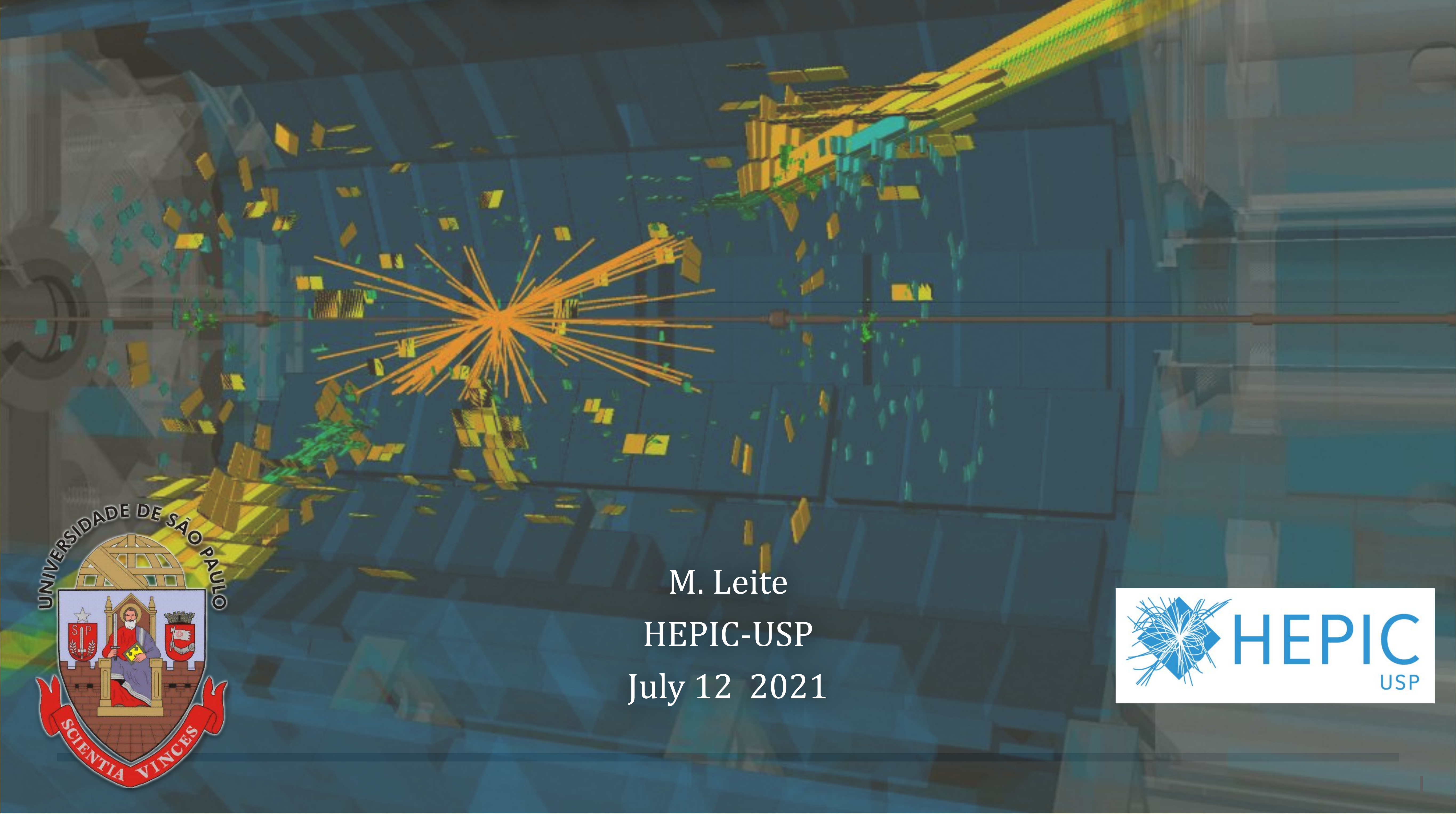
ULTRA FAST SEMICONDUCTOR RADIATION SENSORS FOR HIGH ENERGY PHYSICS AND BEYOND



M. Leite

HEPIC-USP

July 12 2021

The Objectives

- R&D in large area Ultra Fast Semiconductor Detectors (UFSD) with ps timing resolution for collider physics applications ➟ Participation in the construction & commissioning of ATLAS Experiment HGTD Phase-II upgrade. Participate in R&D for ALICE3 TOF Timing Layers.
- Explore new UFSD designs (simulation/fabrication/tests) suitable for local application (e.g. synchrotron light experiments).
- Investigate & test new UFSD structures and materials targeting very high radiation dose applications.

The Local Team

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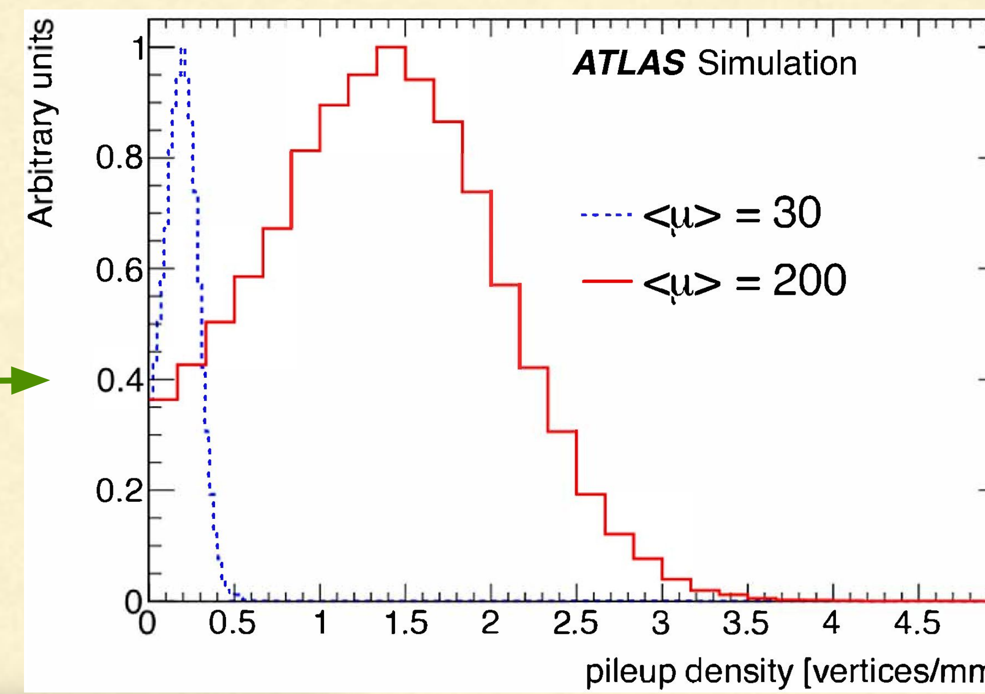
THE MAIN DRIVER : HL-LHC

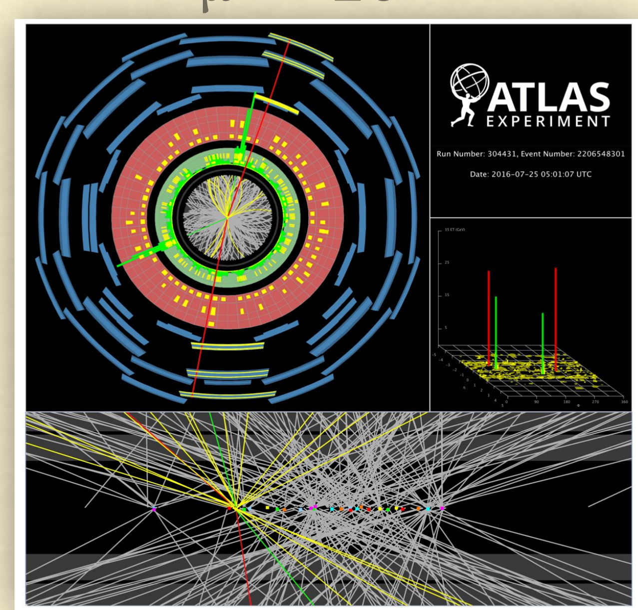
[HL-LHC latest update (01/2021)]

THE MAIN DRIVER : HL-LHC

- So far, we explored only **5%** of expected LHC integrated proton-proton luminosity ($4ab^{-1}$)
- Most of the data will come from HL-LHC (a precision measurements era):
  - Studies of Higgs couplings
  - Studies of Higgs self-couplings (di-Higgs)
  - Probe the EWK sector though VBS and precision SM measurements ($\sin^2\theta_W$)
  - On/Off-shell vector bosons double and triple differential cross -section measurements …
  - Searches for dark matter (monojets) … etc.
  - Needs extended tracker coverage to high rapidities
- Expect to deal with
  - instantaneous luminosity of $\mathbf{7.5\times10^{34}\ cm^{-2}s^{-1}}$
  - **~200**average number of collisions per bunch crossing (<μ>)
- Increase <μ> and you also increase the track and vertex density

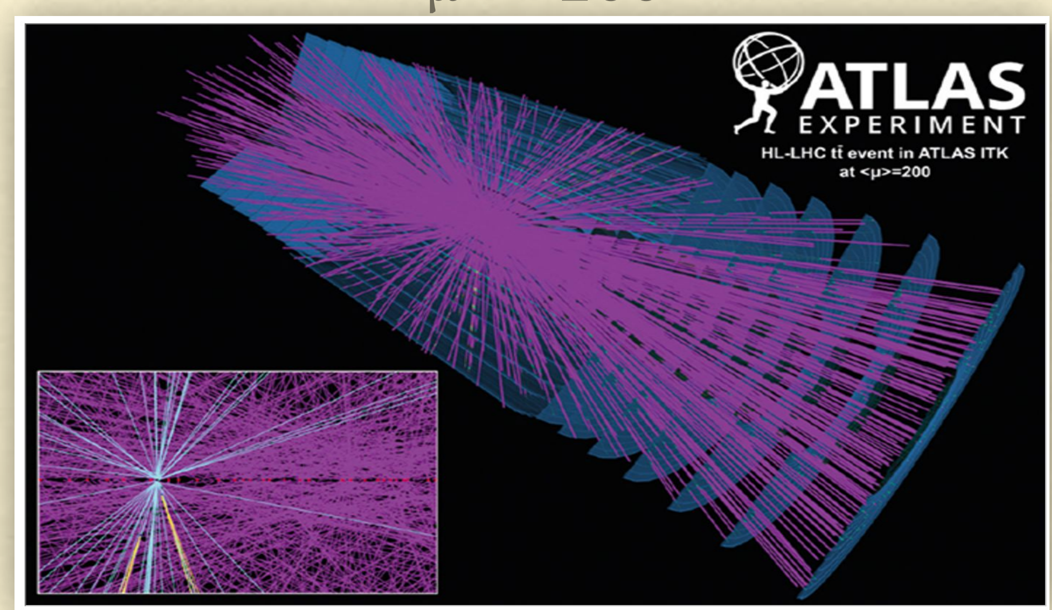


<μ> = 20



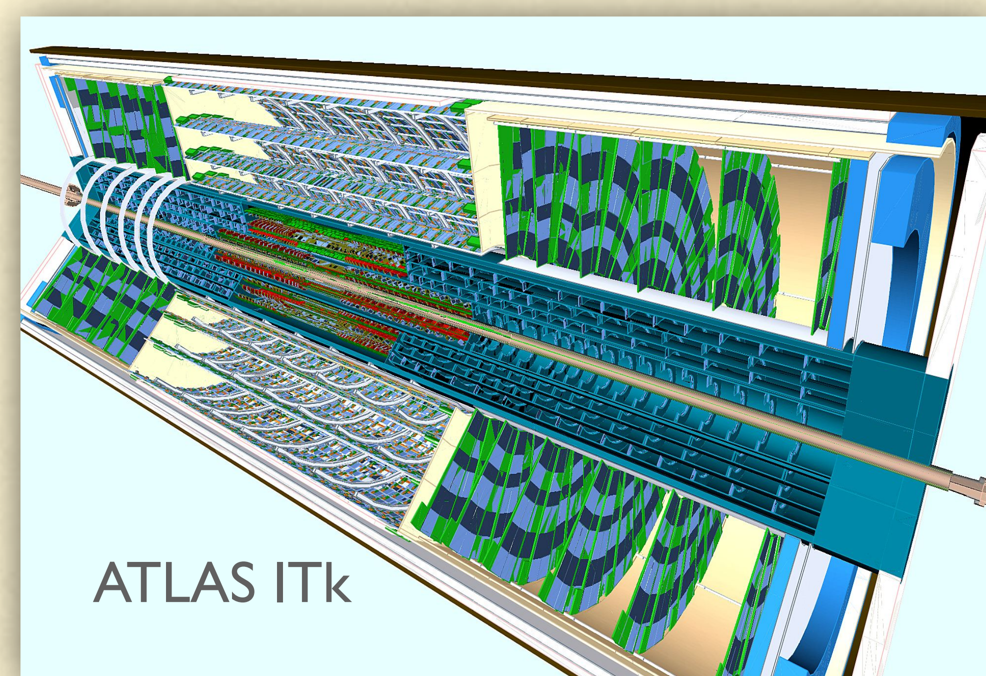
HL-LHC

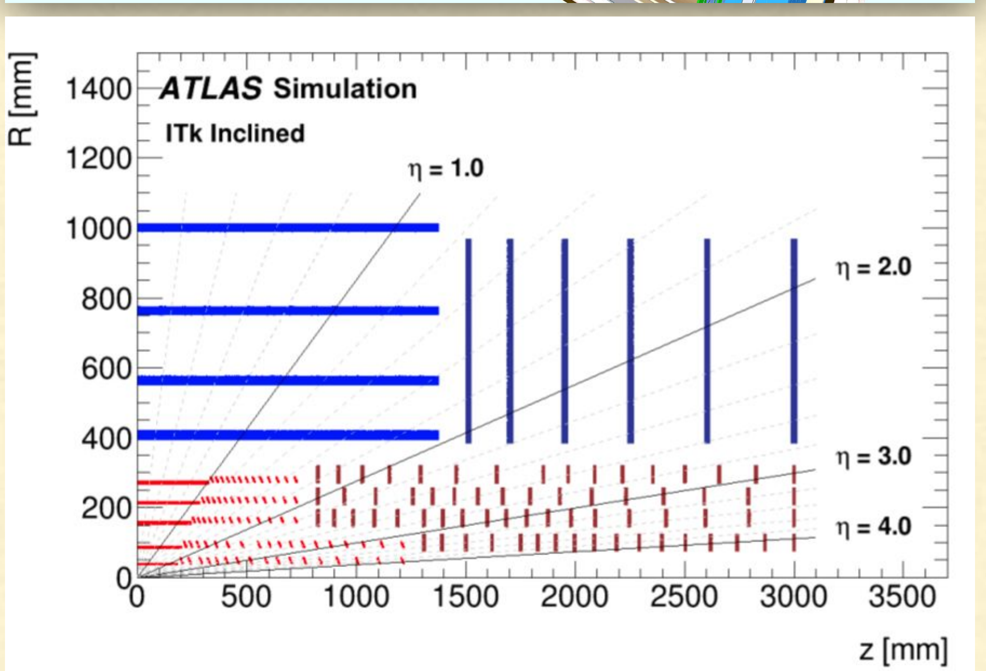
<μ> = 200

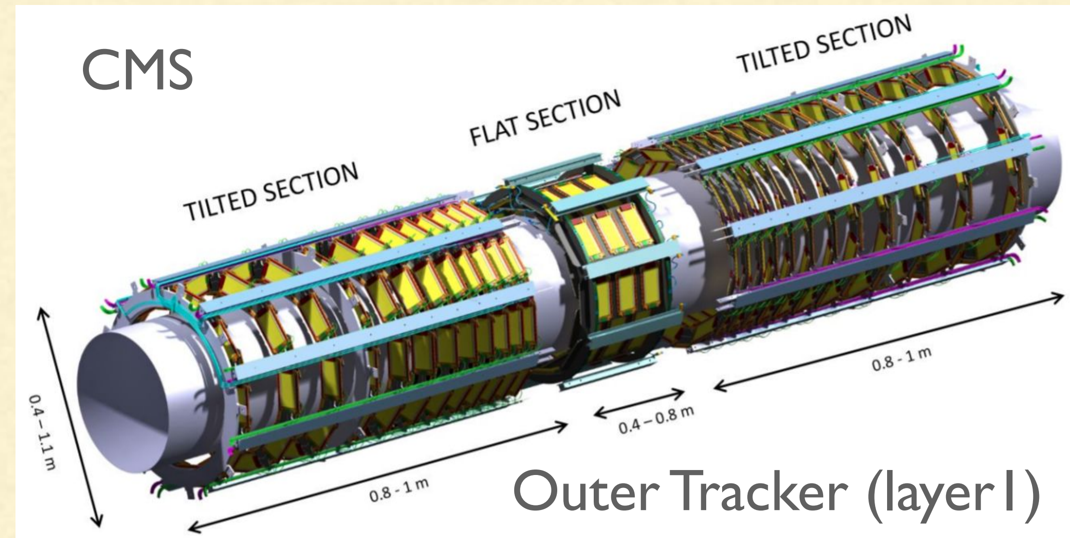


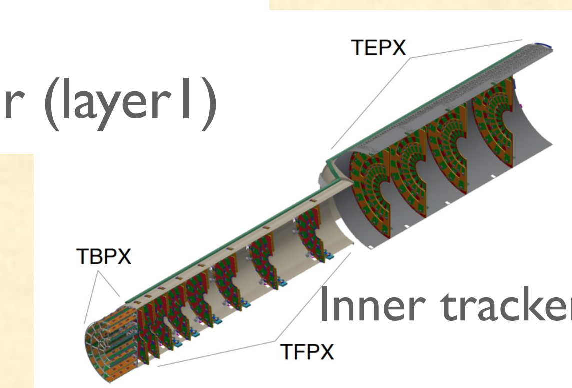
THE MAIN DRIVER : HL-LHC

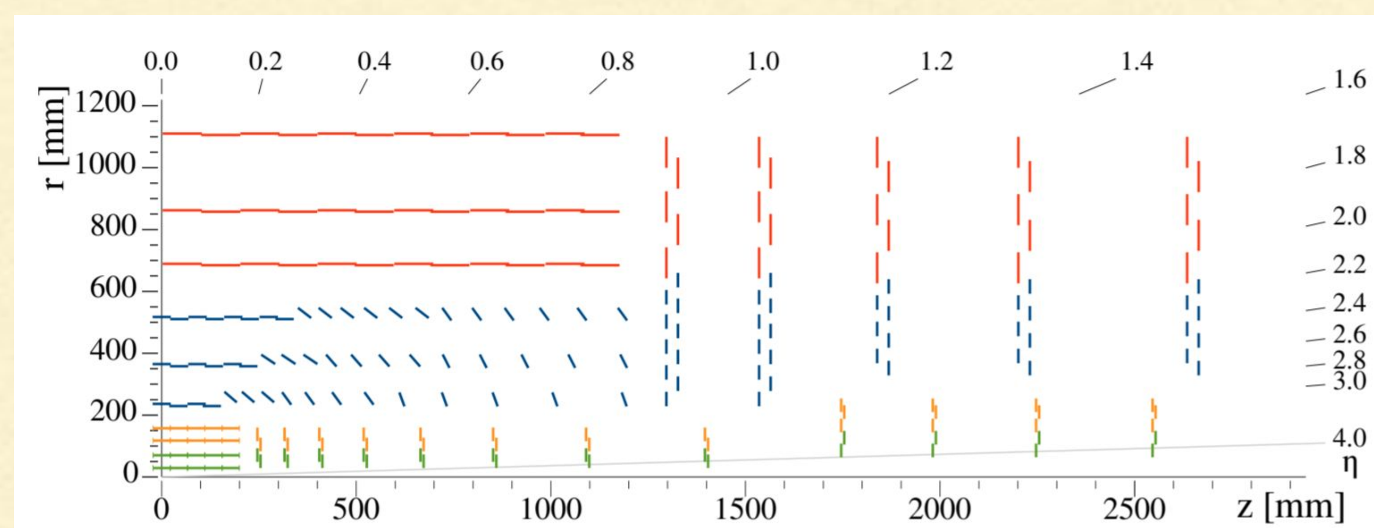
- Good track-vertex association (σz_0) is crucial for pileup mitigation …
- For the HL-LHC operation, ATLAS will replace its inner tracker, extending coverage from $|\eta| < 2.5$ to $|\eta| < 4.0$ (ITk)
- CMS will also replace its tracker systems for HL-LHC, extending the coverage to $|\eta| < 4.0$







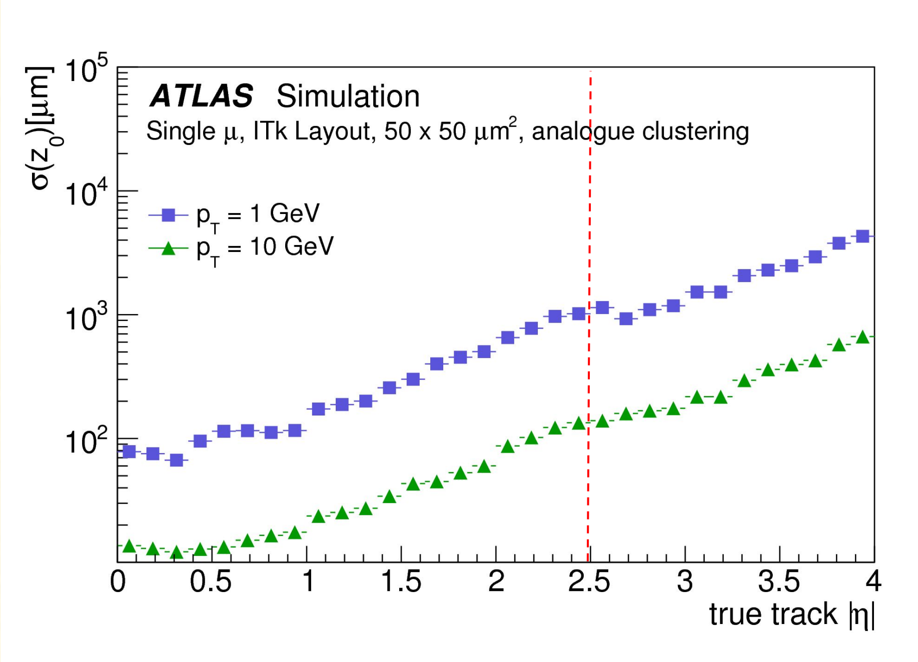


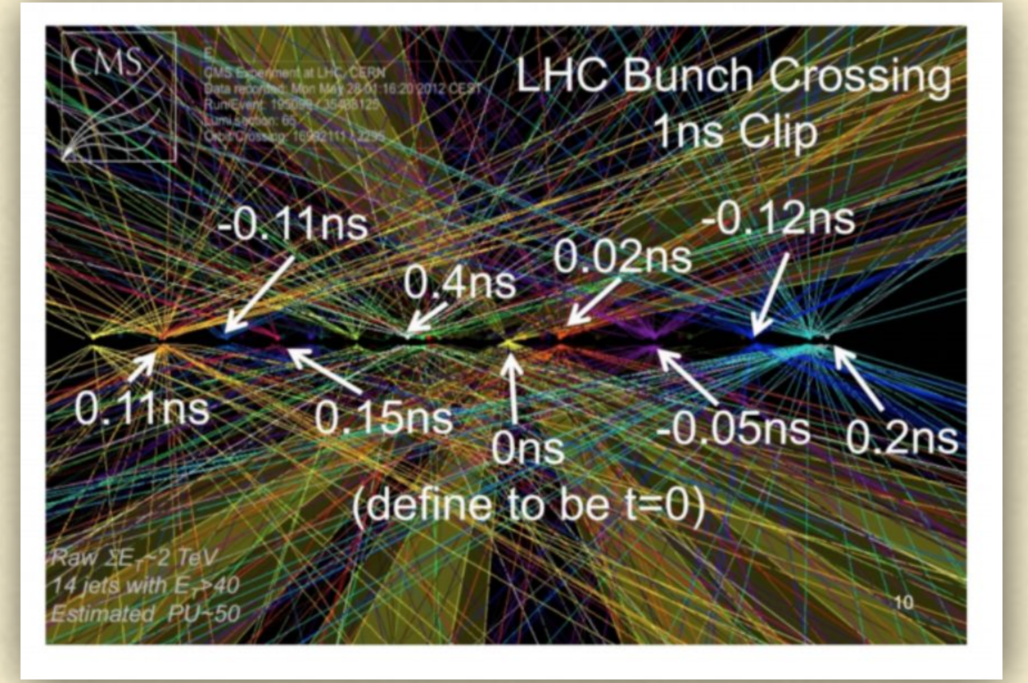


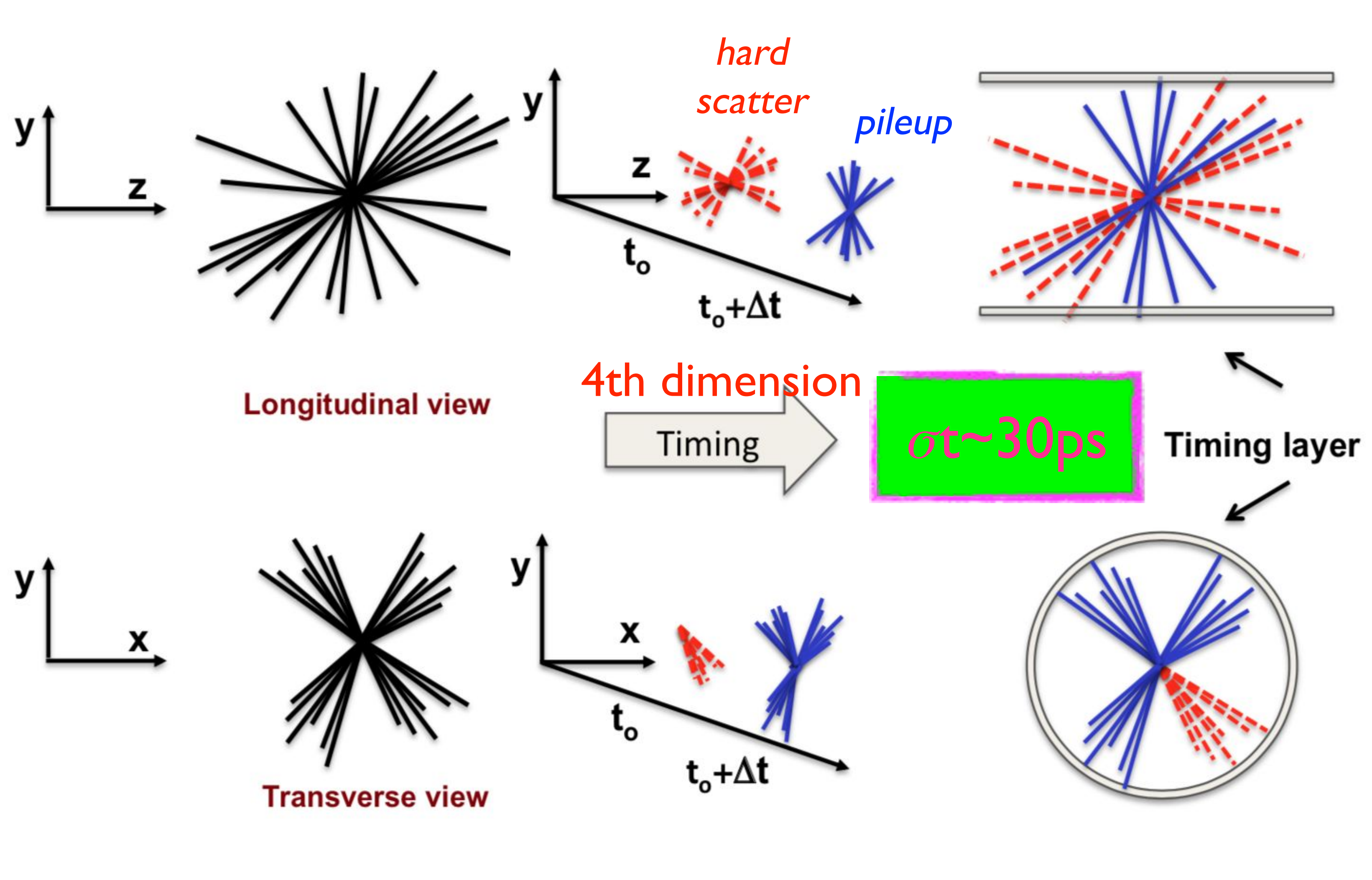
THE NEED FOR TIMING (I)

- ITk spatial resolution in forward region: few mm for low pT particles (bad!)
- Today, track reconstruction relies solely on the spatial (3D) information
- Collisions are distributed in time :
  - HL-LHC: 1.8 col/mm (z), 175ps gaussian spread
  - if we can measure the timing well enough, we can resolve spatial ambiguities
  - … for time-tracking association, this needs to be done with a resolution of 30ps or better

