

# Semiconductor sensors development and applications WG-5.2

Status Report

FAPESP Thematic 2020/04867-2

May 22nd 2024



# WG-5.2.1 & WG-5.2.2 : Recap

- WG-5.2.1 : ATLAS High Granularity Timing Detector (HGTD)
- WG-5.2.2 : Low Gain Avalanche Detectors (LGADs) for low energy applications

*Details on August [kick-off meeting](#)  
and More details on [October 2023 WG 5.2 Workshop](#)*

# WG 5.2.1: People and Action Items (Recap)

## 1. Current Team

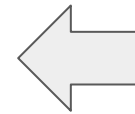
- 1.1. M. Leite (Physicist)
- 1.2. G. Saito (MS,PhD)  DD FAPESP
- 1.3. R. Estevam (DD)  DD FAPESP
- 1.4. H. IMAM (PD)  PD FAPESP
- 1.5. R. Menegasso (TS)
- 1.6. M. Kuriyama (TS)
- 1.7. DD (Dedicated) (1.2)
- 1.8. DD (Sharing with PA) (1.3)
- 1.9. PD (Sharing with PA) (1.4)
- 1.10. IC (TT-2 ?)
- 1.11. TT-4

## 1. Action items

- 1.1. Equipment availability (importation) (DONE!)
- 1.2. Preparing civil infrastructure for Lab (DONE!)
- 1.3. Lab installation (DONE!, but will keep updating)
- 1.4. PD, DD, TT hiring (DONE!)
- 1.5. Start testing sensors (DONE!)
- 1.6. **Significant work to commission local infrastructure (EMU FAPESP)**
- 1.7. **Significant commitment of people on @CERN activities**

## 1. Deliverables

- 1.1. **LGAD Characterization Lab.**
- 1.2. Characterization of LGAD sensors (on-going)
- 1.3. Performance studies on irradiated arrays (on-going)
- 1.4. PEB test stand system
- 1.5. Participation in HGTD assembly facility construction @ CERN (on-going)
- 1.6. Demonstrator construction @ CERN (on-going)
- 1.7. HGTD installation
- 1.8. HGTD commissioning



Almost zero float on these items !(ATLAS HGTD Sensor PRR in June)

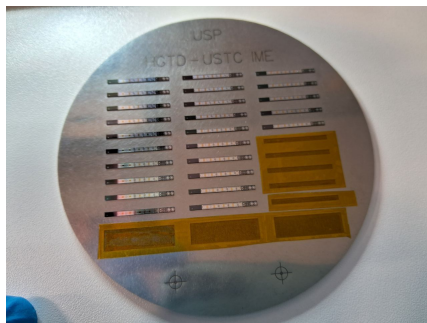
# WG 5.2.1 : ATLAS HGTD - Infrastructure @USP



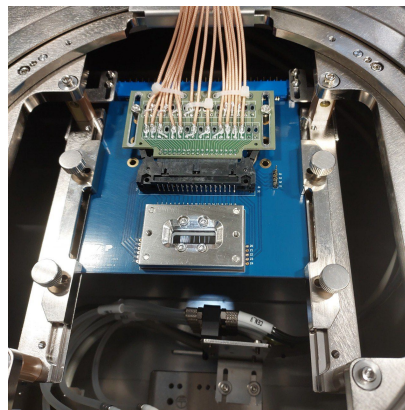
# WG 5.2.1 : ATLAS HGTD - Infrastructure @USP



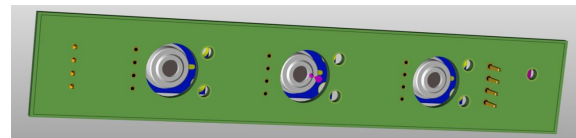
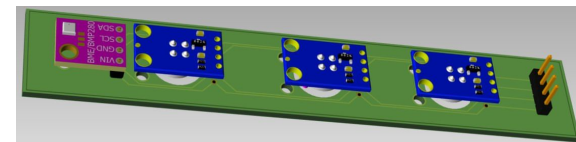
Sensors and structures are arriving from IHEP



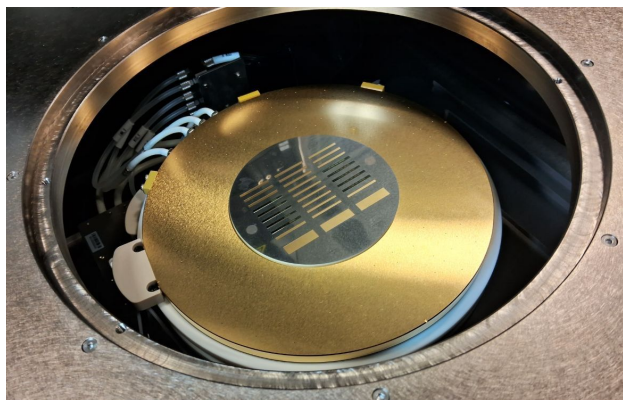
USTC-IME structure holder



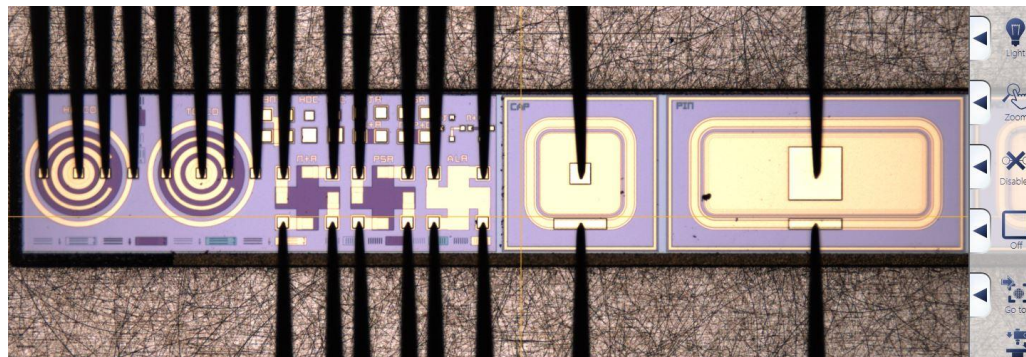
Probe card for QC/QA



Non-contact chuck temperature monitor



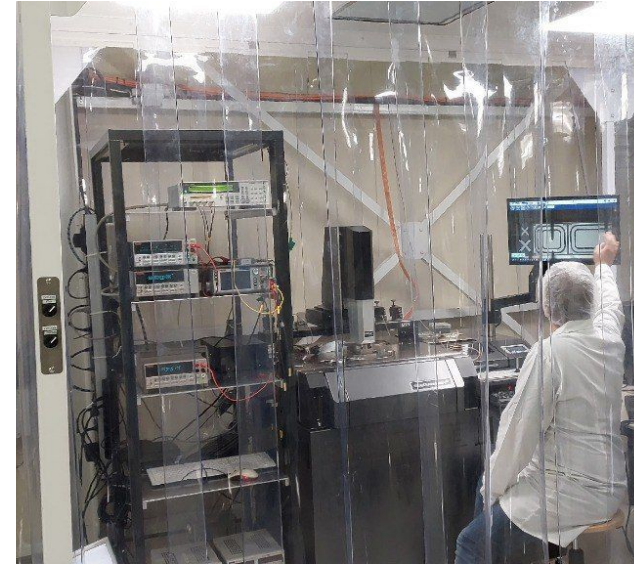
Holder loading in chuck



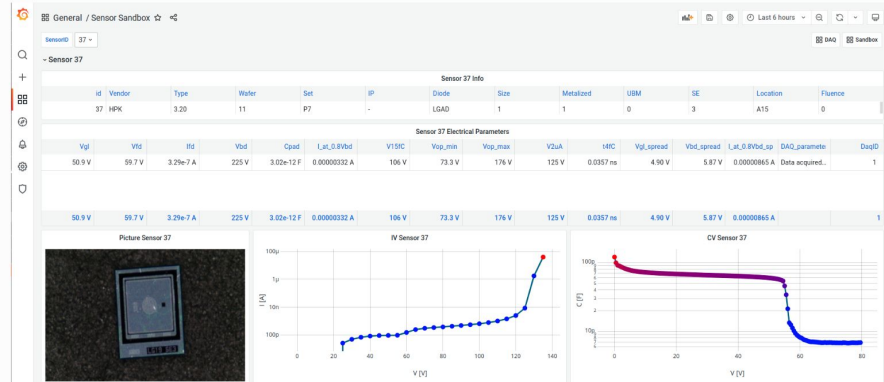
Test structure probing

# WG 5.2.1 : ATLAS HGTD - QA/QC

- **USP is one of the main sites for sensor PQC**
  - Development of DAQ system (hDAQ) from ground up
  - G. Saito ATLAS qualification work
  - System at use at USP-CERN-IHEP-USTC-IJS
  - Data uploaded automatically to CERN DB on-demand
  - Grafana is used to query DB and plot data



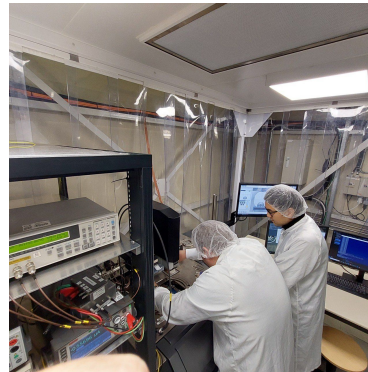
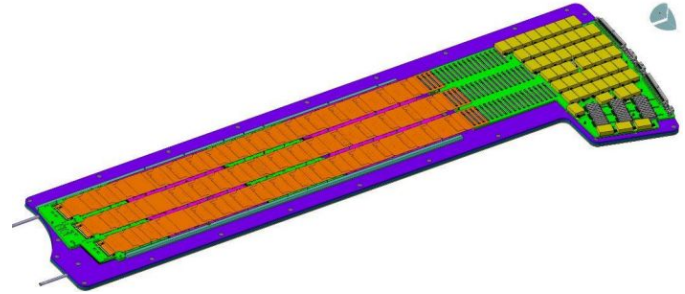
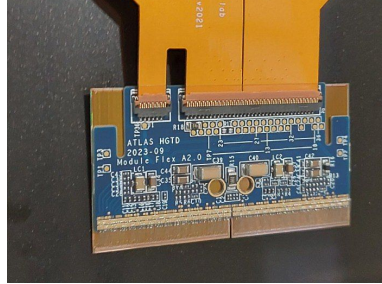
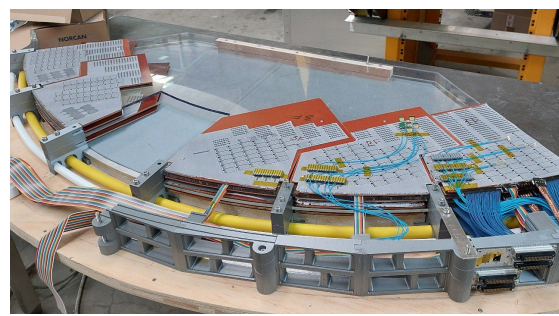
## 2.2. Sensors



Example of a grafana dashboard showing information about sensors.

