Radiation Damage at LANSCE: Applications for Particle Physics

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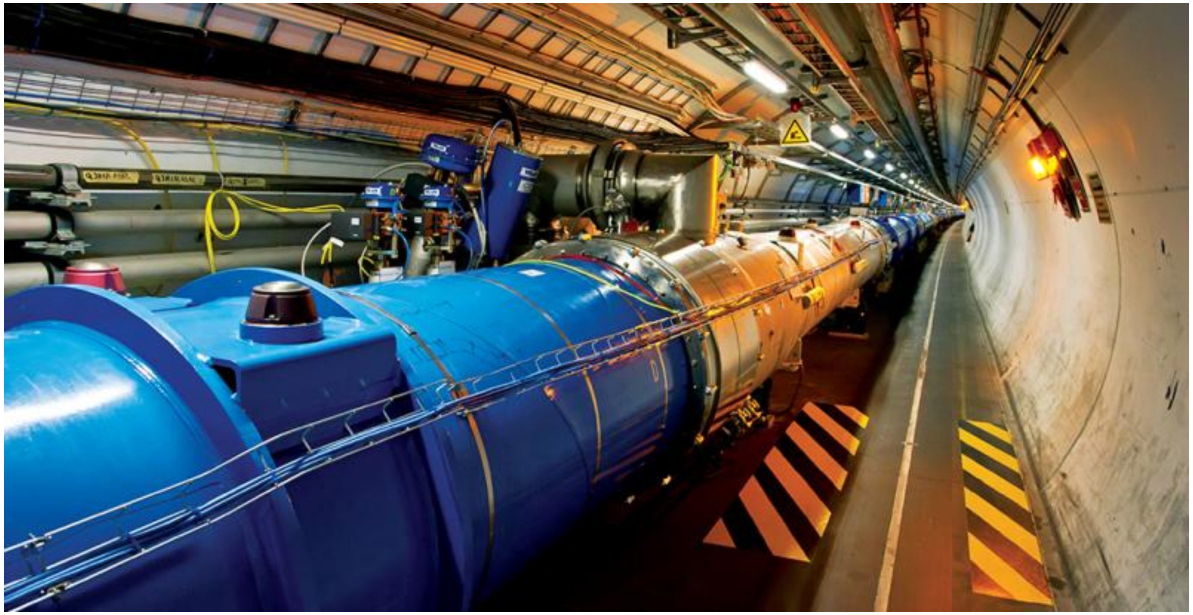
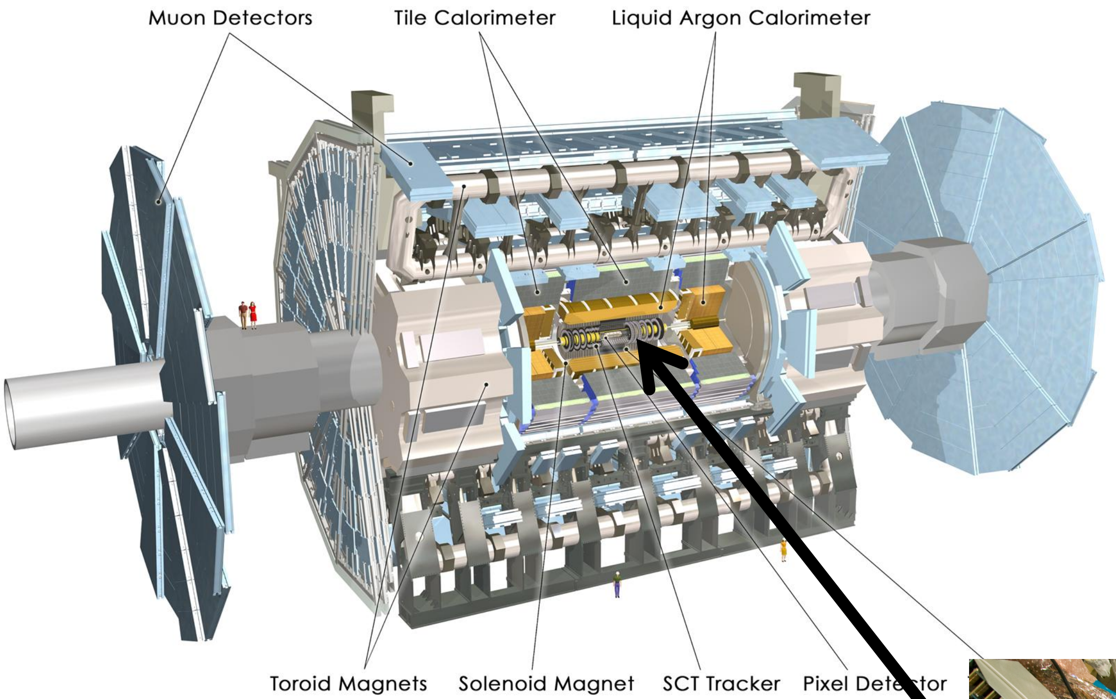
The Large Hadron Collider (LHC) and its experiments began data collection in March 2010 after 16 years of development. The LHC collides protons on protons at CERN (Geneva, Switzerland) to produce conditions that may deepen our understanding of:

- the basis of mass (the Higgs particle)
- symmetries related to unification of fundamental forces (for example, supersymmetry),



- incompletely studied sectors of the Standard Model (heavy quark phenomena and rare Electroweak interactions)
- new phenomena---for example dark matter, dark energy, and extra dimensions.

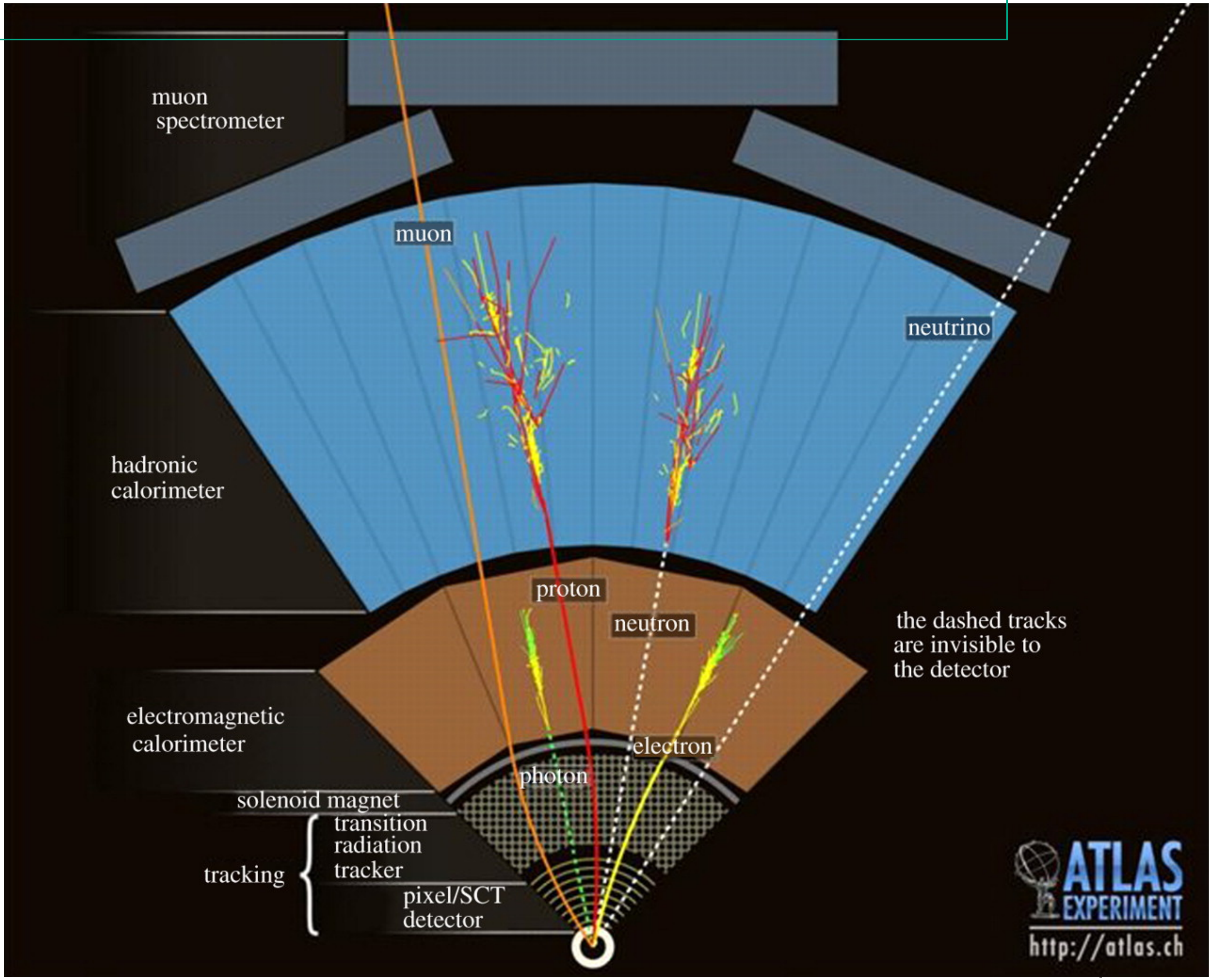
Detectors at the LHC record data by responding to energetic particles - i.e., radiation - that traverse them. Thus: the detectors must be radiation tolerant.