1/6 pileup

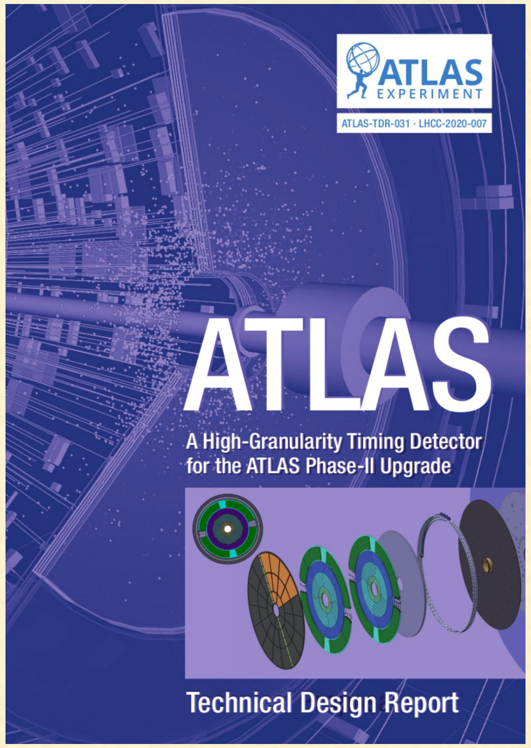


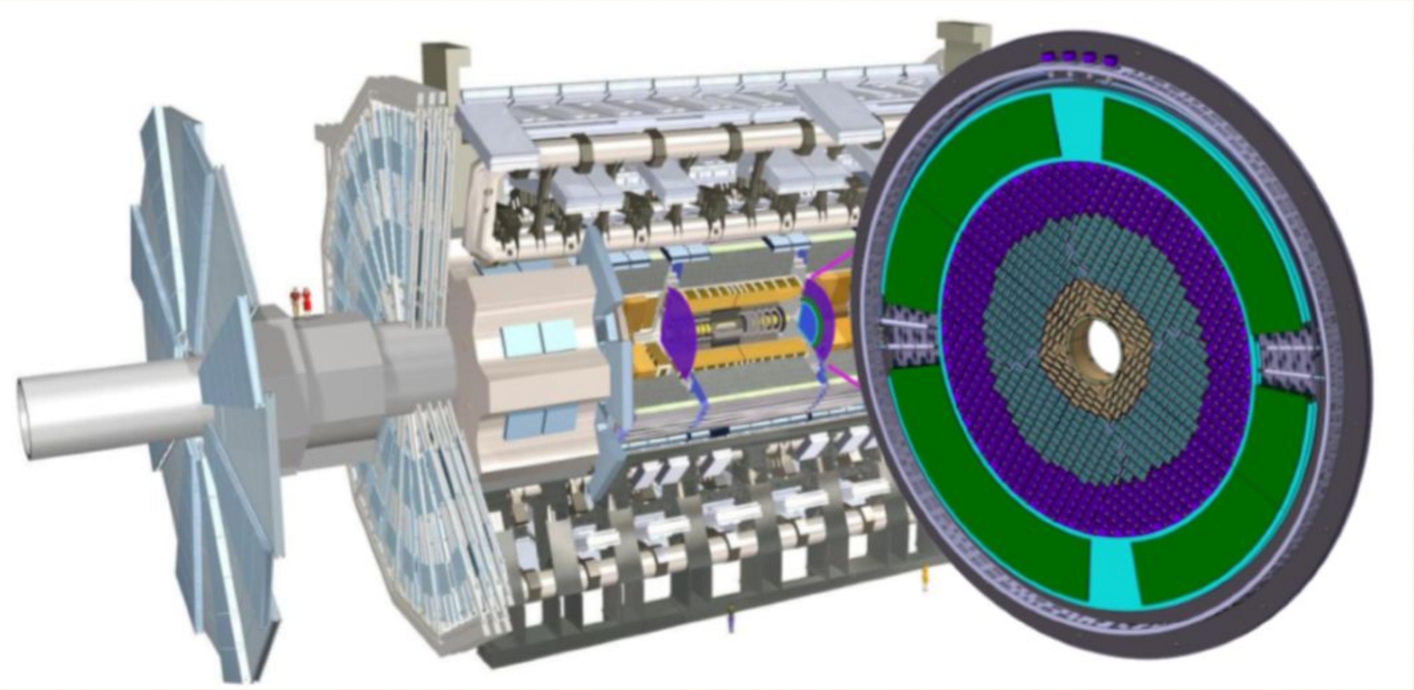


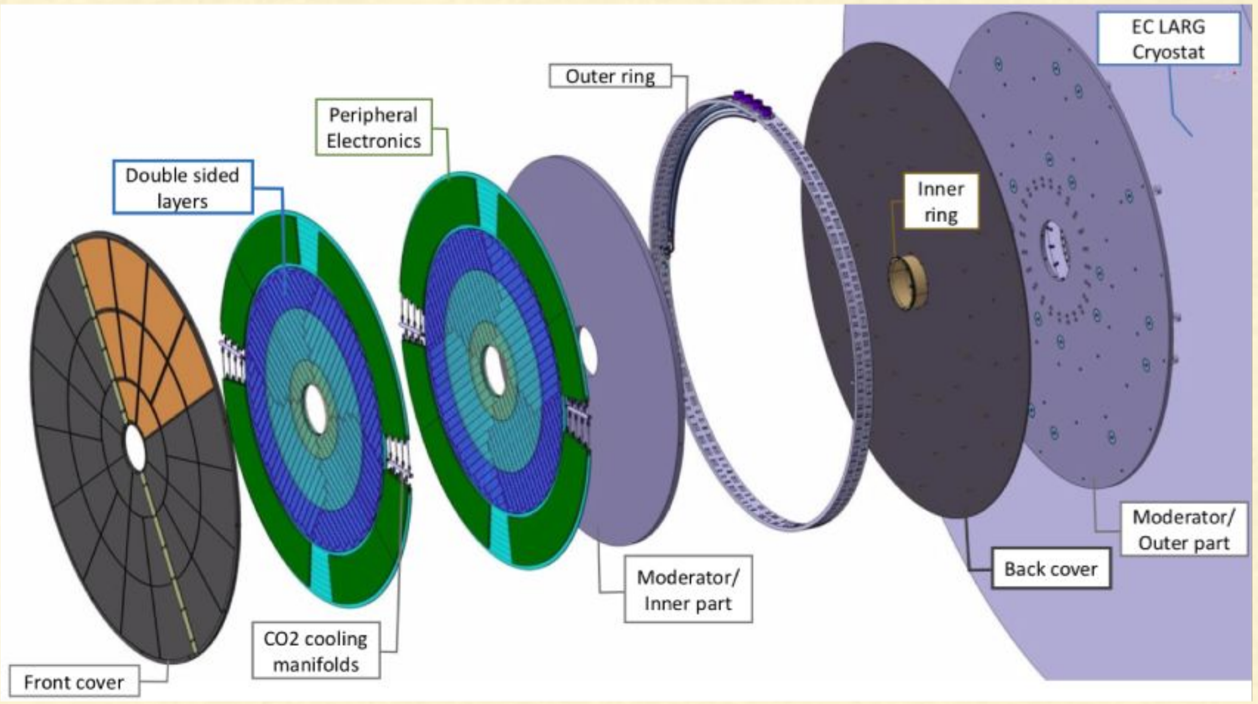


THE NEED FOR TIMING (II) :ATLAS HGTD

- ATLAS needs a new system covering 2.5 < |η| < 4.0 that can associate timing to the ITk reconstructed tracks
  - segmentation of 1.3x1.3mm^2 (for ITk track matching and low occupancy)
  - Should not add significant amount of material in front of EMEC and FCAL
  - Should fit in a constrained space
  - Total thickness ~ 12cm
  - Total radius ~ 1.1m (active radius 0.12-0.64 m)
  - 6 m^2 of Si, 3.5 M channels
  - Should be cope with a neutron fluence of ~ 2.5 x10^{15} 1MeV n_{eq} cm^{-2} and TID of ~ 2MGy
  - Needs very thin, very high timing resolution sensors (~30ps) → **LGAD**
  - Will provide instantaneous luminosity measurement (per BCID)
  - CMS will also install a Timing Detector (MIPS) using different technologies for the Barrel (LYSO + SiPM) and EndCap (**LGAD**)

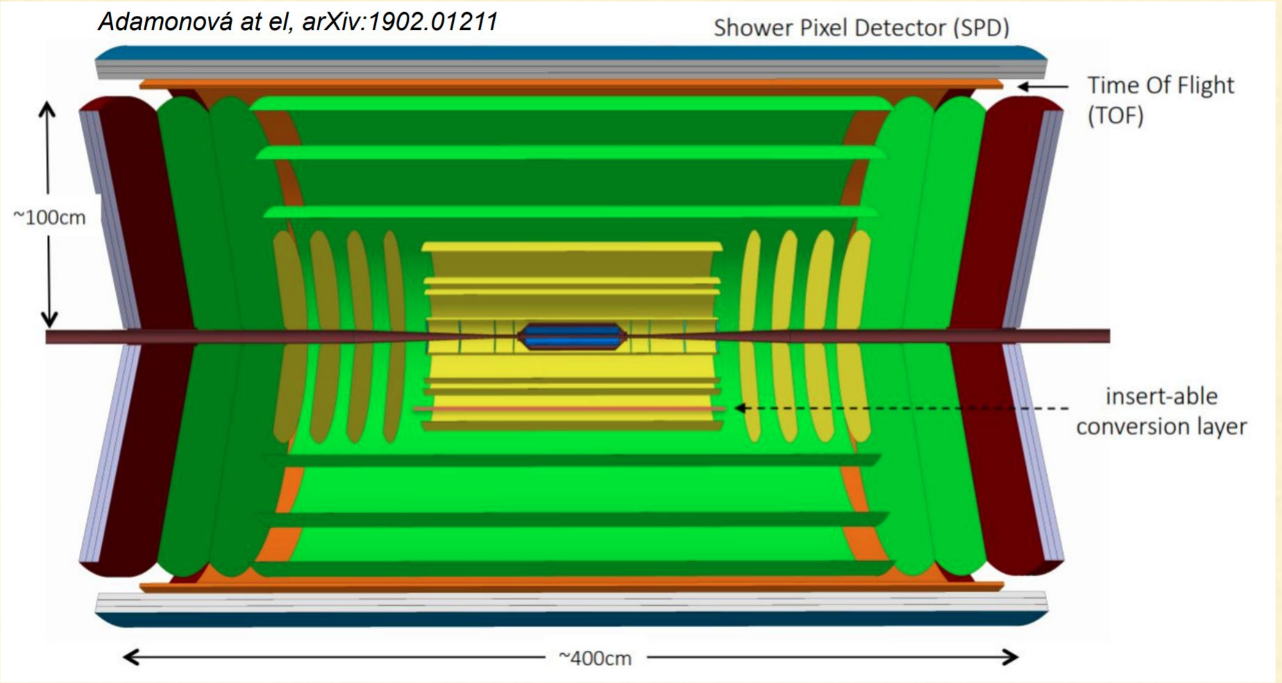


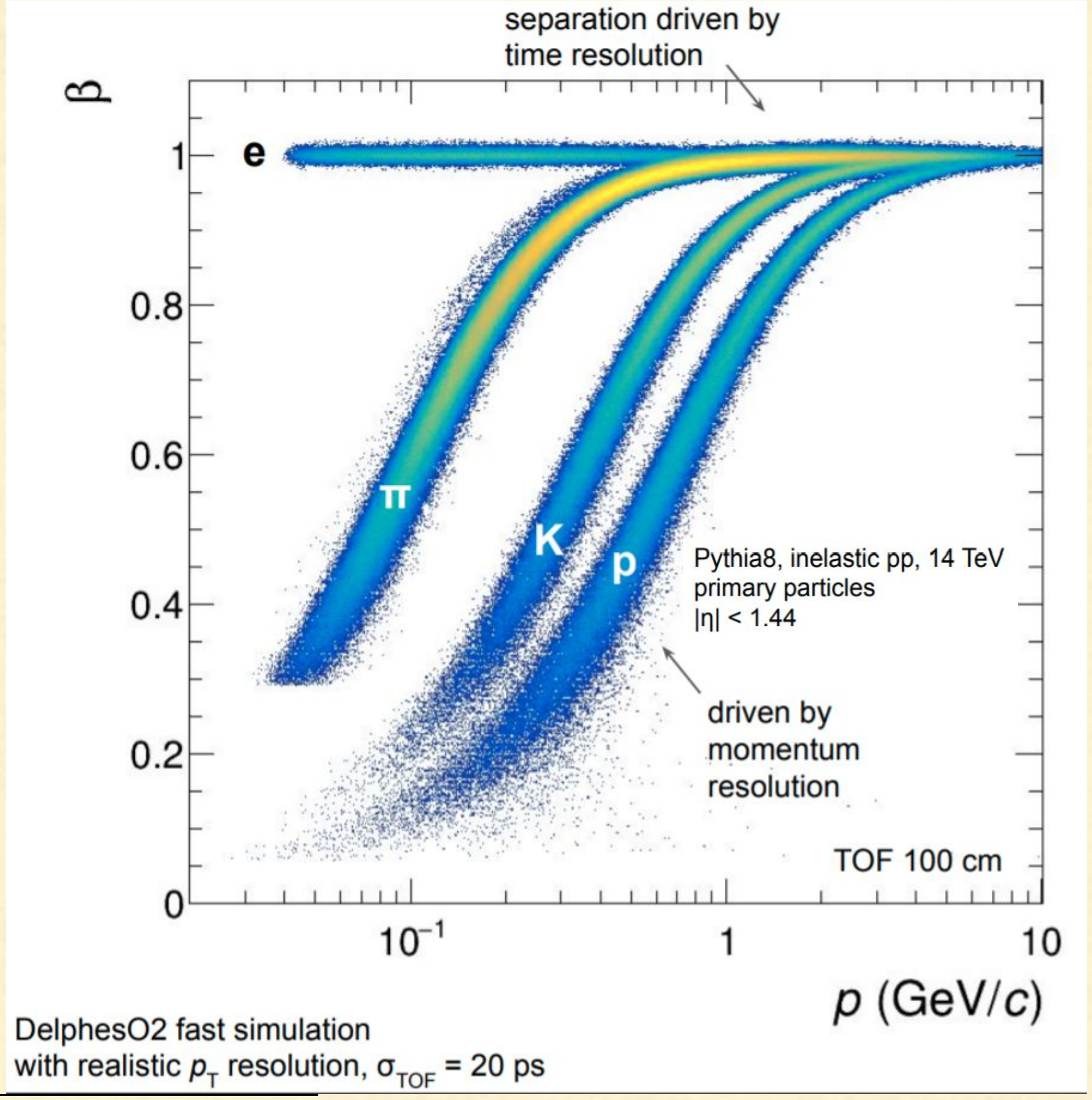




THE NEED FOR TIMING (III) :ALICE3 TIMING LAYERS

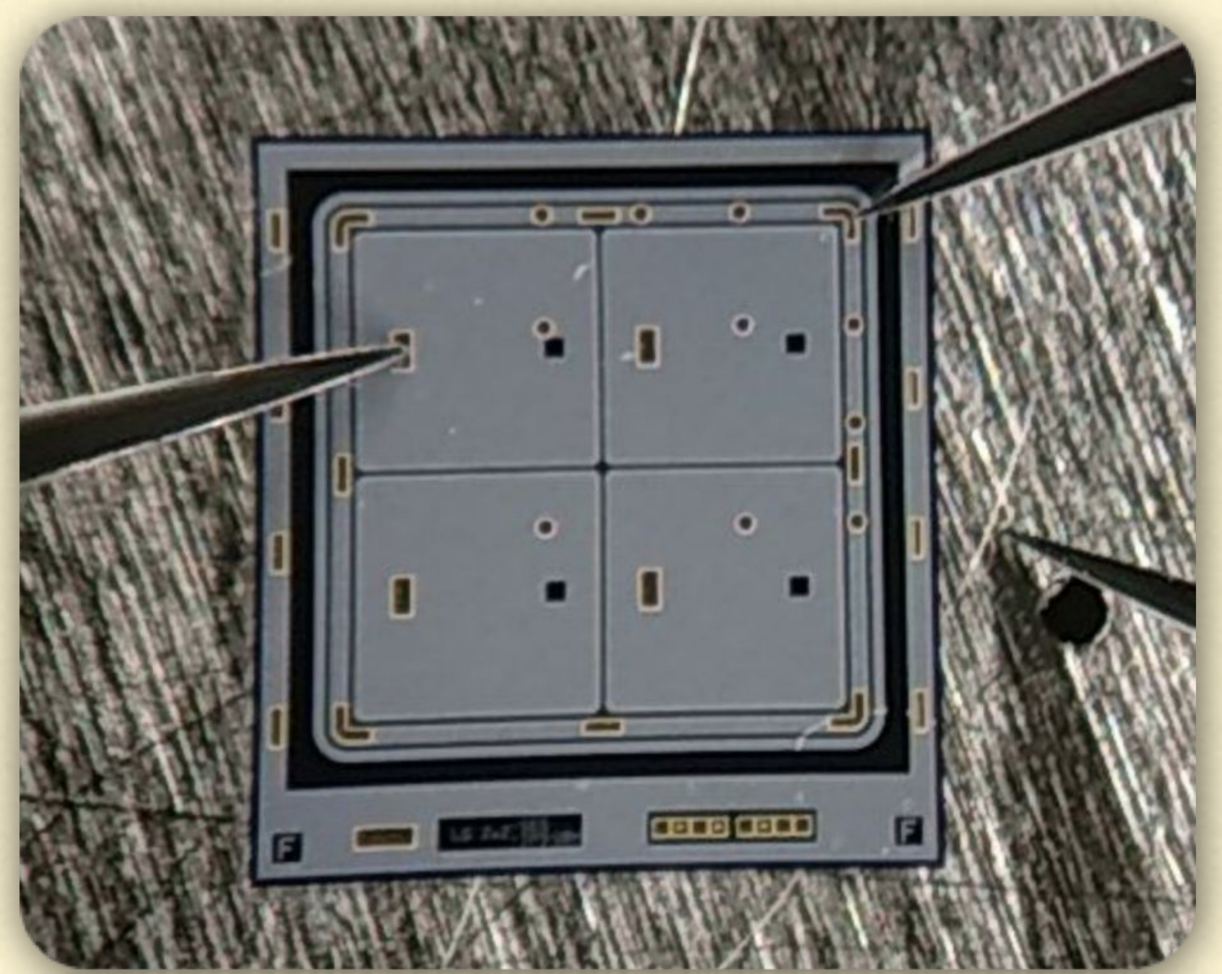
- ALICE3 will be a completely new compact semiconductor based detector (~ year 2030)
- Capable to operate at $L \sim 10^{34}\ cm^{-2}s^{-1}$
- $|\eta| < 4.0$, full azimuthal coverage
- PID implemented by two timing layers (TOF)
    - Technologies under consideration (target : 20ps)
        - LGAD
        - SiPMs (or SPADs)
        - Monolithic
    - Sensor R&D ramping up now





	TOF @ 20 cm	TOF @ 1 m
Pixel pitch	1 mm	5-6 mm
Occupancy	2.7E-03	3.3E-03
Hit rate (kHz/cm-2)	3.7E+03	1.5E+02
NIEL (1-MeV-n_{eq}/cm²)	2.31E+12	9.24E+10
TID (rad)	7.39E+04	2.96E+03
Area (m²)	1.56	16.59
Material Budget (X/X_0)	1-3%	
Power consumption		
Time resolution	< 50 ps	20 ps

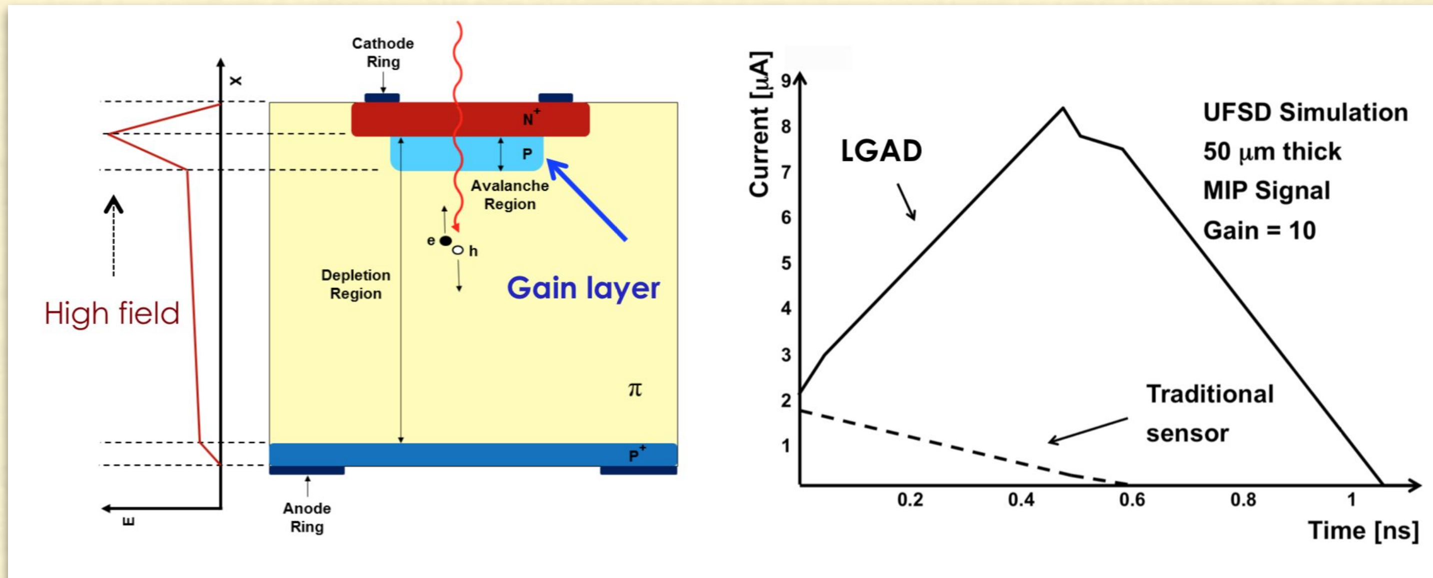
ULTRA FAST SILICON DETECTORS



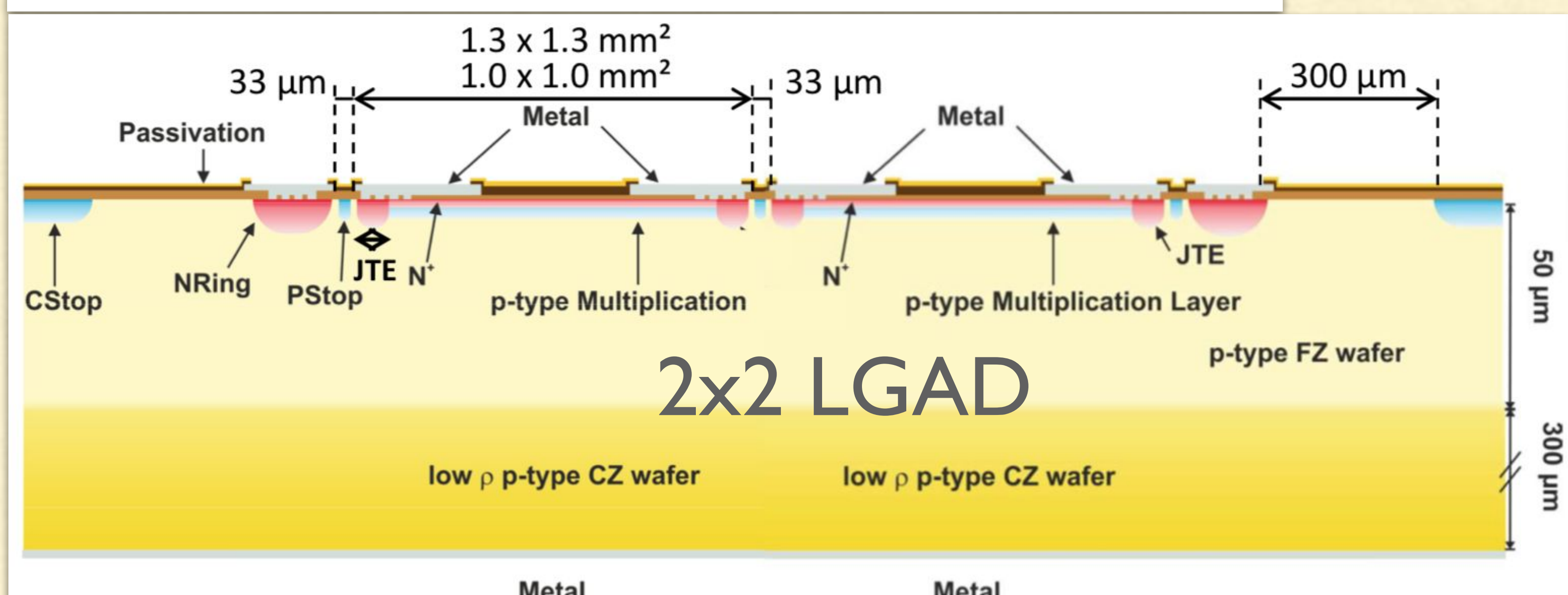
LGAD
(LOW GAIN AVALANCHE DETECTORS)

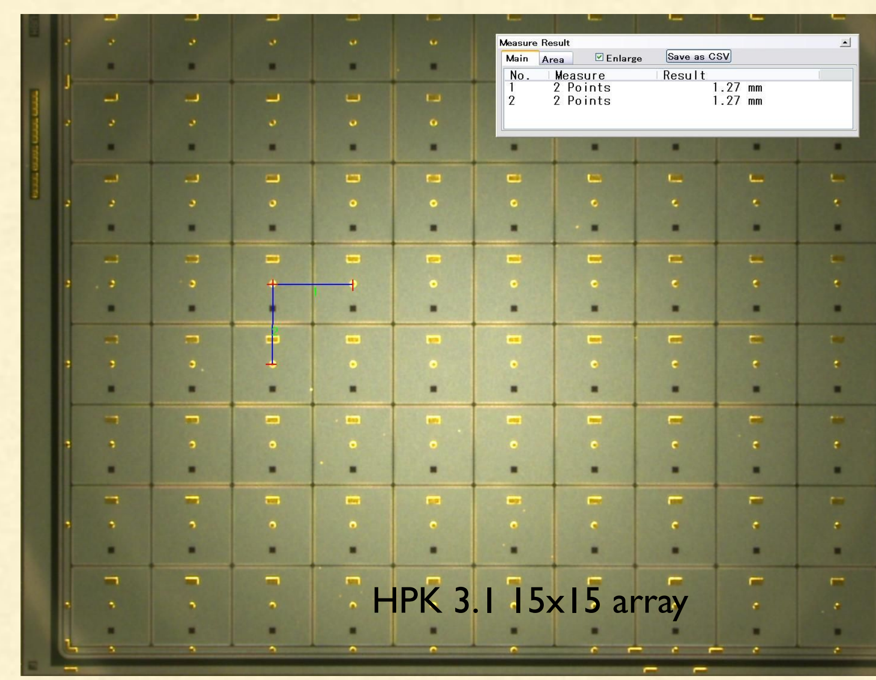
- Sensor requirements
  - timing resolution < 30ps
  - radiation hard
  - low noise
  - possibility of segmentation in arrays

- **Low Gain Avalanche Detector (LGAD)**
  - Proposed by RD50 ~ 2014/2015
  - n-on-p silicon
  - highly doped p-layer under junction
  - low gain, independent of thickness
  - 300μm, 50μm, 35μm or even 20μm
  - 1.3x1.3mm^2 (ATLAS HGTD), 1x3 mm2 (CMS MIP Timing Detector)
  - Several sensor batches by CNM (Spain), BNL, Hamamatsu (Japan), FBK (Italy), IHEP, NDL (China) ...
  - ATLAS HGTD will use 15x30 arrays (2 15x15 chip arrays bump bonded to FE electronics) sensor blocks



N. Cartiglia

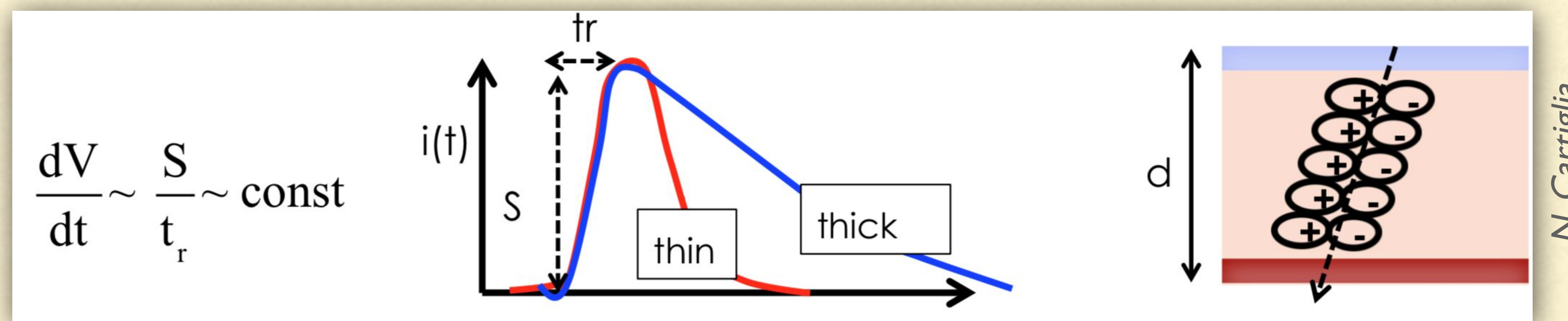




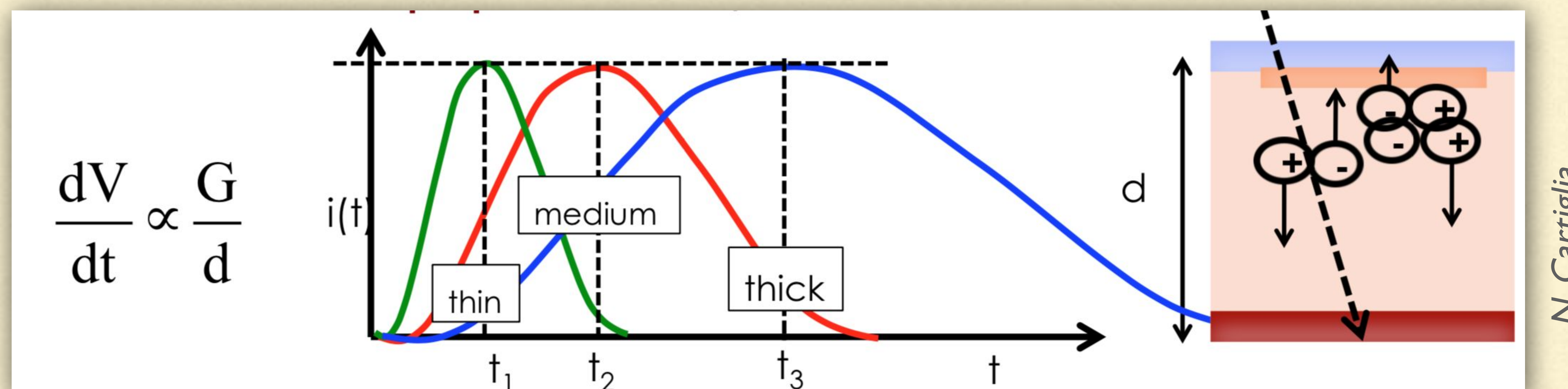
LOW GAIN AVALANCHE DETECTOR (LGAD)