# WG 5.2.1 : ATLAS HGTD - Integration @ CERN

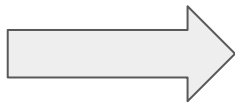
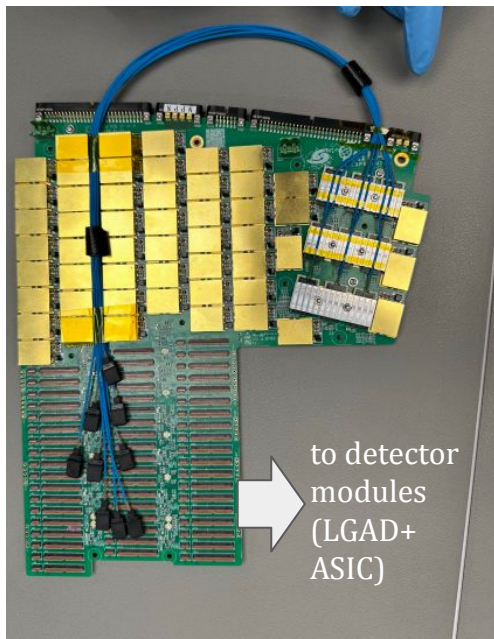
- CERN will be construction site for HGTD
- Need to build infrastructure and tooling
- Agreed as M&O contribution
- First integration @ CERN in April (HGTD expert week)
- Sensor+ASIC+PEB+FELIX readout



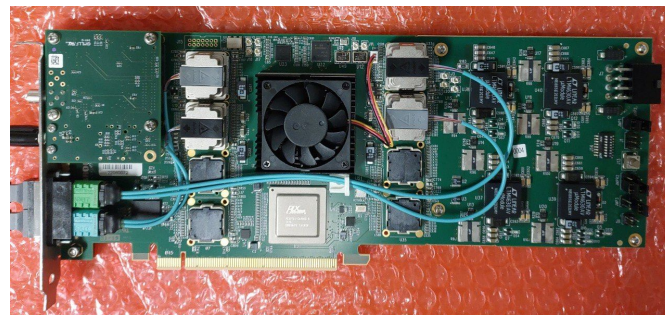
# WG 5.2.1 : ATLAS HGTD - Integration @ CERN

- Monitoring through FELIX
  - We still have sometime, but it would be important to develop some knowledge on high speed DAQ
  - Quite some work when integration time comes

PEB @ CERN



ATLAS Phase-I PCI-E FELIX Card (@ USP)



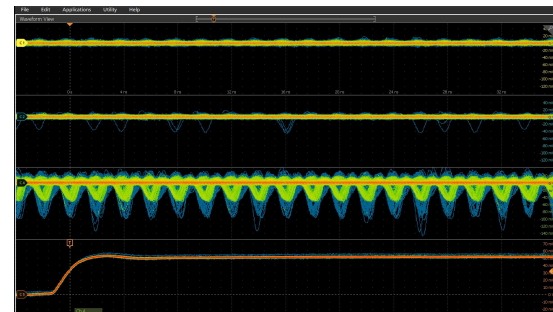
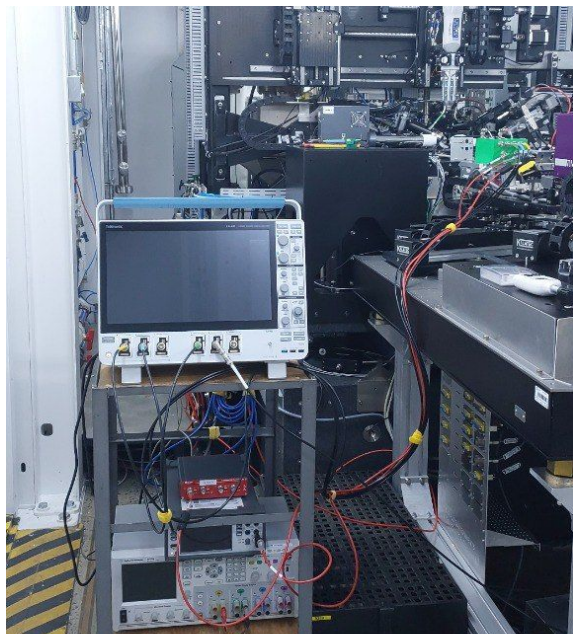
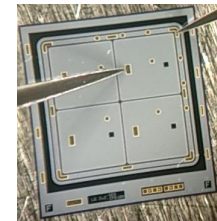
- CNPEM is interested on using these cards for Timepix-4
- We are discussing the possibilities to collaborate on this (both sides winning)



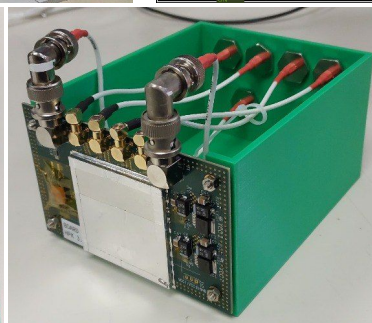
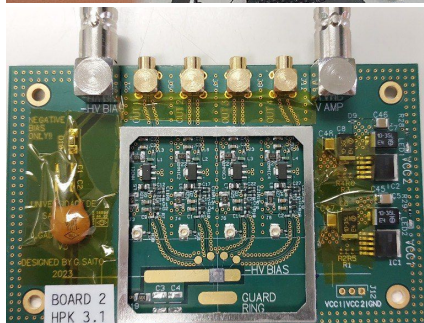
# WG 5.2.2 : UFSD for Applied Sciences

## LGADS for picosecond time resolved X-ray testing

- **New tests** at Carnaúba beamline at CNPEM
- Excellent support from Sirius people and management-> **very efficient (and very intense)** campaign
- Using HPK 3.1 ATLAS prototype sensor



Pad signal  
Pad signal  
Pad signal  
Machine trigger



New board designed for Sirius tests

# WG 5.2.2 : UFSD for Applied Sciences

- Tests performed at [Carnauba beam line](#) at Sirius Light source in São Paulo
- Beam time from Lab. directorate strategic program (so we did not compete with other requests)

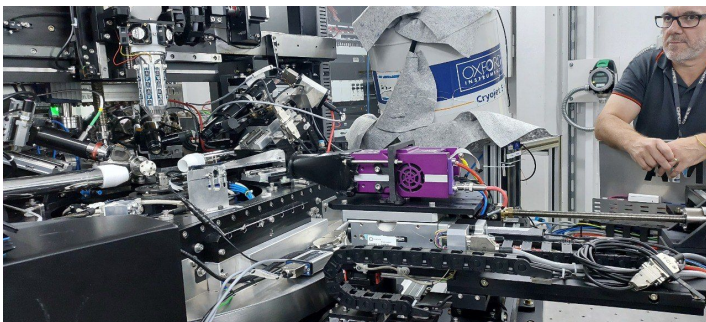
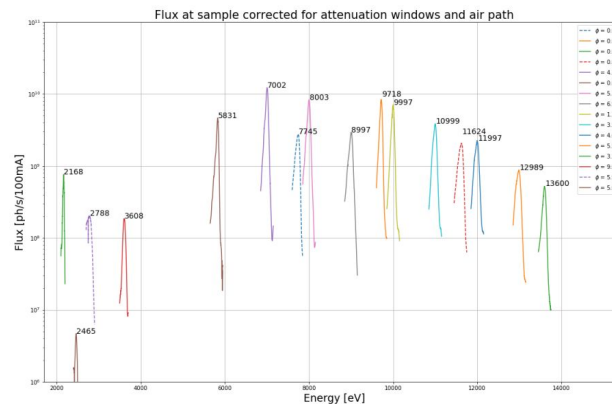


## PARAMETERS

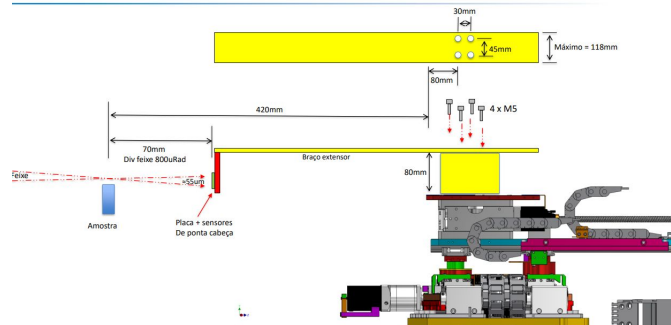
Parameter	Value	Condition
Energy Range	2.05 – 15 keV	Si(111)
Energy Resolution ( $\Delta E/E$ )	$10^{-4}$ – $10^{-5}$	
Harmonic Content	$< 10^{-5}$	Above 5 keV
Energy Scan	Yes	
Beamsize at sample [ $\mu\text{m}$ ] @Tarumã	0.15 x 0.15 (0.55 x 0.55)	8 keV (2 keV)
Beam Divergence at sample [mrad] @Tarumã	(1 x 1)	All energy range
Estimated flux [ph/s/100 mA] @Tarumã	$10^{11}$	–
Beamsize at sample [ $\mu\text{m}$ ] @Sapoti	0.03 x 0.03 (0.12 x 0.12)	8 keV (2 keV)
Beam Divergence at sample [mrad] @Sapoti	5x5 (4 x 4)	$< 10$ keV (12keV)
Estimated flux [ph/s/100 mA] @Sapoti	$10^{12}$	–
Imaging Mode	Scanning	–
Coherence Modes	-1	–



Flux at sample corrected for attenuation (log plot)



Rascunho para o Braço extensor

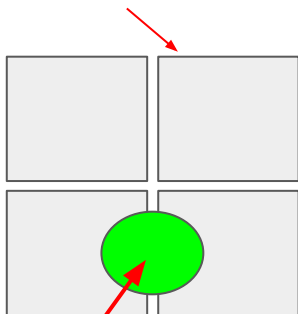


# WG 5.2.2 : UFSD for Applied Sciences

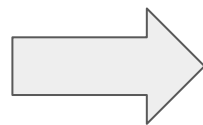
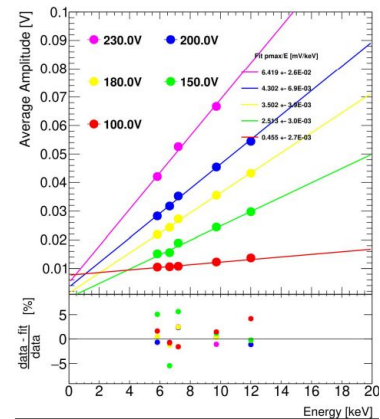
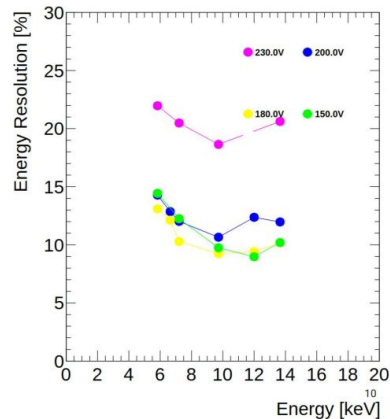
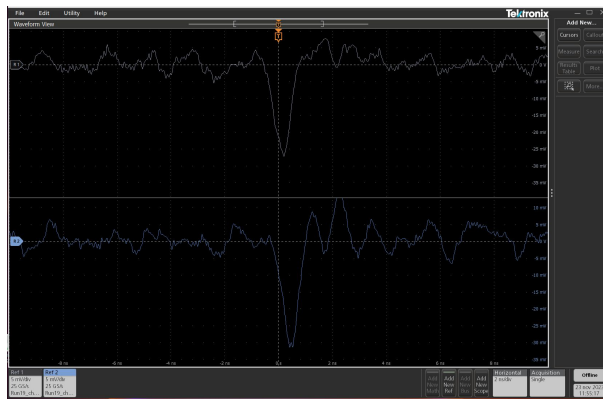
## LGADS for picosecond time resolved X-ray testing

- **First test** in November 2023
- $\sim 500\mu\text{m}$  2ns, 10ps X-Ray bunches
- 1 TB of data being analyzed
- ATLAS HPK 3.1 2x2 array
- **Energy and timing resolution as function of Bias Voltage and Energy**

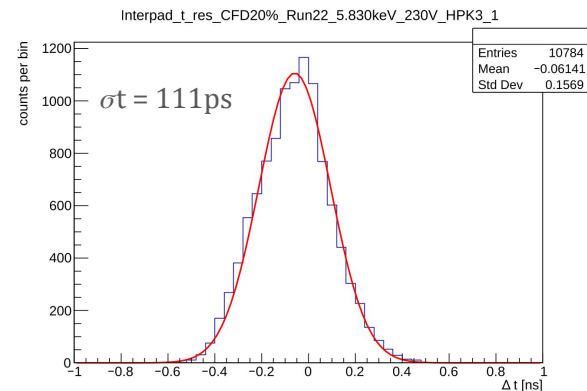
2x2 LGAD array



500um X-ray beam



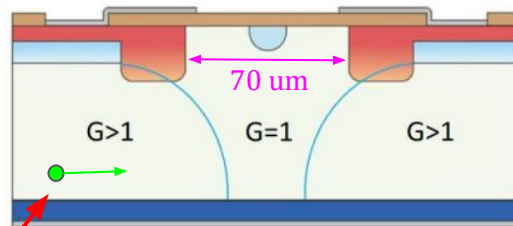
First time ever !!