The ATLAS Detector at the LHC

Installing the Pixel Detector, the system most sensitive to radiation damage

Each detector is unique, but all typically include elements like these:



- The LHC is scheduled for upgrade in 2025 to explore completely new discovery realms.

- New name: High Luminosity LHC (HL-LHC).
  New conditions: 10x higher collision rate --- $10^{35}/cm^2/s$.
  Expected lifetime fluence at the inner detector layers: $2x10^{16}$ 1-MeV-neutron-equivalent (neq).

- A worldwide program is underway to develop radiation-tolerant technologies for detection of particles at the HL-LHC. Designing and building the new detectors takes >10 years.

- The physics potential of the HL-LHC was given *the highest near-term priority* in the DOE US Particle Physics Project Prioritization Panel (P5) report* in May 2014. It is also *the highest priority* of the European Strategy Group for Particle Physics.**

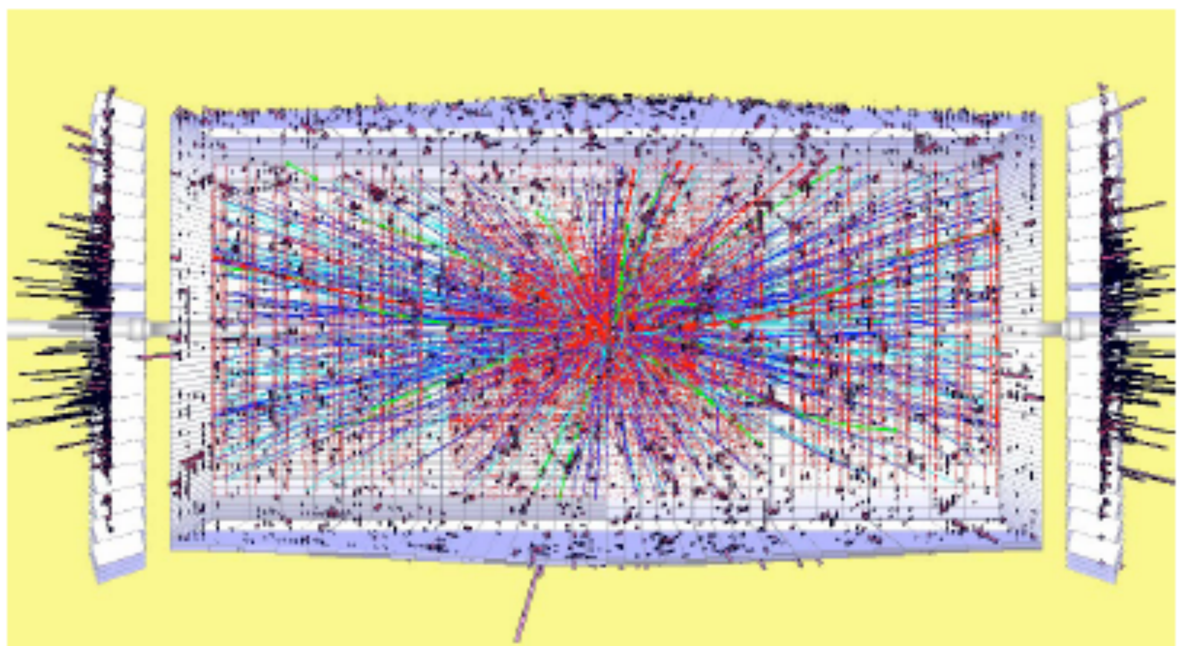
*science.energy.gov/~/media/hep/hepap/pdf/May 2014/FINAL_P5_Report_Interactive_060214.pdf
**council-strategygroup.web.cern.ch/council-strategygroup/

A typical crossing at the HL-LHC will involve *10000 particles, 400 overlap collisions, every 50 ns*.

Pixelated silicon detectors at radii from 4 to 100 cm from the collision help untangle this puzzle by providing:

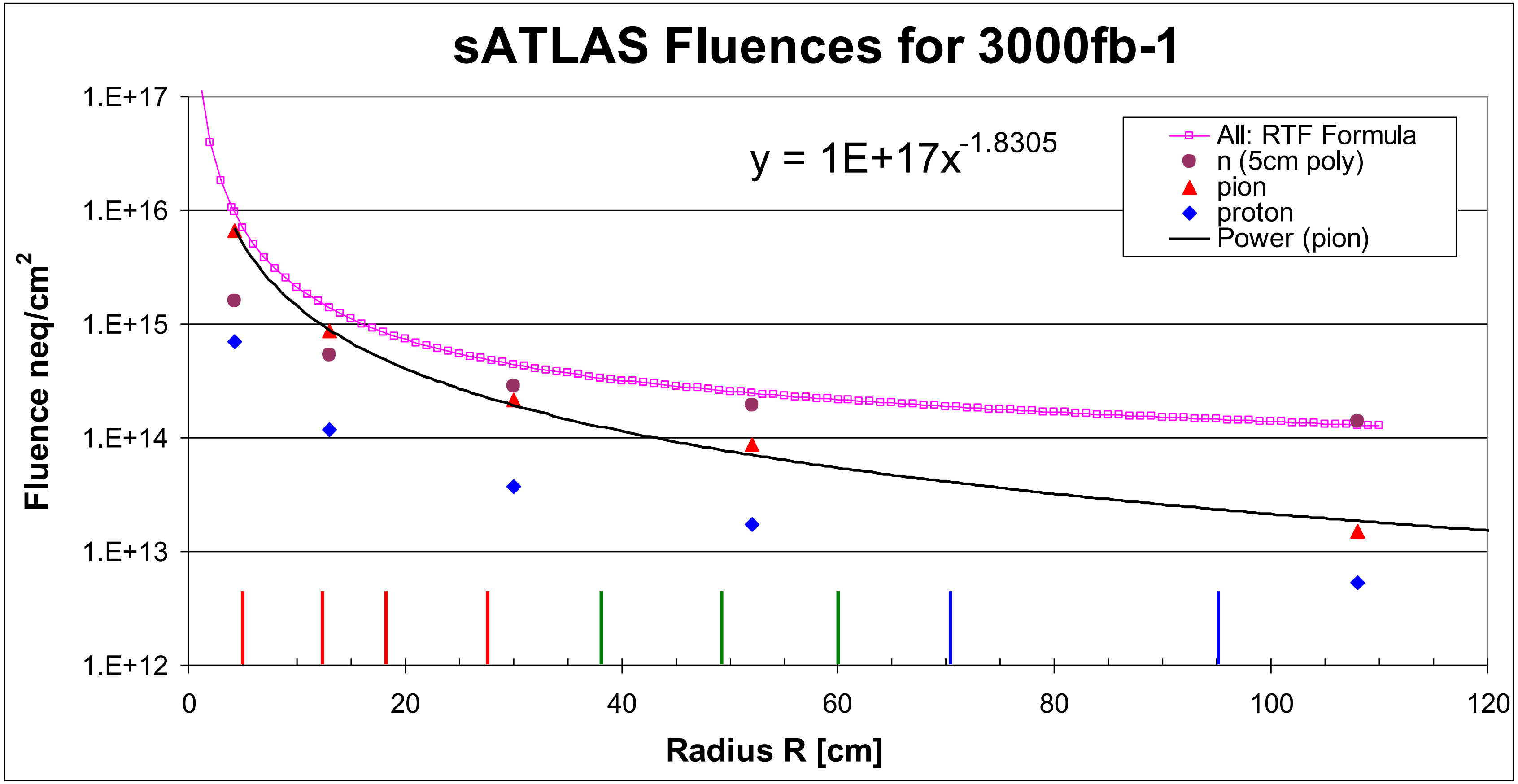
- triggers
- energy loss (dE/dx)
- tracking
- vertexing
- flavor tagging