- Thin sensors ➜ increased radiation hardness
- Intrinsic gain ➜ increased signal/noise

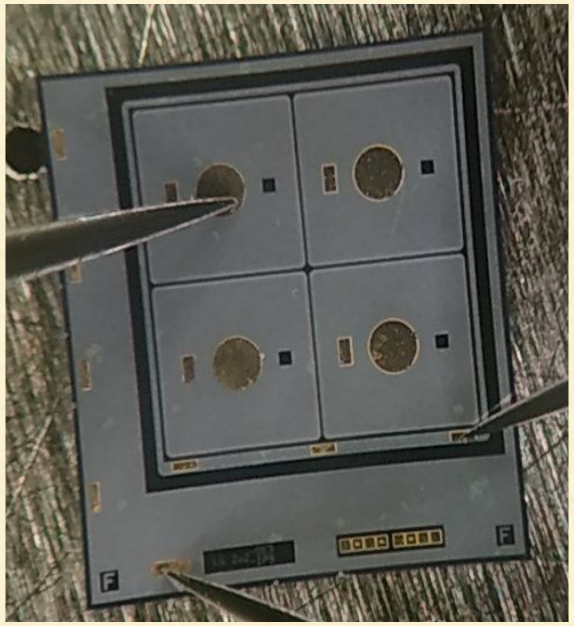
Planar detector: fixed rise time

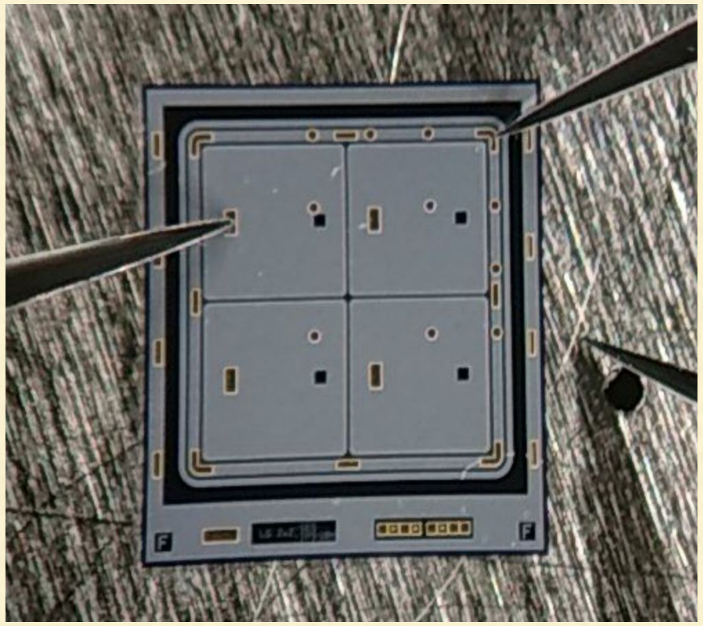


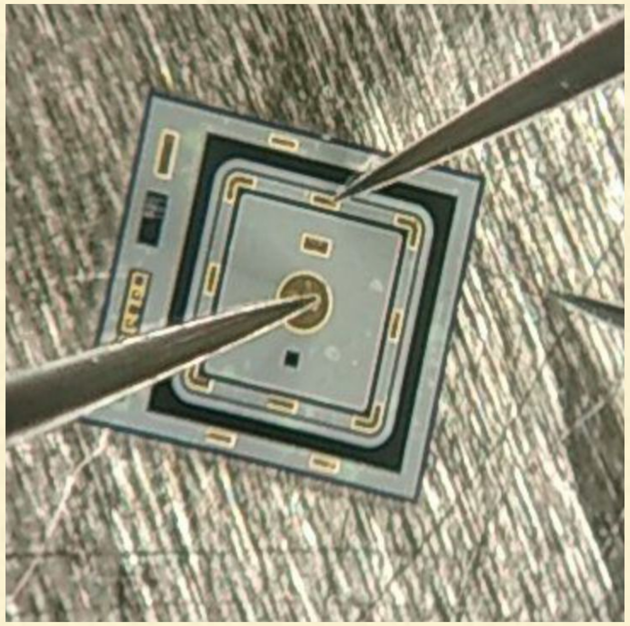
LGAD: rise time proportional to Gain/thickness

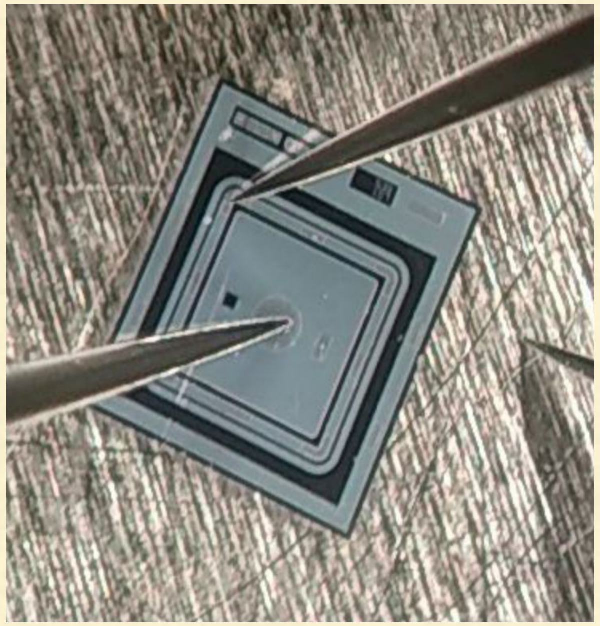


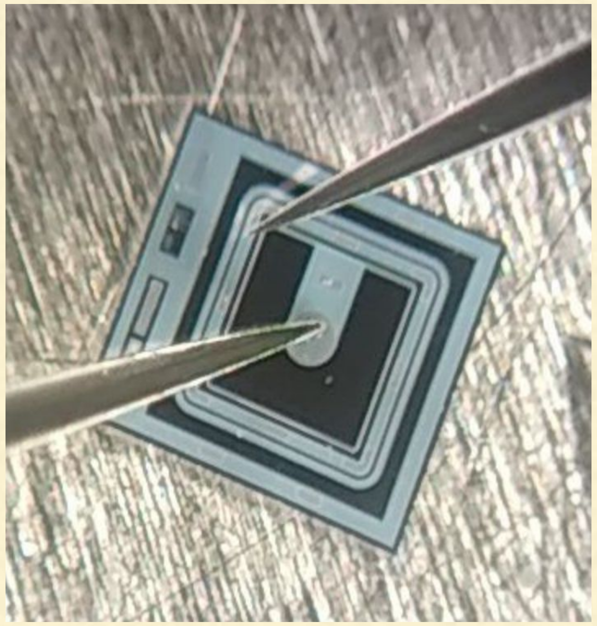
ATLAS LGAD PROTOTYPES TESTS

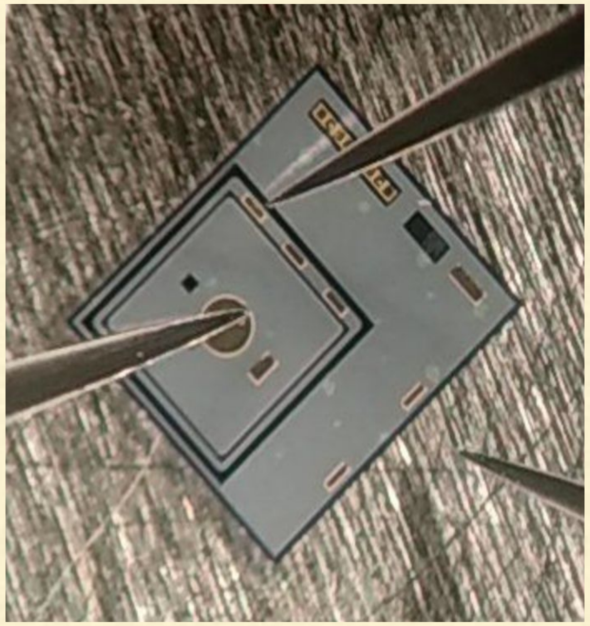






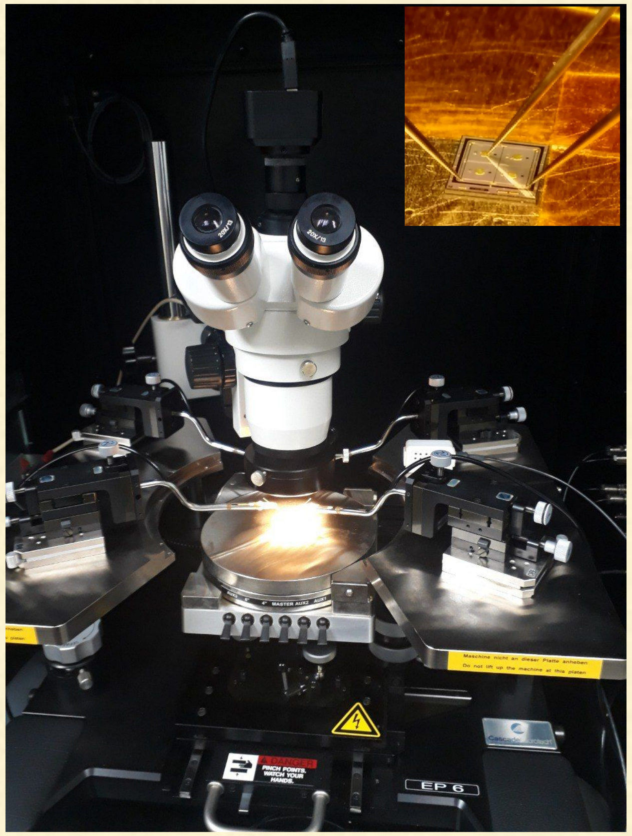


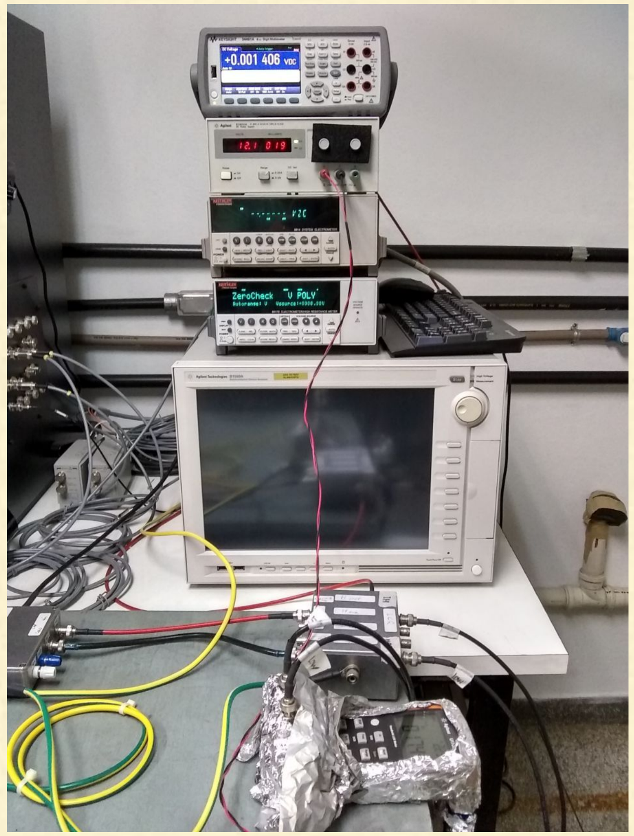


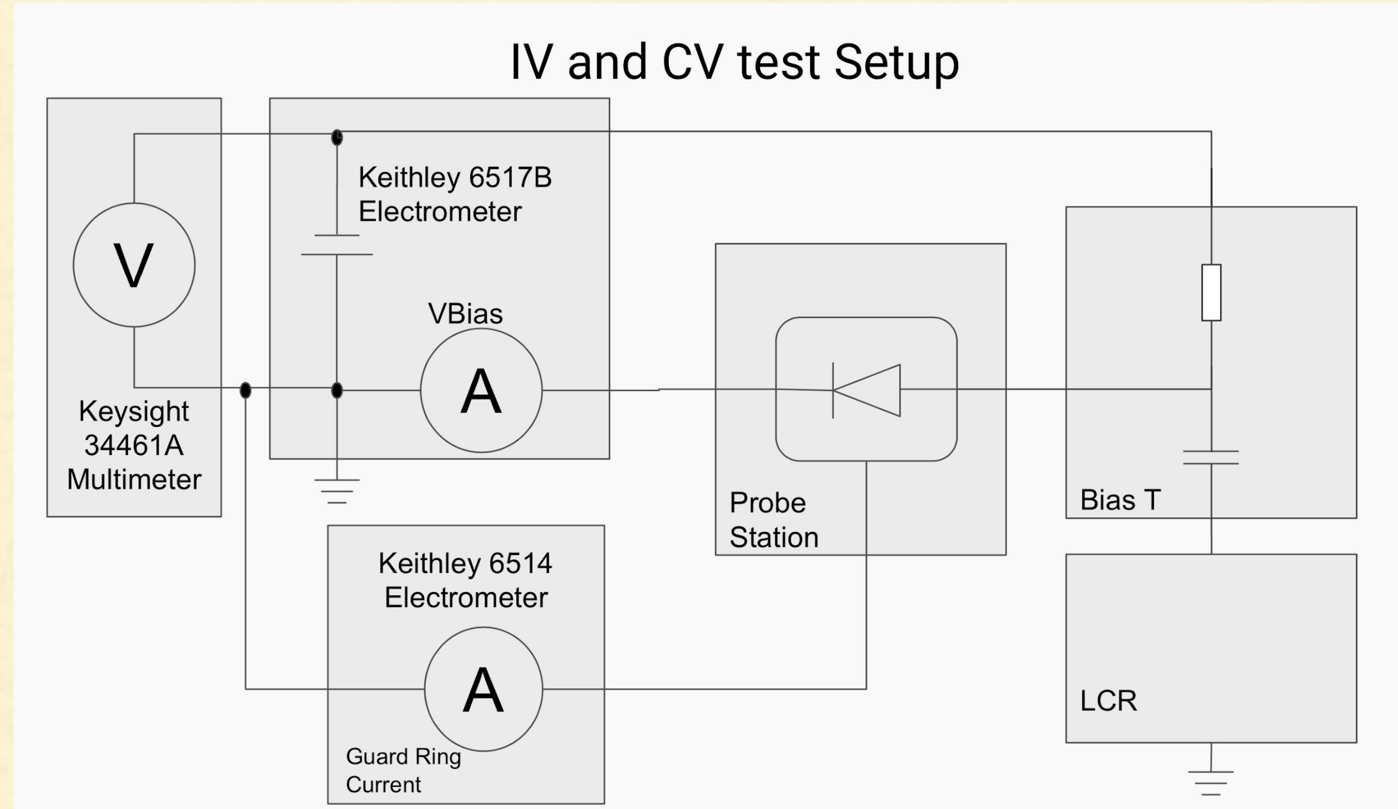


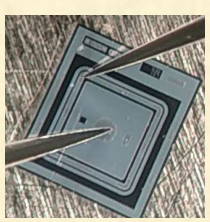
LGAD ELECTRICAL PERFORMANCE

Manual probe station setup setup (USP)



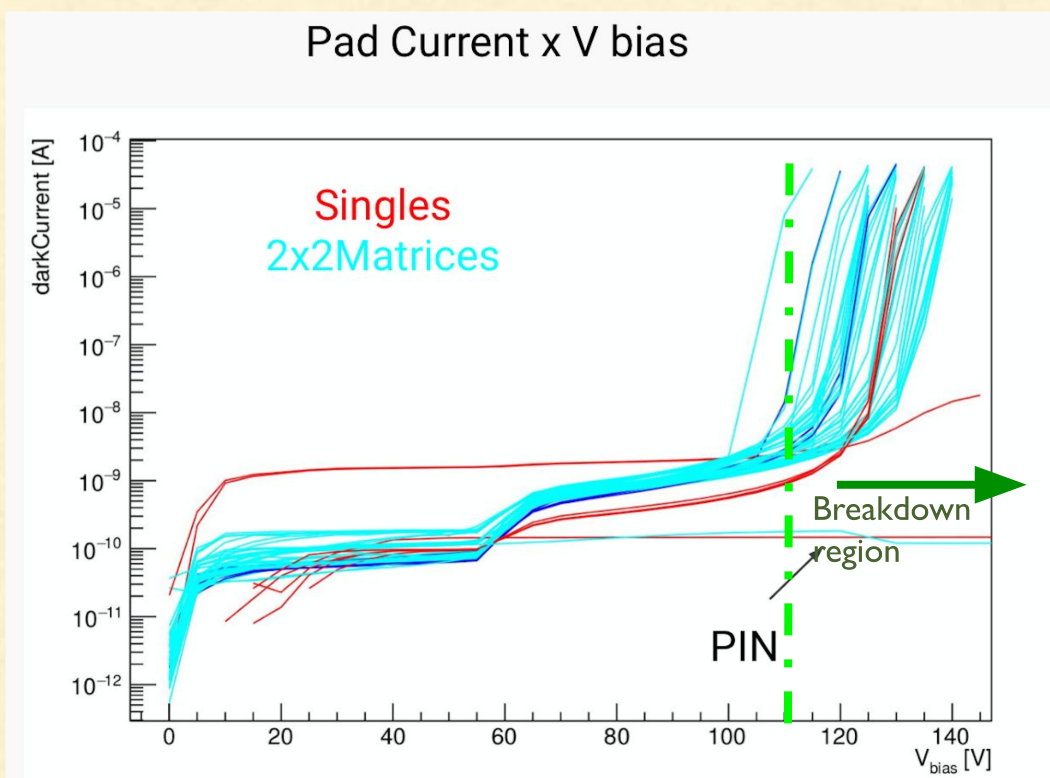


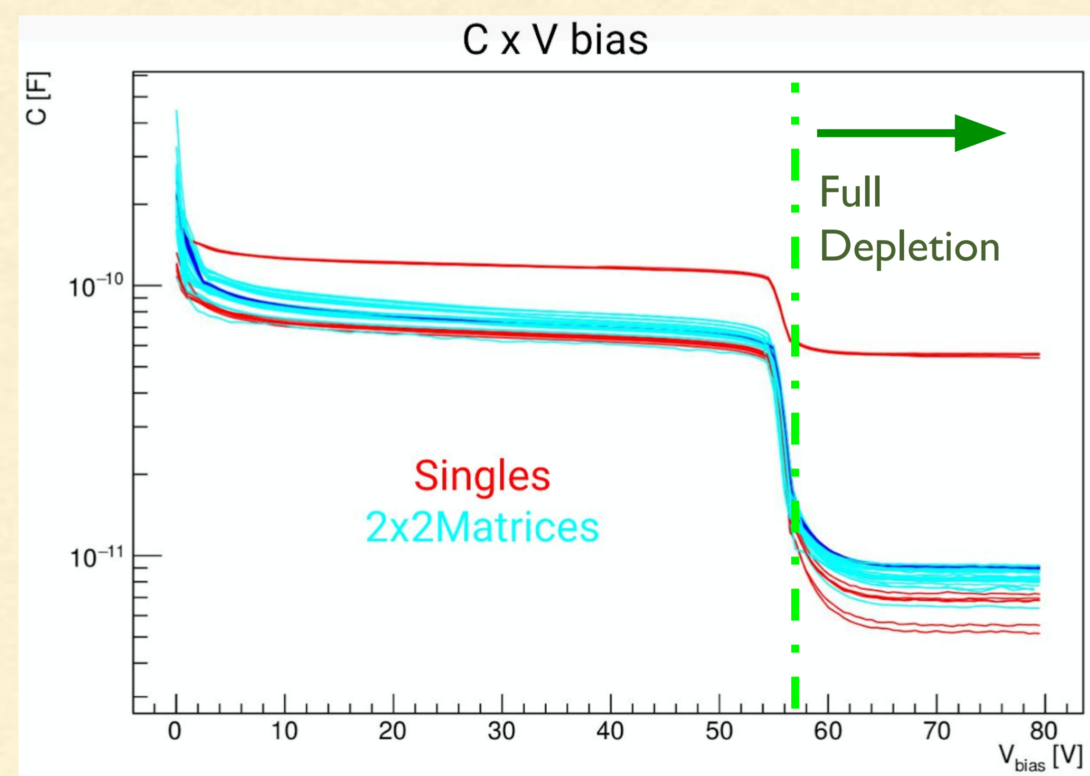




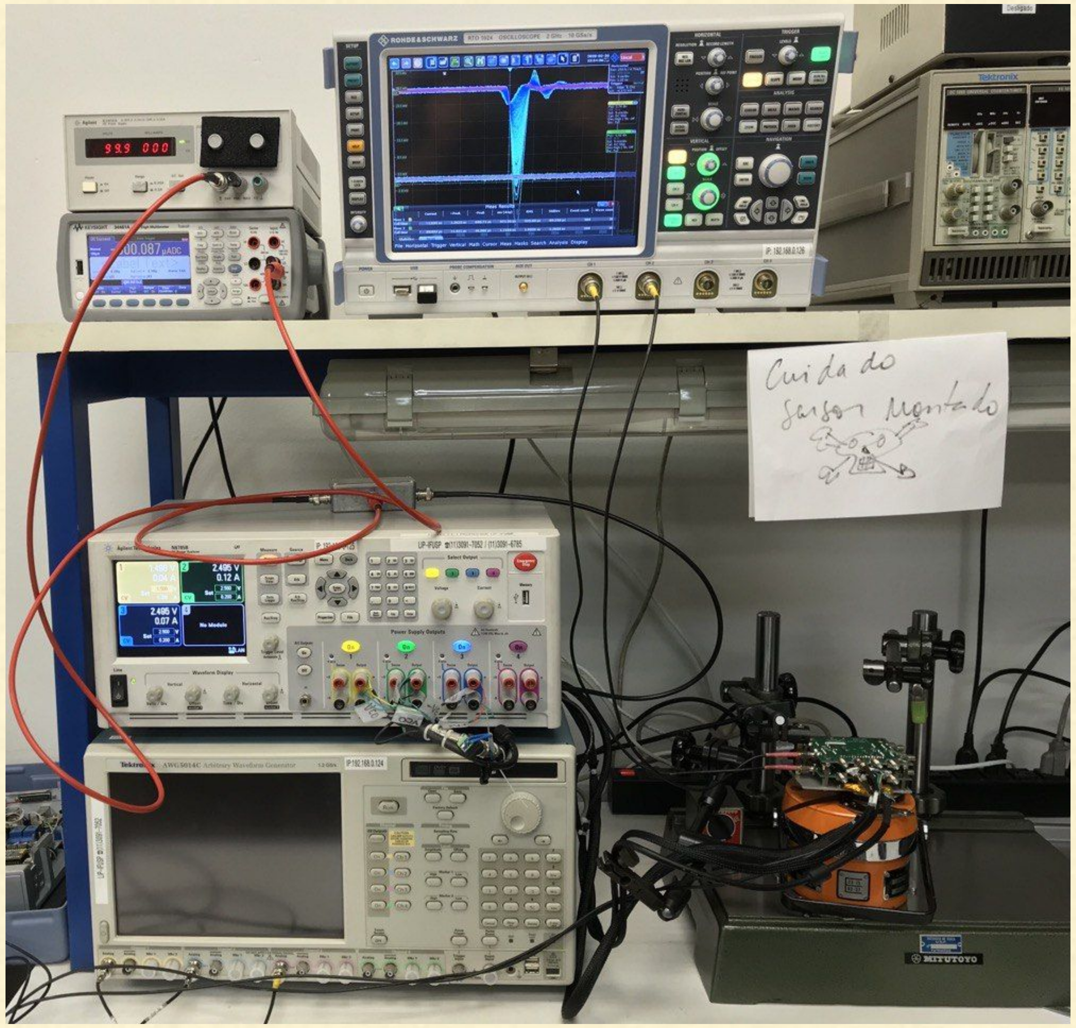
Single pad

2x2 array

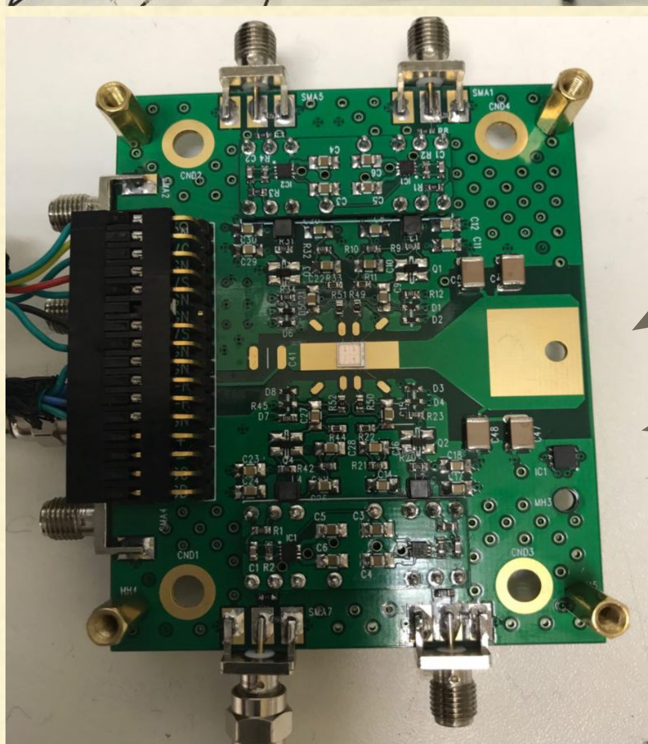




LGAD SIGNAL PERFORMANCE (II)



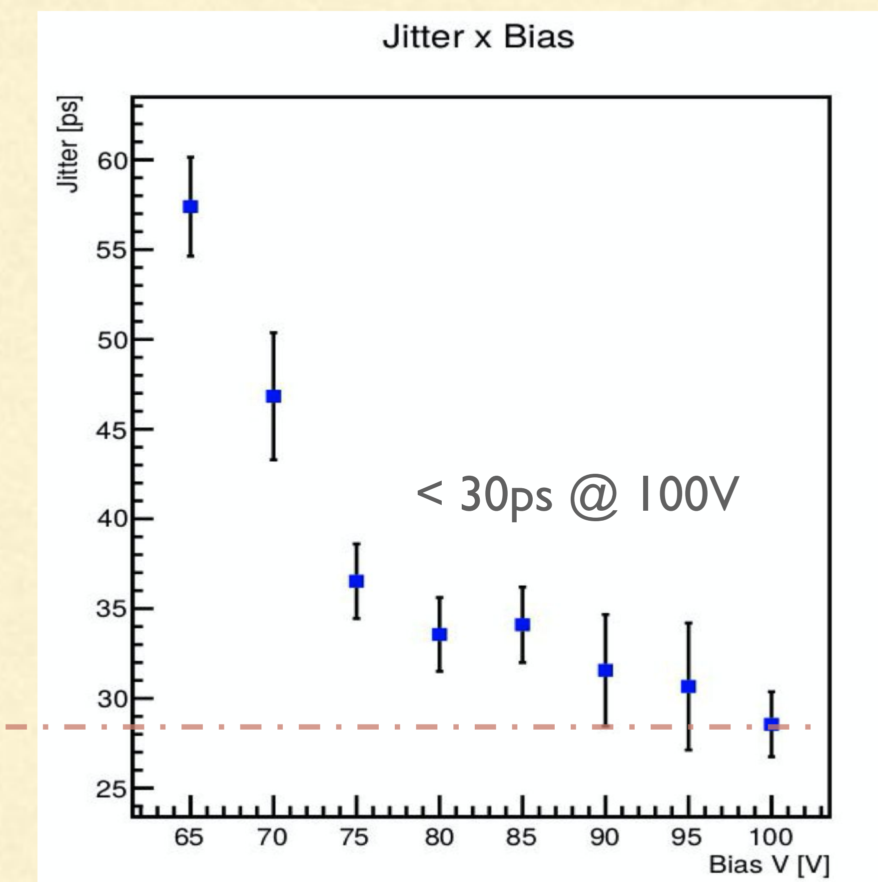
- Setup running @ USP, board designed @USP
- Bias @100V
- Total "**Dark**" Current measured on the board @100V : 145nA
- 1st stage amplification noise : 290uV rms (@ 2 GHz BW scope)
- Test signal : 250mV step (900ps rise time) into 0.5 pF injector cap
- Test temperature = 22°C