# WG 5.2.2 : UFSD for Applied Sciences

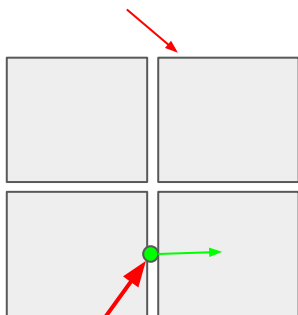
## LGADS for picosecond time resolved X-ray testing

- **Second test beam** in Jan 2024
- ATLAS HPK 3.1 2x2 array
- ~150nm 2ns, 10ps X-Ray bunches
- **Position scan to measure/model the gain**
- Scripting using EPIC by Sirius team
- We are advancing on the TCAD simulation with UC Santa Cruz

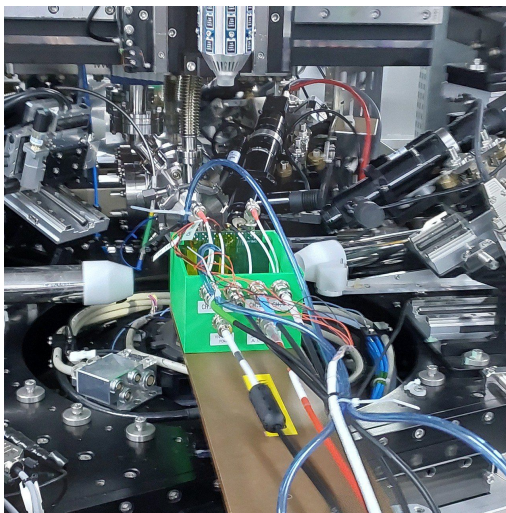


X-ray beam

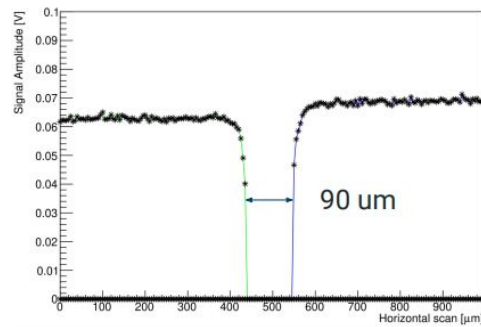
2x2 LGAD array



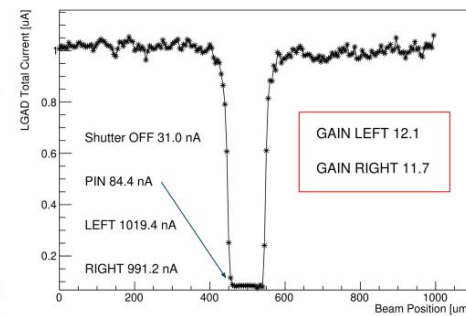
150nm X-ray beam



Waveform scan

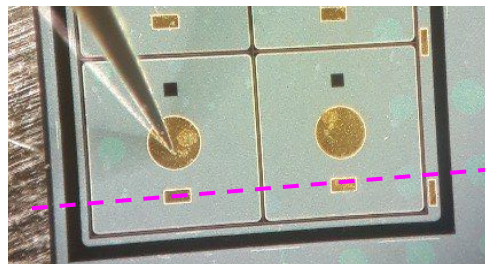
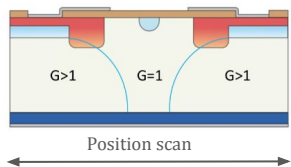


I<sub>bias</sub> scan

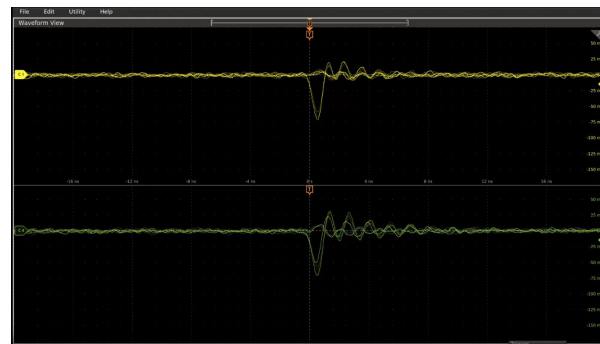


# January LGAD TB at Sirius

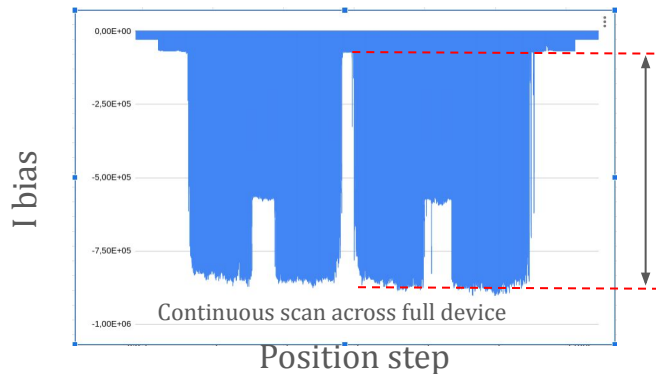
## Interpad position scan



“ORed” scope trigger trigger between 2 ch



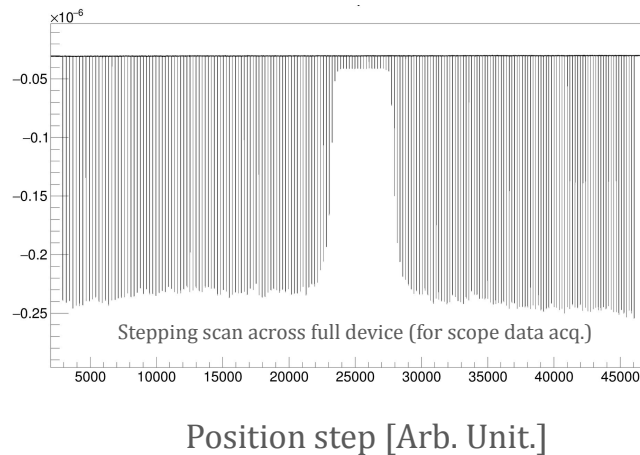
- LGAD **bias current** profile for 50um scan step (230V, 9.75 keV, 150nm beam)



Use for gain estimation  
([Kramberger](#))



I bias [A]

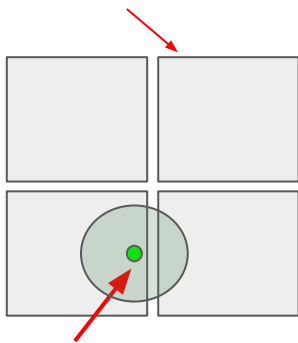


# WG 5.2.2 : UFSD for Applied Sciences

## LGADS for picosecond time resolved X-ray testing

- **Third test** beam in Feb 2024
- ATLAS HPK 3.1 2x2 array
- ~150nm 2ns, 10ps X-Ray bunches
- Scattered by amorphous carbon to provide wider beam
- **Energy/timing resolution wrt temperature**
- Scripting using EPIC by Sirius team

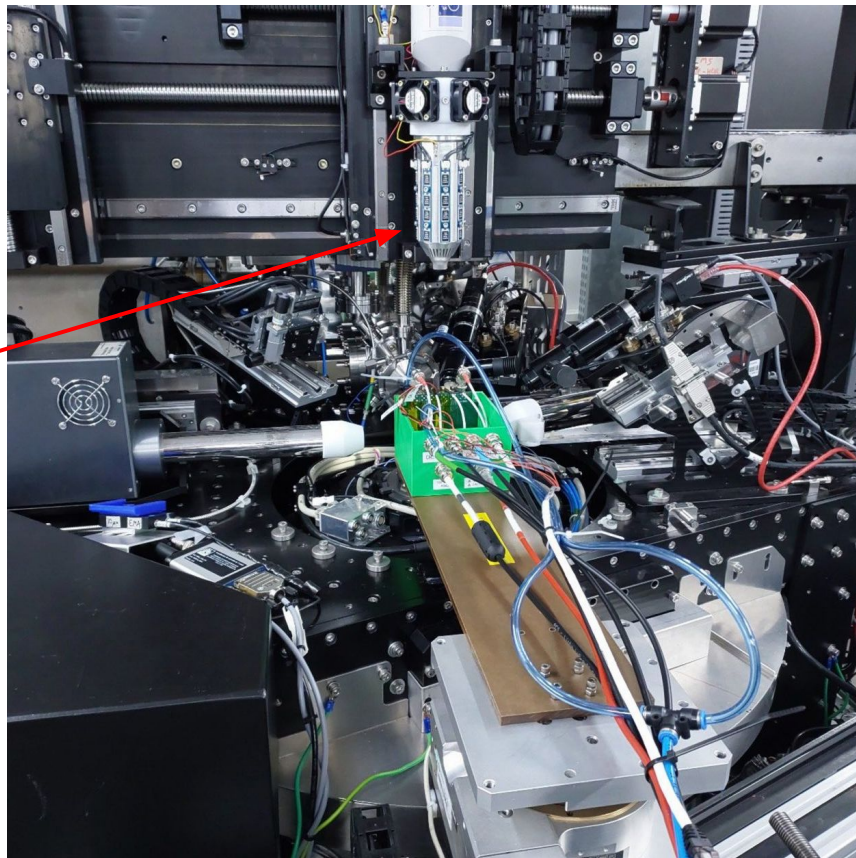
2x2 LGAD array



Temp.  
Controlled  
Cryo Jet

150nm X-ray beam

- Paper to be submitted ~ winter
- Much more to come - many interesting ideas being discussed with LNL team



# WG 5.2.2 : UFSD for Applied Sciences

## LGADS for picosecond time resolved X-ray testing

- New paper out (SSRL) ([link](#))



Full Length Article

### Time-resolved synchrotron light source X-ray detection with Low-Gain Avalanche Diodes

G.T. Saito<sup>a,\*</sup>, M. Leite<sup>a</sup>, S.M. Mazza<sup>b</sup>, Y. Zhao<sup>b</sup>, T. Kirkes<sup>b</sup>, N. Yoho<sup>b</sup>, D. Yerdea<sup>b</sup>, N. Nagel<sup>b</sup>, J. Ott<sup>b</sup>, M. Nizam<sup>b</sup>, M. Morales<sup>c</sup>, H.F.-W. Sadrozinski<sup>b</sup>, A. Seiden<sup>b</sup>, B. Schumm<sup>b</sup>, F. McKinney-Martinez<sup>b</sup>, G. Giacomini<sup>d</sup>, W. Chen<sup>d</sup>

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#### ARTICLE INFO ABSTRACT

**Keywords:**  
Ultra-fast silicon sensors  
Low-Gain Avalanche Diodes  
Charge multiplication  
Thin tracking sensors  
Synchrotron instrumentation

Low-Gain Avalanche Diodes (LGADs) represent the state-of-the-art in timing measurements and will instrument future timing detectors at the High Luminosity Large Hadron Collider (HL-LHC) experiments. While conceived as a sensor for charged particles, the intrinsic gain of LGADs makes it possible to detect low energy X-rays with good energy resolution and excellent timing (tens of picoseconds). Using the Stanford Synchrotron Radiation Lightsource (SSRL) at SLAC, several LGADs designs were characterized with energies from 5 to 35 keV. The SSRL provides 10 ps pulsed X-ray bunches separated by 2.1 ns intervals, and with an energy dispersion ( $\Delta E/E$ ) of  $1 \times 10^{-4}$ . LGADs fabricated by Hamamatsu Photonics (HPK) and Brookhaven National Laboratory (BNL) with different thicknesses ranging from 20  $\mu\text{m}$  to 50  $\mu\text{m}$  and different gain layer designs were read out a two-stage fast amplification circuit and digitized with a high bandwidth, high sampling rate oscilloscope. PIN devices from HPK were characterized as well. A systematic and detailed characterization of the devices' energy linearity, resolution and timing resolution as a function of X-ray energy was performed for different biasing voltages at room temperature.

#### 1. Introduction

Low-Gain Avalanche Diodes (LGAD) were originally developed to be used as sensors in the timing detectors of both ATLAS and CMS experiments at the LHC [1,2]. These silicon detectors offer a time resolution of tens of picoseconds for measuring charged particles by means of a gain layer that provides an intrinsic moderate gain [3]. If maintained these characteristics when measuring X-ray photons, these devices could be used as synchrotron X-ray detectors capable of resolving short pulses in a high repetition rate beam in a broad range of energies. In this work we report the response of different designs of LGADs in a 500MHz repetition rate of 10ps X-ray pulses Synchrotron beamline in energies between 5 keV and 35keV.

