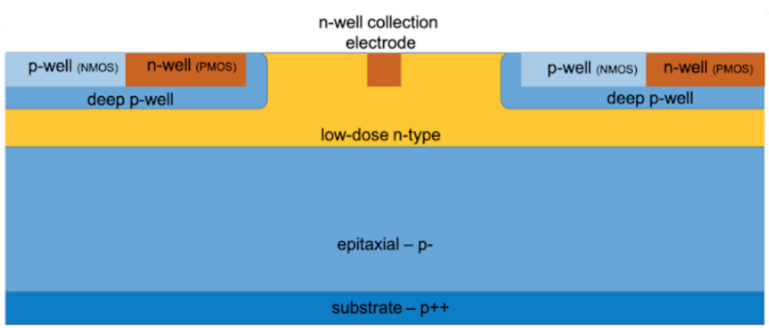
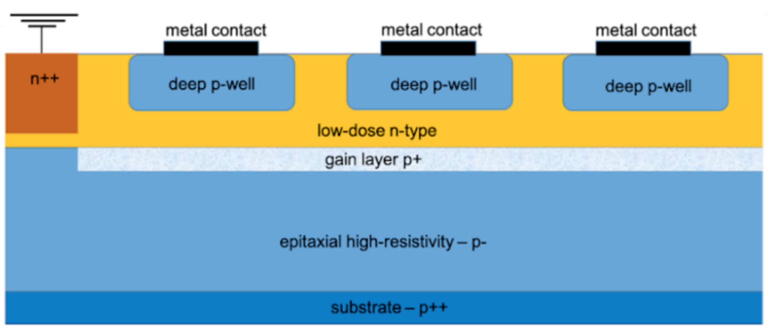
Development of monolithic AC-LGADs

- Develop MAPS sensors in a commercial process that will provide fast timing (10 ps) and precise spatial resolution (5 μm)
  - Target application 4D tracking detectors for future e^+e^- Higgs factories
- Electronics for signal processing are placed in dedicated p– and n-wells contained within a deep p-type well
  - Intrinsic gain will allow MAPS detectors to perform precise time measurements in addition to spatial measurements