Area for cold finger contact

I2C temp sensor (SI7051, ±0.1°C)

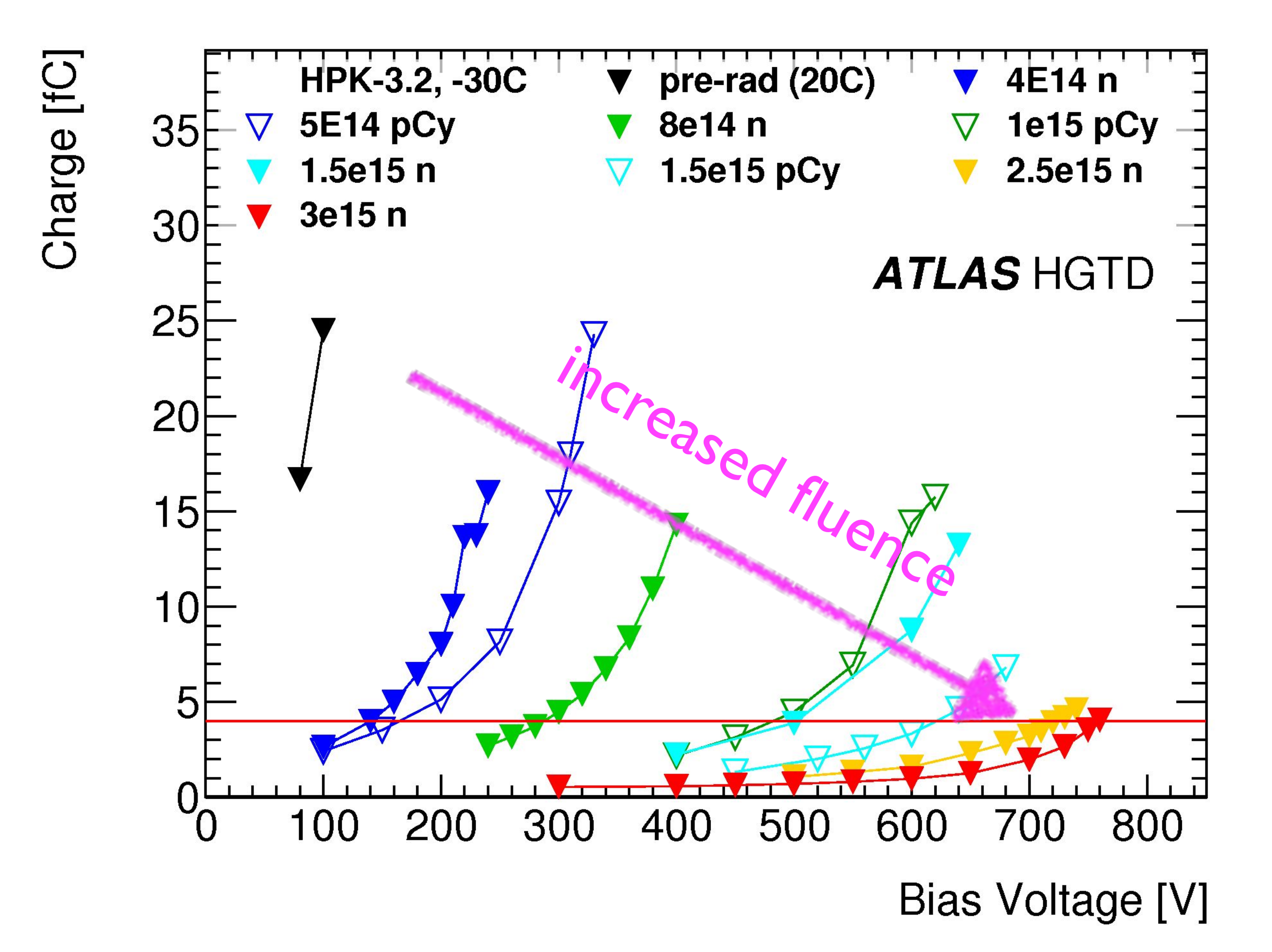
^{90}Sr (β)1st stage sensor response



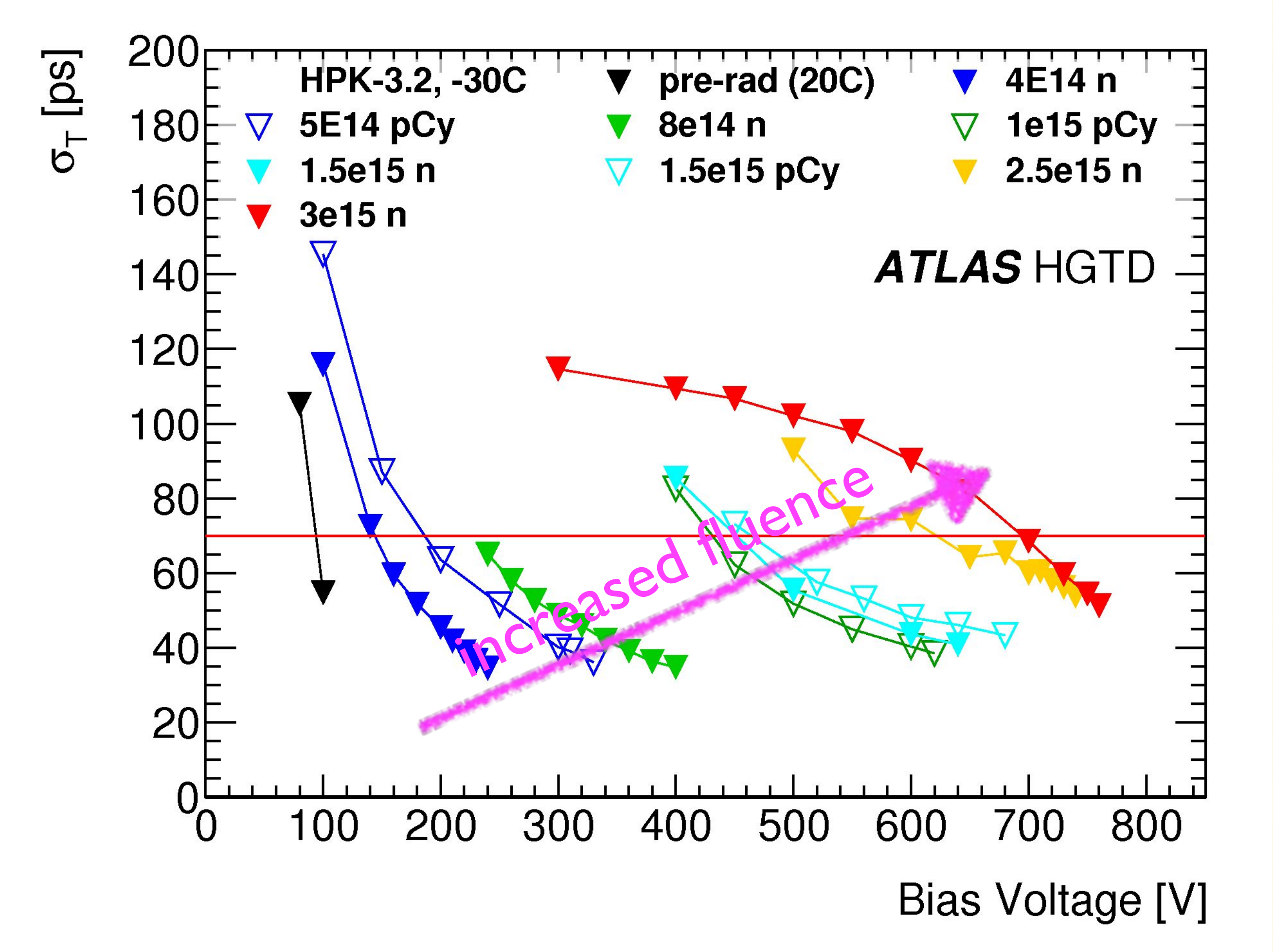
RADIATION EFFECT ON DETECTOR PERFORMANCE

- Very harsh conditions at high luminosity and forward region
- Neutrons de-activates charge acceptors in the gain layer, TID increases the dark current
- Up to certain point, compensated by increasing the bias voltage
- Complex process, can be ameliorated with changes in geometry or addition of Carbon
- For the very forward region, replacement of the sensors during midle-life is the best approach to maintain the system performance throughout the HL-LHC lifetime

Produced charge



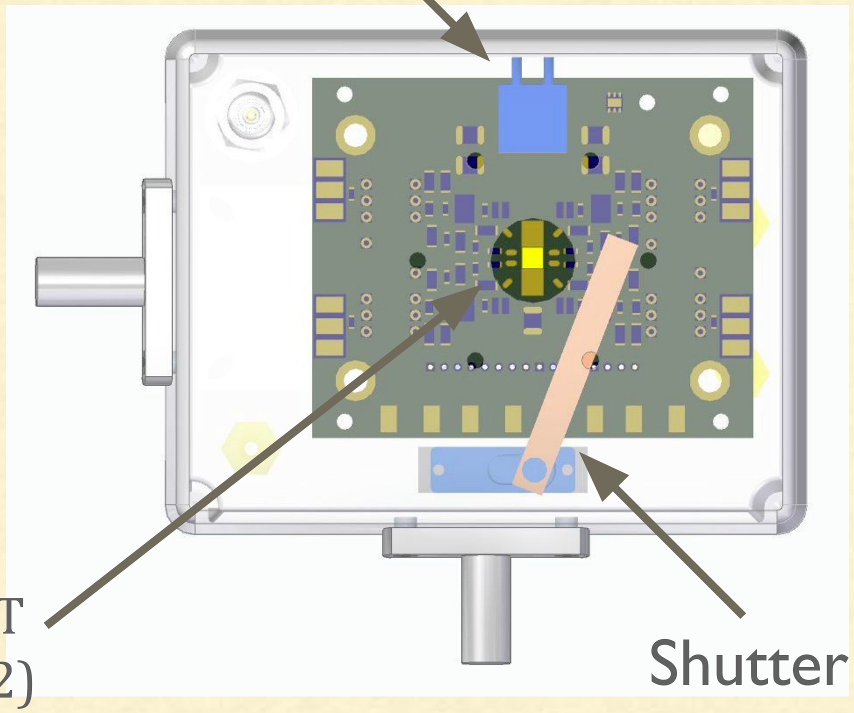
Timing resolution



SETUP FOR RADIATION TESTS @FEI (TID)

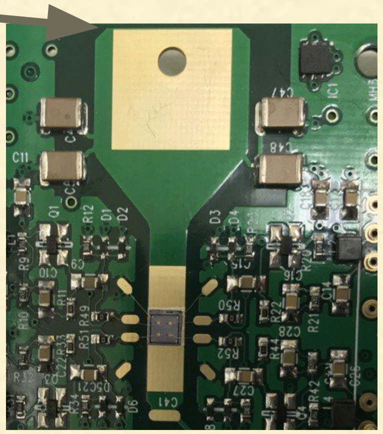
- X-Ray generator (high dose - can get very close to the tube window)
- Sensor cooled to -20oC (liquid/air cooling)
- Sealed chambers N2 filled to avoid condensation
- Dynamic measurements during irradiation (IV, CV, Gain, Timing)
- Waiting for assembly… ( )

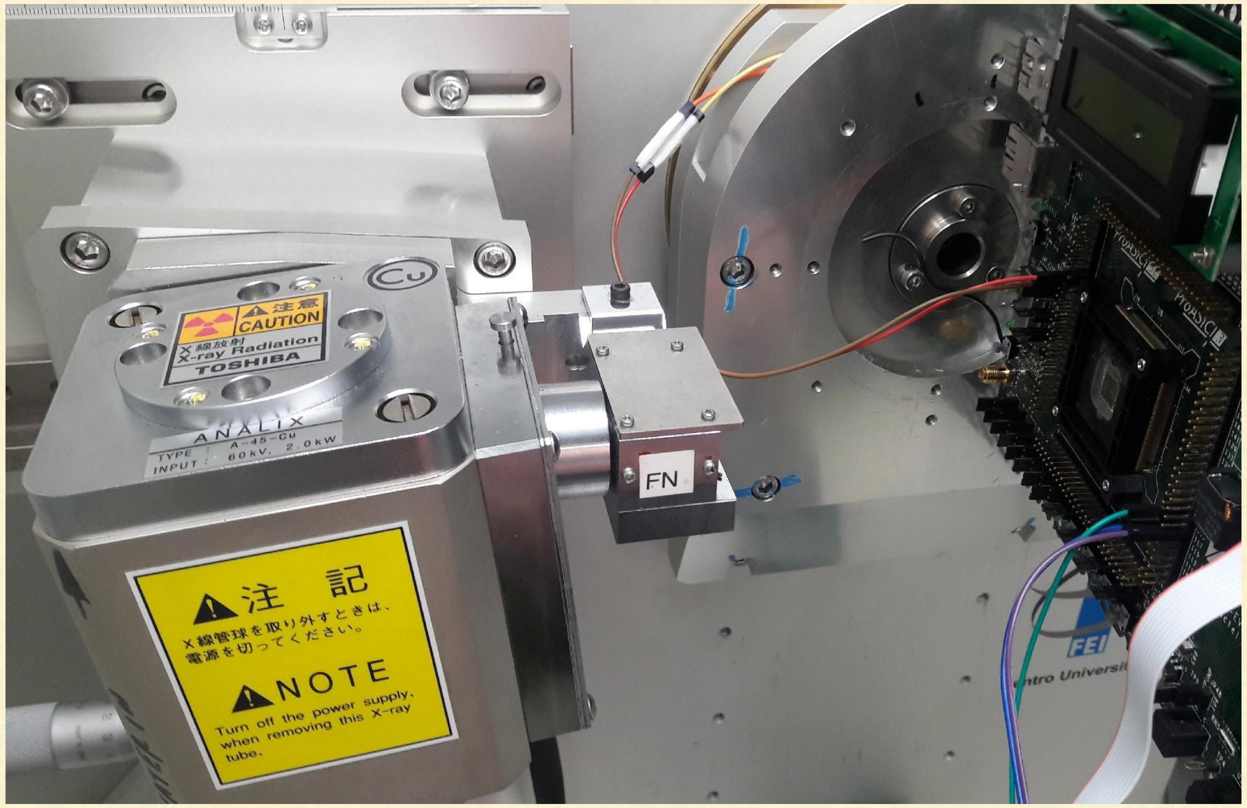
Refrigeration block



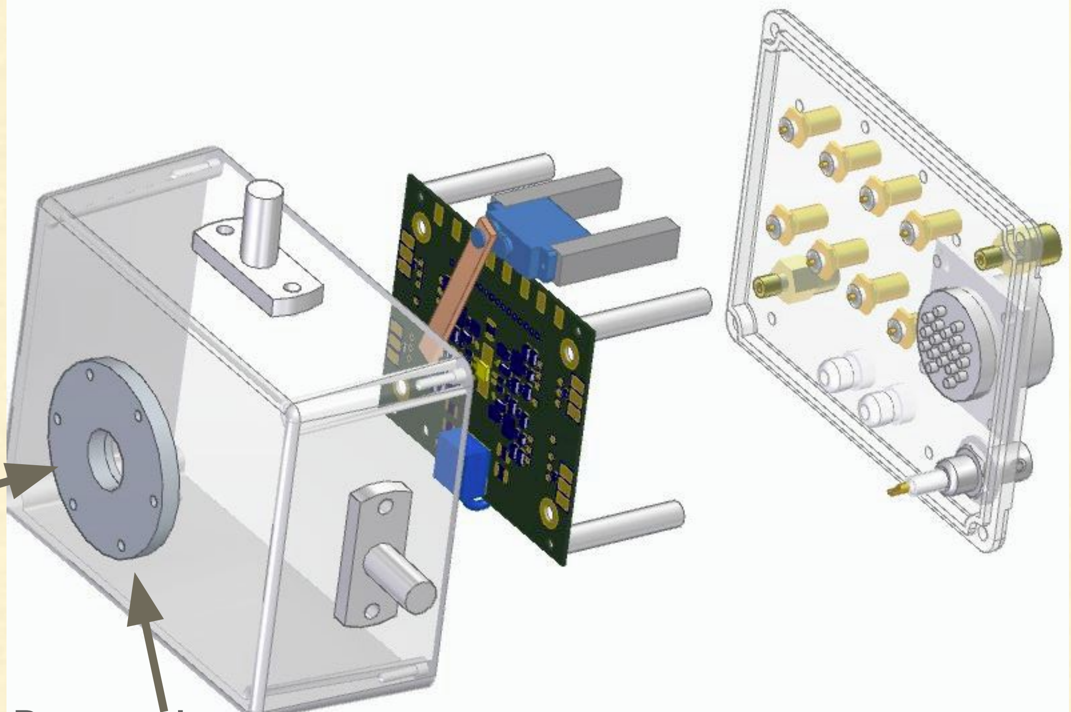
DUT (2x2)

Shutter





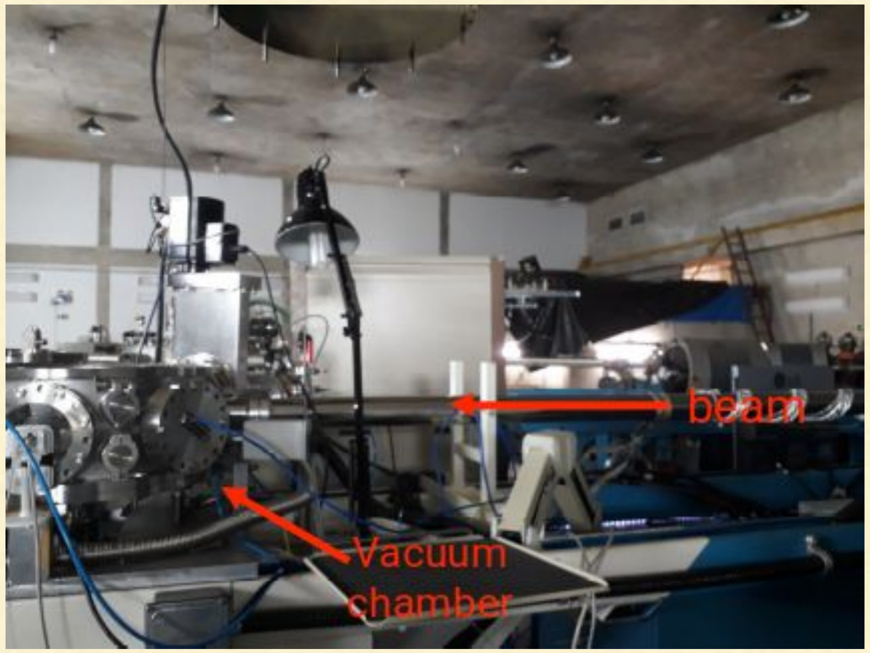
X-Rays

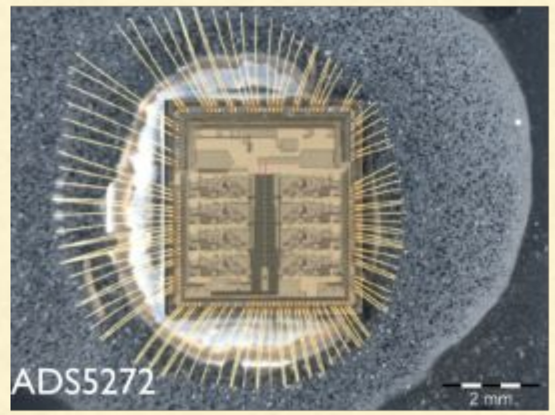


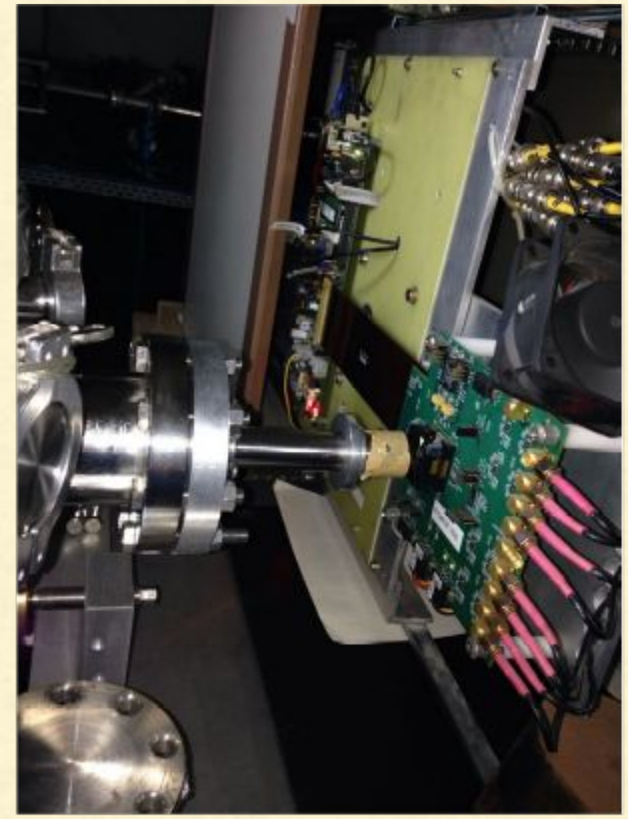
Be window

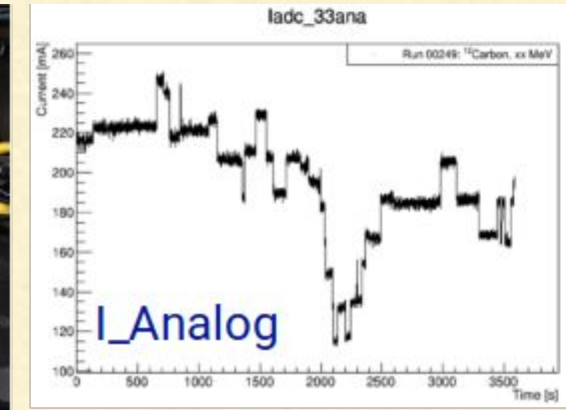
IRRADIATION FACILITIES IN SÃO PAULO

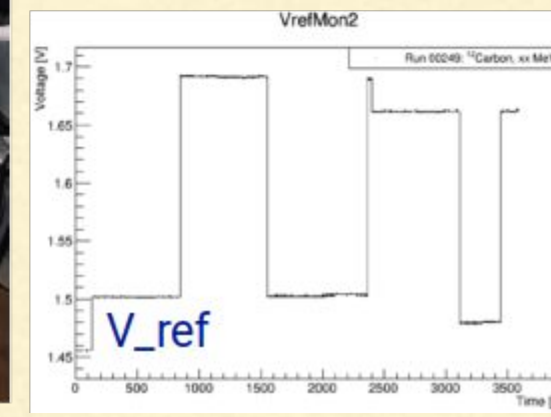
- On site Pelletron accelerator: protons (14 MeV) to Ag (110MeV)
- Allows testing the device while being irradiated



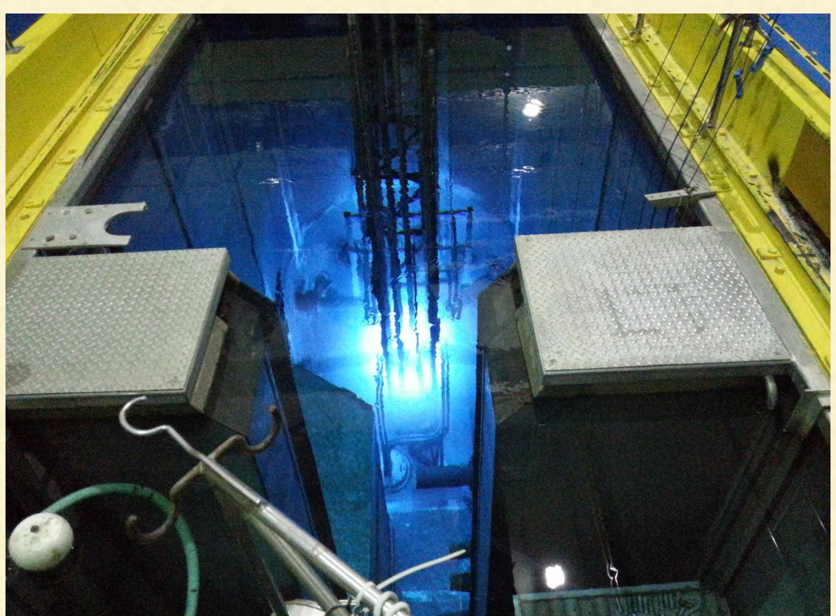






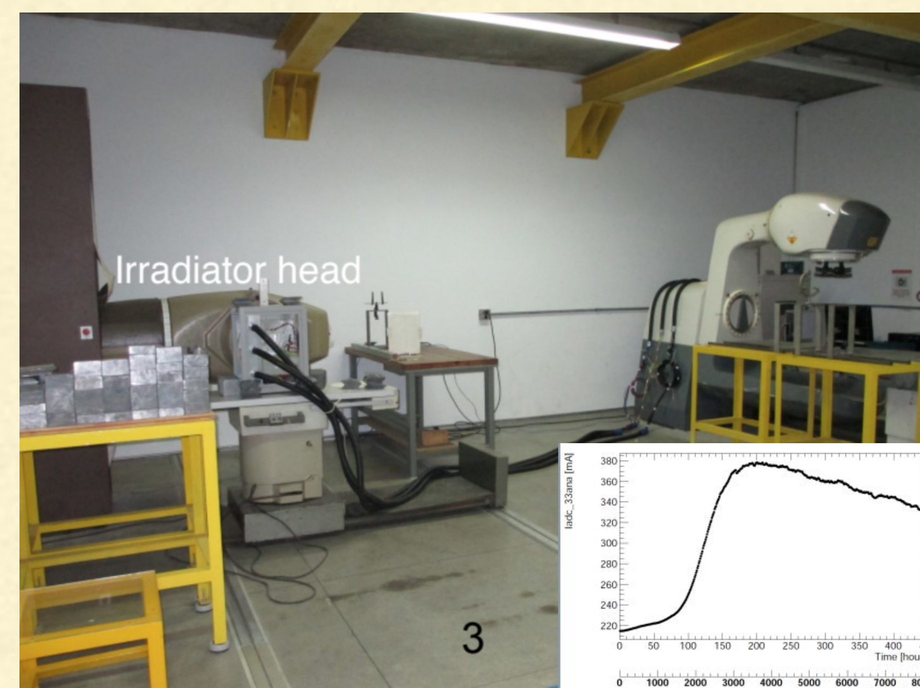


- On site 5 MW research reactor
- $\sim 10^{12}$ n_{eq}/cm^2s (up to 10^{13} near the core)

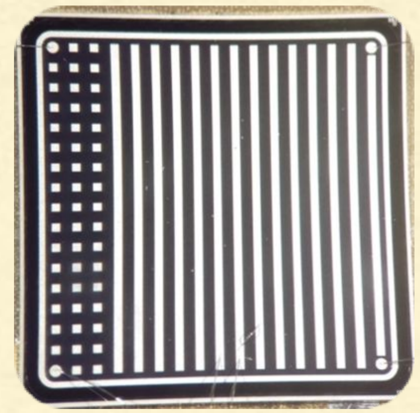


- On site 1 MCu industrial ^{60}Co irradiator

- Off site ^{60}Co source
- ~36 Gy/h collimated
- Device can be tested while irradiated



THE BEYOND :



LGADS FOR LOW ENERGY X-RAY DETECTION

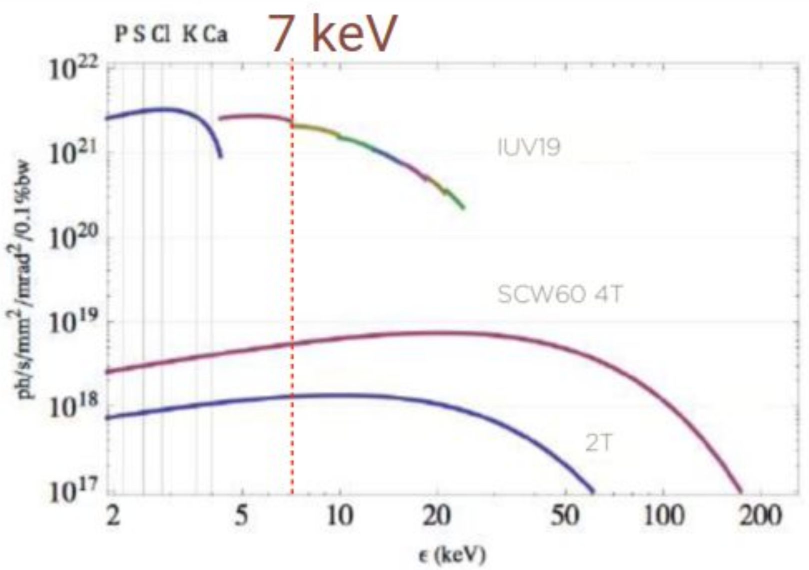
- *Giving the knowledge acquired in HEP by the group …*
- *Giving the significant infrastructure available at the Universities ...*
- *Giving that LGAD design is rather simple…*
- *What level of design/fabrication/qualification can we achieve in :*
    - *simulation*
    - *masks*
    - *implantation*
    - *fabrication*
    - *assembly*
    - *testing (including irradiation)*
    - *readout system*
- *How can we better explore the unprecedented timing and radiation hard characteristics of LGADS for local low energy X-Ray detection (aiming for a full detector system)?*