#### 2. Devices tested

LGADs are thin silicon sensors composed by the bulk, a low-doped volume, typically between 20  $\mu\text{m}$  and 50  $\mu\text{m}$  and a highly doped thin layer (gain layer) just below the PN junction of the device. On Table 1,

the nominal bulk thickness and the depth of the gain layer of the 3 LGADs used on this test (HPK 3.1, HPK 3.2 and BNL 20um) and a PIN diode (HPK PIN) is presented. All 4 sensors are single pad devices having an nominal active area of  $1.3 \times 1.3 \text{ mm}^2$ .

#### 3. Setup at SLAC SSRL

For this test, Beamline 11-2 of the Stanford Synchrotron Radiation Lightsource (SSRL) at SLAC [4] was used for this test. It provides a X-ray beam with energy dispersion  $\Delta E/E$  of  $1 \times 10^{-4}$ . The bunches are about 10ps wide and separated by 2.1 ns. They are bunched in 4 groups of 70 bunches, as seen on Fig. 1. Before the 4 groups there is an isolated bunch that is kept in phase with the signal used as a trigger in this setup.

The 4 devices tested were mounted on PCBs with a  $\approx 2\text{GHz}$  bandwidth TIA amplifier, described on [5], and digitized by a 13GHz bandwidth 128GS/s sampling rate oscilloscope.

- New paper in preparation (Sirius) for Oct. /Nov. 2024

<sup>1</sup> PREPARED FOR SUBMISSION TO JINST

### 2 Performance of LGAD sensors under synchrotron radiation

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<sup>11</sup> ABSTRACT: ABSTRACT..

<sup>12</sup> KEYWORDS: Only keywords from JINST's keywords list please

<sup>13</sup> ARXIV EPRINT: 1234.56789

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<sup>19</sup> 5	Simulation of sensor response (Geovane)	<sup>2</sup>
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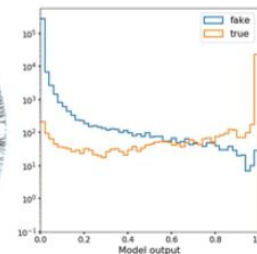
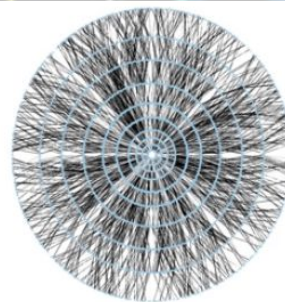
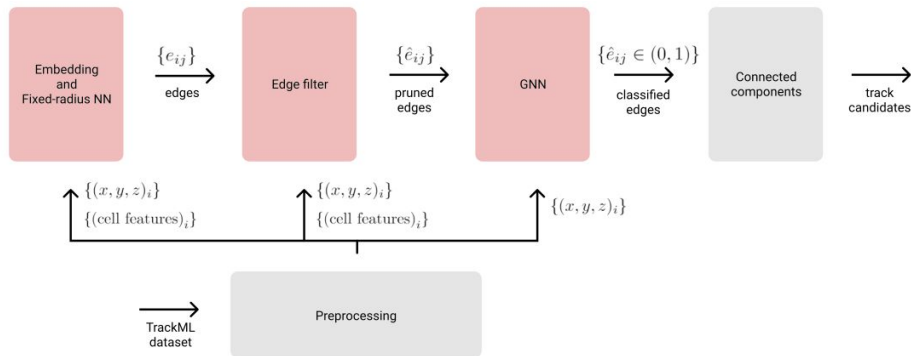
\* Corresponding author.  
E-mail address: g.saito@cern.ch (G.T. Saito).

# WG 5.2.1 & WG 5.2.2 : ACTION ITEMS FOR NEXT MONTHS

new

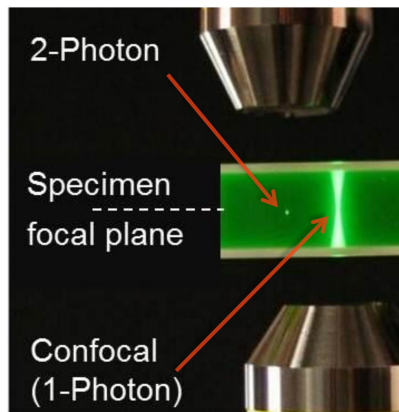
## Graph based Neural Network approach for ATLAS HL-LHC (iTK+HGTD)

- Exa.trk: HEP advanced tracking algorithms at the Exascale
- See Rodrigo's presentation



## Characterization of Semiconductor sensor using TCT and TPA Laser techniques

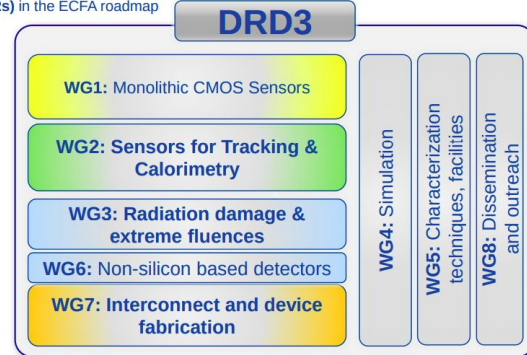
- Conventional TCT:
  - Localized generation of e-h pairs on X-Y
  - We can try to use our MPI to do this
- Two-photon absorption TCT:
  - Localized generation of e-h pairs on X-Y-Z



Photography: Ciceron Yanez, University of Central Florida

## DRD-3 R&D on semiconductor sensors

- We are covering all ECFA DRDTs
- Additional WGs were added to cover simulations, facilities and dissemination corresponding to **General Strategic Recommendations (GSRs)** in the ECFA roadmap





# WG 5.2 - 4D Tracking

- Started officially the work with the HGTD Simulation and Performance work group
- We will contribute to the performance studies of reconstruction methods using ACTS (ATLAS tracking framework)
- Our first task will be to **include HGTD's timing information in the existing reconstruction method (Combinatorial Kalman Filter) and evaluate its performance**
  - Timing information is important for pileup (background effects) rejection

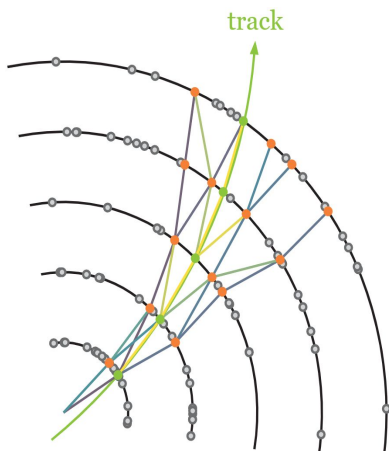


Illustration of the way the CKF iteratively explores measurements from collision point outwards.

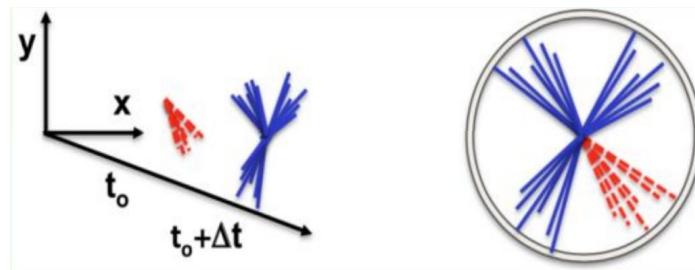
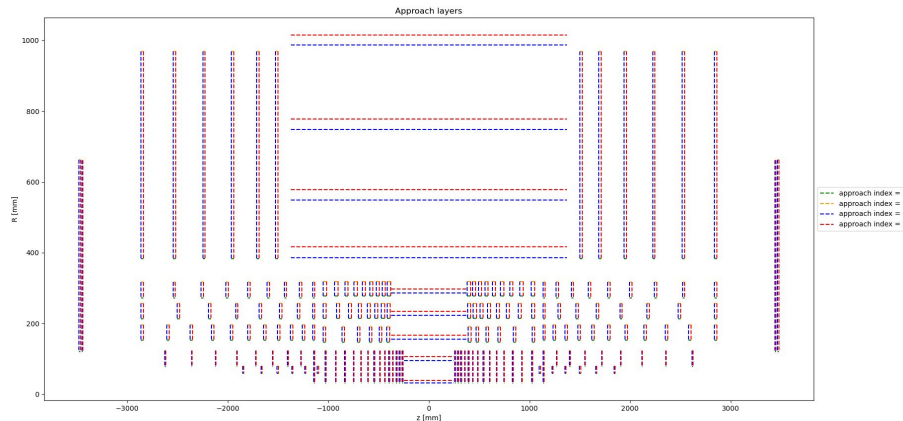


Illustration on how the time coordinate can be used to isolate hard scatter tracks from pileup

# WG 5.2 - 4D Tracking (in intersection with WG2)

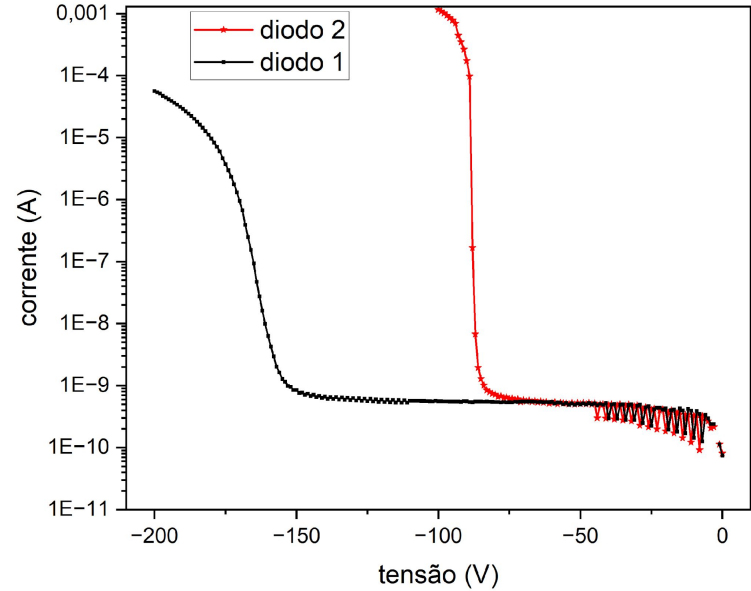
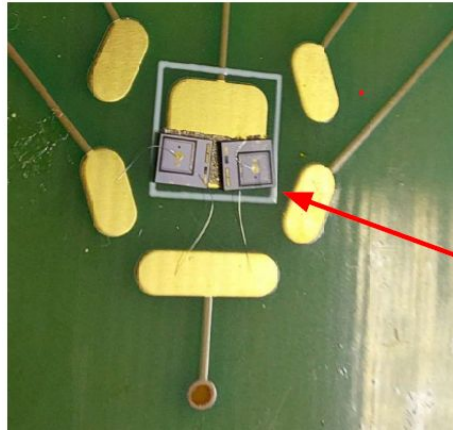
- We managed to setup ACTS with ITk + HGTD geometry
- Next step will be to extract the efficiency of CKF in ttbar events with pileup  $\langle u \rangle = 200$  (simultaneous collisions) in 3D
  - Timing information residual
  - track reconstruction efficiency
- Following that, we will work on the integration of the timing information in the processing chain to have a 4D reconstruction



*ITk + HGTD sensor layout in ACTS*

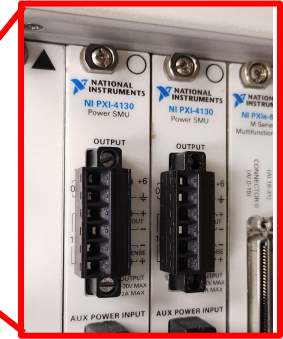
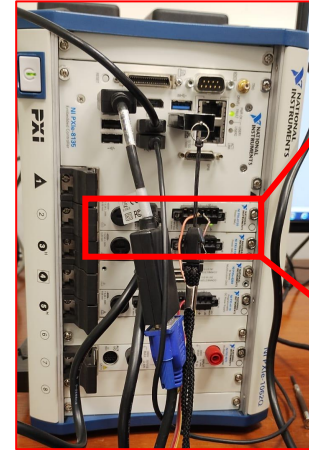
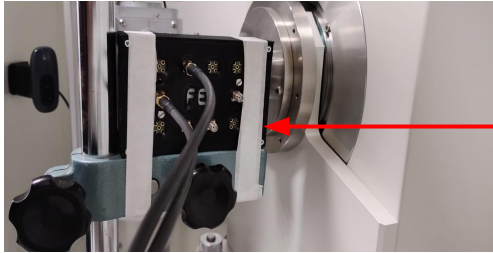
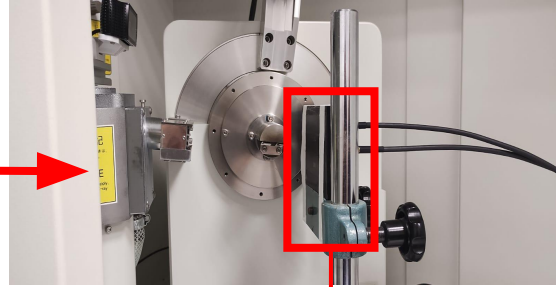
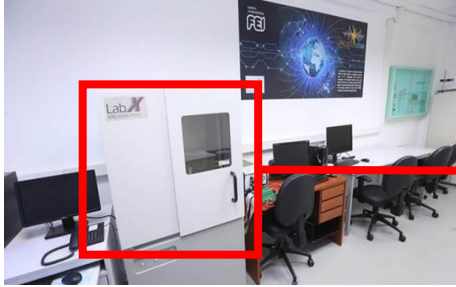
# WG 5.2.2 : Low Energy Applications