These pixel detectors are also the system *most challenged* by the high radiation field.



SLHC, L = 10^{35} cm^{-2}s^{-1}, ~200 MBE

The radiation damage in the tracker volume will range from 10^{13} to a few x 10^{16} neq/cm^{2}:

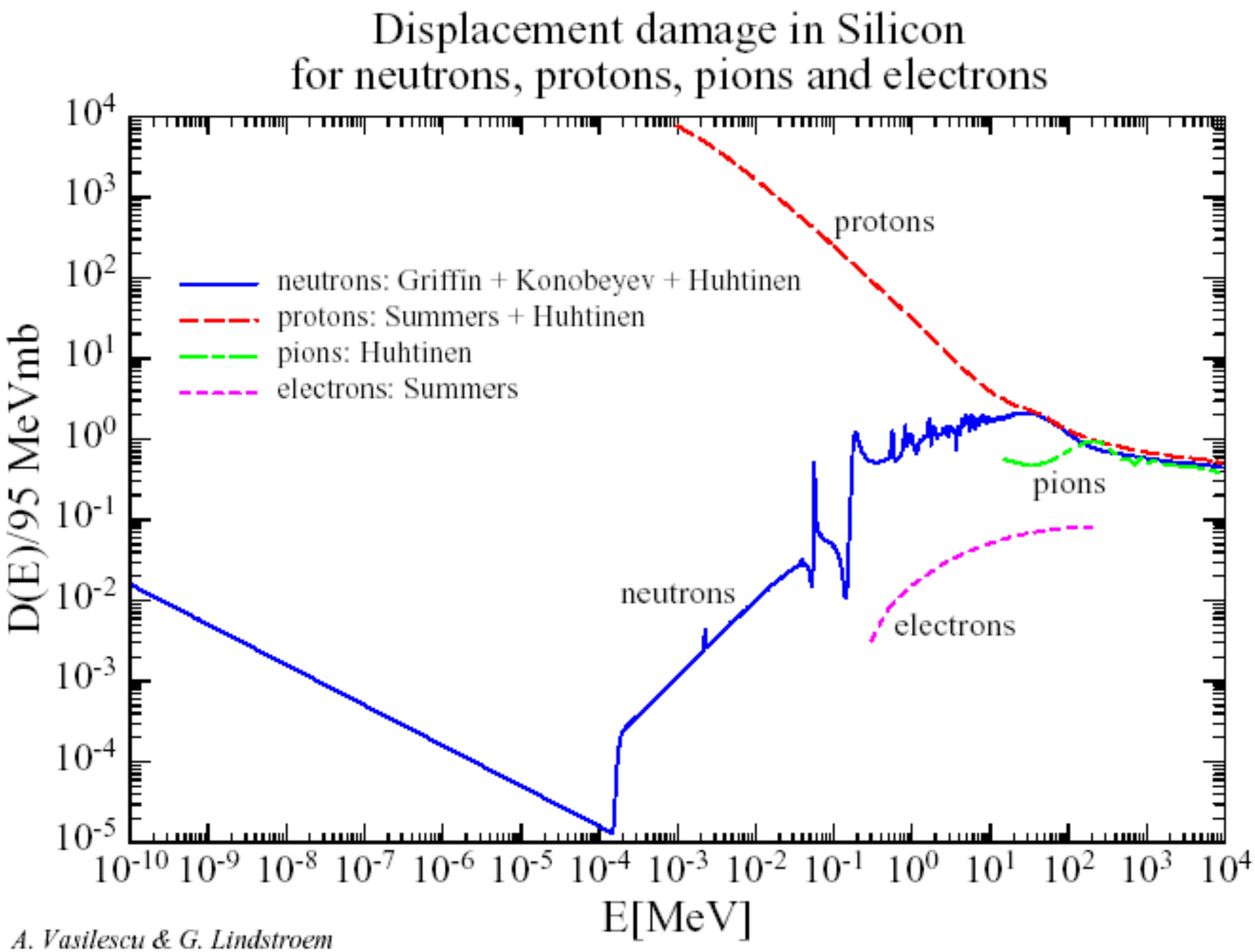


…and this causes charge trapping, high leakage current, noise, temperature dependence, silicon type inversion, and high depletion voltage.

The expected fluences for all hadrons at radius R at the HL-LHC after 10 years = 3000 fb^{-1} are:

R [cm]	F_h [n_{eq}/cm^2]
3.7	1.6E+16
5	6.3E+15
12	1.4E+15
18	7.7E+14
27	4.5E+14
38	3.0E+14
49	2.3E+14
60	1.9E+14
70	1.7E+14
95	1.4E+14

Different radiation species cause different levels and types of damage:



Pions are the most abundant species in the LHC trackers.
Note: 800 MeV protons have almost identical effect.

- Since 2007, teams of physicists from LHC experiments have been coming to LANSCE every year to irradiate prototype technologies for our upgrades.

- The "UNM team" has grown in that time from 1 ATLAS institute to an annually-increasing consortium of institutes working together on the LHC experiments ATLAS, CMS, and LHCb.

- Institutes participating up to now have included UC Santa Cruz, UC Berkeley, Purdue, Colorado, Brookhaven, Fermilab, Ohio State, SLAC, UT Arlington, Brown, Boston, Penn, Mississippi, Max Planck Inst. (Munich), Trento, Humboldt (Berlin), Tech. U. Dortmund, CPPM (Marseille), LPHNE/CNRS (Paris), Josef Stefan Inst. (Ljubljana), KEK (Tsukuba), LANL, and UNM.

- Data from our upcoming Dec 2015 run will contribute to 11 students' theses. Data from 2007-14 have produced 33 instrumentation publications.

The results of these irradiations are leading to development of detectors that are used by a community of 7000 scientists.

41 US institutions belong to the ATLAS Experiment.

50 US institutions belong to the CMS Experiment.

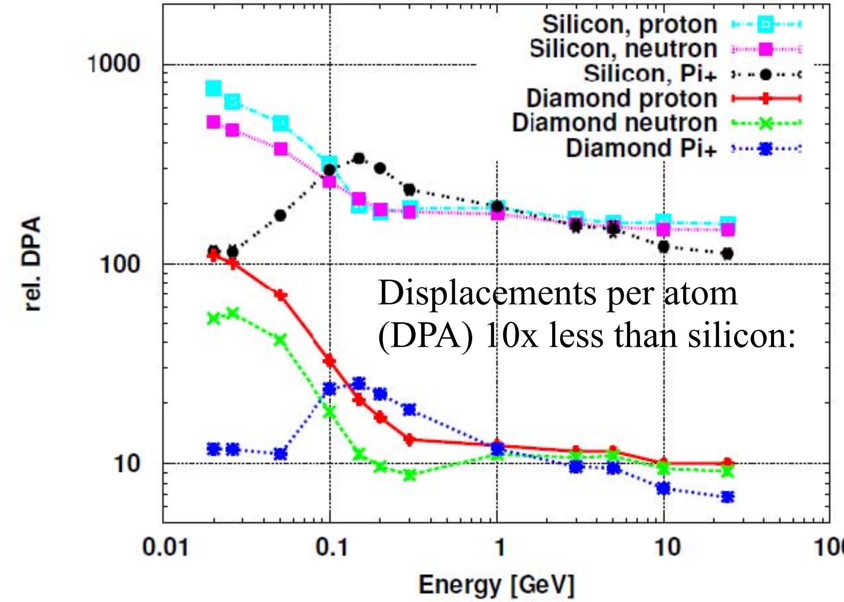
13 US institutions belong to the ALICE Experiment.