→ *Towards a facility for semiconductor radiation detectors R&D*

- Low energy X-Rays detection
- Internal gain allows detection of X-Rays that deposit a charge that is too small for Si planar detectors (noise)

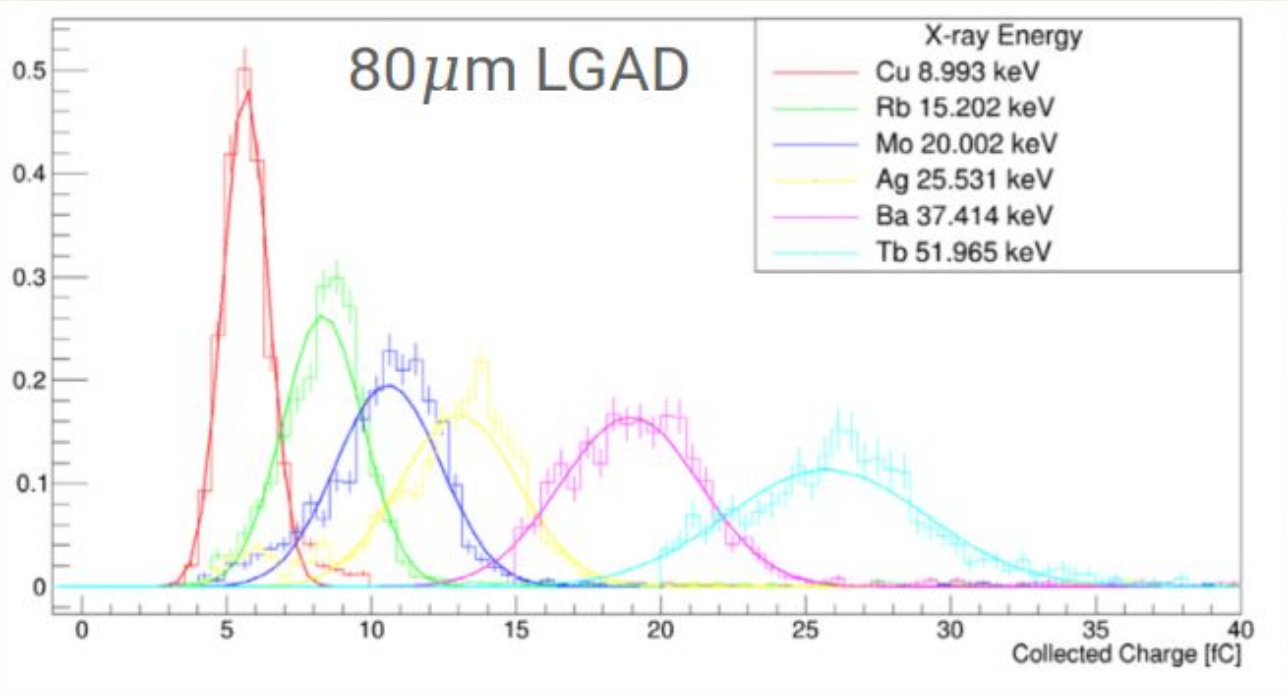
X-Ray absorption for several LGAD thicknesses

	2keV	5keV	7keV
50um	100%	94%	67%
100um	100%	100%	89%
300um	100%	100%	100%



Brilho das fontes de raios X do Sirius: IVU19: onduladores de raios X em vácuo, SCW60: wiggler de 4T e 2T: dipolos de 2 T. A posição das bordas K de absorção de elementos químicos importantes estão apresentadas no canto esquerdo superior da figura

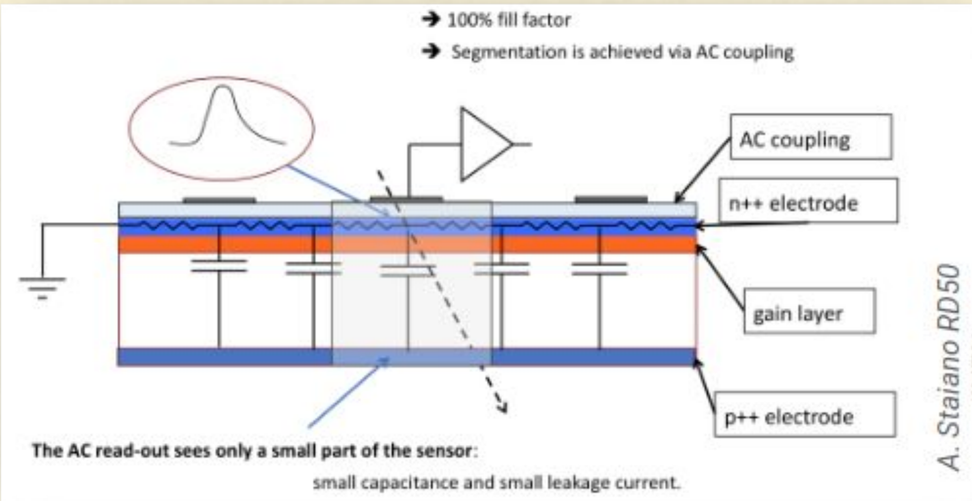
^{241}Am - Aversham variable X-Ray source

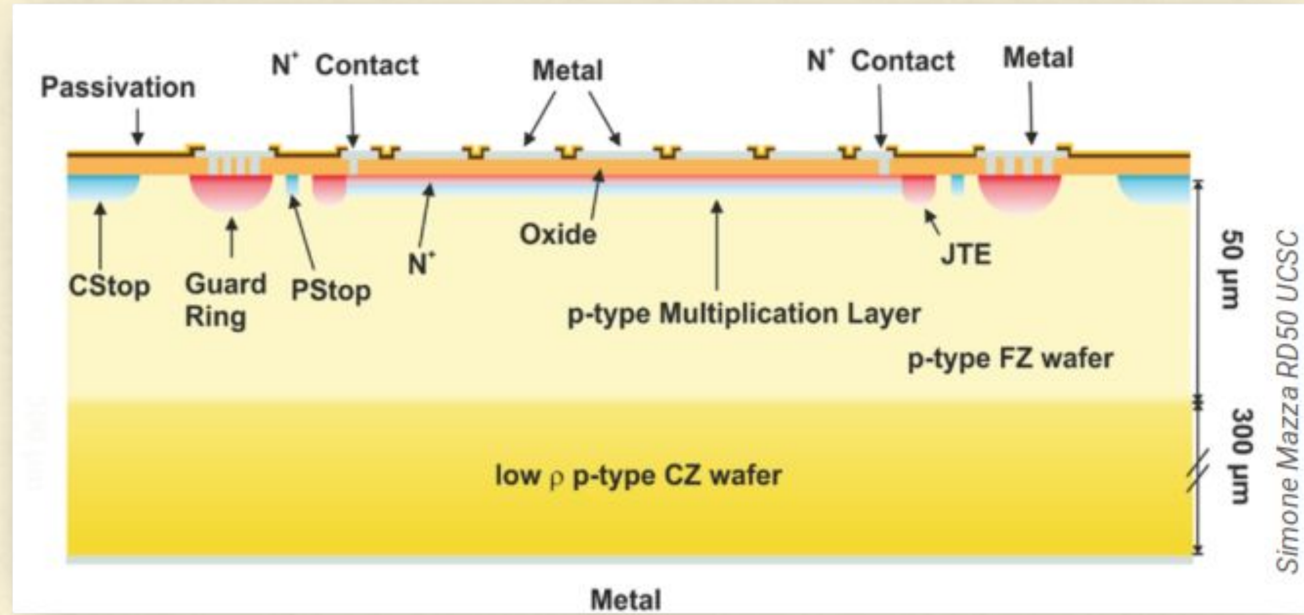


Hartmut Sadrozinski - UCSC

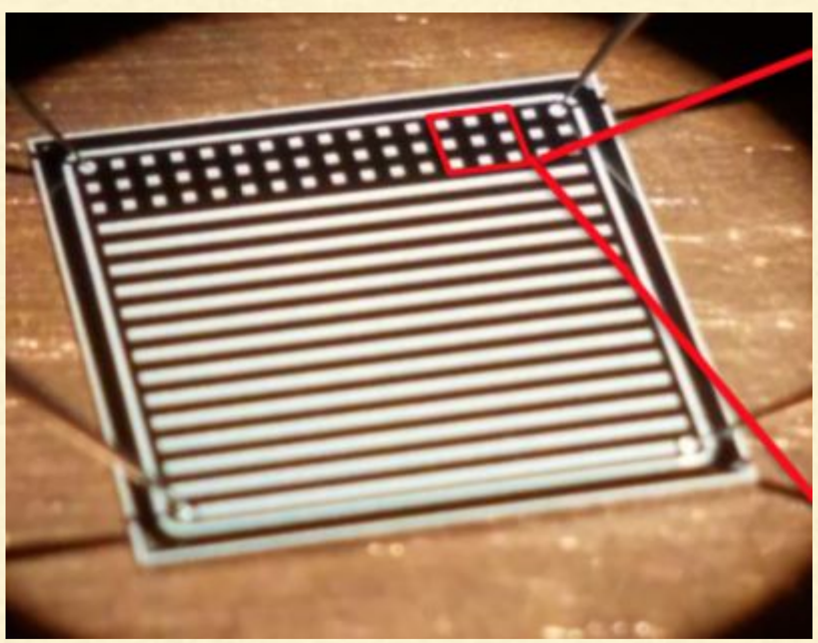
LGADS FOR X-RAY APPLICATIONS

- Geometry allows high segmentation in electrodes
- Segmentation in readout pads
- AC coupling through a continuous oxide layer above the multiplication layer





- Prototype of 8.4x8.4 mm2
- 14 strips (50μm width)
- 49 pixels (0.2x0.2 mm2, 0.5 mm gap)



H. Sadrozinski - UCSC

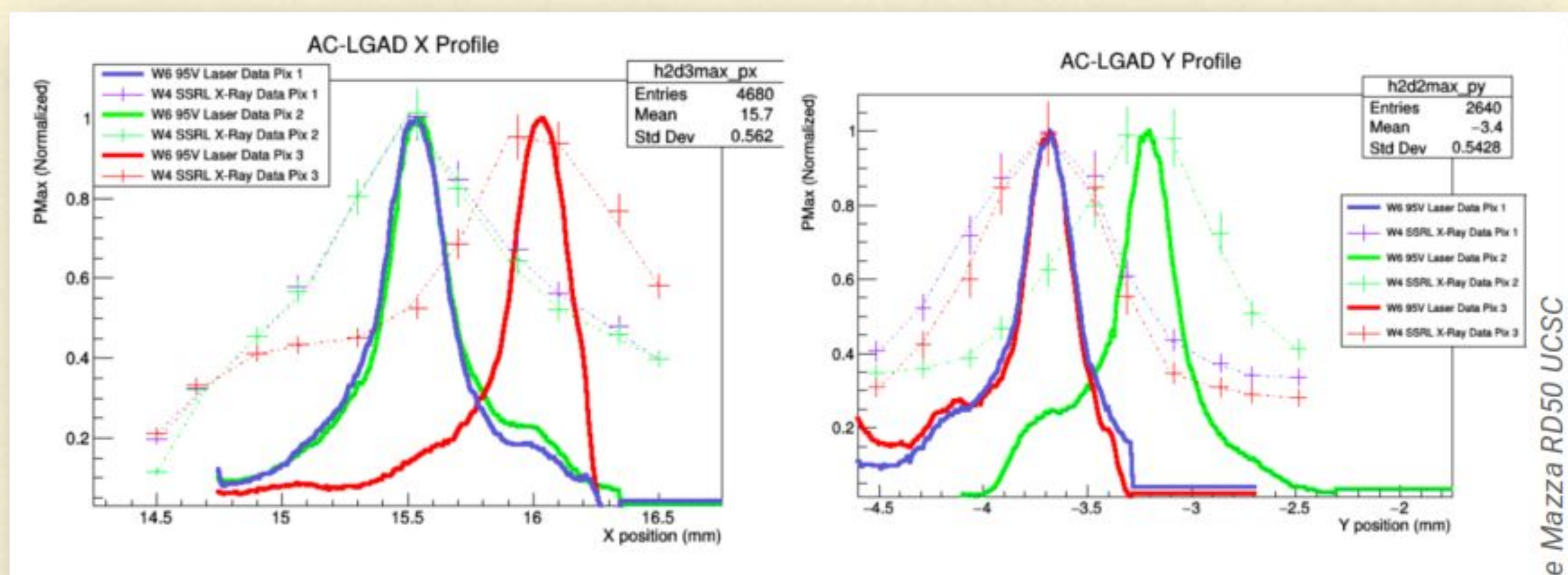
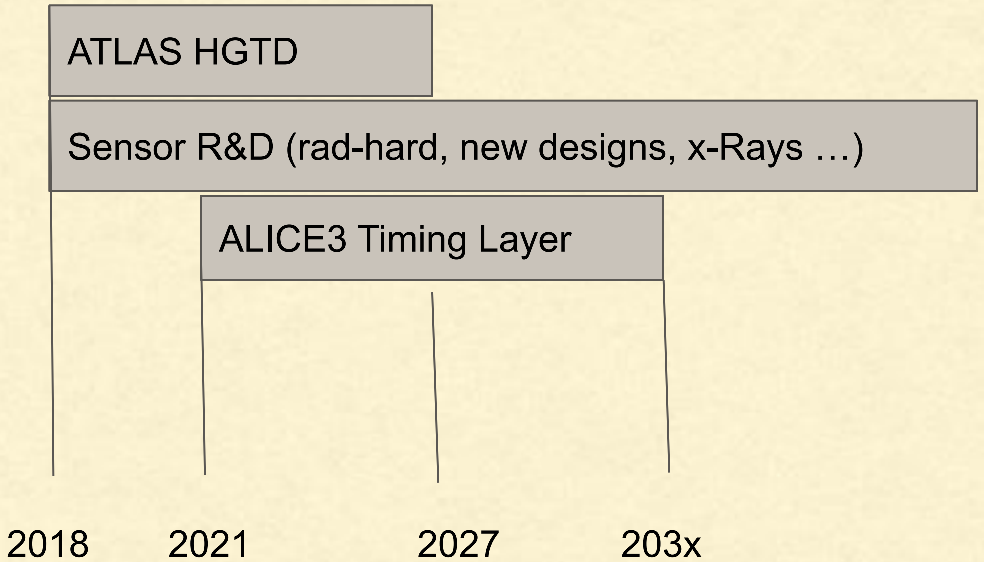


Fig. x: AC-LGAD Pulse height vs. x (left) and y (right) position, as measured by SCIPP's IR Laser (solid lines) and SSRL x-ray (dotted line).

FINAL REMARKS

- 4D tracking presents the best strategy for pileup mitigation @ HL-LHC experiments
- Needs state-of-the-art, radiation-hard ultrafast (ps) semiconductor detectors
- The group activities are currently focused on sensor testing and qualification preparation for ATLAS, soon to start irradiation with neutrons at IPEN reactor.
- New LGAD concepts allows fine pixelation; a very interesting solution for for very high intensity, low energy X-Ray applications. **This has already been discussed with the Sirius instrumentation group**.
- Very new technology with many opportunities for contribution :
  - Timing (low resolution …)



- Costs (variation expected)
  - Sensors, installation and electronics : ≈US$ 250k
  - Infrastructure for all local labs (HV, low T) : ≈US$ 450k (and beyond …)
  - Materials & services : ≈US$ 250k
  - Manpower & Mobility : TBD ...

Strategic R&D

Dez. 2018

3.1 Silicon Detectors (WP1)

Most future experiments will rely on silicon technology for tracking and vertexing. To address the main challenges outlined above, four activities are foreseen.

- Development of **hybrid pixel sensors** with advanced features to be combined with high performance readout ASICs. These developments target small pixels, high-resolution timing and high-rate applications and comprise studies of various planar and LGAD sensor designs, as well as an ASIC development for very high speed and fine timing.

BACKUP

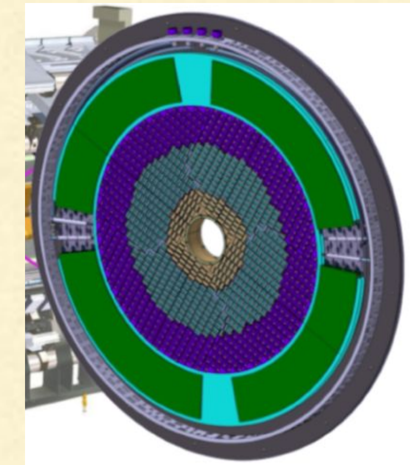
HGTD PARAMETERS

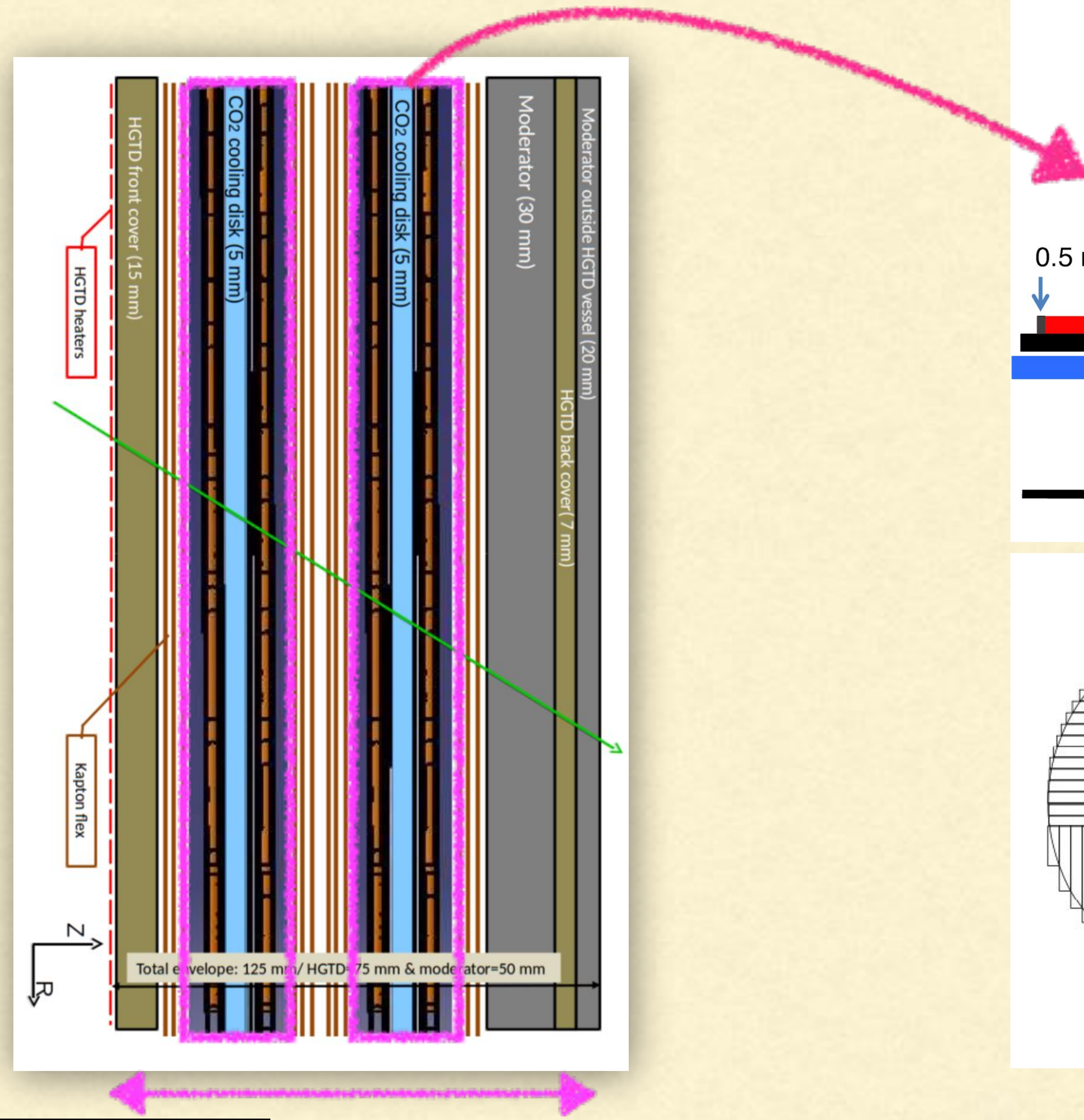
Pseudorapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	$3435 \text{ mm} < z < 3485 \text{ mm}$
Radial extension:	
Total	$110 \text{ mm} < R < 1000 \text{ mm}$
Active area	$120 \text{ mm} < R < 640 \text{ mm}$
Time resolution per track	30 ps
Number of hits per track:	
$2.4 < \|\eta\| < 3.1$	2
$3.1 < \|\eta\| < 4.0$	3
Pixel size	$1.3 \times 1.3 \text{ mm}^2$
Number of channels	3.54M
Active area	6.3 m^2

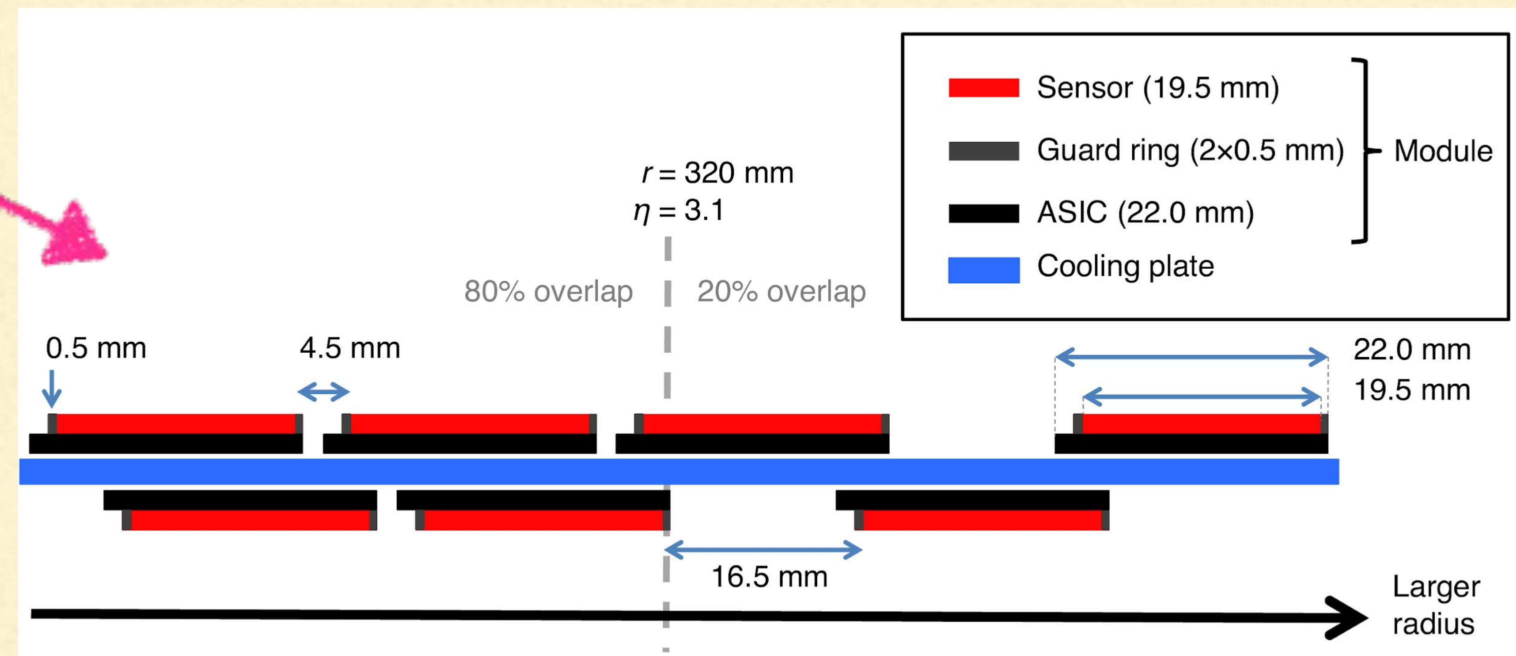
Table 2.1: Main parameters of the HGTD.

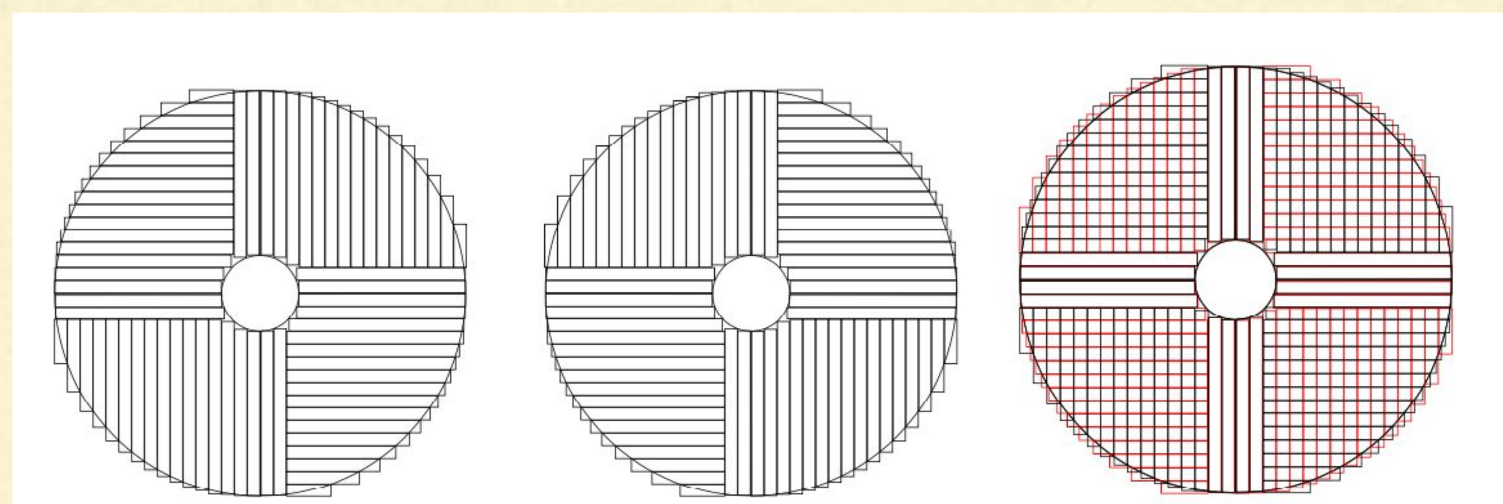
ATLAS HIGH GRANULARITY TIMING DETECTOR - HGTD

- Silicon based sensors of 1.3x1.3mm2 in active area
- Grouped in a matrix of 30x15 sensors (40x20mm2)
- 2 double layered disks (6m^2 silicon)
- sensors variable overlap (larger in the internal region)
- Separate in 3 rings that can be replaced to preserve the performance after irradiation
- Coolled to -30 C









(a) First cooling disk

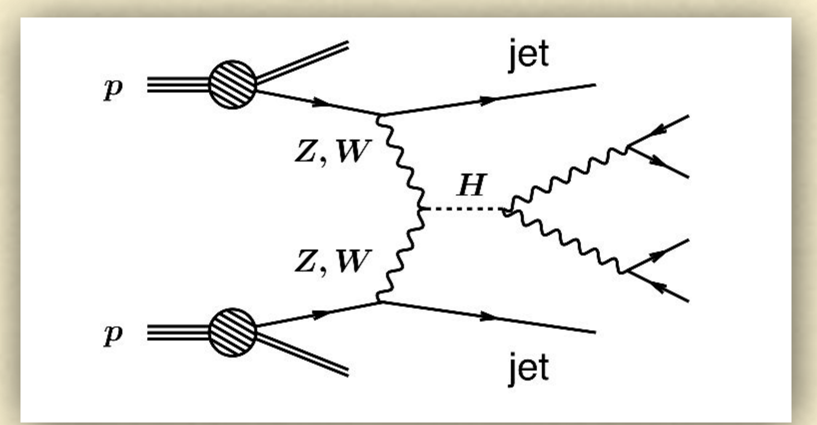
(b) Second cooling disk

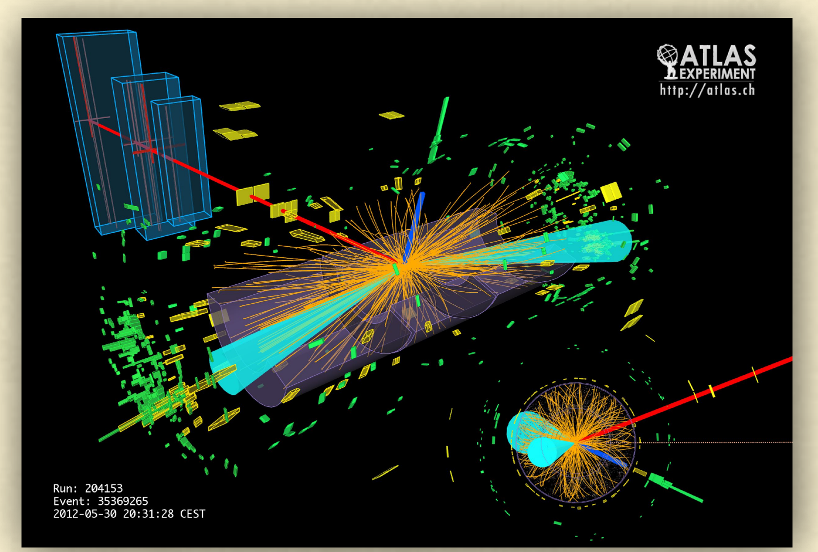
(c) Overlay

PHYSICS IMPACT OF HGTD

(I)