- LGAD TID tests (X-ray) @ FEI board with HPK 3.1 & 3.2 wire bonded



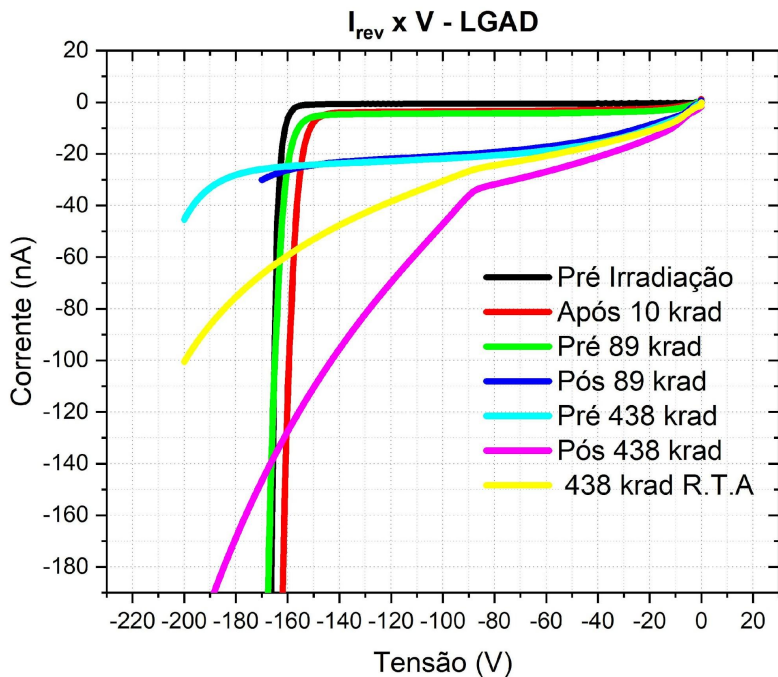
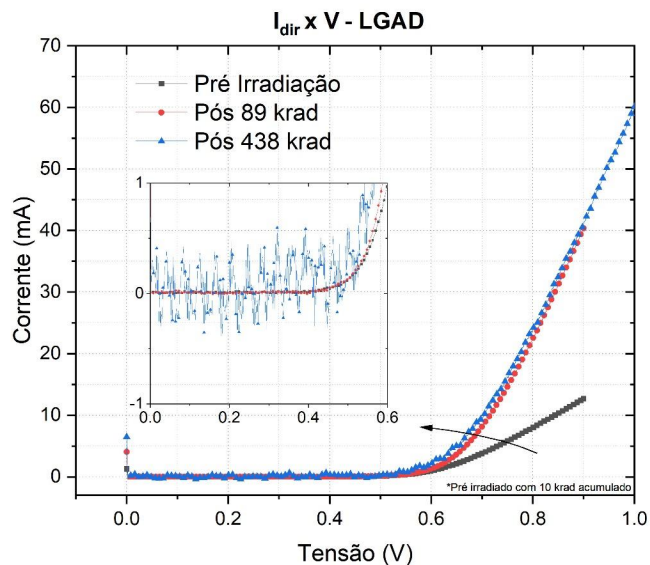
# WG 5.2.2 : Low Energy Applications

- LGAD TID tests (X-ray) @ FEI board with HPK 3.1 & 3.2 wire bonded -
  - 10 keV x-rays irradiation at several doses
  - IV with SMU (NI)



# WG 5.2.2 : Low Energy Applications

- LGAD TID tests (X-ray) @ FEI board with HPK 3.1 & 3.2 wire bonded : IV before/after irradiations



# WG 5.2.1 & WG 5.2.2 : ACTION ITEMS FOR NEXT MONTHS

ATLAS  
HGTD

- USP infrastructure
  - Most critical item
  - Involves space, import and equipment purchase
  - Needs to prepare lab infrastructure while space discussion is on-going
- DAQ development and DB integration @ USP (in sync with CERN/IHEP/USTC/JSI)
- Infrastructure (baby demo and mockup) @ CERN
- Build the laser system with motorized stages + position measurement (**critical!**)
- Studies on 4D tracking integration (ACTS for iTk, HGTD)

on track

critical

new

New  
applications

- Validate first functional TCAD and Geant4 simulation
- Add Ad-hoc simulation code for multiplication mechanism
- Analyze data from TB @SLAC, resume discussion with Sirius (more people involved...)
- Understand irradiation needs and prepare infrastructure/tests at local facilities
- Explore/Converge designs for fabrication (WG 5.2.3 - see Ronaldo's presentation)

New  
involvements

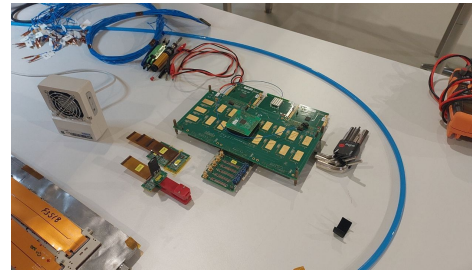
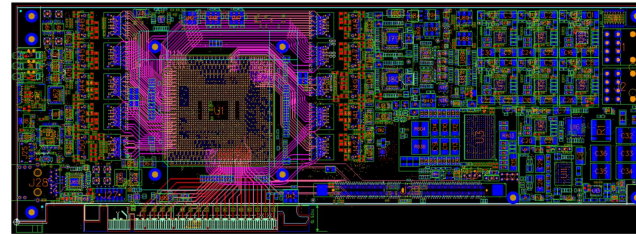
- ECFA Detector Roadmap : DRD3 R&D on Solid State Detectors (on-going)
- First workshop @CERN in June 17-21
- EOI on WG2 (Hybrid silicon technologies) and WG5 (Characterization techniques and facilities)
- FELIX Fase-II (see next slide)

# WG 5.2.1 & WG 5.2.2 : ACTION ITEMS FOR NEXT MONTHS

- FLX-182 prototype for DAQ
- Lauquen has accepted the challenge to fabricate a few boards in SP (24 layers, 2 stackup assembly)
- Xilinx Versal FPGA
- Ongoing discussions with Eldorado to assemble/test the hardware
  - subcontract to company in Campinas (Hwit)
  - Eldorado may also help on firmware
- Very good case of industry involvement for a high complex project useful across many areas
- Readout exercise @ USP with PEB development board



Figure 5.1: Fully assembled FLX-182 prototype card.



STACKUP(DETAILS - 24 LAYERS [NOT TO SCALE])	
SOLDERMASK	L01 TOP
PR1C353/PR1C75	L02 GROUND1
CORE1078	L03 POWER1
24PR1C035/PR1C75	L04 GROUND2
CORE1078	L05 SIGNAL 1
24PR1C035/PR1C75	L06 GROUND3
CORE1078	L07 SIGNAL2
24PR1C035/PR1C75	L08 GROUND4
CORE1078	L09 SIGNAL3
24PR1C035/PR1C75	L10 GROUND5
PR1C353/PR1C75	L11 SIGNAL4
24PR1C035/PR1C75	L12 GROUND6
CORE1078	L13 POWER2
24PR1C035/PR1C75	L14 POWER3
CORE1078	L15 GROUND7
24PR1C035/PR1C75	L16 SIGNAL5
CORE1078	L17 GROUND8
24PR1C035/PR1C75	L18 SIGNAL6
24PR1C035/PR1C75	L19 GROUND9
CORE1078	L20 SIGNAL7
24PR1C035/PR1C75	L21 GROUND10
CORE1078	L22 SIGNAL8
PR1C353/PR1C75	L23 GROUND11
SOLDERMASK	L24 BOT

95.46 +/- 0.1mm  
2.902mm +/- 0.021  
0.52mm +/- 0.04  
1.07mm +/- 0.03mm

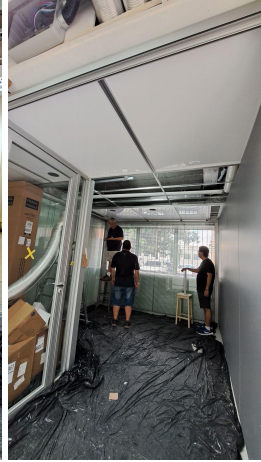
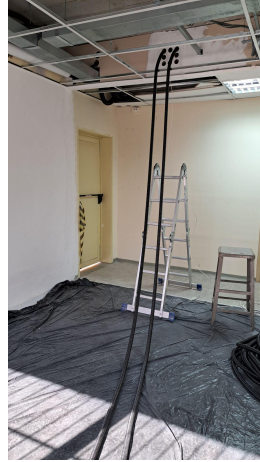
**Any Questions ?**





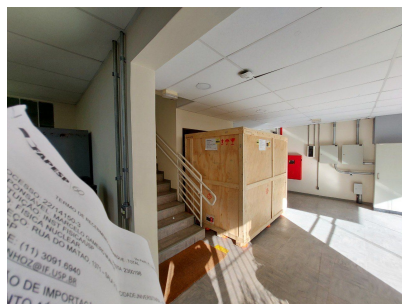
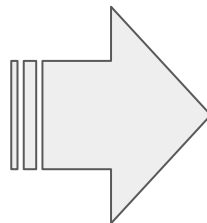
**BACKUP**

# WG 5.2.1 : ATLAS HGTD - Infrastructure @USP



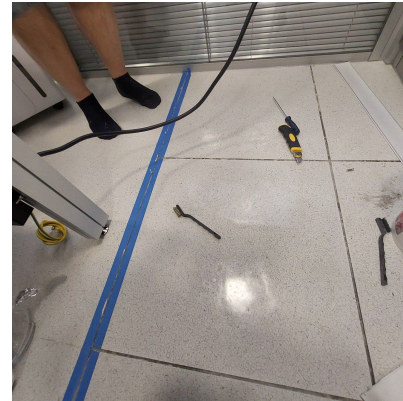
# WG 5.2.1 : ATLAS HGTD - Infrastructure @USP

- After more than one and half year we finally got the area to install the probe station
- Area is far from ideal
  - Nonetheless we made it work



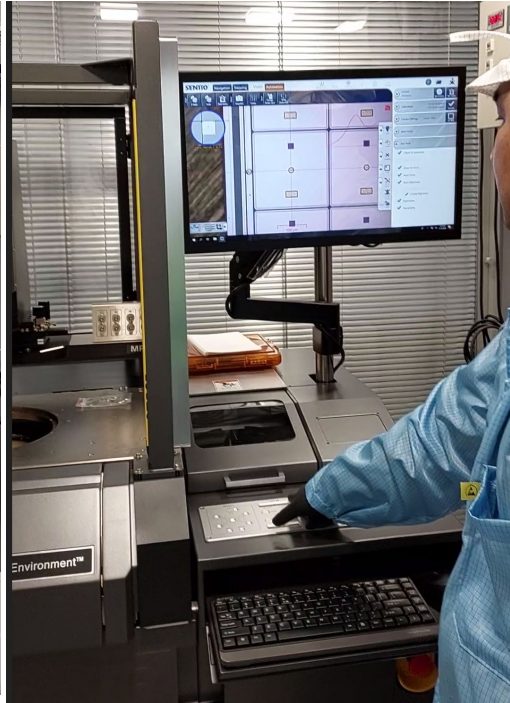
# WG 5.2.1 : ATLAS HGTD - Infrastructure @USP

Water leaking from tile joints ....