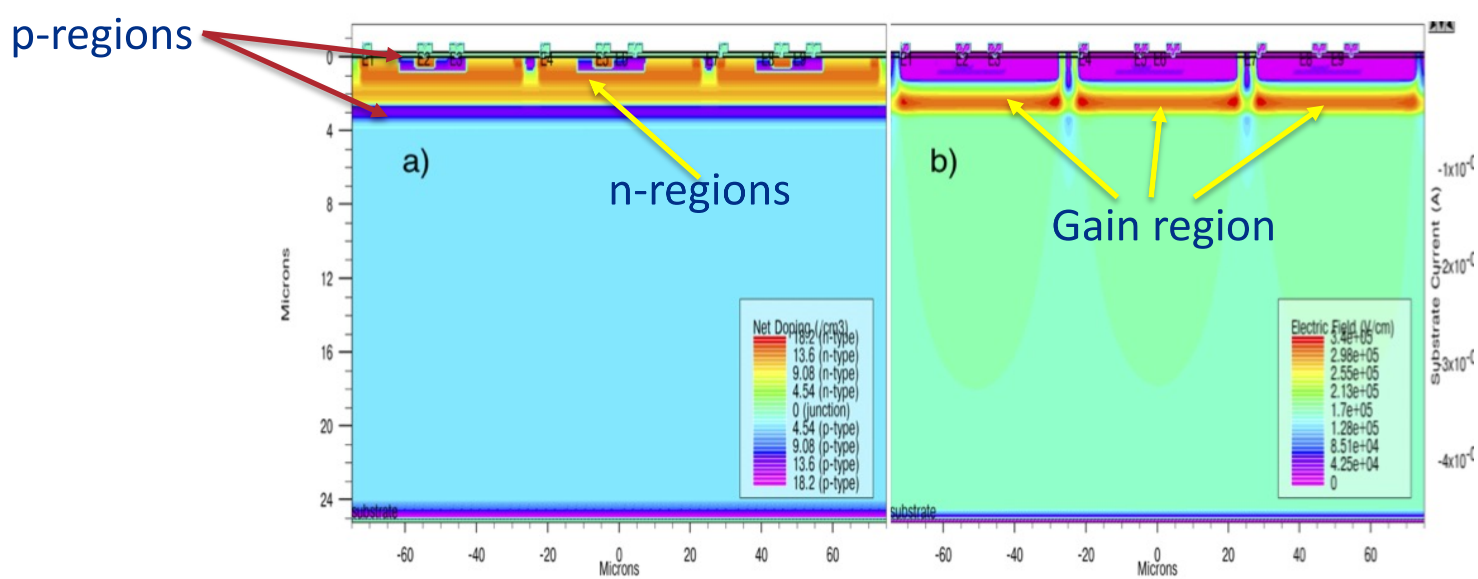
CMOS sensor



Monolithic AC-LGAD

US-Japan funded R&D

- Within this research program, the main activities of our proposal:
  - Optimize the design and geometry of AC-LGADs that will serve as the basis of the MAPS design.
  - Produce small-scale MAPS prototypes, from which the most promising architectures will be determined. Optimize the isolation of the signal collection in the sensing parts of the chip from the readout electronics.
  - Produce and characterize the full-scale prototypes

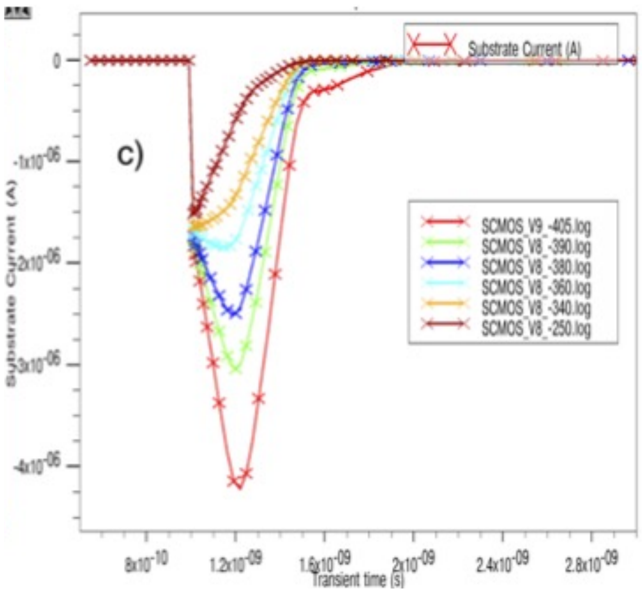


Net doping density of the structure

Electric field profile

Simulations

- TCAD simulations were used to establish the feasibility of the proposed work, and we started discussions with a US vendor.
  – The initial TCAD studies are based on our previous work to establish designs for 8” sensor wafer production



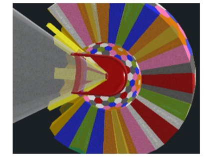
- Substrate current pulses for bias voltages from 250 (brown) to 405 (red) volts showing the onset of gain.
- Rise time of the top electrodes will be determined by the details of the CMOS well capacitance

R&D program for 2024-2025

- In the coming calendar year, the goals are:
  - BNL will design and produce AC-LGAD sensors with 55x55 μm^2 and 100x100 μm^2 pixel sizes, and flip-chip to available readout
  - Fermilab will focus on ASIC design and electronics for testing
  - KEK will design and manufacture AC-LGAD sensors, and flip chipping with readout ASIC

- The goal is to work with SkyWater to towards HEP sensors
  - Adapt and optimize SkyWater process to develop particle detectors
  - Use thicker, higher-resistivity epitaxy with deep-well implants on a standard CMOS substrate