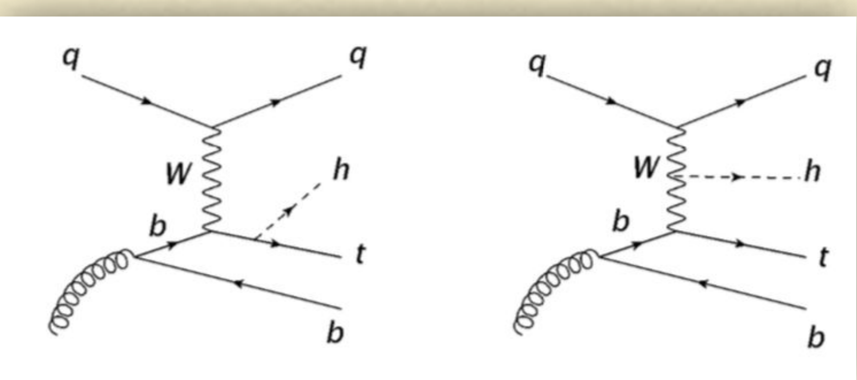
- **Vector Boson Fusion (VBF)**
  - VBF: 2 forward jets, bosons reconstructed in the central region
  - H → WW*
- HL-LHC enters the era of precision measurements in the Higgs sector

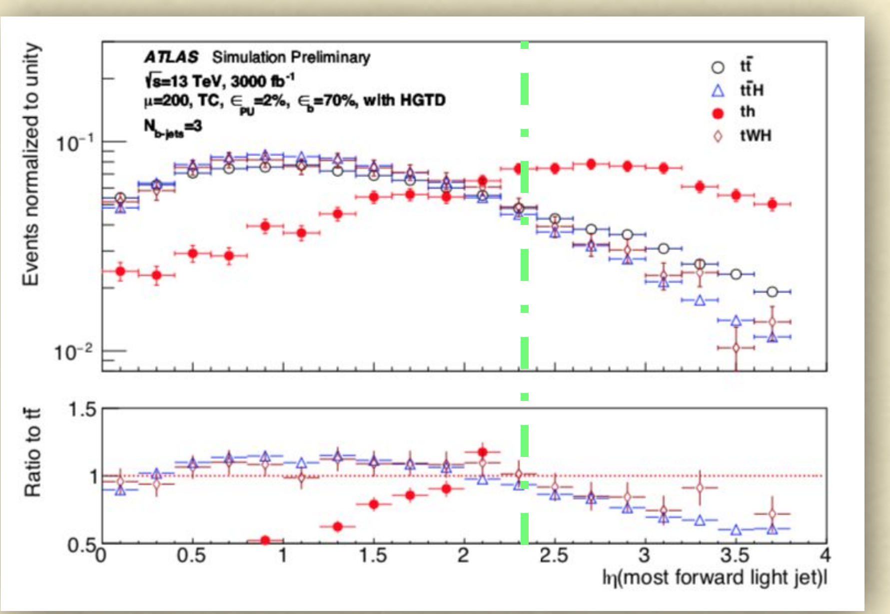




(II)

- **Yukawa coupling top - Higgs**
  - tH → bbar
  - Signature: 1 lepton and 4 ou 5 jets (2 b-tagged)
  - One of the jets |η|>2.4





(III)

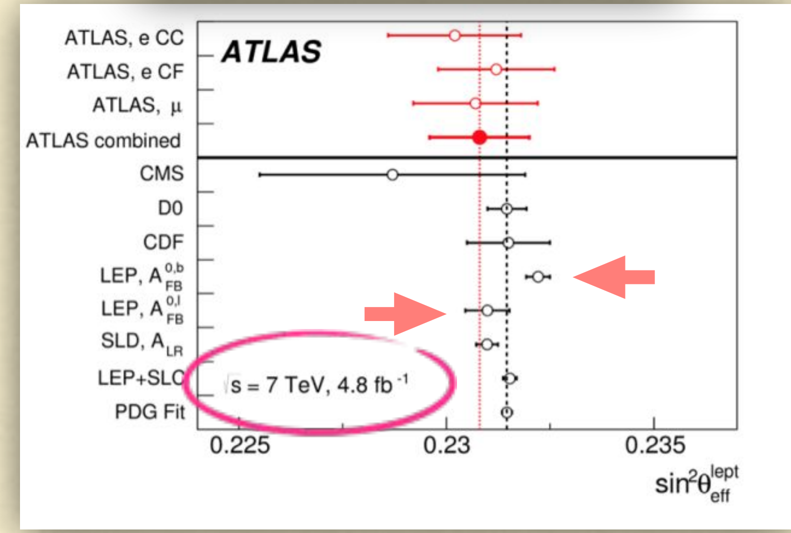
- **Weak mixing angle ($\sin^2\theta$) meas.**
  - asymmetry in angular distribution of l^+ and l^- from Z decay (forward/backward assymetry)
  - leptons are classified in CC, CF, FF (C→ central → |η|<2.4, F →2.5<|η|< 4.2)
  - the 2 most precise measurements differs 3 σ

$$\cos\theta^*_{CS} = \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m_{\ell\ell}\sqrt{m_{\ell\ell}^2 + p_{T,\ell\ell}^2}}$$

$$cos\theta^*_{CS} \geq 0 \rightarrow \text{Forward}$$
$$cos\theta^*_{CS} < 0 \rightarrow \text{Backward}$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B},$$

$$A_{FB} = \frac{N_{\cos\theta^*_{CS}\geq 0} - N_{\cos\theta^*_{CS}<0}}{N_{\cos\theta^*_{CS}\geq 0} + N_{\cos\theta^*_{CS}<0}}.$$

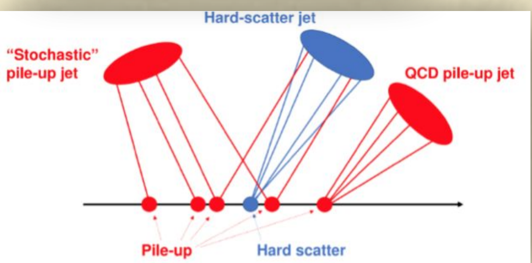


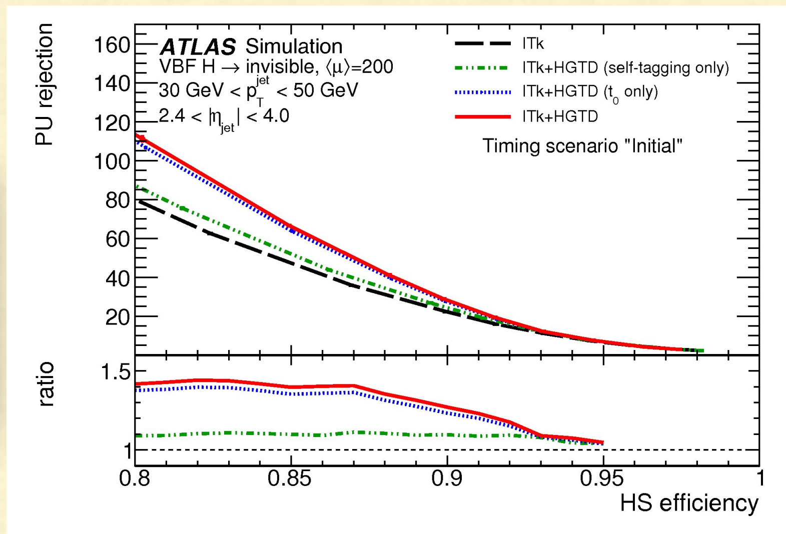
HGTD IMPACT ON PERFORMANCE OBJECTS

Pileup jet suppression

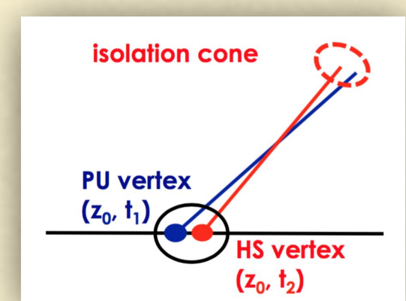
$$R_{p_T} = \frac{\Sigma p_T^{trk}(PV_0)}{p_T^{jet}}.$$

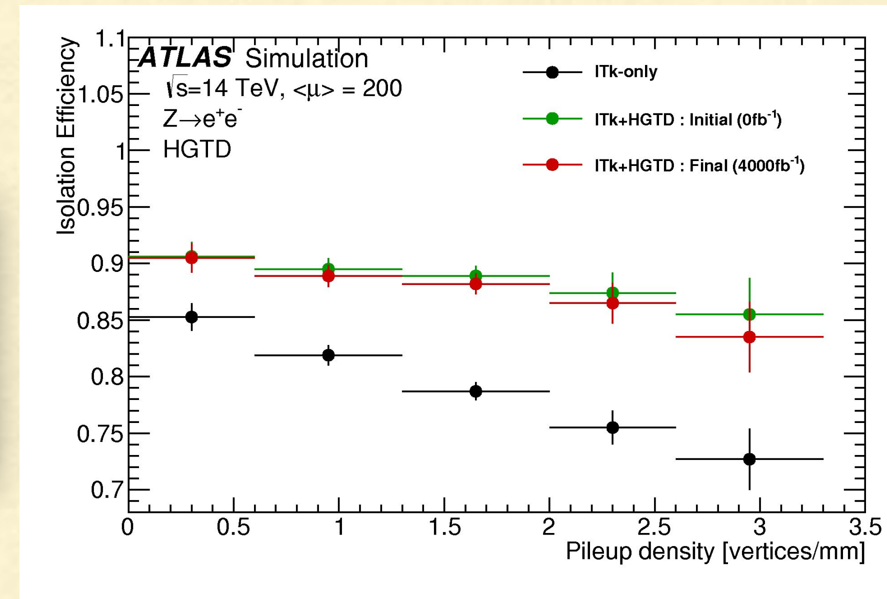
Rpt very powerful discriminant, but requires rigorous track-vertex association



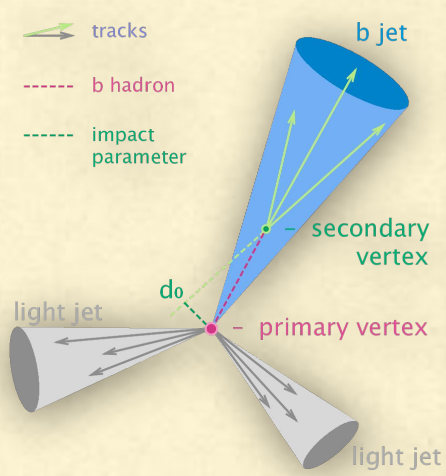


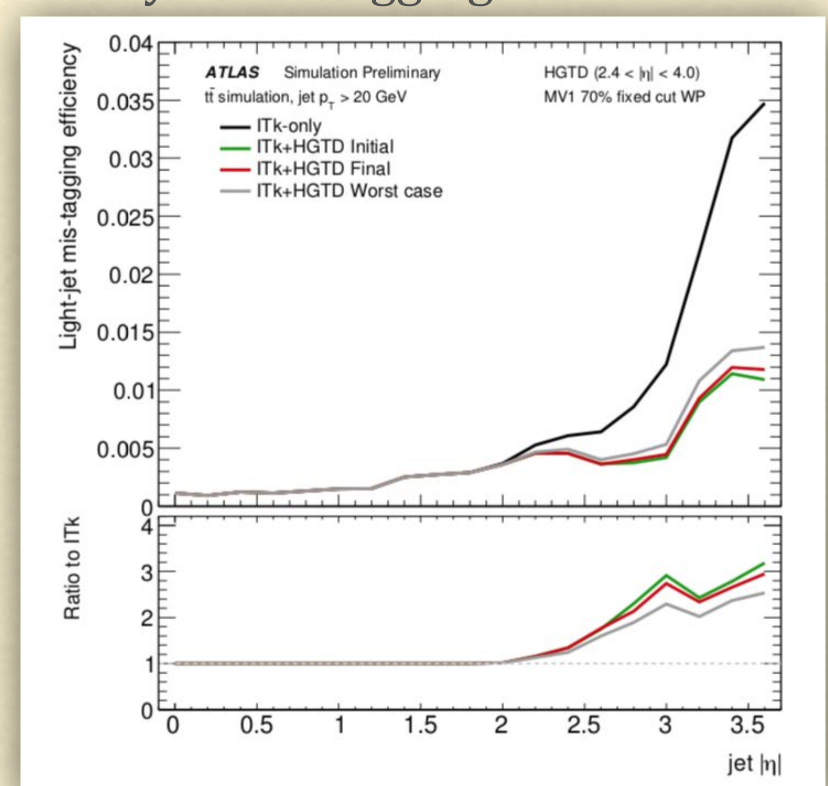
Leptonic isolation



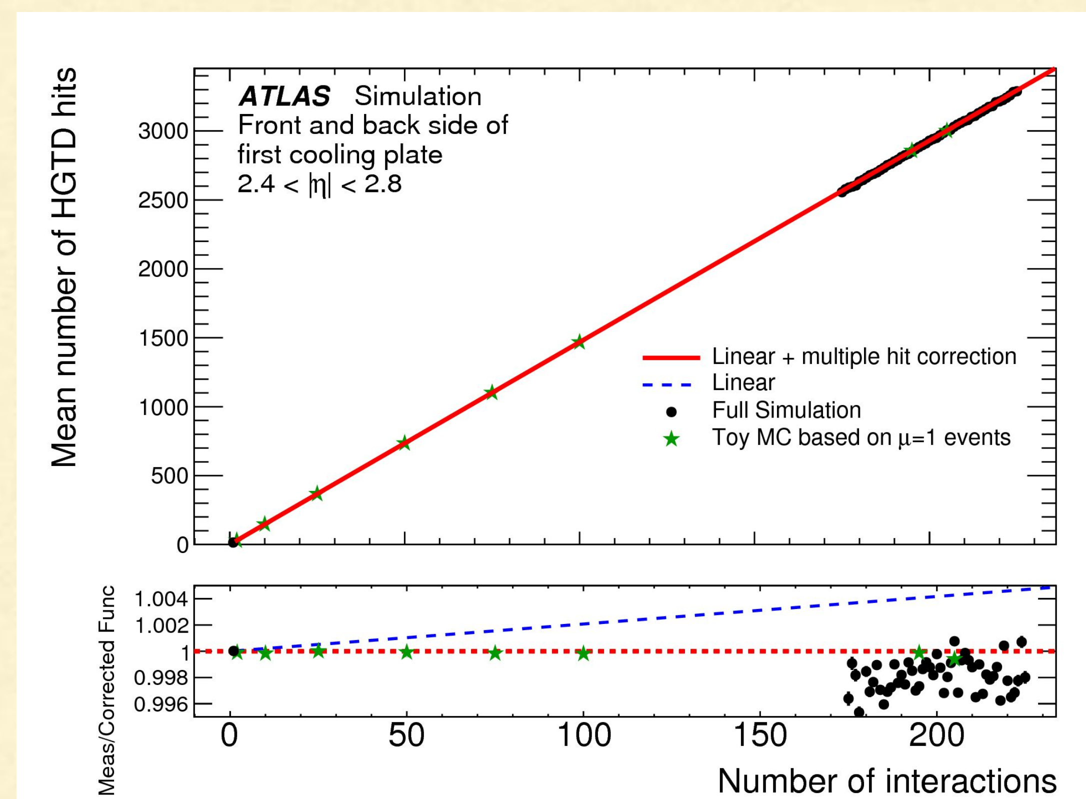


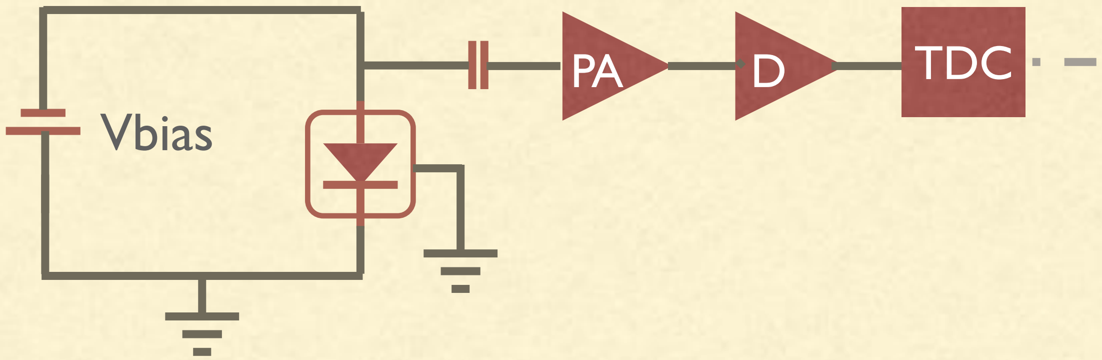
Heavy flavor tagging

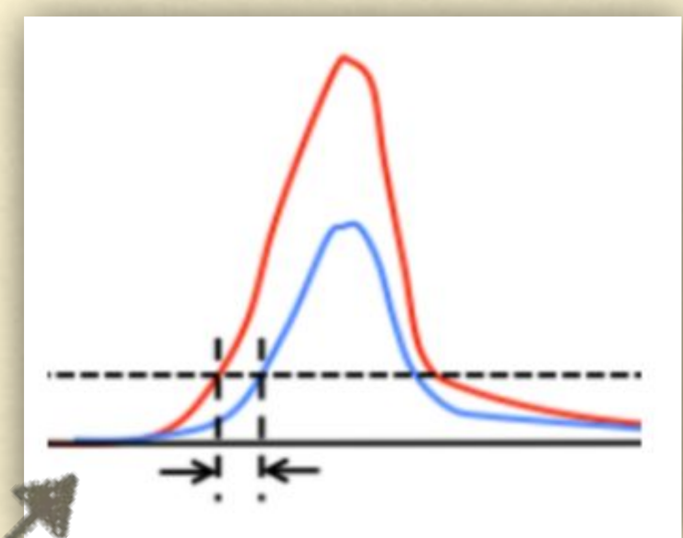


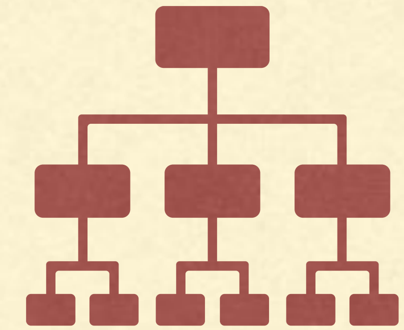


Instantaneous luminosity measurements (per BCID)



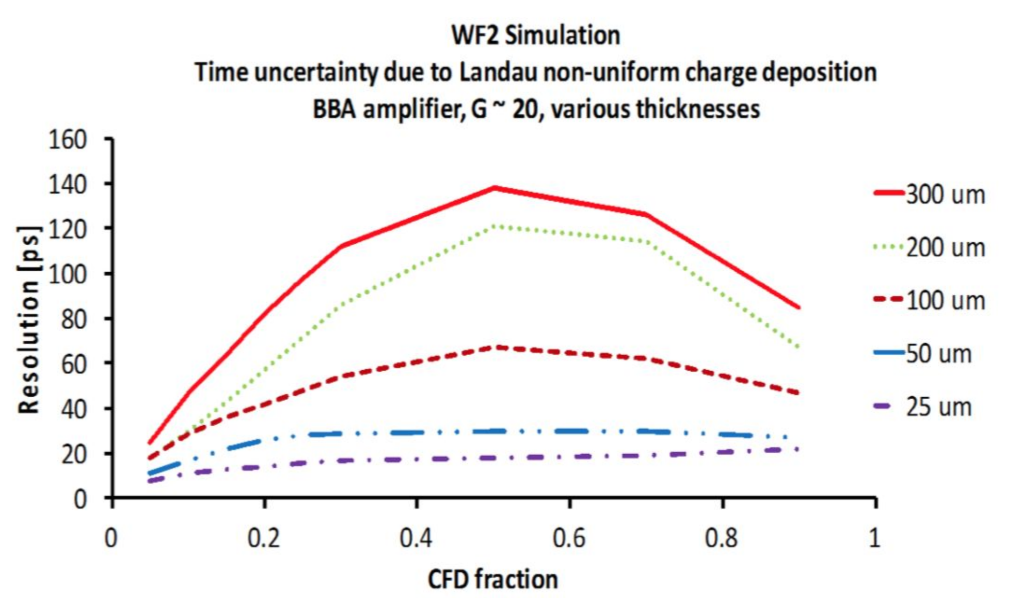






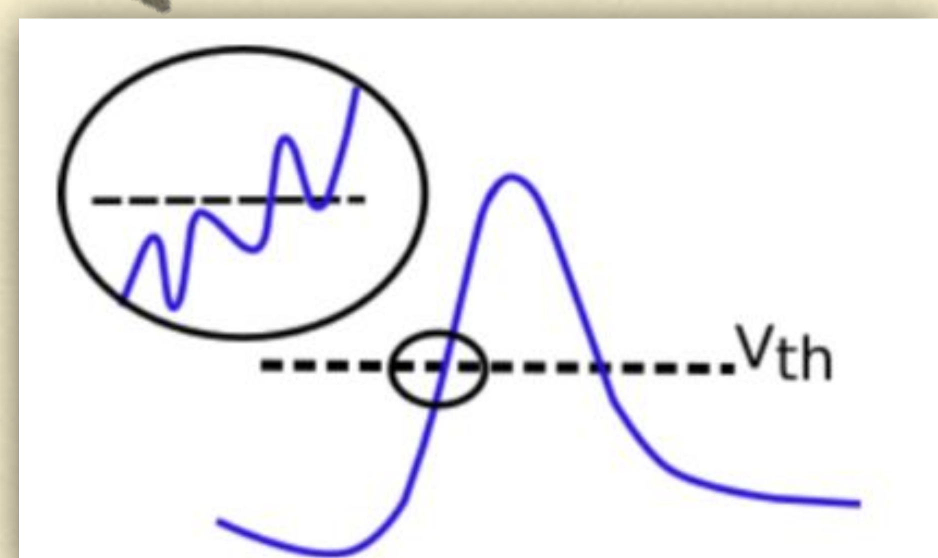
Total Timing Resolution:

$$\sigma_T^2 = \sigma_L^2 + \sigma_{TW}^2 + \sigma_{jitter}^2 + \sigma_{clock}^2$$



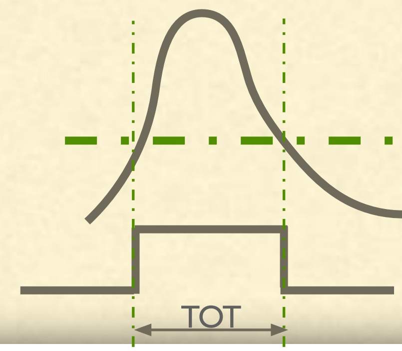
Contributions of Landau fluctuations to the time resolution as a function of the Constant Fraction Discriminator value for different detector thicknesses. Based on simulations.

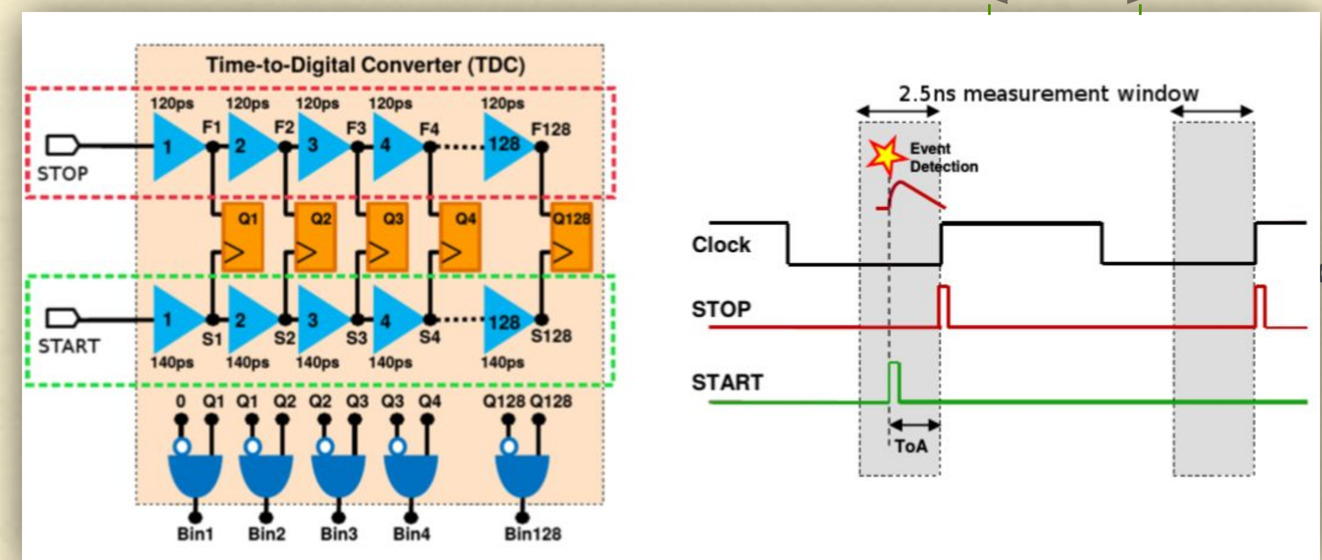
H. Sadrozkinsk



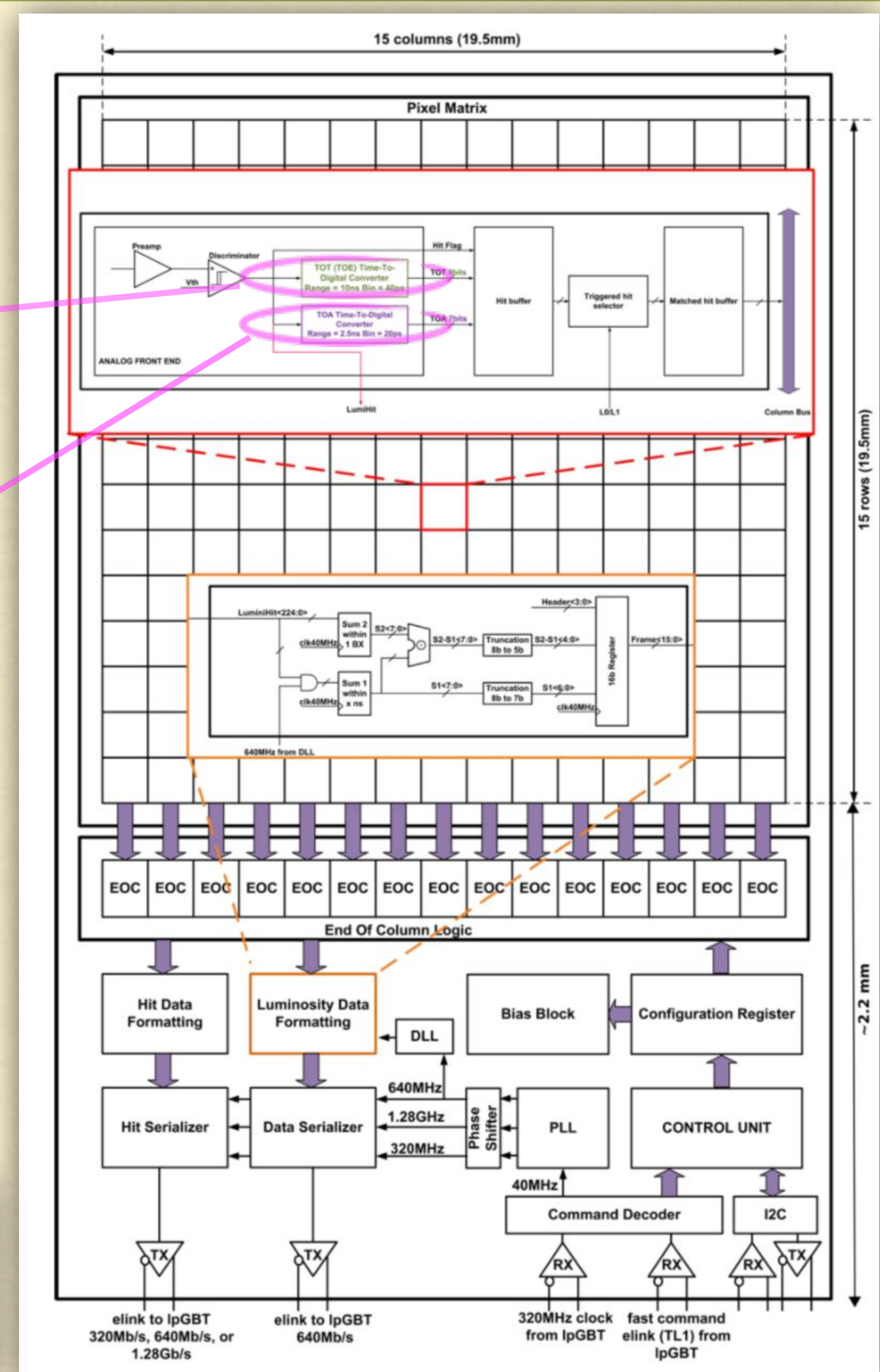
FRONT END ELECTRONICS

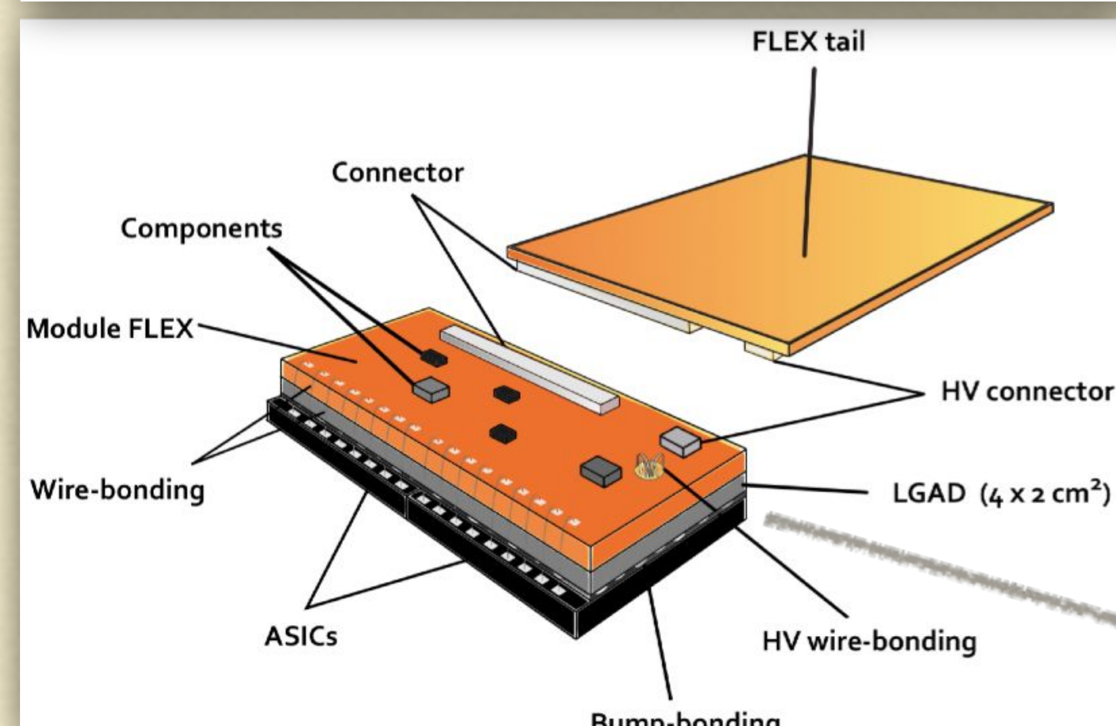
Front End

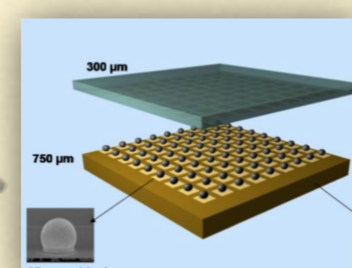




correction)