4 US institutions belong to the LHCb Experiment.

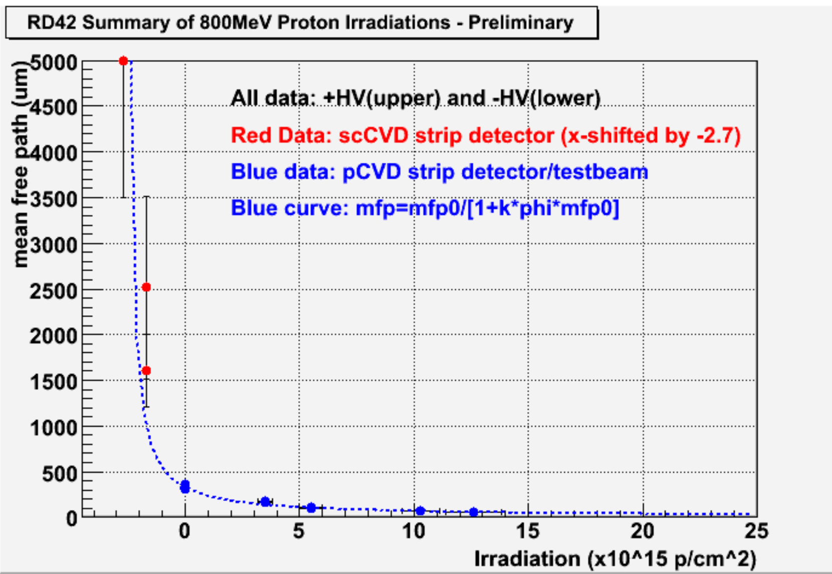
Here are some of the technologies under development. All of them have taken beam at LANSCE.

Diamond substrate sensors

5.5 eV band gap and resistance to lattice displacement leads to small leakage current and no space charge to deplete (no V_{bias}, no cooling)



Displacements per atom (DPA) 10x less than silicon:



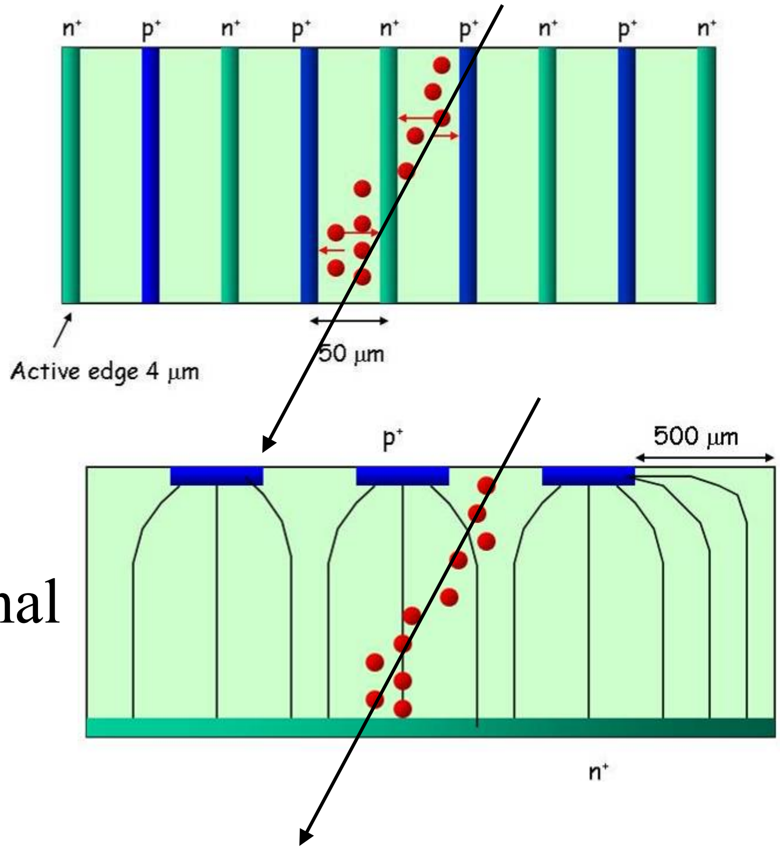
The measurement of the mean free path of charged particles, which used LANSCE data, led to approval to install diamond luminosity monitors in LHC experiments operating right now.

Major issue right now: Single-crystal exhibits a rate dependence, polycrystalline does not. New fabrication process, to be tested at LANSCE in 2015, may solve this.

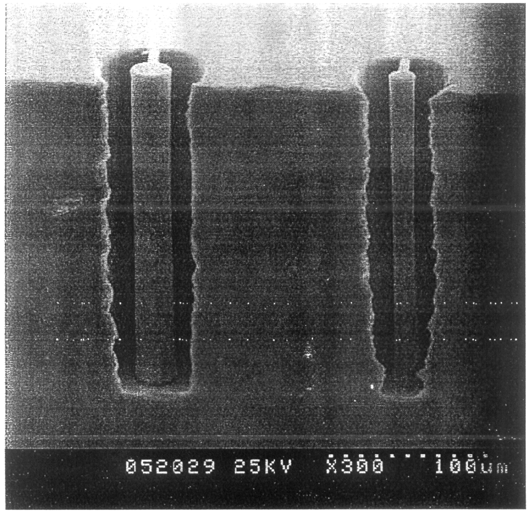
3D silicon technology: Maximum depletion voltage determined by electrode spacing rather than substrate thickness