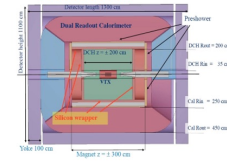
LGAD technology and development - UCSC

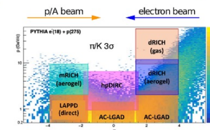


PIONEER

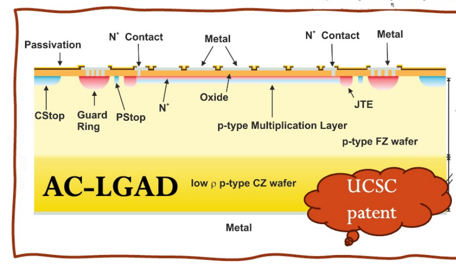
https://arxiv.org/abs/2203.01981

FCCee IDEA Si Wrapper



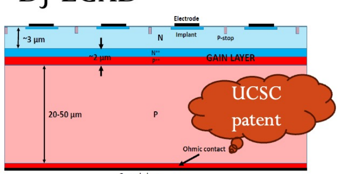


- Issues to solve: **low granularity** of traditional LGADs and **readout power dissipation**
  - Solution for both: **AC-coupled LGADs (AC-LGADs)**
- Continuous sheets of multiplication layer and resistive N+ layer, **AC-coupled readout**
  - **Collected charge is shared** between electrodes **(position resolution << pitch)**
- New concept: **sparse readout, high precision and low power** (Works in low occupancy environment)
  - Event reconstruction can be made with complex algorithms and ML
- **UCSC activities d**evelopment of AC-LGAD for: the ePIC (@ EIC) and PIONEER (small-scale) experiments, long range: FCCee IDEA detector Si Wrapper
- New technology needs to be developed for future colliders with high radiation hardness requirements ($10^{16\text{-}17}$ N_{eq}/cm^2) and high occupancy (e.g.: FCC-hh or muon collider)
  - Need for order of magnitude increase in radiation hardness and at the same time achieve higher granularity for high pileup environment
- **Critical need to continue developing LGAD sensor technology for far future applications: many options are being investigated!**