# WG 5.2.1 : ATLAS HGTD - Infrastructure @USP

February 13th 2024 - The machine is installed by MPI USA engineers



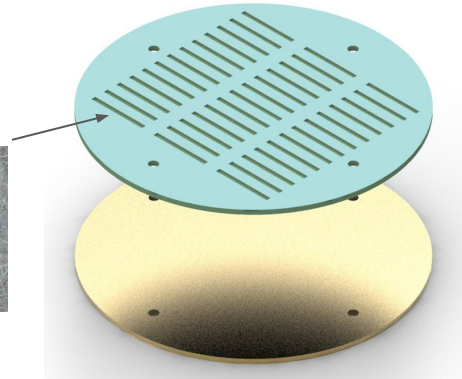
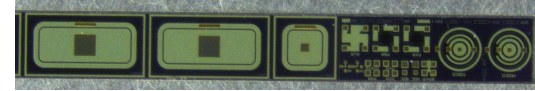
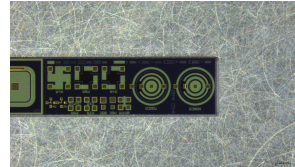
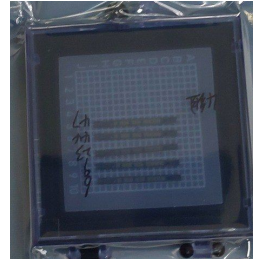
- Iso-6 cleanliness (filtered air)
- Thermal isolation provides +/- 0.5C stability
- 30% humidity
- 2 Ethernet connected PLC systems controls and monitors everything in the the room (developed by us)
- Many other nice improvements on the way...

# WG 5.2.1 : ATLAS HGTD - Infrastructure @USP



# WG 5.2.1 : ATLAS HGTD - QA/QC

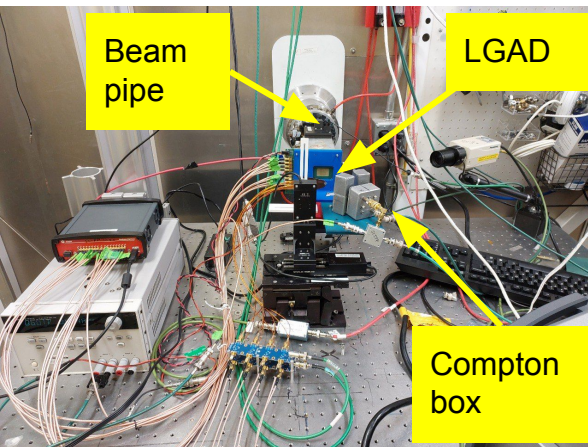
- There is a lot of work ahead
- Structures from pre-productions are already being sent to USP for testing
- HGTD sensor PRR mid March
- Need to evaluate
  - systematics on parameter extraction
  - calibration impact on repeatability and accuracy
  - automation achieved by structure holder
- Probe card holder just arrived yesterday
- Cabling will be done in the next days



# WG 5.2.2 : UFSD for Applied Sciences

## Part-I - LGADS for picosecond time resolved X-ray testing

SSRL BL 11-2



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### Synchrotron light source X-ray detection with Low-Gain Avalanche Diodes

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<sup>a</sup>SCIPP, University of California Santa Cruz,  
1156 High Street, Santa Cruz, CA, U.S.A.

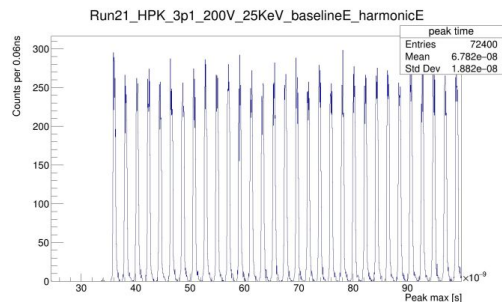
<sup>b</sup>Universidade de São Paulo,  
São Paulo, SP, Brazil

<sup>c</sup>Brookhaven National Laboratory,  
Upton, NY, U.S.A.

<sup>d</sup>IPEN-CNEN,  
São Paulo, SP, Brazil

E-mail: simazza@ucsc.edu

- Paper on SLAC test with UCSC published on JINST Oct. 2023
- Since then, results were also presented at :
  - 13th International Conference on Position Sensitive Detectors
  - 13th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors
  - 43rd RD-50 Workshop
  - 33rd RAU LNLS/CNPEN



Bunch structure



## Equipe FEI

Marcilei a Guazzelli

Marcelo Pavanello

Marco Assis

Renato Giacomini

Roberto Baginski

Thalia Alves – Mestrado

Alexis Vilas Bôas – Doutorado

Paulo Garcia – Iniciação Científica + Mestrado

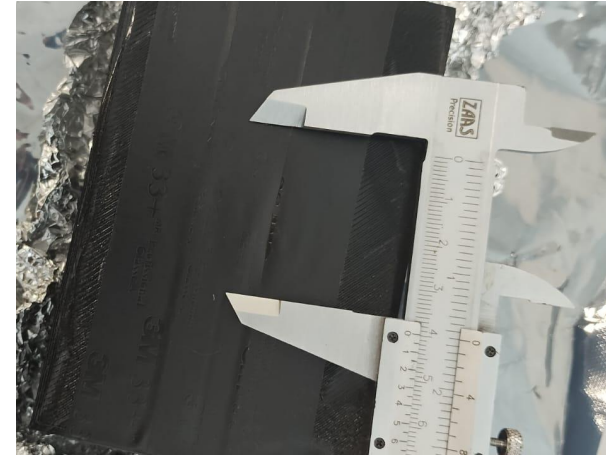
STUDY OF THE EFFECTS OF 10 keV X-RAY IONIZING RADIATION ON AN  
LGAD  
Low-Gain-Avalanche-Diode

**Objetivo Geral:** Com o objetivo de explorar as diversas possibilidades de aplicação de um LGAD, este estudo busca estabelecer uma metodologia de teste para avaliar as perdas na eficiência funcional de um detector de raios X na faixa de 10 keV, bem como explorar o dispositivo como um possível dosímetro.

**Objetivo específico:** este trabalho mostra resultados de medidas de capacitância e da corrente em função da tensão, operando no modo reverso e direto. Essas caracterizações foram feitas antes e após três etapas de irradiação com raios X de 10 keV.

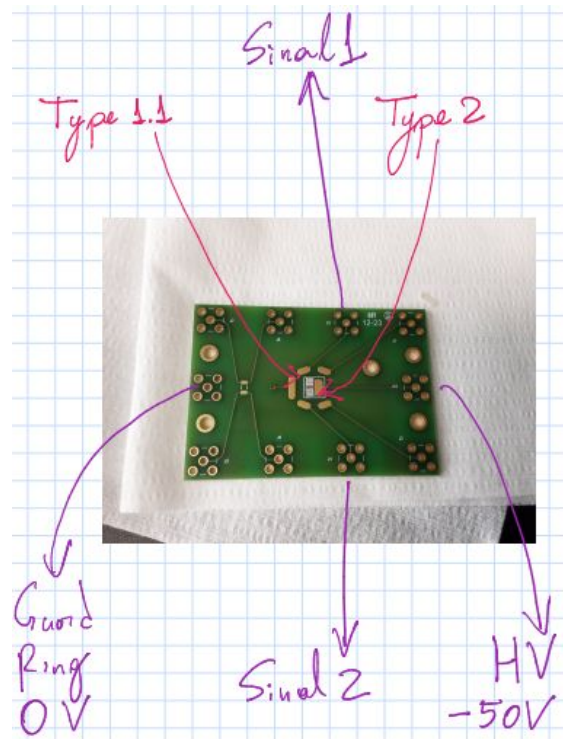
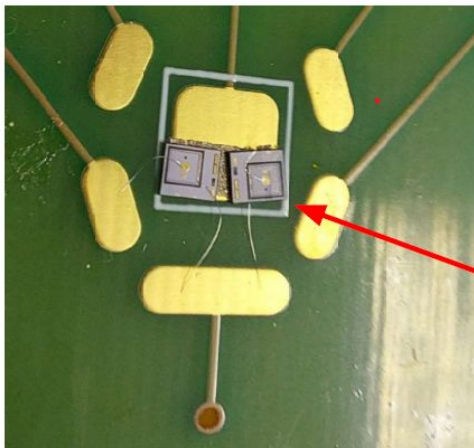
A caixa que guarda o LGAD, sofreu algumas modificações.

Para permitir mais passagem de radiação, foi realizado um furo de 4 cm de diâmetro na parte inferior da caixa. Este orifício foi isolado por uma fita isolante 3M 33+, com espessura total de 0,178 mm, “bloqueando” cerca de 26,36% da incidência de radiação.



## Procedimento Experimental - LGAD 1.

Preparação da placa de teste e do aparato de proteção aos efeitos de luz de fundo.





**Primeira irradiação:** TID1 = 10 krad  
28 krad/h (Si)

**Segunda irradiação:** TID3 = 89 krad  
60 krad/h (Si)

**Terceira irradiação:** TID3 = 333 krad  
115 krad/h (Si)

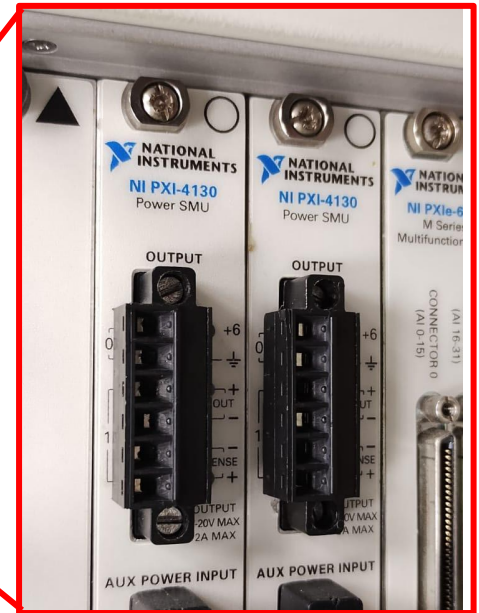
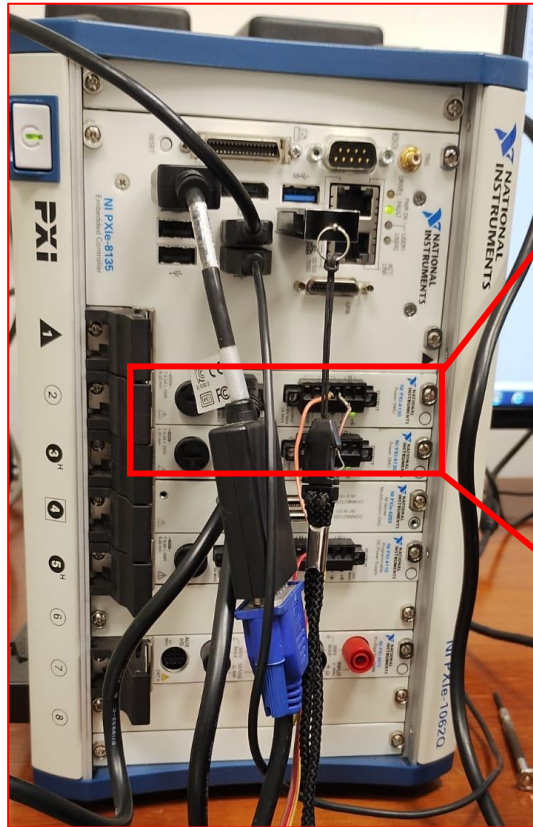
As medidas de capacitância e corrente reversa foram realizadas antes e após cada irradiação. As irradiações foram realizadas de 7 em 7 dias, para analisar o efeito de annealing térmico em temperatura ambiente, avaliando o sistema após as cargas aprisionadas no diodo entrarem em equilíbrio.