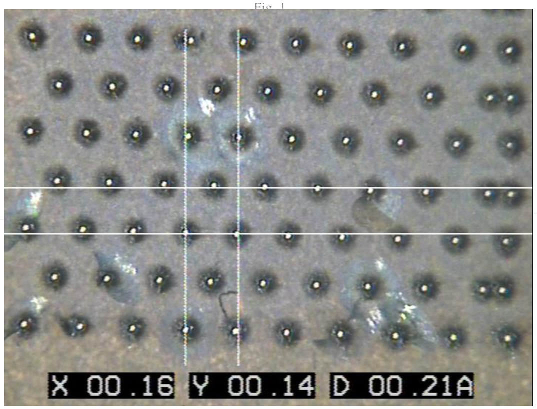
3D

Traditional planar



3D process photos: reactive ion etching



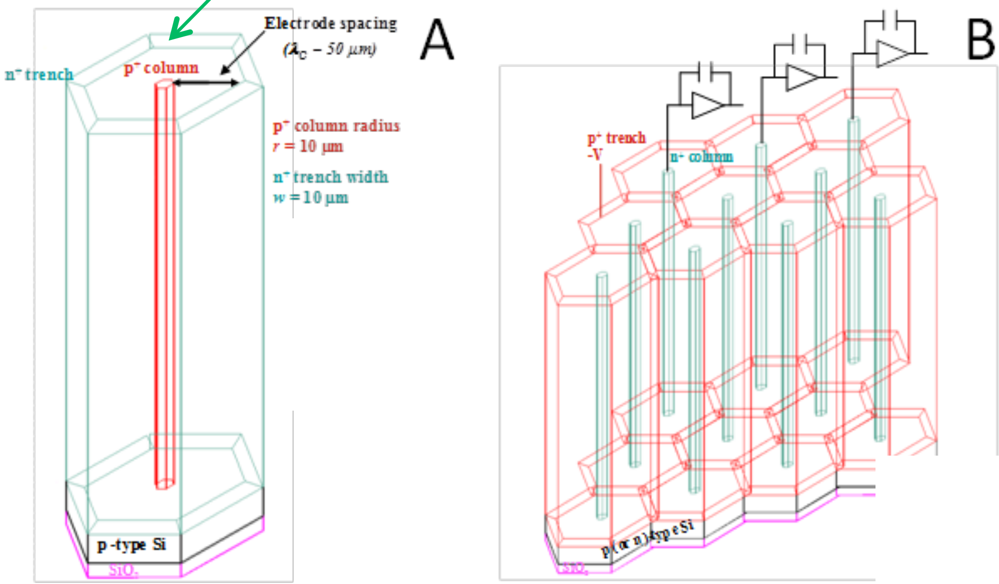


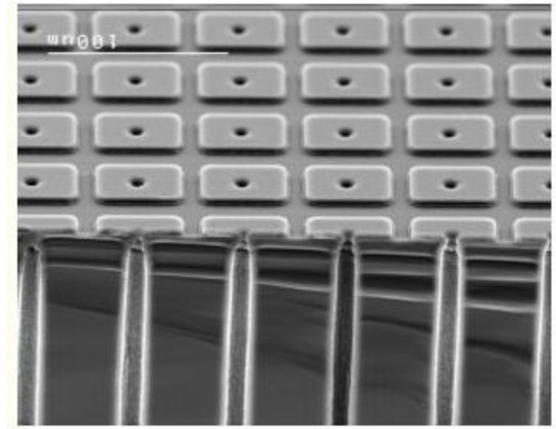
Data rates at the HL-LHC require smaller cells, closer proximity of electrodes. In Dec. 2015 at LANSCE, we'll test a new technology to suppress breakdown.

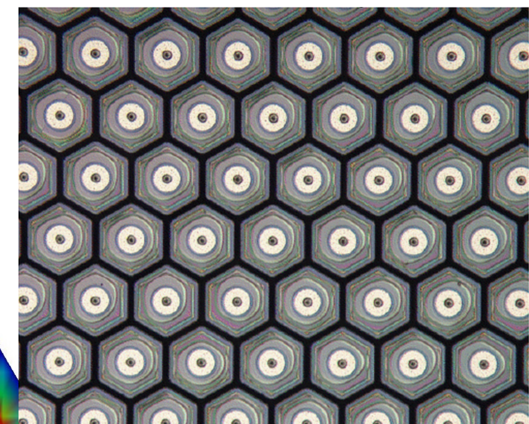
Trench Technology: An application of 3D geometry to multiplexing and detection

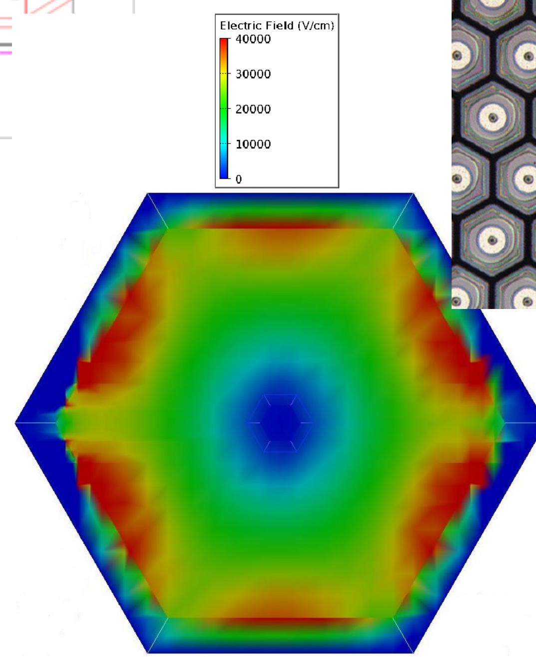
"Trench" Electrode

Hexagonal array forms 3D Trench Detector





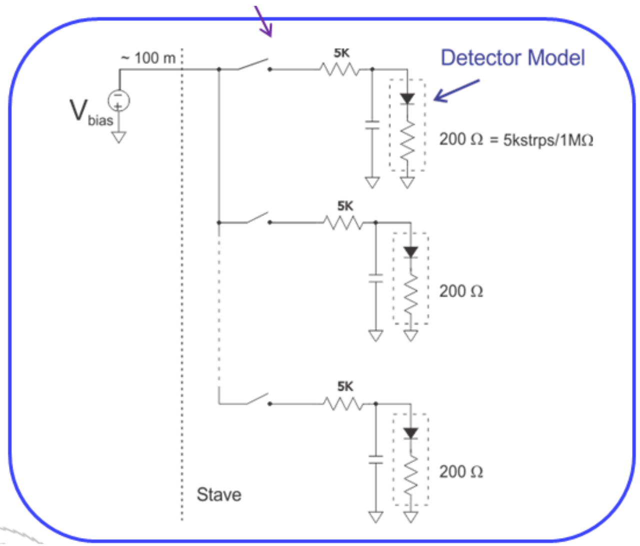


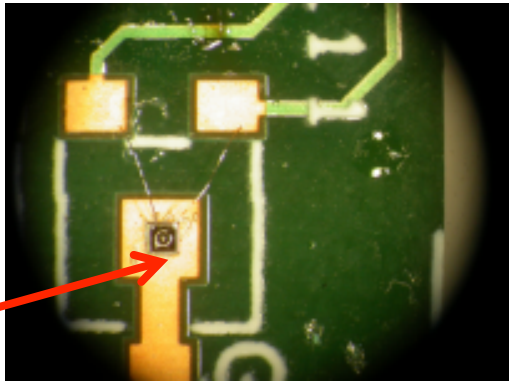


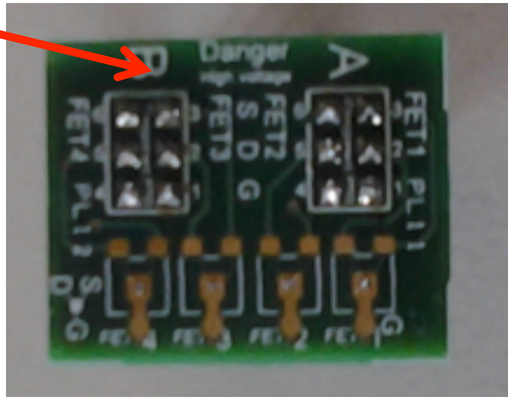
Hexagonal trench makes each detection cell independent, improves E field homogeneity and isotropy.

A new high voltage multiplexing scheme for the ATLAS Silicon Strip Tracker

Motivation: power delivery with ability to remotely disable malfunctioning detectors. Three candidate GaN devices have been identified as most promising, on the basis of the LANSCE data from 2012, 13, and 14.







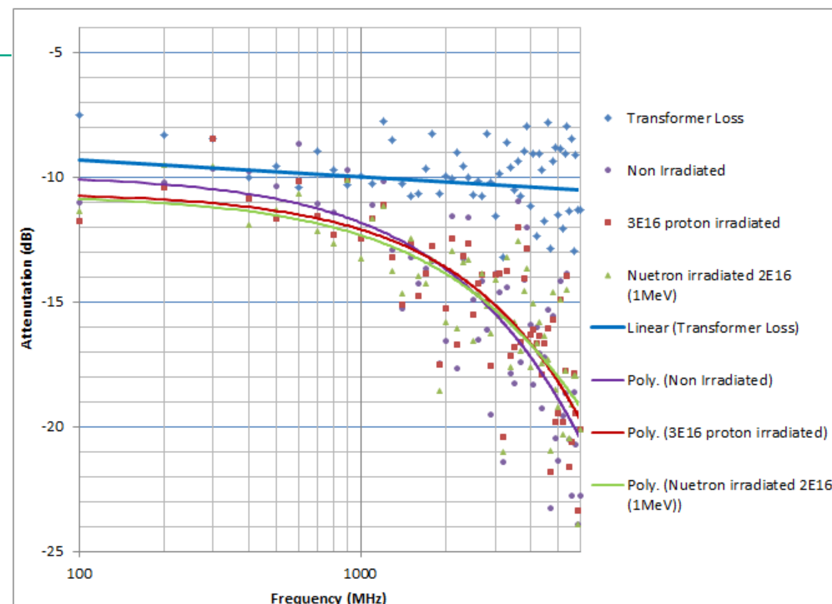
Low mass high-speed data transmission cables

Custom cables operating *in the center of the active detector* have to transmit data at 5 Gbps over a distance of 4m.