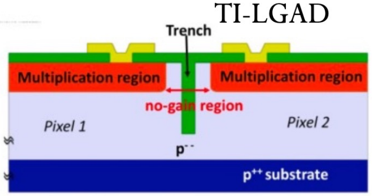


High granularity

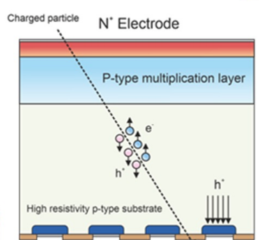
DJ-LGAD



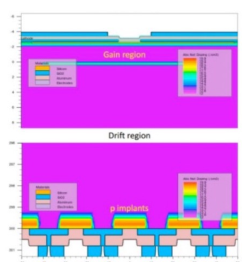
TI-LGAD



iLGAD



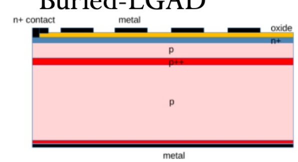
DS-LGAD



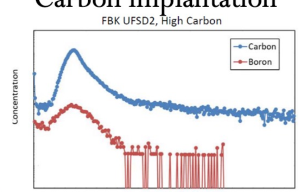
Snowmass papers: 4D tracking paper

Radiation hard

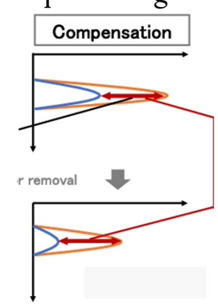
Buried-LGAD



Carbon implantation



Compensated gain layer

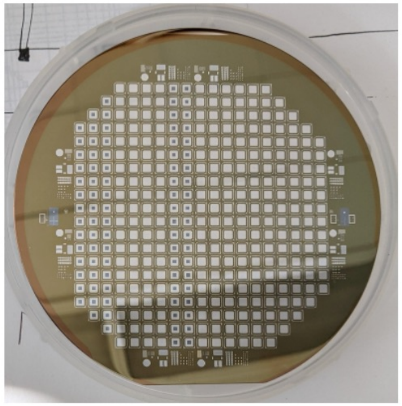


Adaptive gain layer
Inactive Boron,
Low diffusion…

LGAD CMOS

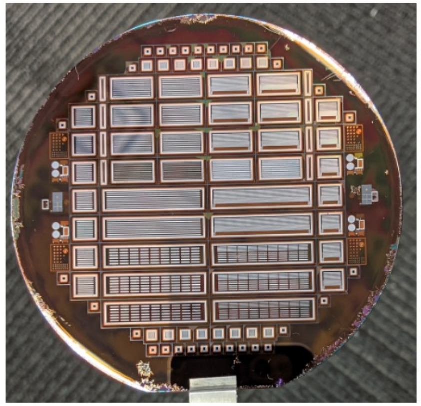
LGAD-based devices produced at BNL

DC-LGAD



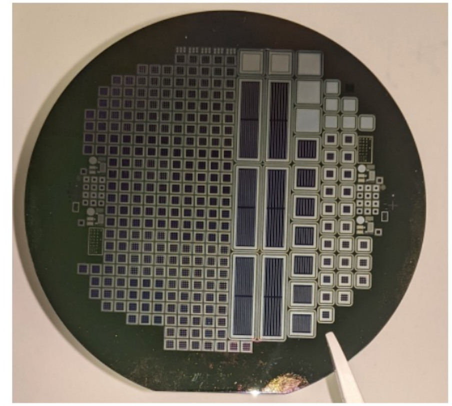
Small devices to test new technologies

AC-LGAD strips



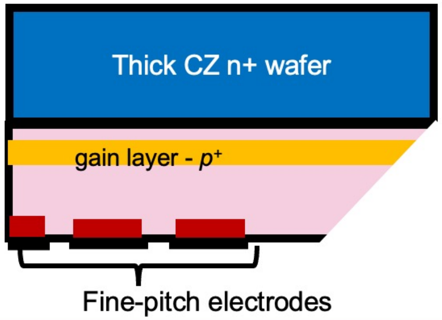
Variety of geometries produced (pitch, width)

AC-LGAD pixels



EICROC compatible (EIC R&D)

- Other AC-LGADs under way: large area for calorimetry, pixelated for other read-out ASICs
- Modification to standard technology possible for crosstalk reduction and yield improvement
- New flavors of LGAD-based sensors
- Beyond HEP: photon science, astrophysics, medical



In progress: "inverted" LGAD with buried gain layer allows for fine-pitch DC-coupled electrodes

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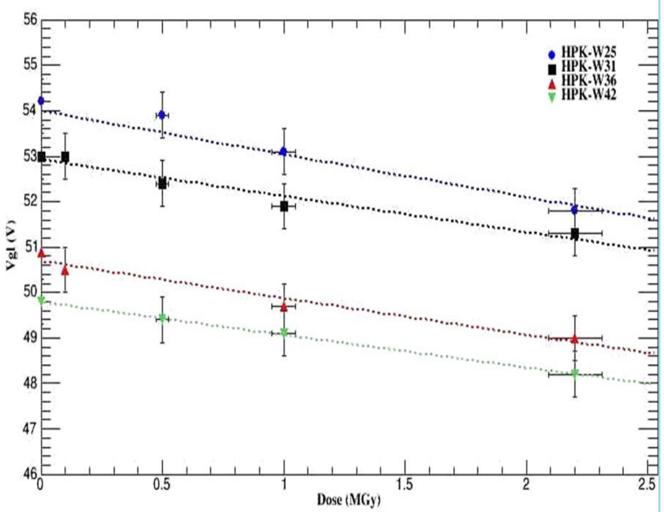
Brookhaven National Laboratory

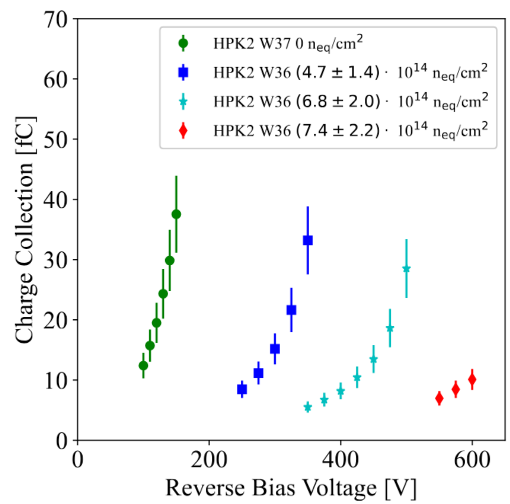
Front. Phys. Vol 10, 2022
JINS 19 P05012, 2024
Presentations at CPAD
and IEEE NSS/MIC