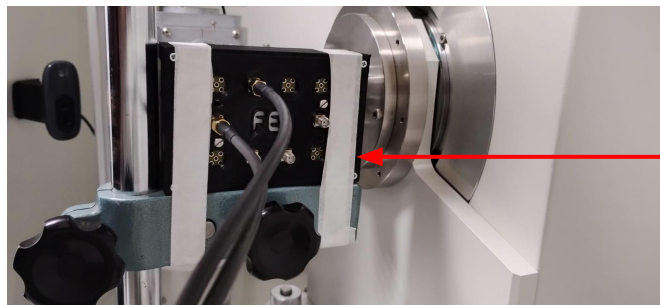
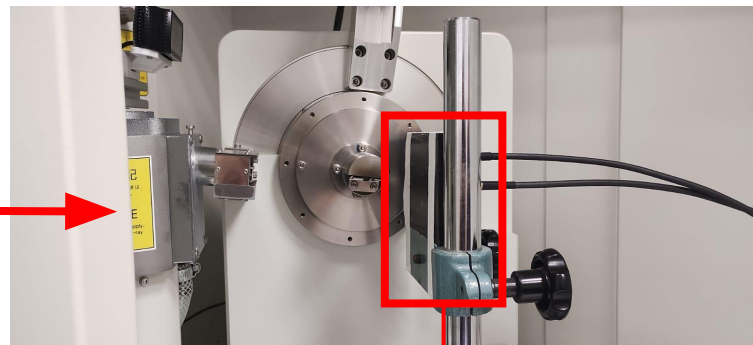
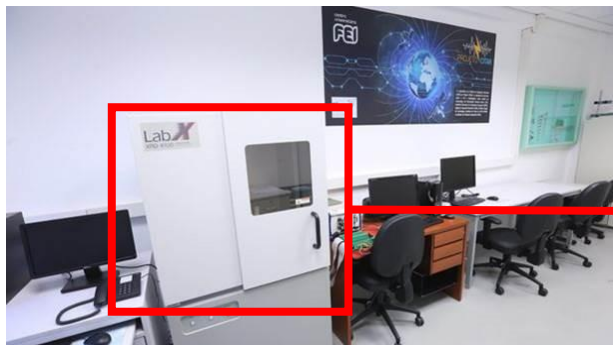
Caracterização do LGAD utilizando a infraestrutura de teste do Laboratório de Efeitos da Radiação Ionizante (LERI) da FEI.

Durante o processo de irradiação, foi utilizado a NI PXIe-8135 com as SMU 4130, para extrair as curvas de corrente direta.



Os testes de radiação, contaram com o auxílio dos equipamentos do Laboratório de Efeitos da Radiação Ionizante (LERI) da FEI.

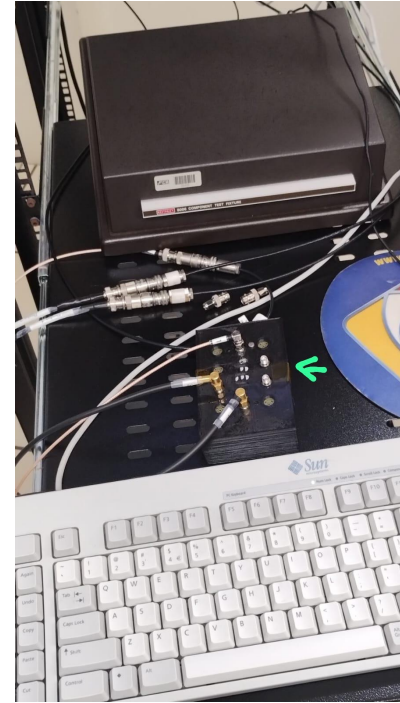
Fonte de Raio-X de 10 keV





Caracterização do LGAD utilizando a infraestrutura de teste do Laboratório de Microeletrônica da FEI, antes e após cada fase de teste de radiação.

Com o auxílio do equipamento Keithley 4200 – SCS, foi possível extrair as curvas características de capacitância e corrente reversa, antes e após a cada fase de teste de radiação.



## Resultados e Análise

Gráficos de capacitância antes e após todas as irradiações

As caracterizações estáticas por I-V e C-V são realizadas para verificar a qualidade do dispositivo. Nos LGADs, essas medições elétricas permitem estudar algumas propriedades importantes do dispositivo, como tensão de ruptura ( $V_{BD}$ ), tensão de depleção completa ( $V_{FD}$ ), tensão de depleção da camada de ganho ( $V_{GL}$ ), corrente de fuga ( $I_d$ ), capacitância (C) eregião de transição e espessura do dispositivo.

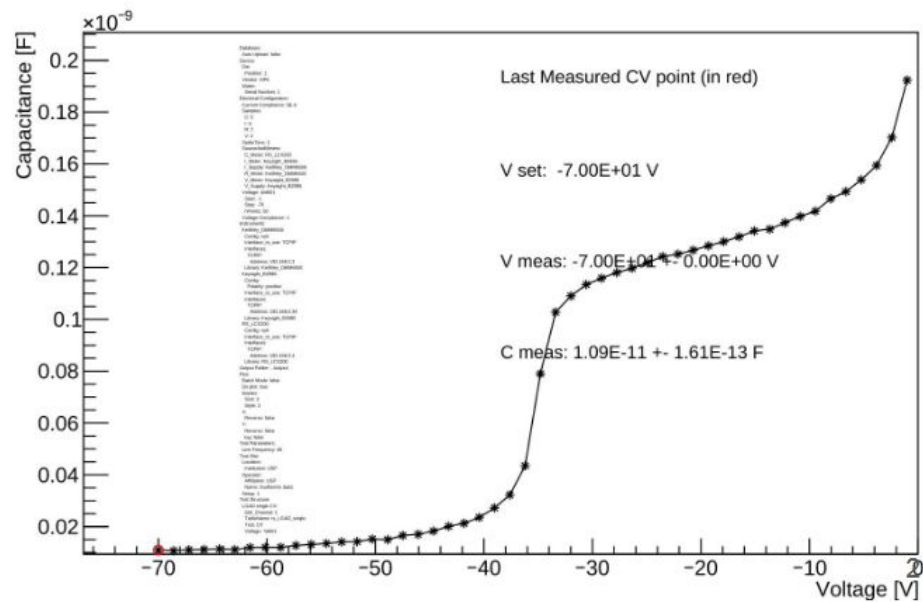
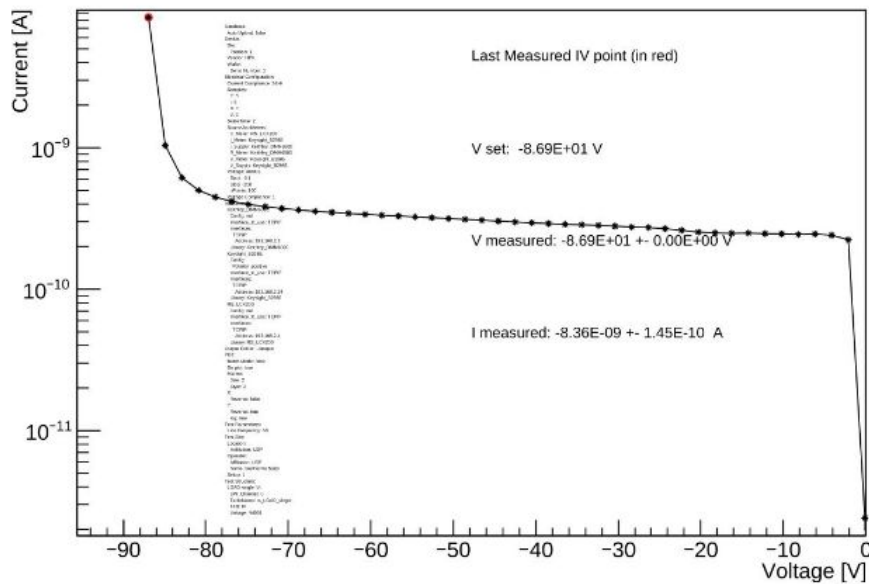
A concentração de dopagem da camada de ganho e do substrato pode ser calculada pela seguinte equação:

$$N_c(x) = -\frac{C(V)^3}{\epsilon_{Si} \cdot q \cdot A^2 \cdot \frac{dC(V)}{dV}} \quad d = \frac{\epsilon_{Si} \cdot A}{C(V)}$$

Onde  $N_c(x)$ ,  $d$ ,  $A$ ,  $\epsilon_{Si}$  e  $q$  são, respectivamente, a concentração de dopagem da camada de ganho ( $N_c$ ) como função da espessura do dispositivo ( $x$ ), a profundidade de depleção ( $d$ ) na tensão  $V$ , a área da junção ( $A$ ), a constante dielétrica do silício ( $\epsilon_{Si}$ ) e a carga elétrica elementar ( $q$ ).

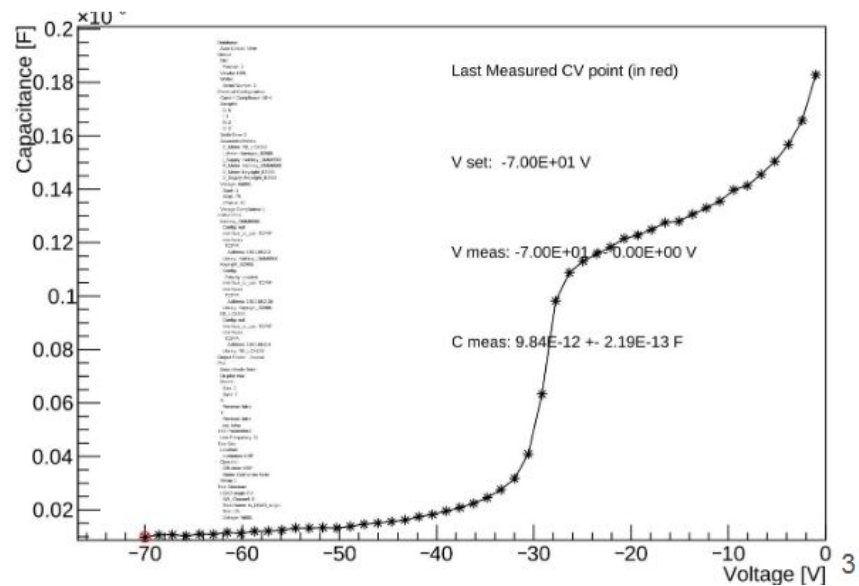
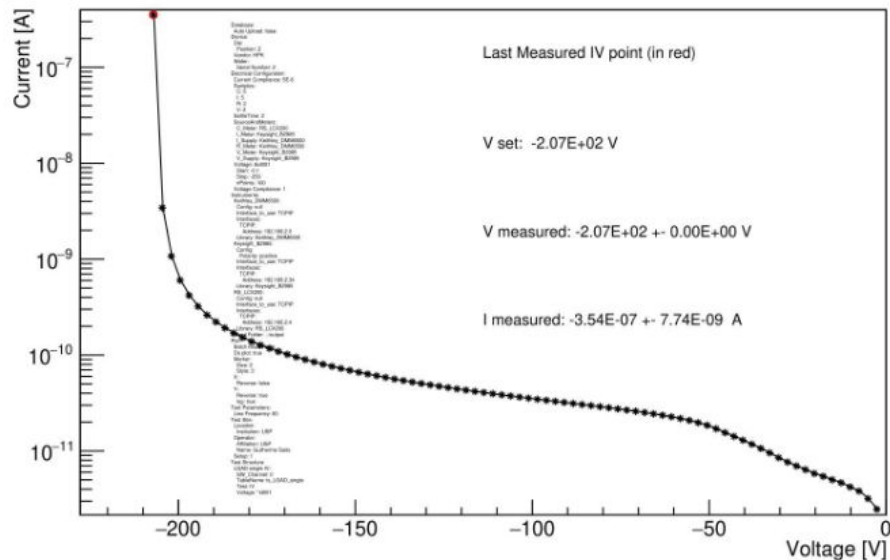
# Gráficos obtidos na USP