Being in the active volume, the cable mass must be minimized to reduce multiple scattering that damages tracking precision.

In Dec 2015 at LANSCE, we will expose flex in a new teflon-kapton substrate.

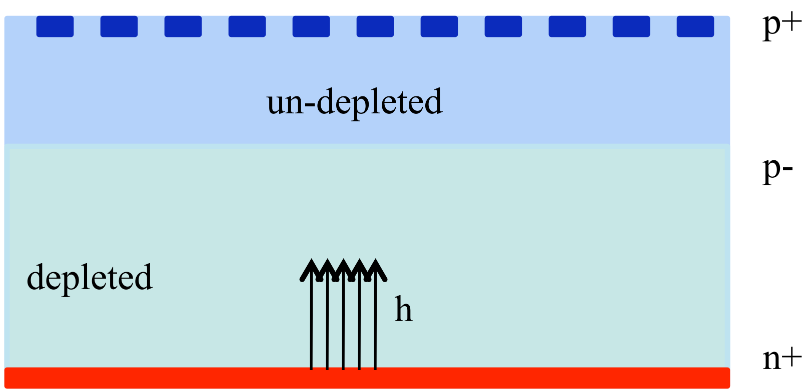
Some of our attenuation measurements after the 2014 irradiations:



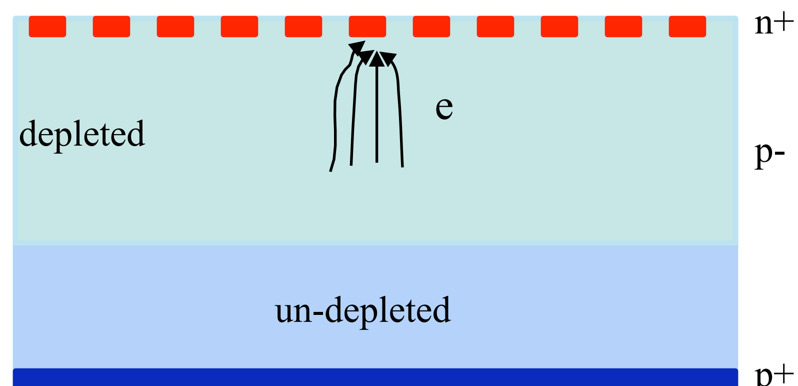
Silicon sensor + readout modules on p-type substrate

- no type inversion: high field region is always on the implant side.
- collect electrons
- single sided processing: cost savings

With thresholds as low as 1000 e, these are now being assembled into prototype modules (integrated sensor + chip). Post-irradiation data on their power dissipation are needed to develop engineering requirements of the cooling system.



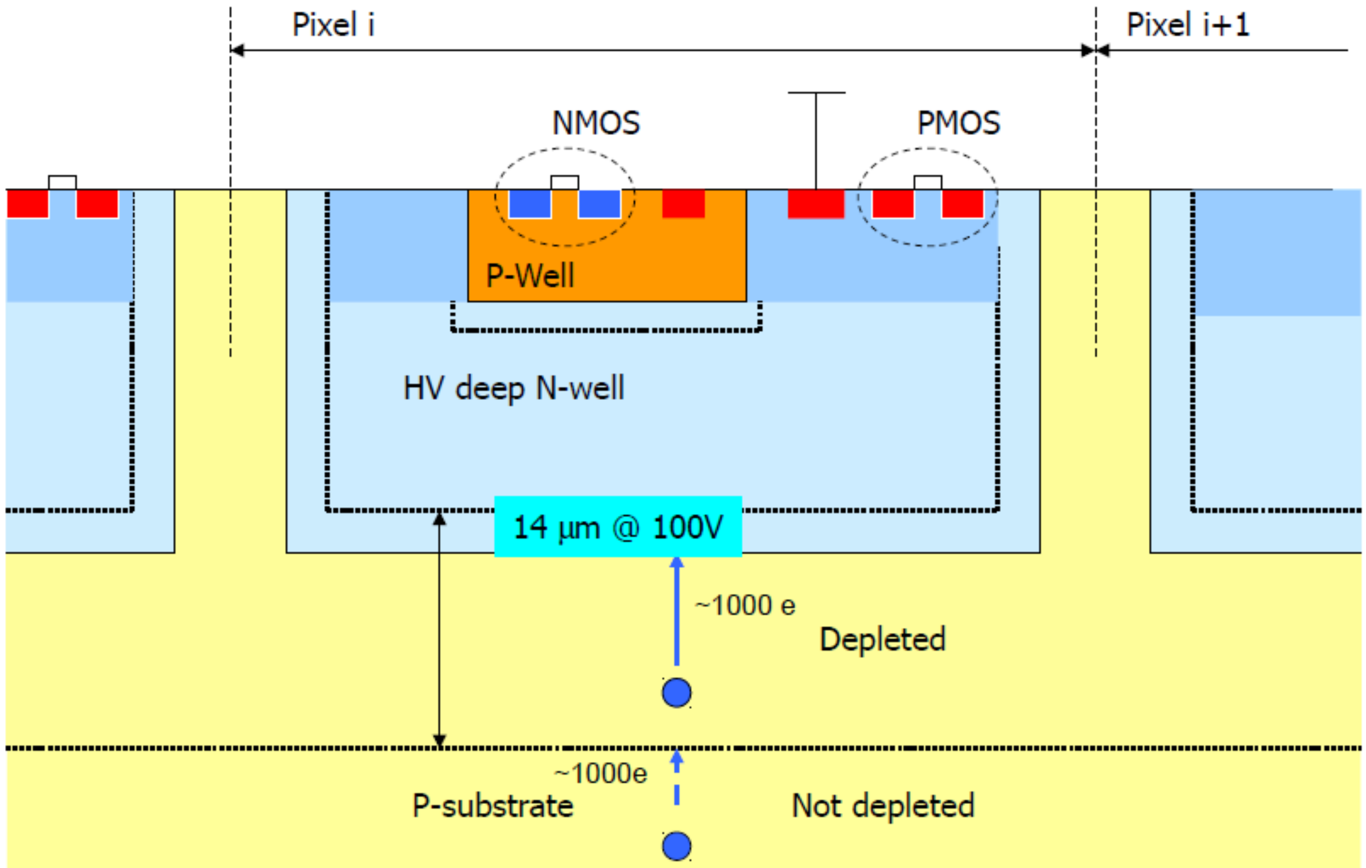
p-on-n geometry (after type inversion)



n-on-p geometry

n-on-n geometry (after type inversion)