University of New Mexico LGAD studies

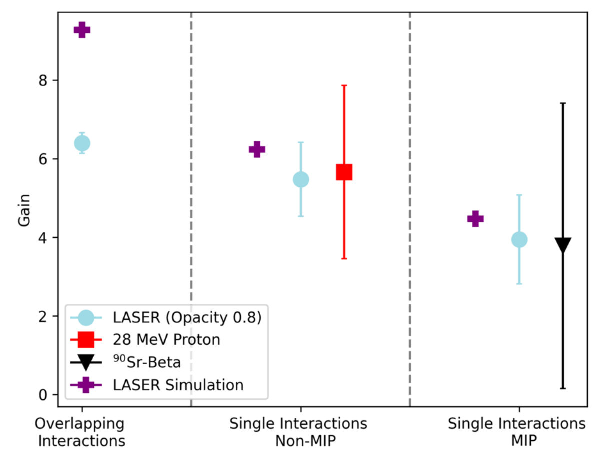
- Studies of radiation damage with Jozef Stefan Institute
  - Gamma irradiation; evaluation of acceptor removal
  - Proton irradiation, timing resolution and charge collection eff.
- Collaborating with Brookhaven, studies of AC-LGAD response to gamma and proton irradiation, studies of response to MIP and non-MIP stimuli



Gamma irradiation



Proton irradiation



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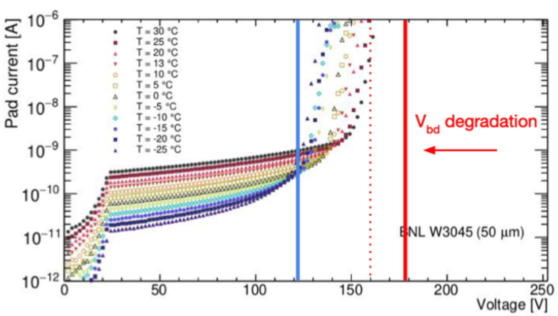
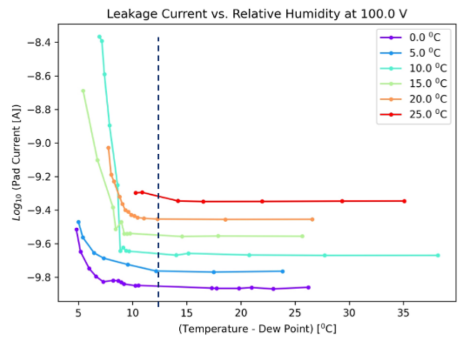
Brown University

- Past R&D work related to 4D trackers:
  - RSD, AC-LGAD, LGAD characterization and readout
  - Strips/Pixel R&D for LHC (CMS) Experiments
- Infrastructure/equipment/software available, FTE
  - Characterization facilities: probe stations, TCT (partial), climate chambers (partia
  - Computing cluster.
  - Currently: ~1 FTE: 0.2 supervisory – 0.8 supervisee, with extension planned with
- Characterization stress tests with (extreme) environmental conditions and irradiation campaigns.
  - Collaborations with UNM, BNL, UniGe, and DRD3.

Barone et al, PSD13



Barone et al, 1st DRD3 Week



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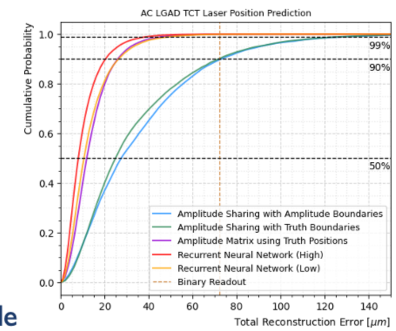
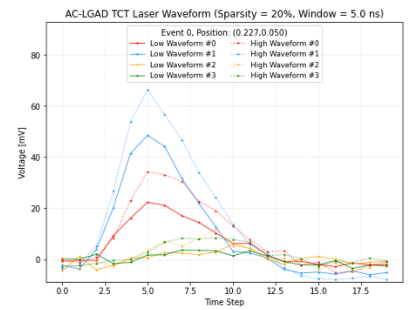
Li et al, 1st DRD3 Week