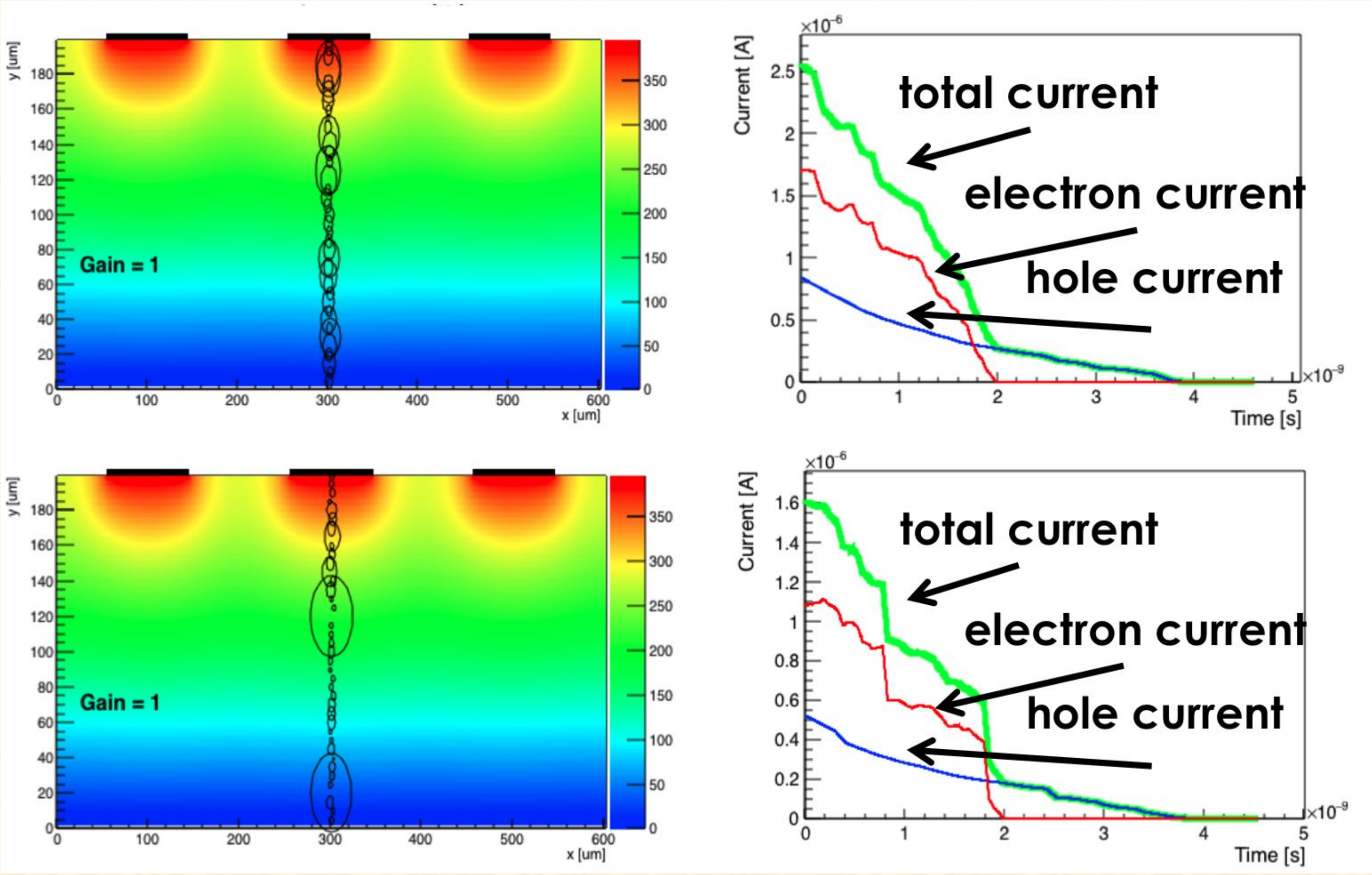


SENSOR SIMULATION

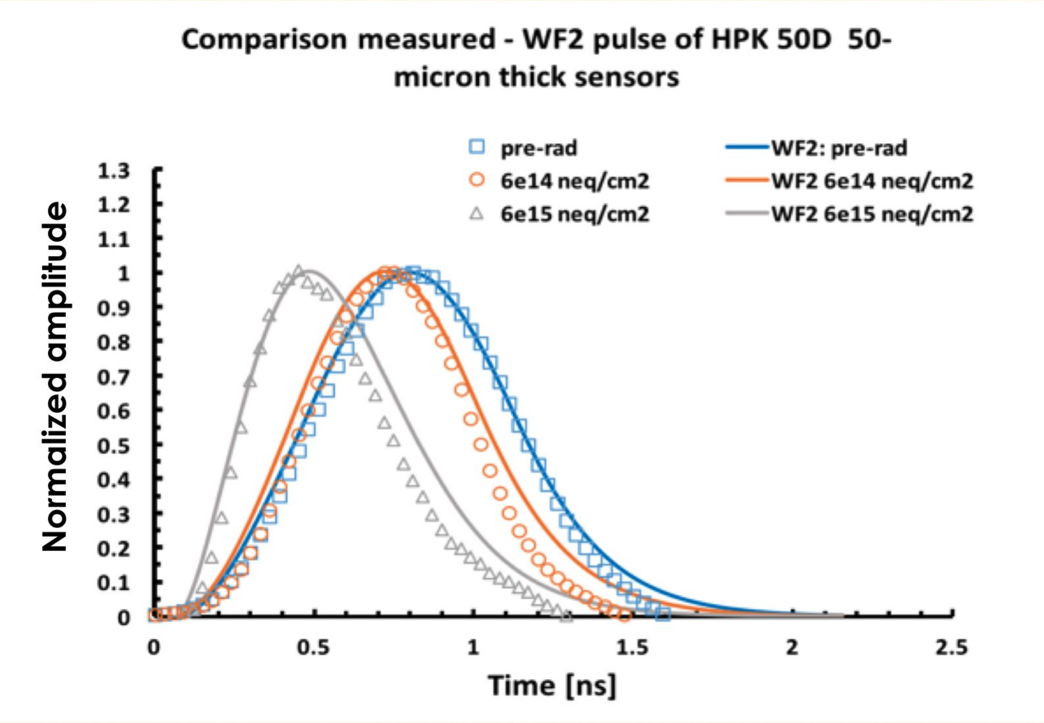
WeghtField2

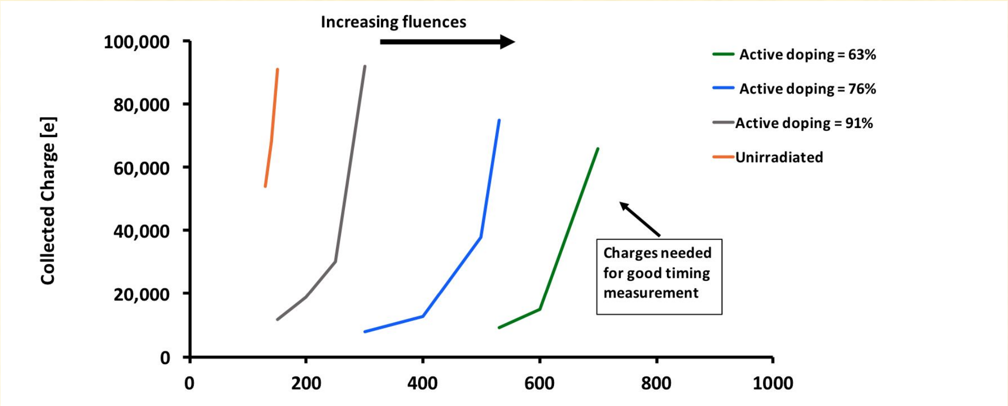
http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html

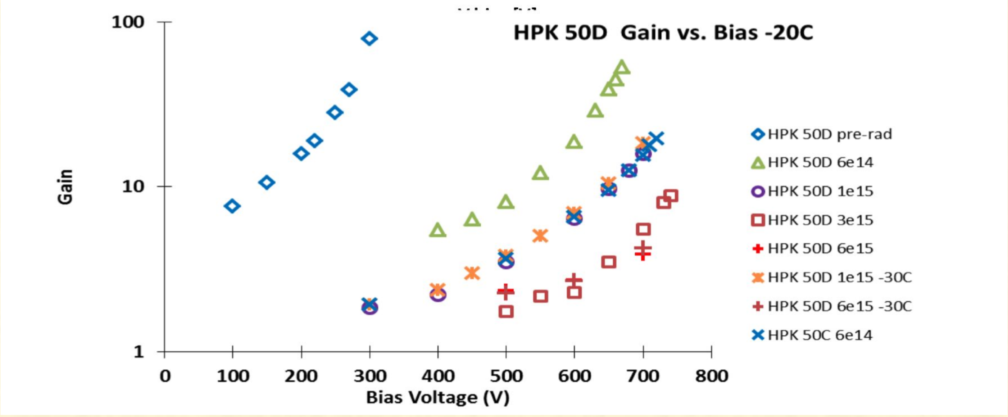
- Allow for sensor response evaluation
- Geometry
- Bias Voltage
- Diferent topping profiles
- Can simulate passage of charged particles
- Response of electronics
- Radiation effects



N. Cartiglia - Picosecond Workshop 2018

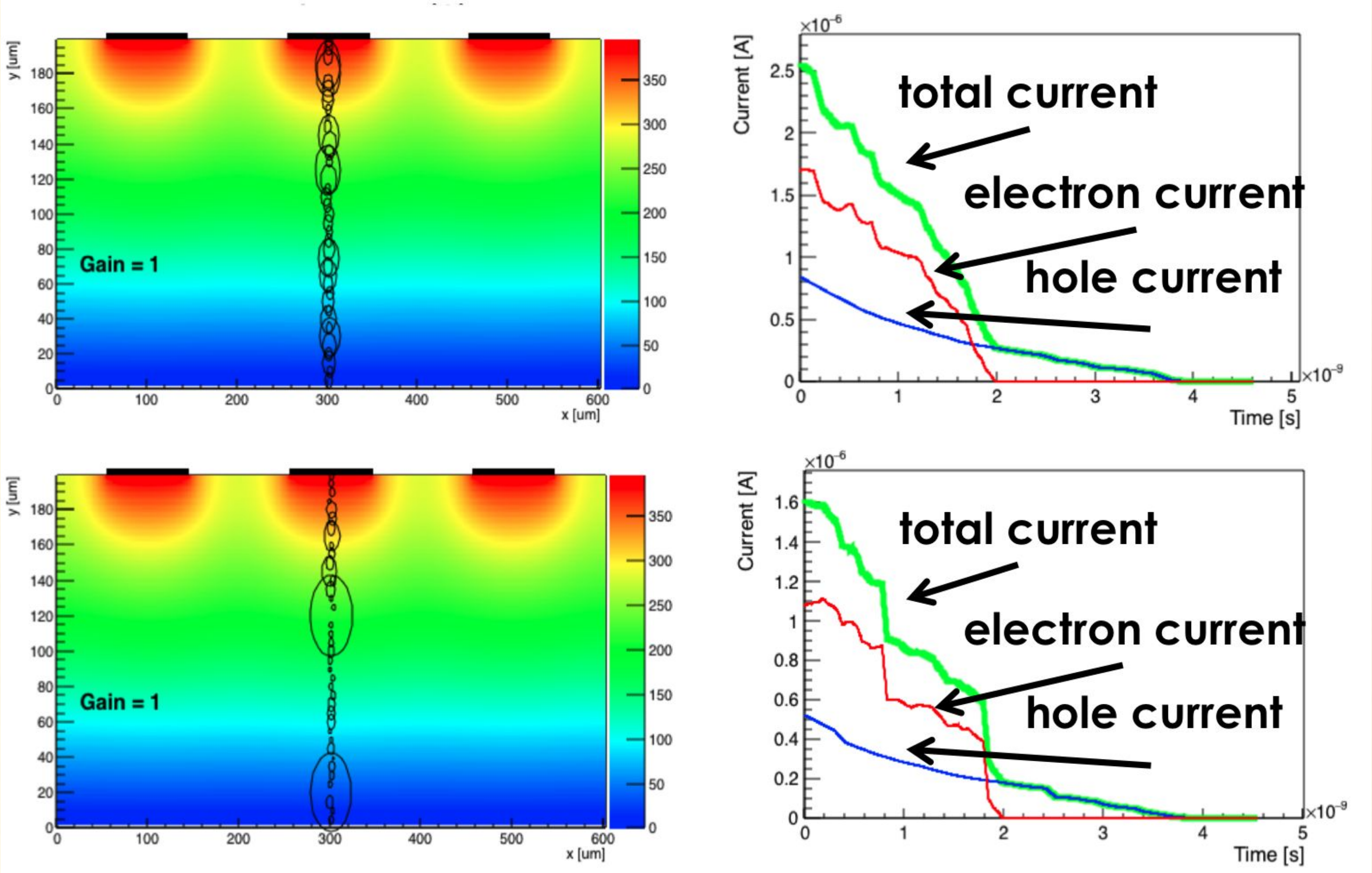






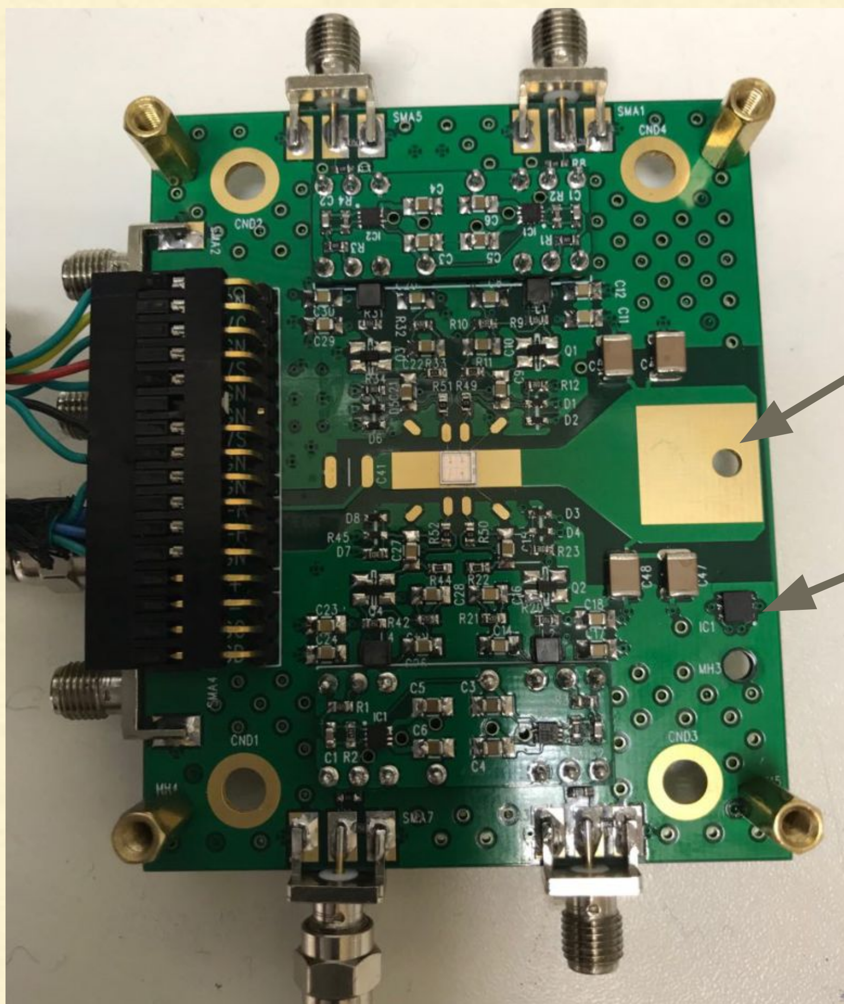
Investigate new UFSD structures and materials targeting very high radiation dose applications

- Simulation
- Rad Hard design (geometry, doping material…)
- Understand the radiation damage process
- Mask project (LGAD, AC-LGADs, etc.)
- Implantation
- Thinning, slicing
- Bonding
- Testing
- what else ?



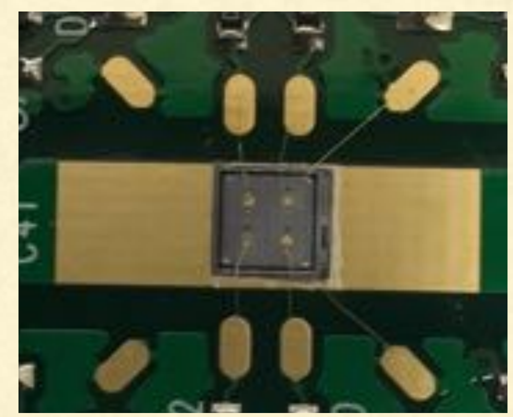
LGAD SIGNAL PERFORMANCE (I)

- 4 channel board developed @ USP, LGAD wire bonded directly
- Guard ring grounded
- 1st stage amplification based on 80GHz RF transistor
- Added a 2nd stage fast voltage op-amp (8GHz GBW) module on board (may be replaced by other op amp or by-passed)
- 4 electronic injection channels
- Cooling pad for cold finger attachment and temperature monitoring

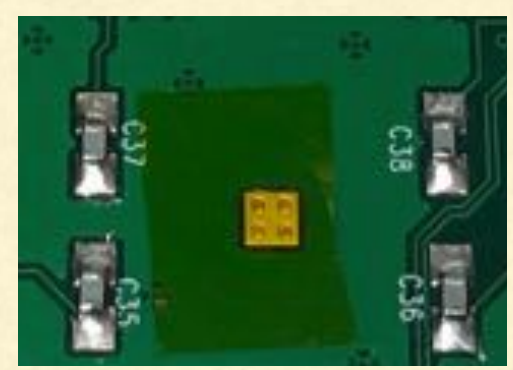


Area for cold finger contact

I2C temp sensor (SI7051, ±0.1°C)

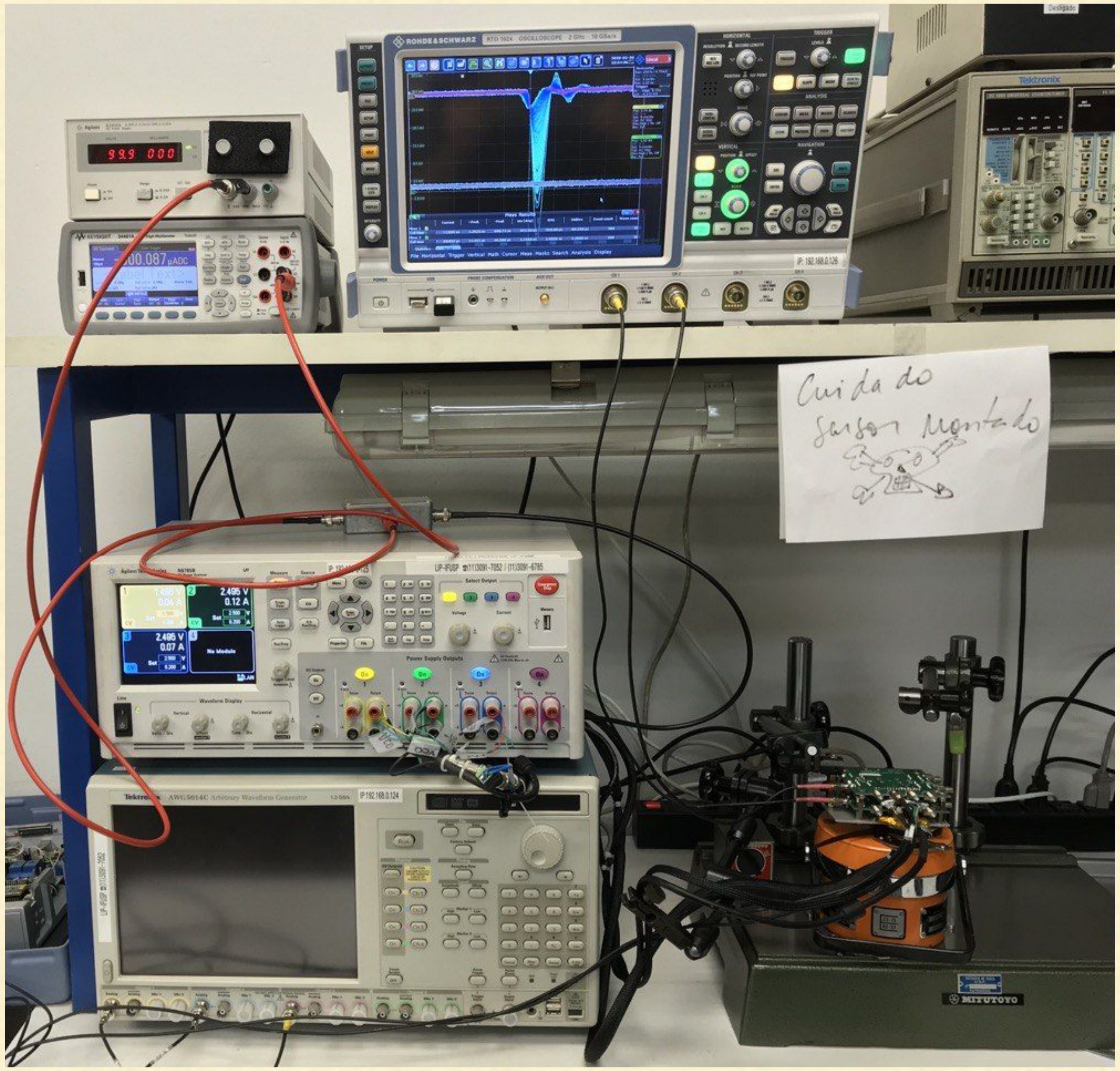


Sensor glued on the thermal pad and wire bonded

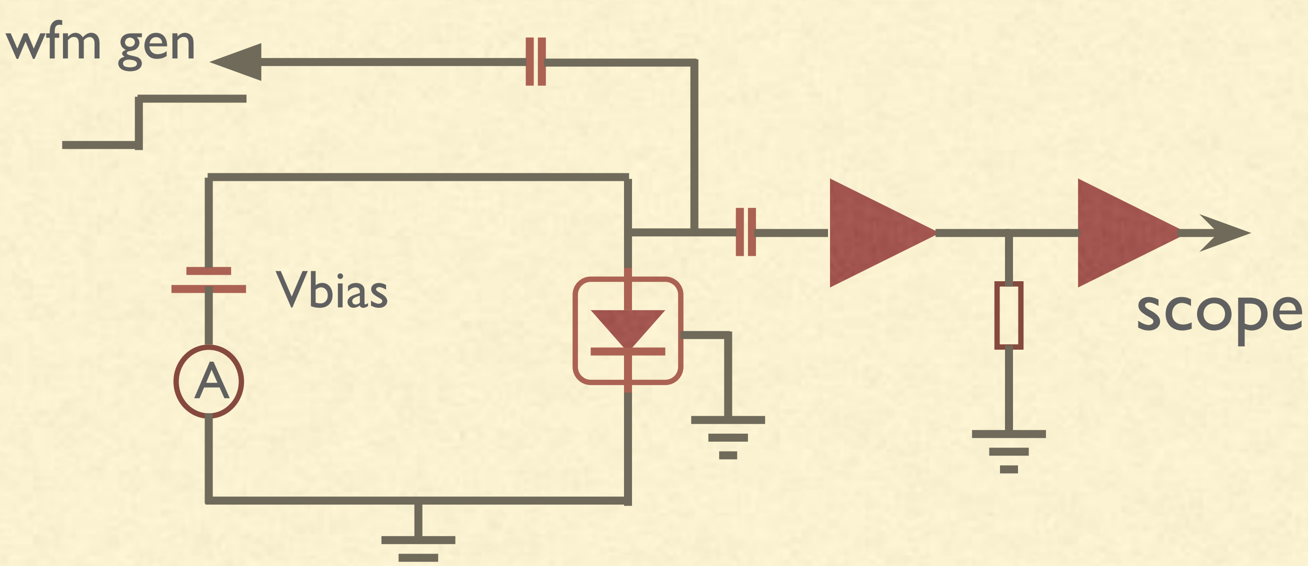


Back with openings for radiation passing

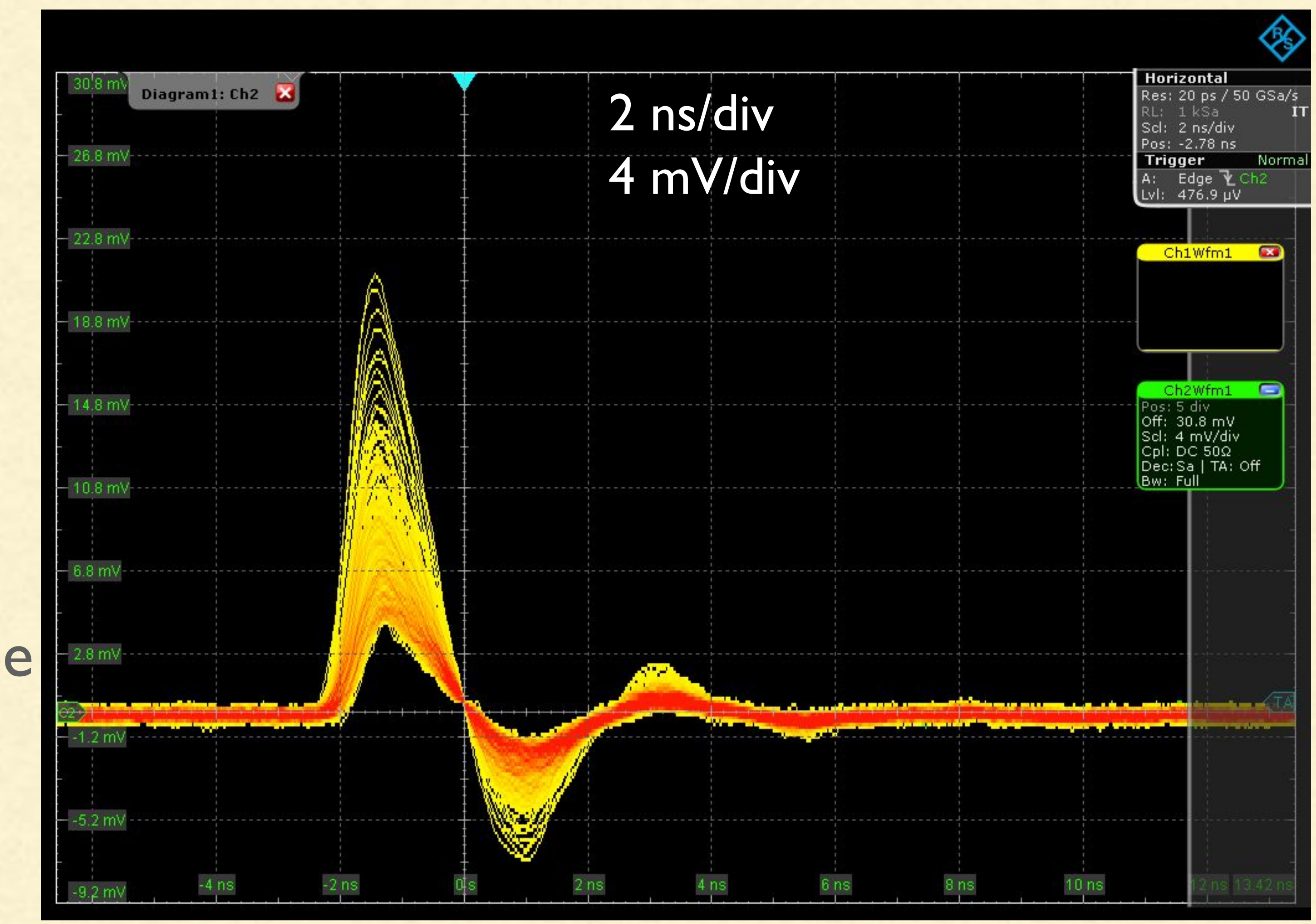
LGAD SIGNAL PERFORMANCE (II)