## LGAD -tipo 1

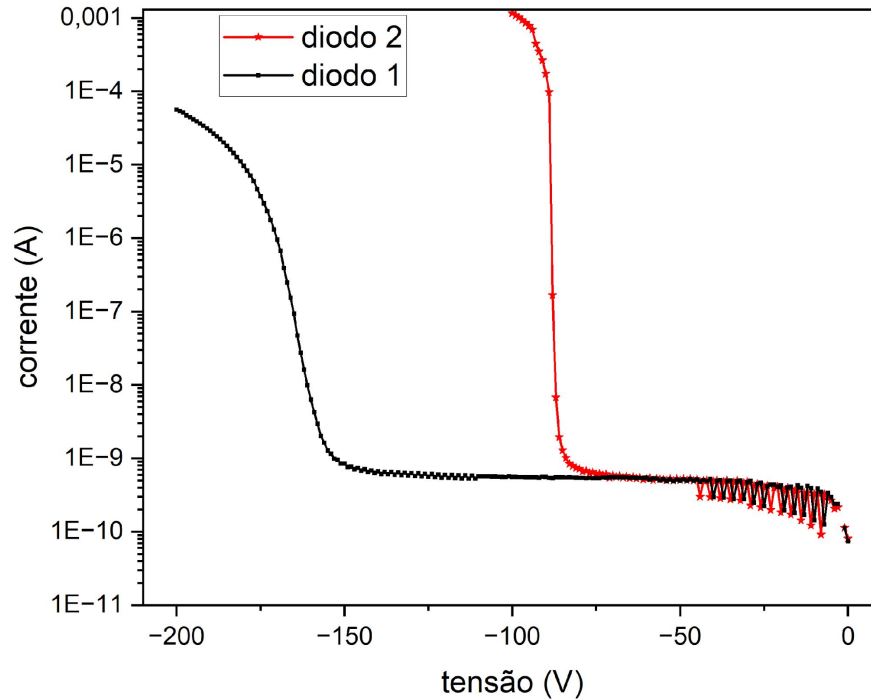


# Gráficos obtidos na USP

## LGAD -tipo 2



## Gráficos obtidos na FEI

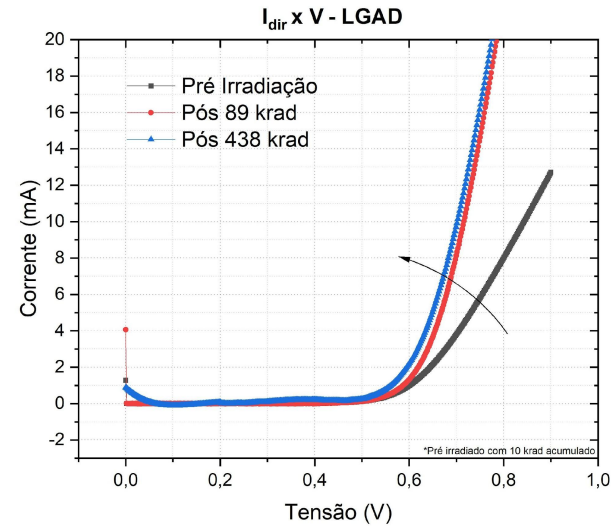
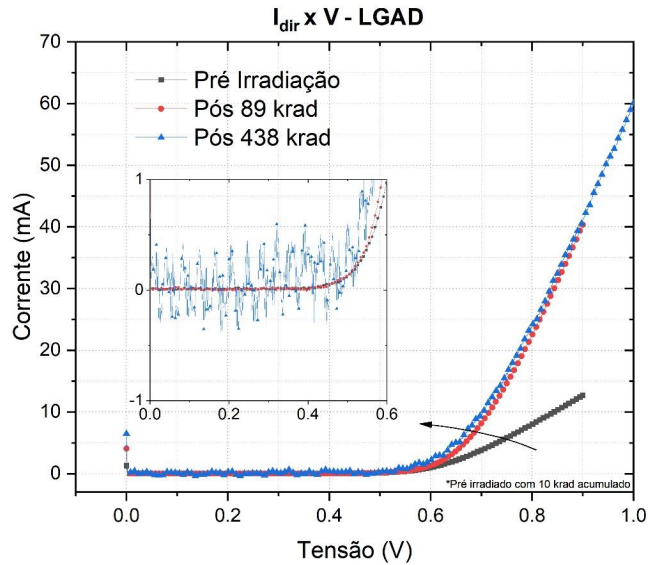


Estamos assumindo as condições iniciais de nossos experimentos com uma corrente escura um pouco maior do que a determinada na USP. Porém, todos os resultados e alterações relativas a essas condições iniciais continuam valendo. Temos um maior ruído no início das medidas: não é relevante para nossas análises

Gráficos de  $I_d \times V_d$  durante as três irradiações.

## Resultados e Análise

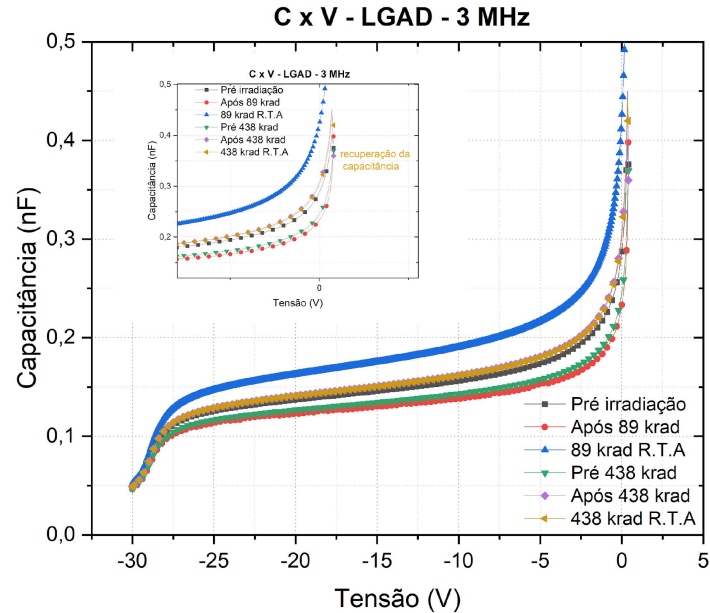
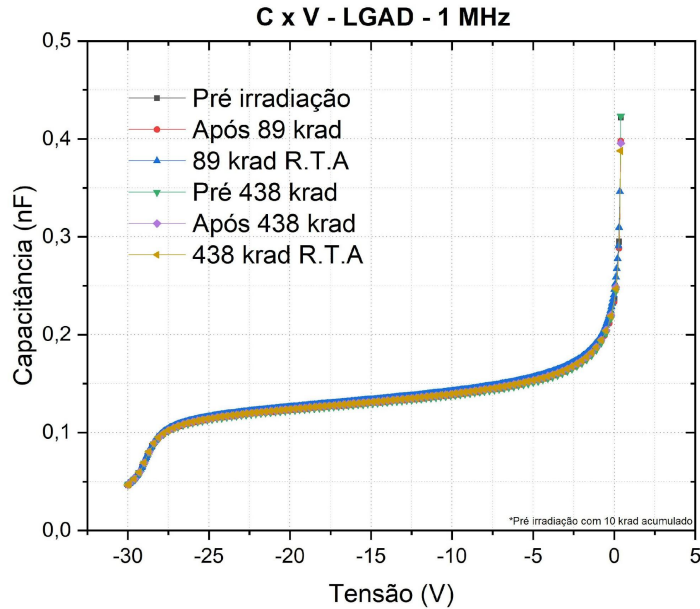
Foi retirado o ruído apenas para destacar a “rapidez” da subida da corrente com a tensão.



Os resultados de operação em modo direto demonstram que as cagas estão aprisionadas na região da junção, modificando a depleção e a resistência da característica do diodo. Com o aumento de portadores, em modo direto, podemos notar o aumento da corrente para uma mesma tensão aplicada, podendo ser consequência de alterações de funcionalidade devido irradiação. Obs: durante a radiação até 10 krad não são observadas variações relevantes nas curvas  $I_d \times V$  modo direto.

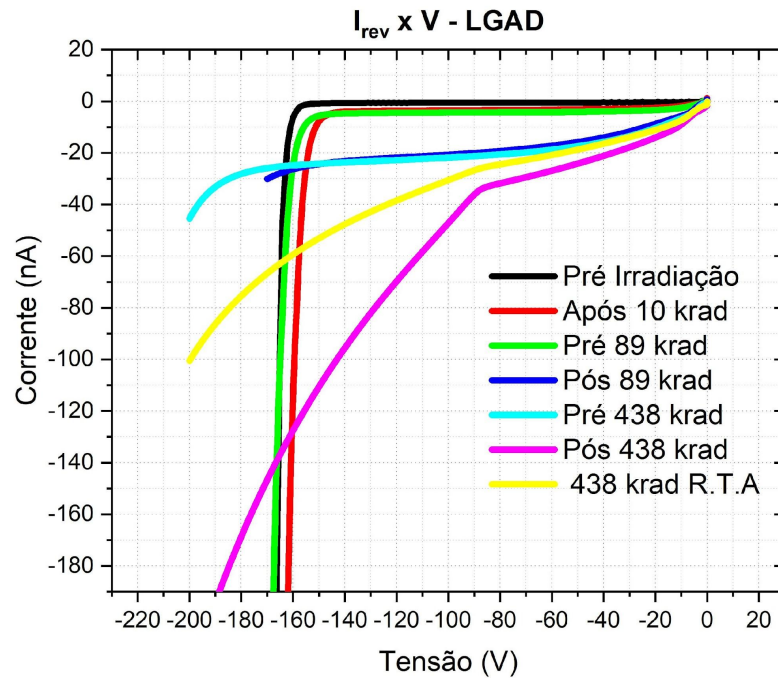
Conforme previsto no projeto, devermos adquirir uma SMU mais precisa em corrente.

## Resultados e Análise



Medidas da capacitância revelam a dependência do tempo de resposta das cargas aprisionadas por radiação em função da frequência, a qual será explorada com mais cuidado em função da dose. As curvas que aumentam um pouco mais rápido e atingem o platô, representam uma resistividade de bulk maior. Esta propriedade está relacionada às profundidades de depleção alteradas pelas cargas acumuladas devido a TID. Este comportamento deverá ser investigado metodicamente com cuidado.

## Resultados e Análise



Gráficos de corrente reversa antes e após as três irradiações

A curva da corrente em função da tensão em modo reverso mostra a degradação desta funcionalidade em função da TID (Total Ionizing Dose), embora após 7 dias de annealing em temperatura ambiente demonstre uma recuperação parcial.

Para doses de até 89 krad existe uma faixa de tensão para a qual pode ser possível explorar este dispositivo como dosímetro. Para isso será realizado um estudo sistemático utilizando taxas de dose adequadas para este estudo.

**A corrente “escura” aumenta com o aumento de TID.**



## Sumário

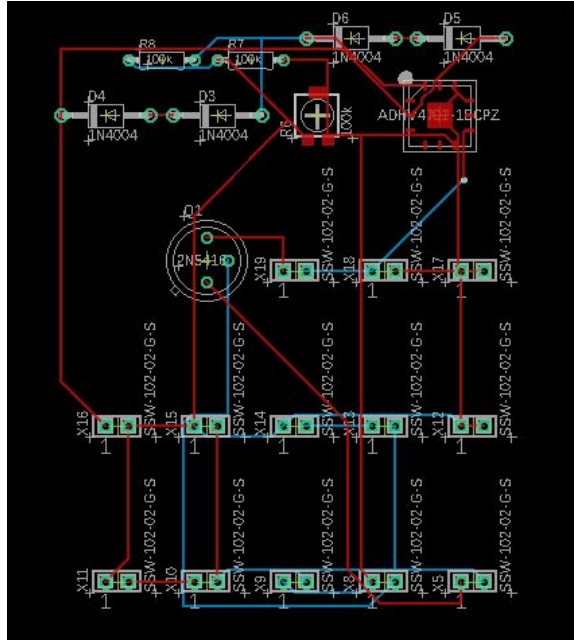
- Verificamos uma grande alteração na corrente reversa, especialmente após acumular 89 krad, sem apresentar recuperação total, em temperatura ambiente. Analisaremos o comportamento em baixas taxas de dose. Assim, poderemos determinar até que ponto a radiação compromete a funcionalidade do diodo como detector.
- Este mesmo estudo será utilizado para avaliar o comportamento e a precisão do diodo como dosímetro de radiação para raios X com energias na faixa de 10 keV.
- Observamos alterações significativas na capacitância, especialmente em frequências de 3 MHz. Portanto, realizaremos um estudo detalhado do dispositivo, antes e após cada etapa de exposição à radiação, em diferentes frequências, com o objetivo de compreender os mecanismos físicos de aprisionamento de cargas na interface do diodo e como essas cargas são mobilizadas em diferentes frequências.
- Obs: devemos monitorar também a temperatura durante o processo de irradiação.

## Em andamento

Preparo de uma placa de aquisição de dados que permita caracterizar a corrente reversa em função da tensão durante o processo de irradiação, e desta forma verificar o comportamento da corrente, em uma tensão fixa, para utilização como dosímetro. Desta forma, verificaremos os danos em LGAD por efeitos da radiação ionizante de raios X de 10 keV .

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Preparo de uma placa de aquisição de dados que permita caracterizar a corrente reversa em função da tensão durante o processo de irradiação.



Layout da placa

A placa tem como objetivo alimentar e controlar a corrente/tensão que vai para o dispositivo LGAD, além de fazer a comunicação com as SMU's 4110, 4130 e 4072

- SMU 4130 usada para controlar a corrente no DUT
- SMU 4110 usada para controlar a tensão no DUT
- 4072 voltímetro do PXI