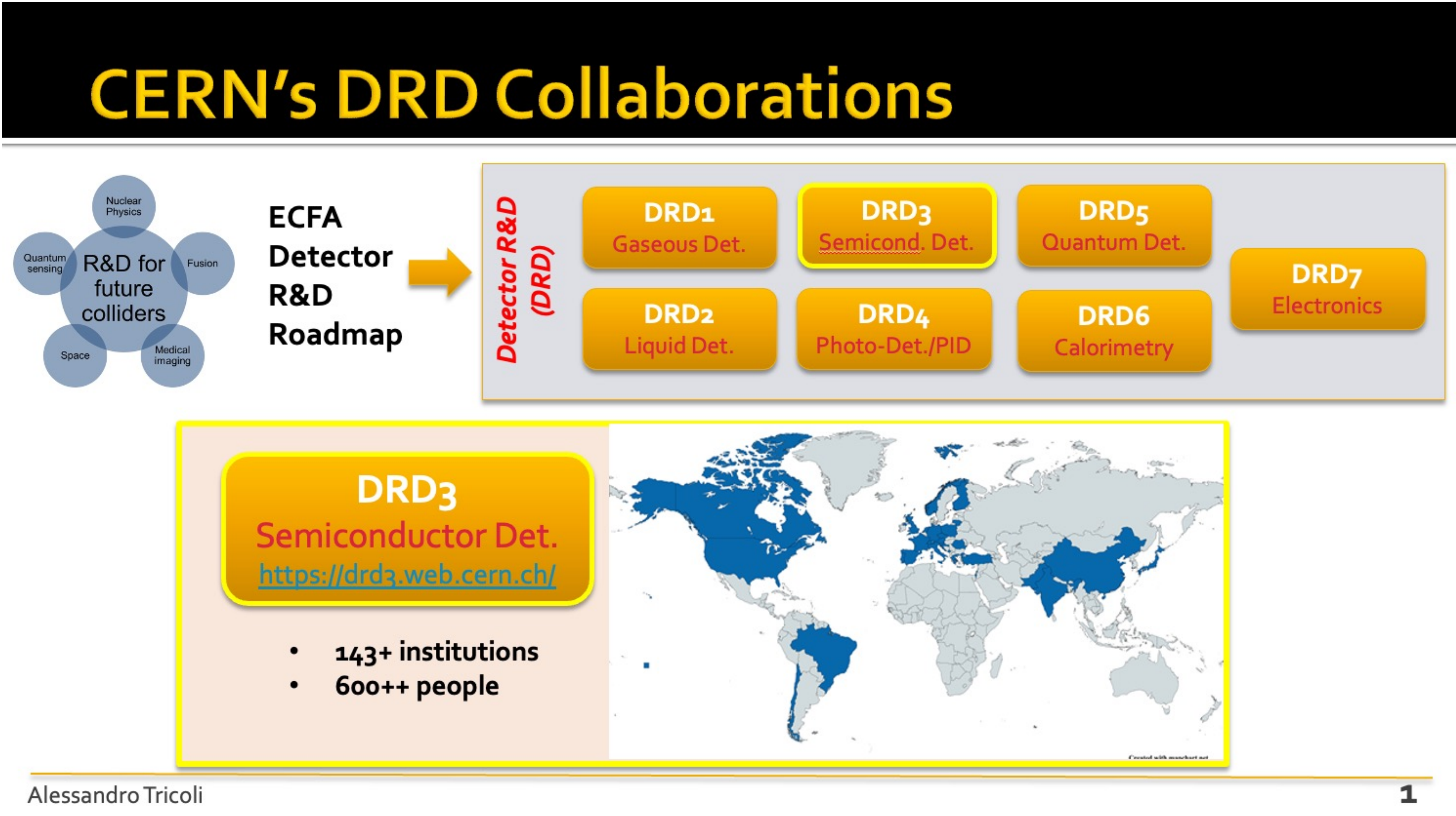


Barone et al, 1st DRD3 Week



- Reconstruction algorithms of AC-LGADs/RSDs with ML-based compression and regularisation of readout.
  - Full waveform processing → harness shape correlations between leading and all pads.
  - Harness all the information from all the pads, including correlations → improvement of the position resolution.
  - Ongoing collaborations with BNL, University of Zurich, and DRD3; planning collaboration with Freiburg, Thessaloniki.
  - Landau fluctuations:
    - Use laser-assisted test beam (MIP) training.
    - Parametrization as a function of deposited charge.
  - ASIC/readout electronics limitation:
    - Collaboration with ASIC designers to embed processing unit on the chip.
    - Wave-form compression in training/evaluation: Preliminary still 10-15 μm resolution on 500 μm x 500 μm pixel
- **Open to collaborating with any interested party.**

International landscape



International landscape

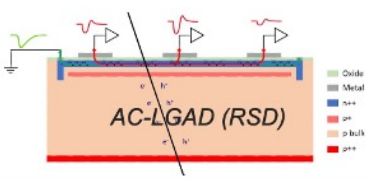
WG2 – Activities (LGAD detectors)

RG 2.3

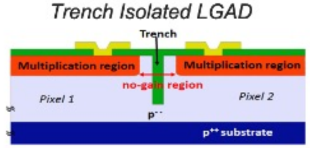
- **Full scale detector with pixelated LGAD sensors to achieve a position resolution <10 µm, with a timing resolution <30 ps before irradiation, also in high occupancy environments.**