- Bias @100V
- Total “**Dark**” Current measured on the board @100V : 145nA
- 1st stage amplification noise : 290uV rms (@ 2 GHz BW scope)
- Test signal : 250mV step (900ps rise time) into 0.5 pF injector cap
- Test temperature = 22ºC

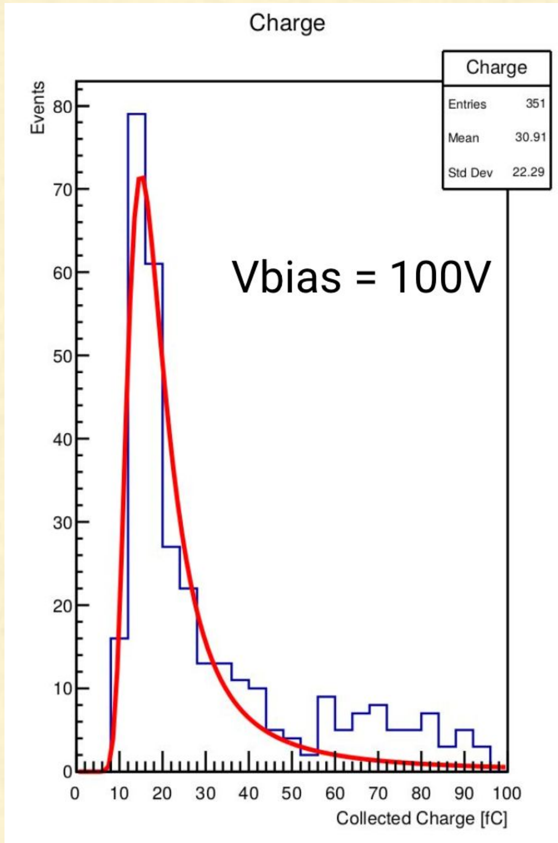


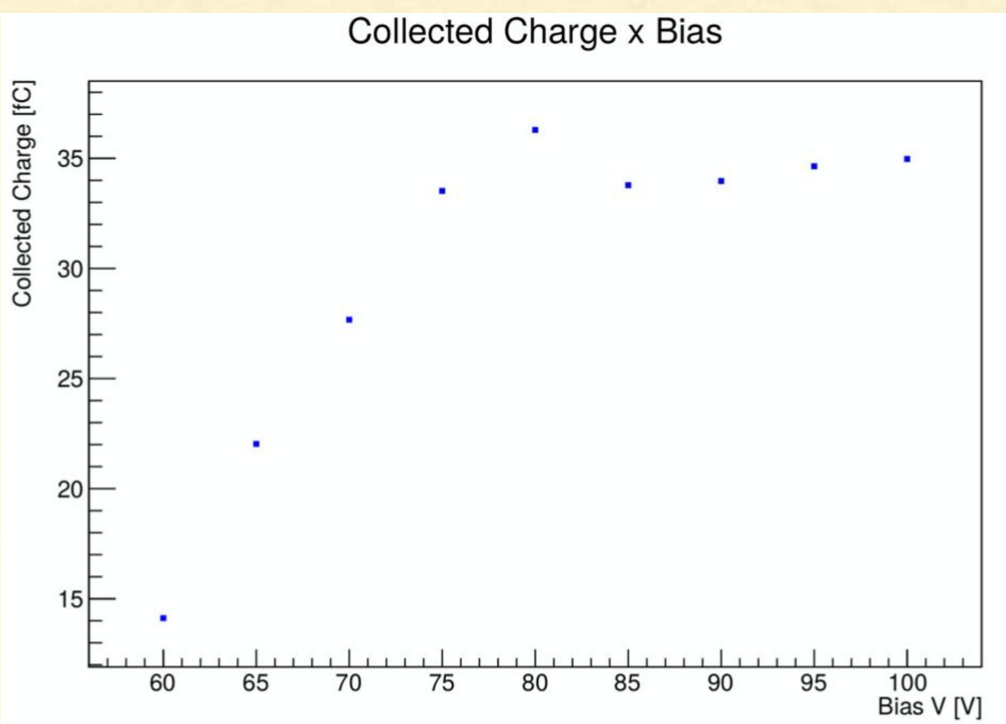
^{90}Sr (β)1st stage amplifier response



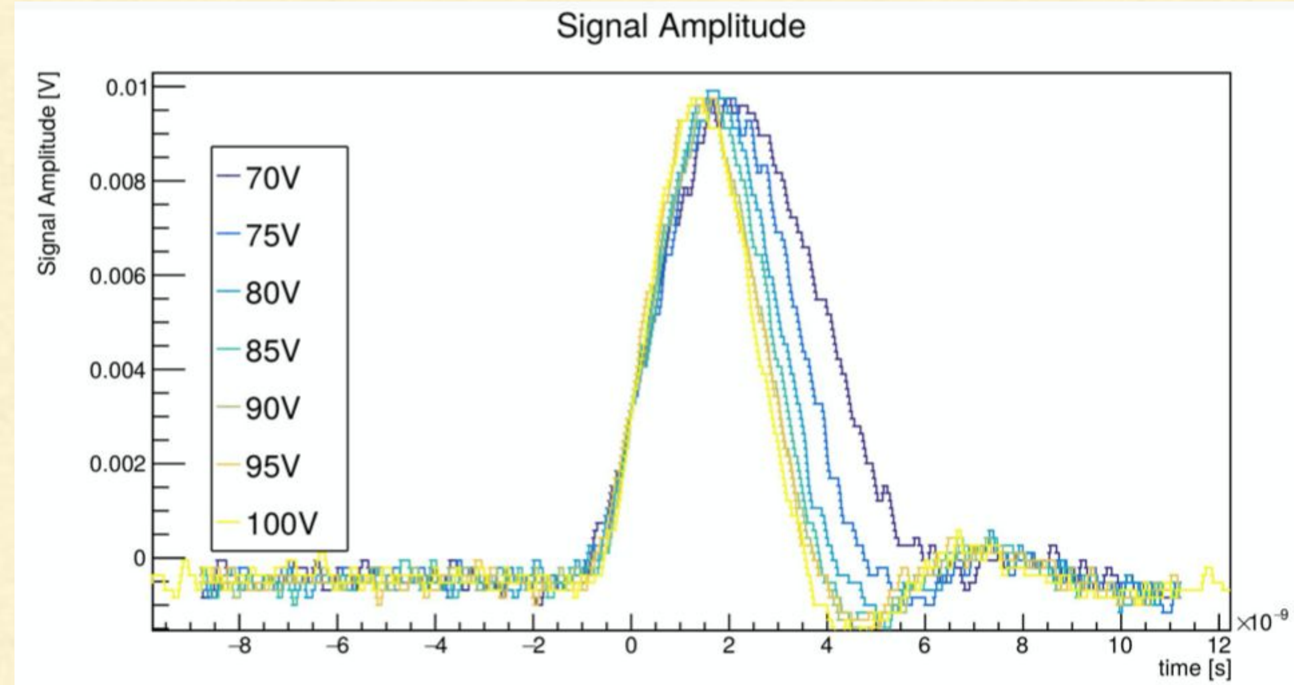
LGAD SIGNAL PERFORMANCE (III)

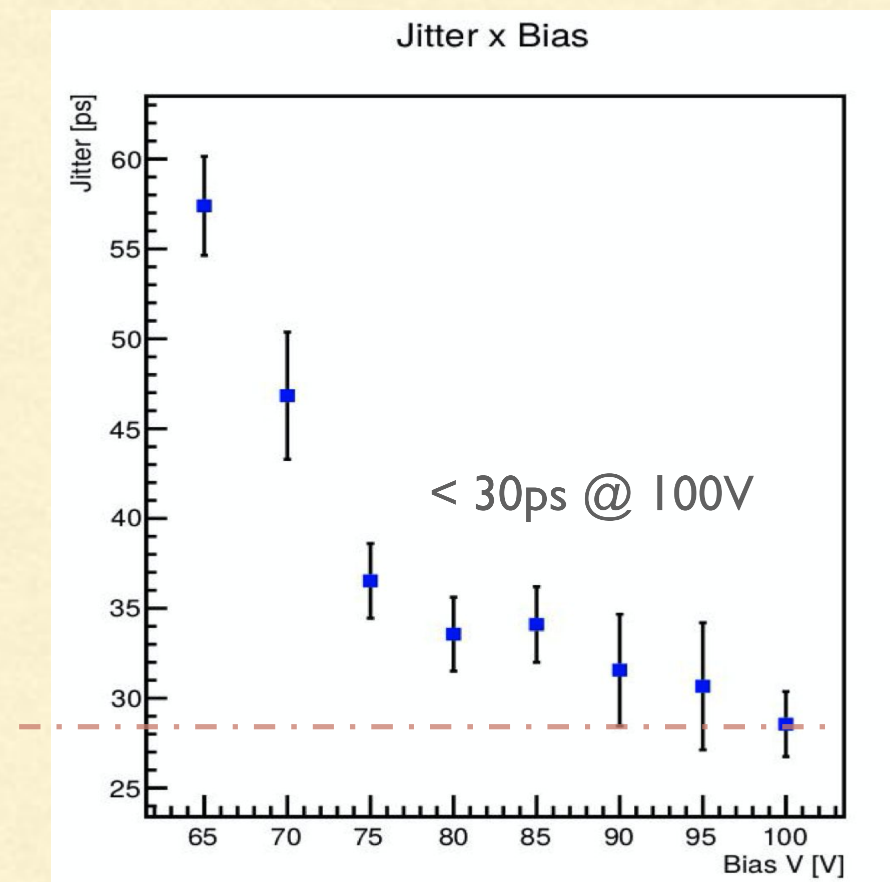
- Collected charge (^{90}Sr) vs bias (HPK 3.2)
- Minimum of 4fC for electronics...





- Jitter (^{90}Sr) vs bias (HPK 3.2)

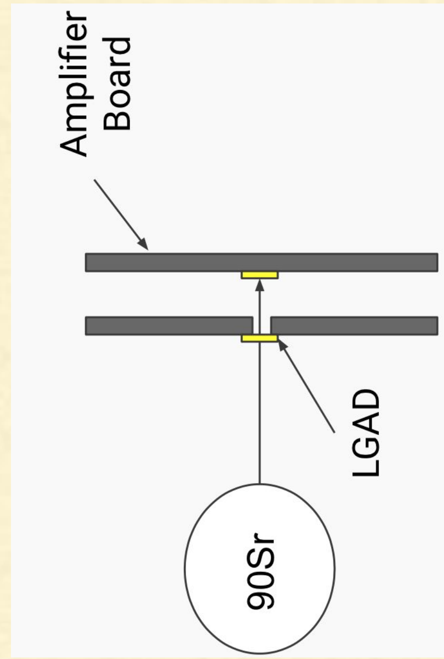


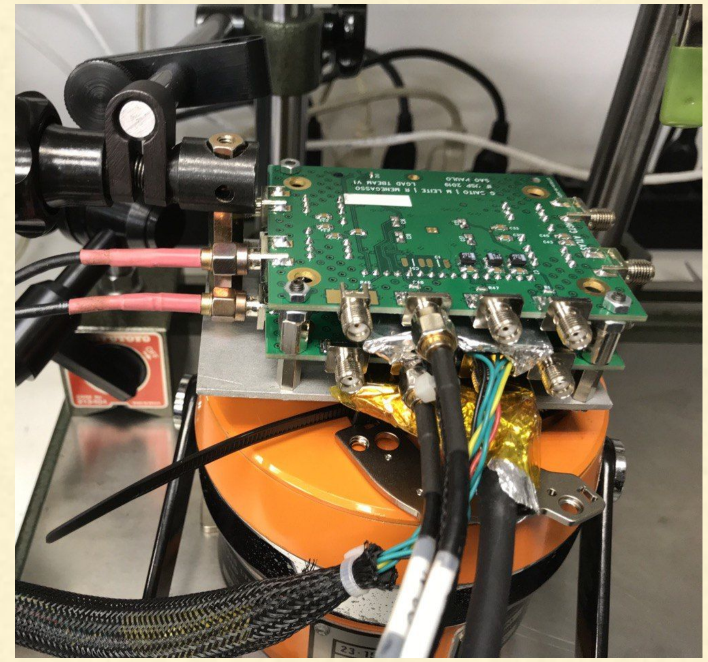


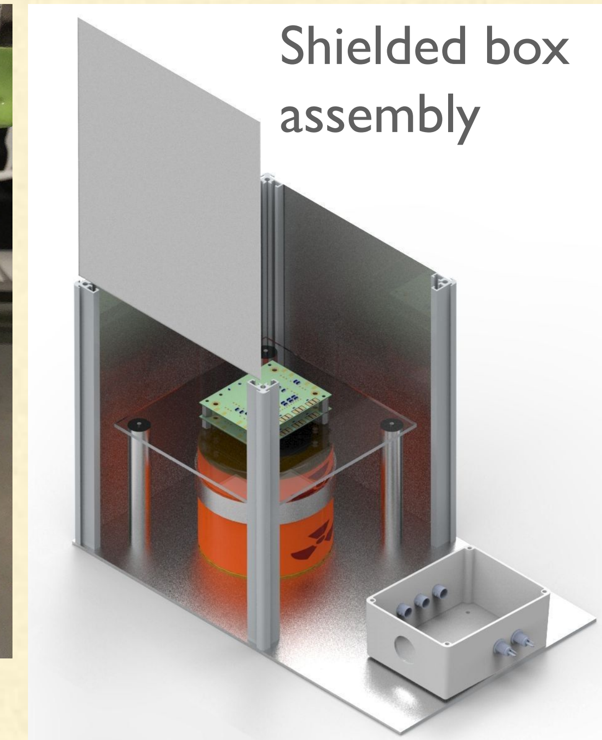
LGAD SIGNAL PERFORMANCE

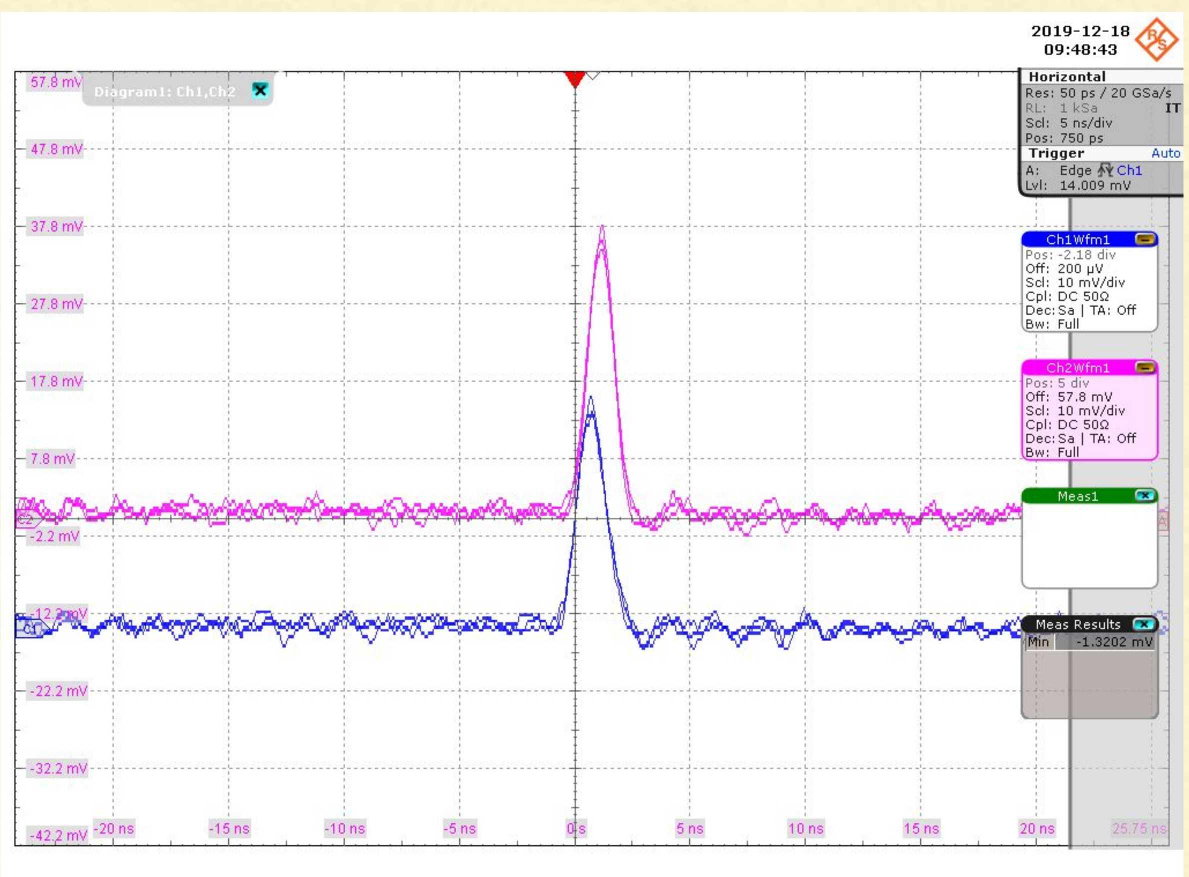
Timing coincidence using 2 sensors

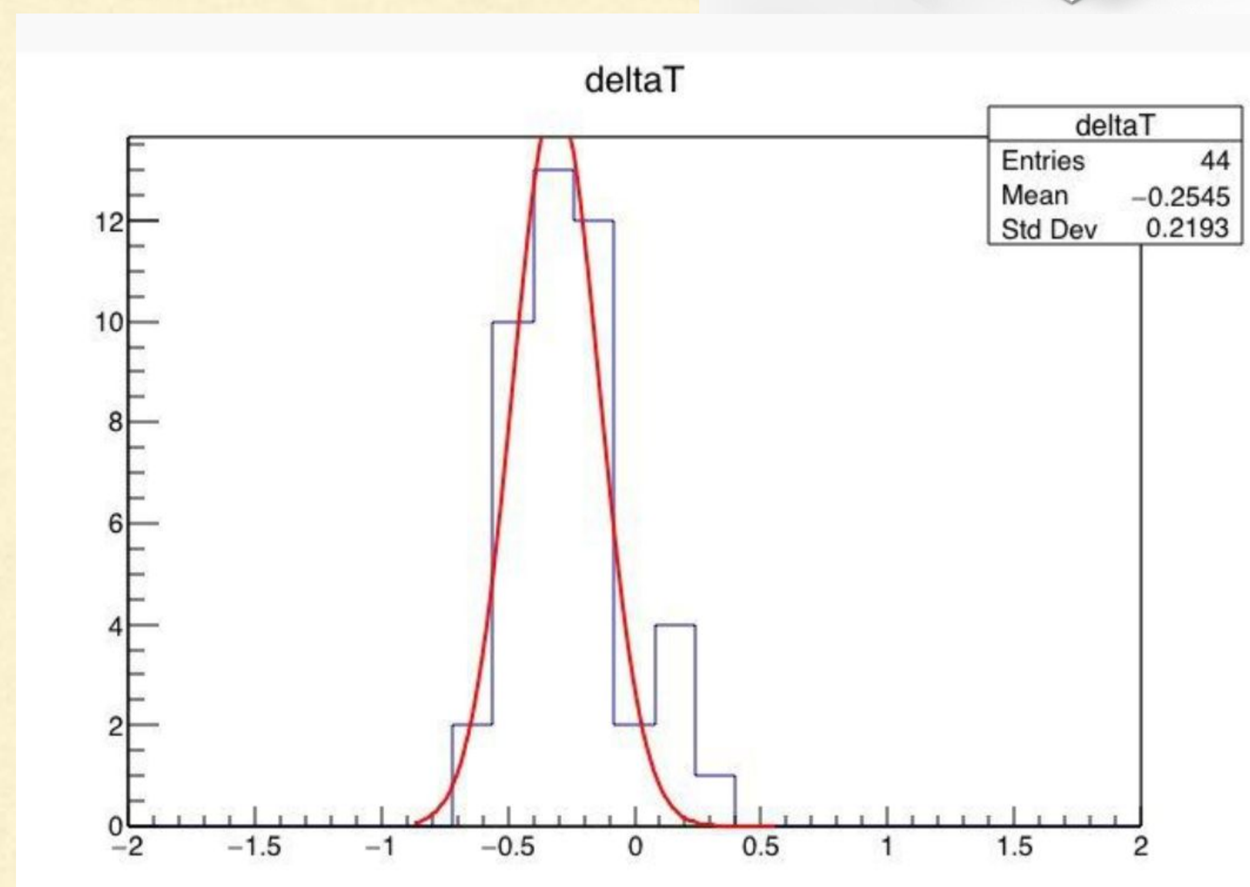
- Electrons from 90Sr source
- Triggered by second detector layer
- Store scope waveforms and measure timing using a "software" CFD (frac. 0.6)
- Timing resolution ~150ps/[sensor,elec.] @ 100V (highly **NOT** optimized…)











SENSOR TESTS AT USP

^{244}Cm Source (in air)

1 Half-life, Q-value and Decay mode

$T_{1/2}$	:	18.11	(3)	y
Q_α	:	5901.74	(5)	keV
α	:	100		%
SF	:	1.36		$\times 10^{-4}$ %

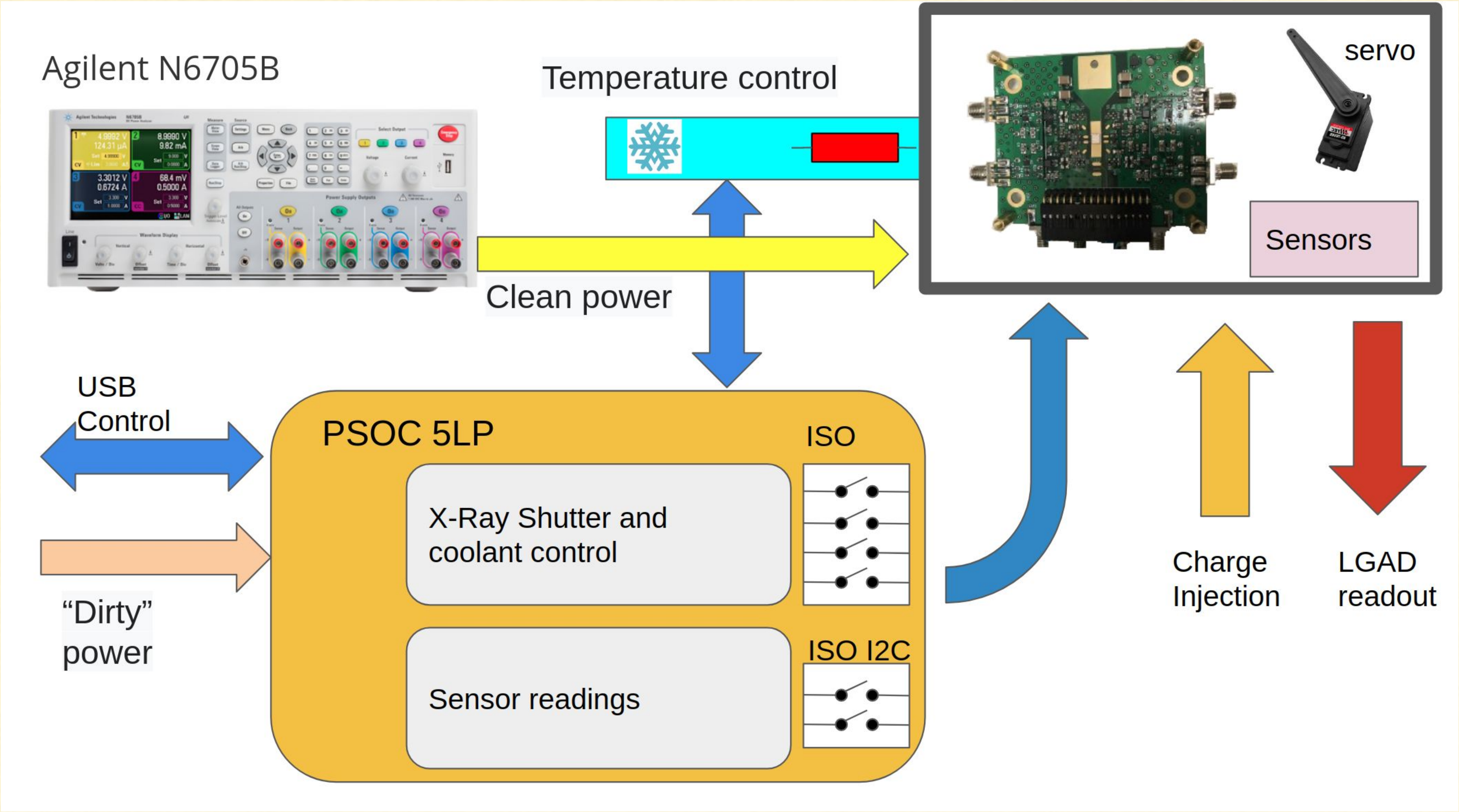
2 α Emissions

	Energy keV	Probability × 100
$\alpha_{0,9}$	4882.12 (8)	0.0000047 (11)
$\alpha_{0,8}$	4919.24 (7)	0.000050 (5)
$\alpha_{0,7}$	4958.20 (9)	0.000149 (16)
$\alpha_{0,6}$	5166.58 (7)	0.0000042 (30)
$\alpha_{0,5}$	5217.24 (7)	0.000055 (9)
$\alpha_{0,4}$	5315.3	0.00004
$\alpha_{0,3}$	5515.29 (6)	0.00352 (18)
$\alpha_{0,2}$	5665.41 (5)	0.0204 (15)
$\alpha_{0,1}$	5762.65 (5)	23.3 (4)
$\alpha_{0,0}$	5804.77 (5)	76.7 (4)

https://www-nds.iaea.org/act_ddl/data/Cm-244.pdf

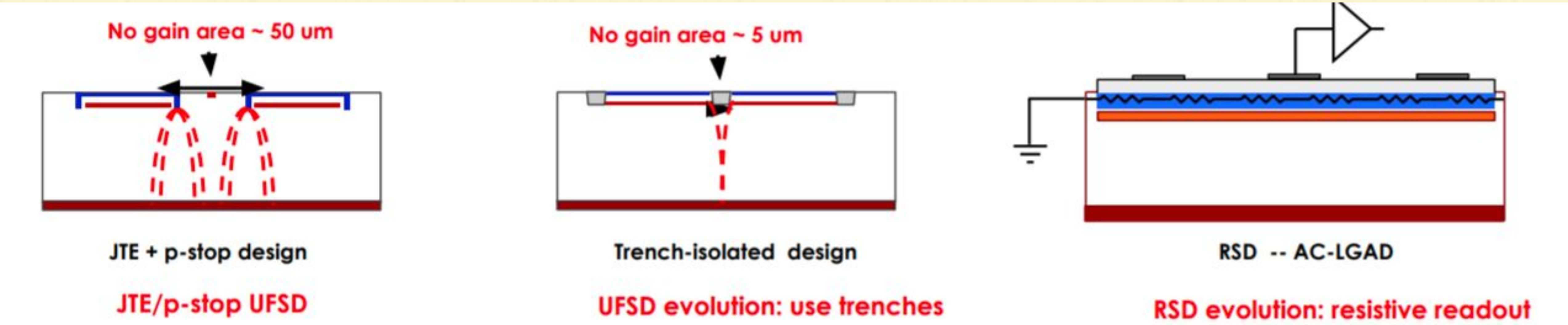
RADIATION TESTS (TID)

- Dedicated controller (temperature, cooler circulation, shutter, switch slow control and voltage monitor
- Same system to be used on charged particle (proton, ion) tests



THE LGAD VARIANTS

- Very new technology with many opportunities for contribution :



N. Cartiglia - 2021

Rad-hard, "simple" (ATLAS & CMS)

100% fill-factor

~5μm spatial resolution