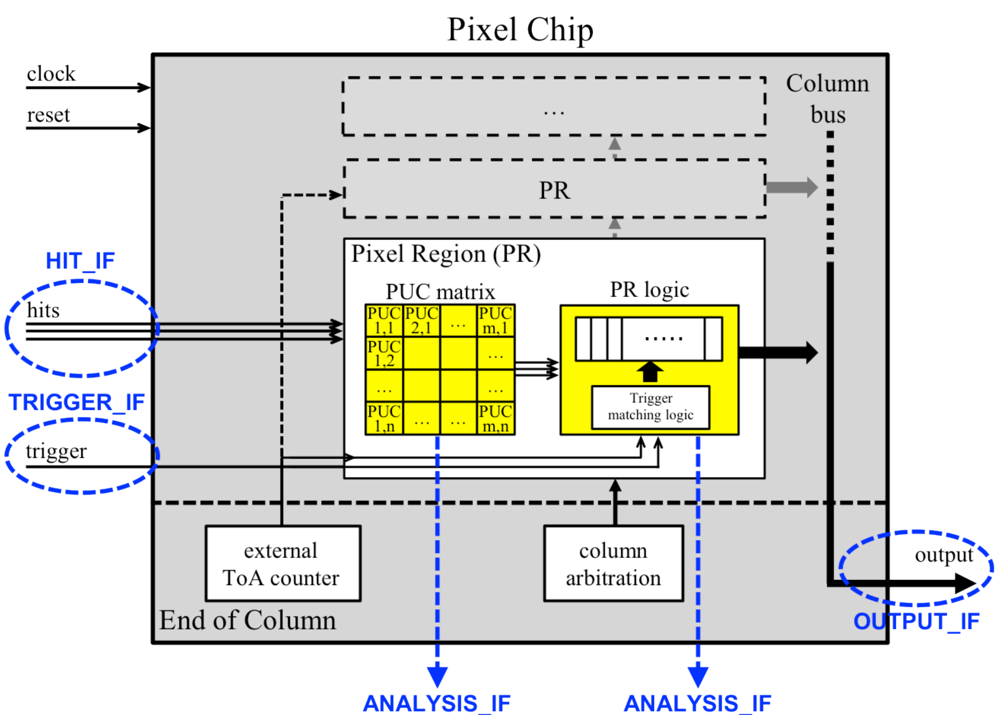
High Voltage CMOS: uses substrate resistivity higher than in commercial ASICs, leading to radiation tolerant features including growth of depletion region with fluence.



CMOS electronics placed inside the diode (inside the n-well)

Pixel readout integrated circuits in 65 nm CMOS technology

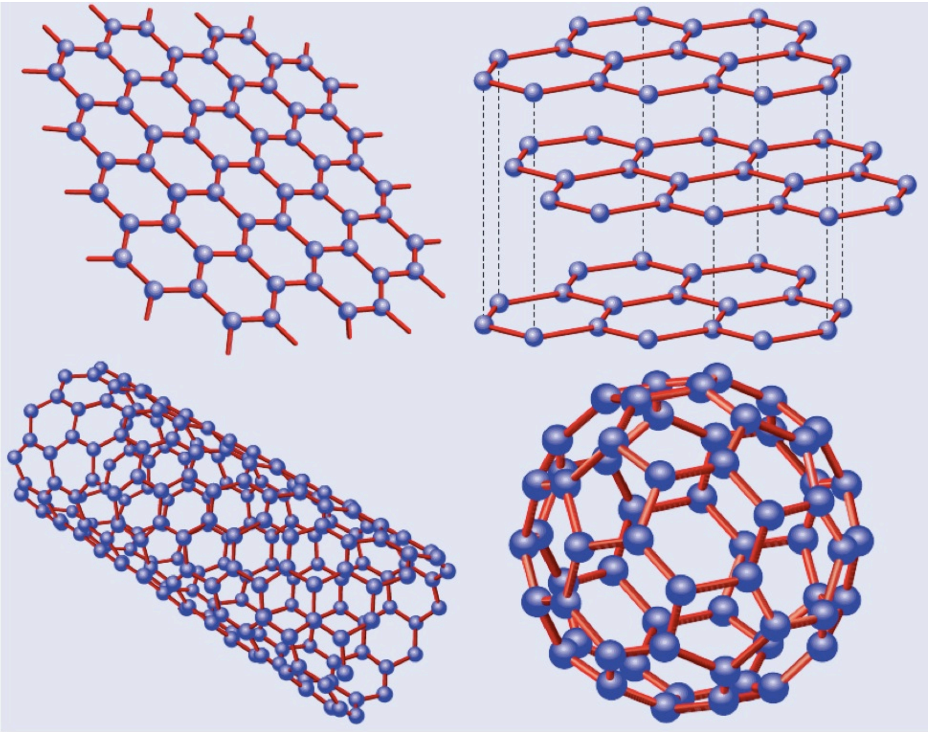
These will form the foundation for multiple implementations at the HL-LHC that require partial readout at every crossing, 2 GHz/cm^2, 10 MGy radiation tolerance, high output bandwidth, reduced pixel size, and large IC with low power consumption.

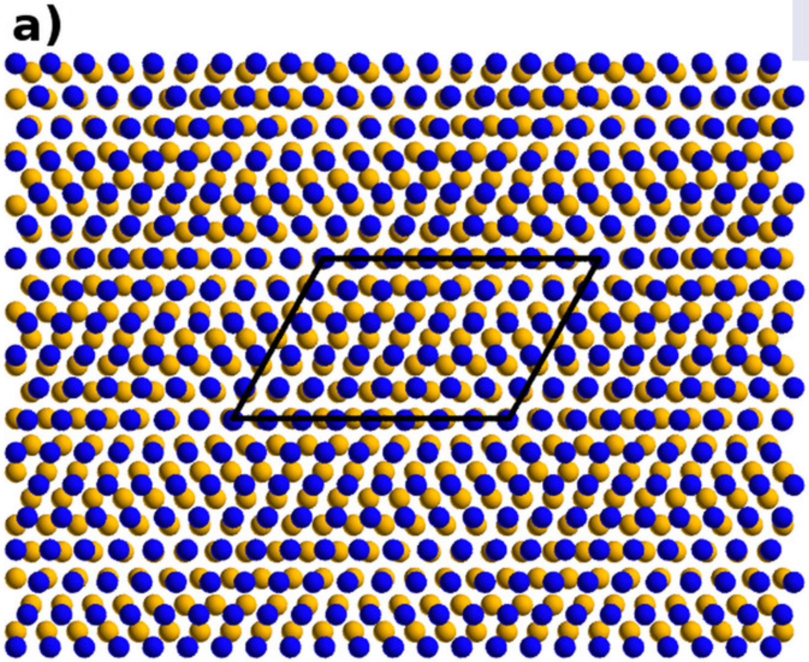


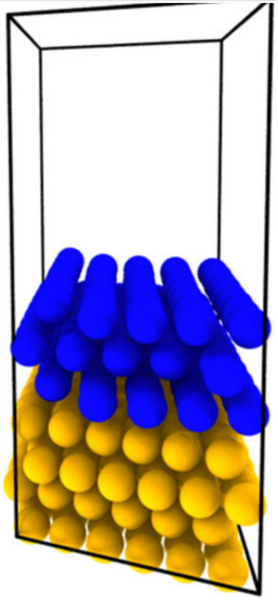
Synergy with LANL collaborators Jeff Wang et al:

Nano-structured materials

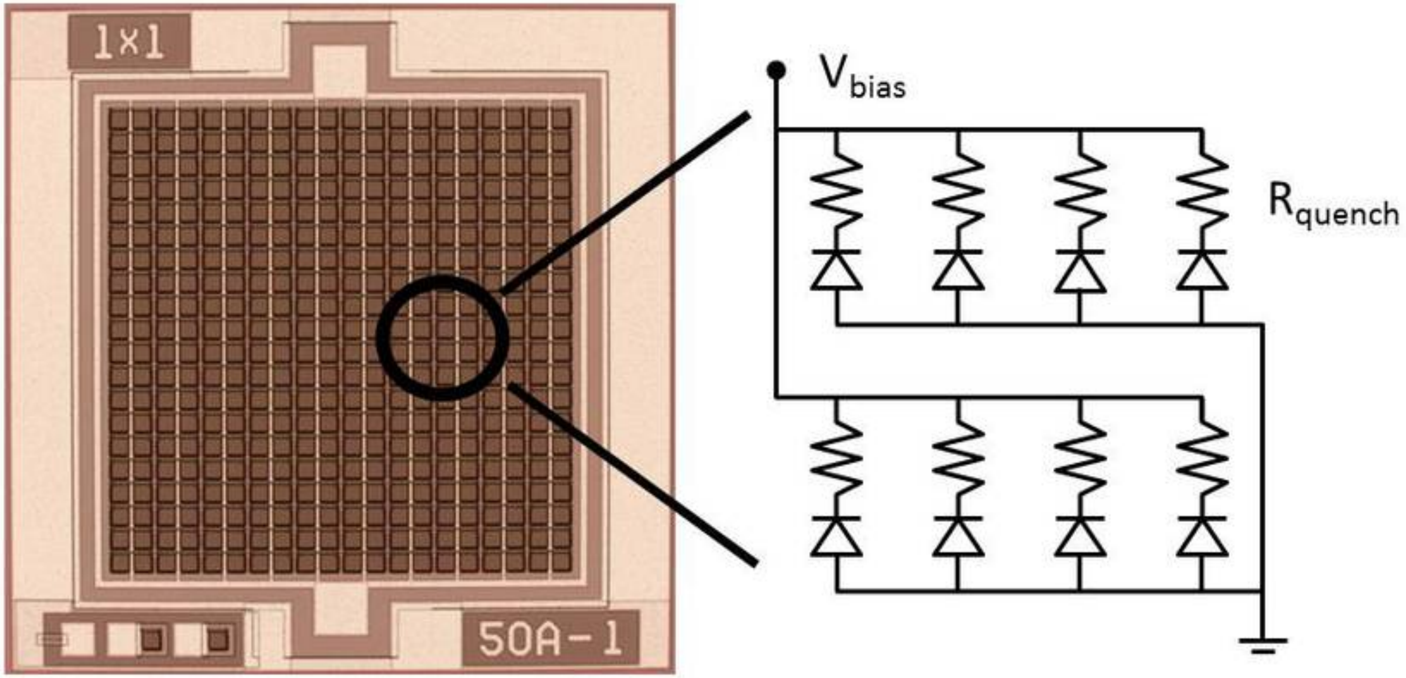
Graphene for ultrafast applications, Cu-Nb and Zr-Nb nanolayered composite light emitters for charged particle, X-ray, and gamma-ray detection







More synergy with LANL collaborators Ming Liu, Michael McCumber, et al.: Silicon photomultipliers and scintillating strips



Single photon sensitive structures built from an array of sequentially connected avalanche photodiodes. Each APD is coupled through a quenching resistor and operates in Geiger mode, providing a dynamic range from 1 to 1000 photons per mm^2. Can be used in a compact calorimeter in a high magnetic field.

Some publications based on the 2007-2014 “UNM team” LANSCE proton irradiations:

[1] V. Fadeyev et al., “Scribe-Cleave-Passive (SCP) Slim Edge Technology for Silicon Sensors,” NIM A731 (2013) 260-265.
[2]A. Macchiolo et al., “Performance of n-in-p pixel detectors irradiated at fluences up to 5×10^{15} n_{eq}/cm^2 for the future ATLAS upgrades,” Ph. Proc. 37, pp. 1024-1031 (2012).
[3] P. Weigell, "Recent results of the ATLAS Upgrade planar pixel sensors R&D project,” NIM A 731 (2013) 177-182.
[4] J. Albert et al., "Prototype ATLAS IBL modules using the FE-I4A front-end readout chip," JINST 7, P11010 (2012).
[5] V. Zivkovic et al, "The FE-I4 pixel readout system-on-chip resubmission for the insertable B-Layer project," JINST 7, C02050 (2012).
[6] M. Barbaro et al., "The FE-I4 pixel readout chip and the IBL module," PoS VERTEX2011, 038 (2011).
[7] M. Garcia-Sciveres et al., "The FE-I4 pixel readout integrated circuit," Nucl. Instr. and Meth. A 636, S155-S159 (2011).
[8] M. Obertino et al., "Test of 3D Sensors," Proc. 12th Pisa Meeting on Advanced Detectors, 2012.
[9] G.-F. Dalla Betta et al., "3D Diode Studies," IEEE NSS 2012.

More example particle physics pubs using LANSCE irradiation data:

[10] M. Obertino et al., “Performance of CMS 3D silicon pixel detectors before and after irradiation,” NIM A 730 (2013) 33-37.
[11] ATLAS IBL Community, "ATLAS Insertable B-Layer Technical Design Report," CERN-LHCC-2010-013 (2010).
[12] R. Wang et al., "Temperature Effects on the Operational Characteristics of CVD Diamond Sensors," poster, IEEE NSS 2010.
[13] J. Metcalfe et al., "Silicon Detectors for the sLHC," Nucl. Phys. B Proc. Suppl 215 (2011) 151-153.
[14] J. Metcalfe et al., "Annealing Effects on Depletion Voltage and Capacitance of Float Zone and Magnetic Czochralski Silicon Diodes after 800 MeV Proton Exposure," IEEE Nucl. Sci. Symposium Conference Record, 2010.
[15] H. Kagan et al., RD42 Status Report to the LHCC", CERN, 18 Feb. 2010.
[16] S. Seidel for the RD50 Collaboration, "Silicon Detectors for the Super LHC," Proc. Vienna Conference on Instrumentation, 2010.
[17] V. Fadeyev et al., "Charge Collection Studies and Annealing Effects in Heavily Irradiated Planar Silicon Strip Sensors," IEEE NSS 2009.
[18] D. Menasce et al., "Tracking Performance of a Single-Crystal and a Polycrystalline Diamond Pixel Detector,” 2013 JINST 8 P06006.

Still more:

[19] M. Bubna et al., "Testbeam and laboratory test results of irradiated 3D CMS pixel detectors," NIM A 732 (2013) 52-56.
[20] A. Macchiolo et al., "Development of thin n-in-p pixel modules for the ATLAS Upgrade at HL-LHC," 9th Trento Workshop on Advanced Silicon Radiation Detectors, 2014.
[21] S. Seidel, "Recent results on diamond radiation tolerance," 2014 JINST 9 C01013.
[22] P. Palni et al., "A method for real time monitoring of charged particle beam profile and fluence," NIM A 735 (2014) 213-217.
[23] R. Wang et al., "Effect of temperature and charged particle fluence on the resistivity of polycrystalline CVD diamond sensors," NIM A 735 (2014) 610-614.
[24] V. Fadeyev et al., "Low resistance strip sensors for beam-loss event protection," submitted to IEEE NSS (2014).
[25] V. Fadeyev et al., "Studies of irradiated alumina layer for development of silicon sensors with slim edges," submitted to IEEE NSS (2014).
[26] G.-F. Dalla Betta et al., "Characterization of new FBK double-sided 3D sensors with improved breakdown voltage," Proc. IEEE NSS-MIC 2013, N41-1 (2013).

Yet more:

[27] H. McDuff et al., "Effect of Humidity on Reverse Breakdown in 3D Silicon Sensors," Nucl. Instr. and Meth. A 735 (2015) 1-4.
[28] J.M. Rafi et al., "Studies of Irradiated Alumina Layer for Development of Silicon Sensors with Slim Edges," IEEE NSS-MIC, Seattle, 2014.
[29] G. Kramberger et al., "Radiation Effects of Low Gain Amplification Detectors After Hadron Irradiations," submitted to Nucl. Instr. and Meth., May 2015.
[30] V. Greco et al., "Devices Optimized for Avalanche Multiplication," submitted to Proceedings of Science, April 2015.
[31] B. Paschen, "Investigation of the Performance of Pixel Modules from Thin Silicon Sensors with Active Edge," thesis, Ludwig Maximillian University, Munich (2014).
[32] S. Terzo et al., "Thin n-in-p Planar Pixel Sensors and Active Edge Sensors for the ATLAS Upgrade at HL-LHC," arxiv.org/abs/1409.8579.
[33] C. Aidala et al., "The PHENIX Forward Silicon Vertex Detector," arXiv: 1311.3594v2, submitted to Nucl. Instr. and Meth.

The LANSCE 800 MeV proton beam is annually providing data to the worldwide particle physics effort that is absolutely essential to progress.

Thank you.