  - Possible application for the replacement of outer pixel layers or disks in the CMS/ATLAS pixel dets. in Phase-III. Requested radiation tolerance for HL-LHC can be in the range of 1-5x10^{15} n_{eq}/cm^2

RG 2.4

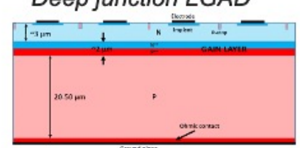
- **LGADs for particle identification (Time of Flight)**
  - Possible applications: *ALICE 3 (Run5), Belle2, Electron Ion collider (Tracking+TOF@ePIC) >2031) and Future Lepton colliders (>2040)*.
  - Larger surfaces (several m^2) have to be covered
  - Yield and reproducibility of the process have to be demonstrated while radiation hardness is less of a problem
  - *Electron Ion Collider*: a spatial resolution ~30 µm and timing resolution <30 ps are required. An area up to 13 m^2 has to be instrumented. Proposal: pad size of 0.5 mm with a spatial resolution ~ 10 µm
  - *Future lepton colliders*: a ToF could be placed as the most external tracking layer, with a surface of around 100 m^2, < 30 ps, and spatial resolution ~10 (90) µm (r-ϕ, z).



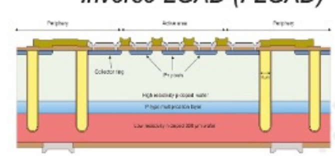
Trench Isolated LGAD



Deep junction LGAD



Inverse-LGAD (I-LGAD)



Alessandro Tricoli 6

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Summary

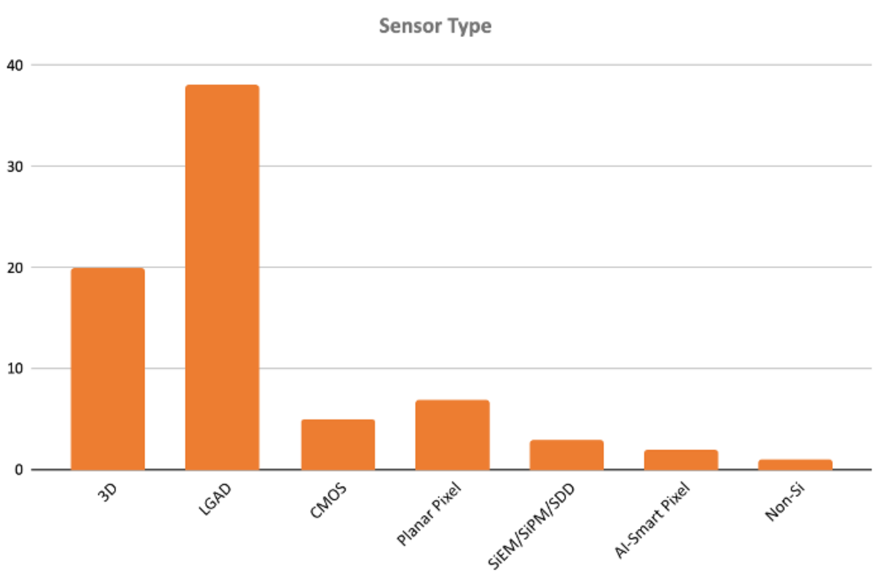
- LGAD is a new technology that has revolutionized the detector designs in LHC and beyond
  - Applications for HL-LHC demonstrated readiness and first applications

- Several new "flavors" of LGADs bring expanded features and capabilities towards realization of 4D-detectors in the future

- Collaborative efforts are the key for progress in many challenging directions
  - Integration with ongoing international efforts within DRD and RDC efforts are crucial!

Backup

DRD3 WG2 – Scientific Interests



Most of institutes have extensive experience in silicon tracking or timing detectors in LHC experiments

- **LGAD** and **3D** dominates
- Interest also in **Planar Pixel, passive/active CMOS** and *other technologies*
- **New and alternative ideas are also welcome**

EoIs: https://drive.google.com/drive/folders/1vQMFlwzgQ33M7aJ1KxKt9Ye4B5Lz1Xj8?usp=sharing

Alessandro Tricoli 10

DRD3 WG2 – Structure and Liaisons

- **No subgroups (for the time-being)**
  - Discussions open to the whole community, regardless of specific research interests
  - We may have dedicated meetings on specific technologies, specific Research Goals or WP to keep meetings focused
- **Liaisons:**
  - Advice WG2 members on available facilities, techniques, platforms, tools etc.
  - Provide bi-directional communication with other DRD3 Working Groups or DRDx Coll.
  - Provide technical support to community by linking with experts
  - Maintain support web pages

Liaisons

- **Test-beam and Characterisation facilities** → link to WG5
  - **Jordi Duarte-Campderros** (IFCA, Santander), jorge.duarte.campderros@cern.ch
  - **Ryan Heller** (LBL), rheller@lbl.gov
- **Irradiation Coordination** → link to WG3
  - **Leena Diehl** (CERN), leena.diehl@cern.ch
  - **Simone Mazza** (UCSC), simazza@ucsc.edu
  - **Xuan Li** (Los Alamos), xuanli@lanl.gov
- **Interconnections** → link to WG7
  - **Mathieu Benoit** (ORNL), benoitm@ornl.gov
- **Simulation** → link to WG4
  - **Jörn Schwandt** (Uni Hamburg), joern.schwandt@desy.de)
- **Readout Systems** → link to DRD7
  - **Abderrahmane Ghimouz** (PSI), abderrahmane.ghimouz@cern.ch
  - **Manwen Liu** (IMECAS), liumanwen@ime.ac.cn

Alessandro Tricoli 12

DRD3 WG2 – Plans

- **In the near future we want to learn about**
  - Main application drivers (e.g. HL-LHC, CEPC, FCC, ILC/CLIC, Muon Collider etc.),
  - Research goals and directions the community wants to pursue,
  - Level of needed vs available effort/person-power for specific developments,
  - Specific interests of various institutes in specific technological areas
  - What proposals for Work Packages are submitted and what effort will be provided
- **We also want to encourage the community to get an overview of all on-going activities before we compartmentalize into focused groups**
  - Cross-fertilization among different R&D areas
  - Boost cooperation spirit
  - Encourage the formation of institute clusters around specific research goals

❖ DRD3 Collaboration Week: Mon-Fri, 2nd -6th Dec. (CERN), https://indico.cern.ch/event/1439336/

Alessandro Tricoli 13

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