Detectores semicondutores em física de altas energias

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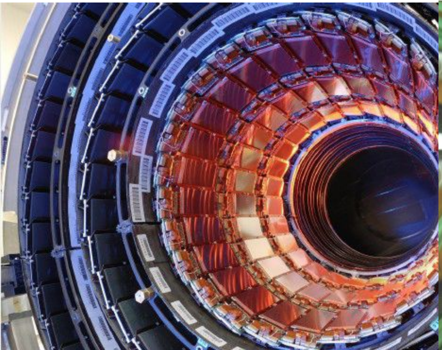
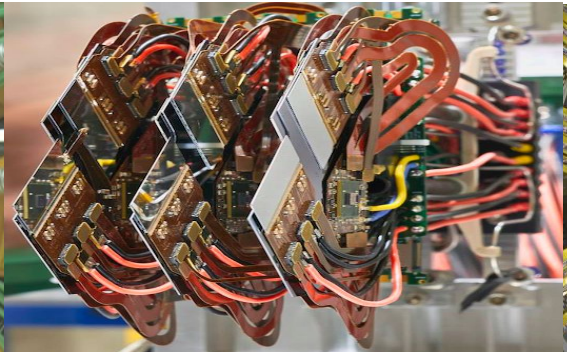
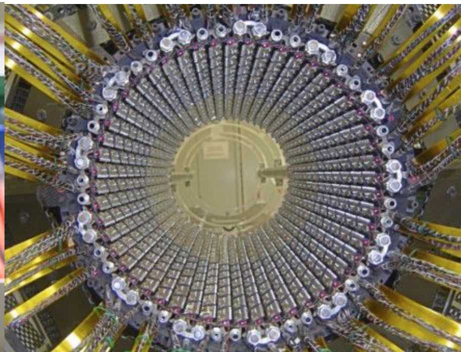
Irina Nasteva (LHCb, CONNIE & UFRJ), Marco Leite (ATLAS & USP)



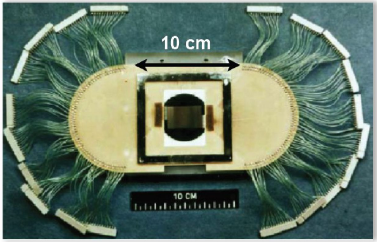



Detectores semicondutores

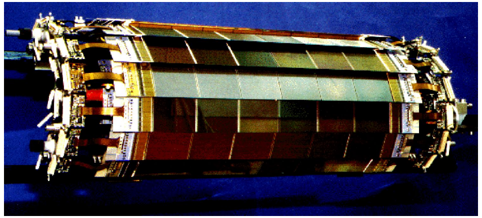
A tecnologia mais avançada de detectores, com amplo uso na física de altas energias devido a sua precisão e características favoráveis:

- Altíssima resolução espacial – segmentados em pequenos elementos (pixels/tiras).
- Reconstrução precisa de vértices primários e secundários (tempo de decaimento), parâmetro de impacto.
- Boa resolução temporal – curtos tempos de coleta.
- Excelente resolução de energia – linearidade, grandes amplitudes dos sinais.
- Mecanicamente estáveis – facilidade de manusear, podem operar em vácuo.
- Compactos, pouco material para não deteriorar medidas de trajetórias.
- Usados perto do ponto de colisão – o desafio é obter alta resistência a radiação (resfriamento).

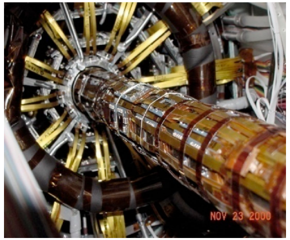
1982
Primeiro uso em NA11



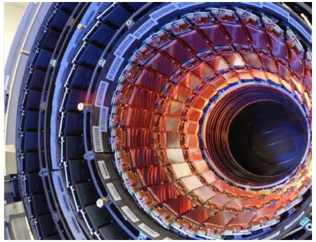
1989
Experimentos no LEP
(DELPHI)



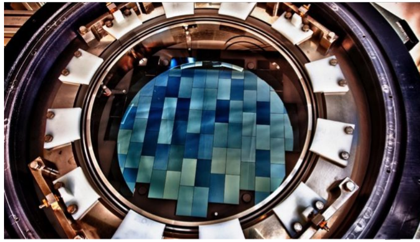
1989
Tevatron (CDF)



2008
LHC (CMS)

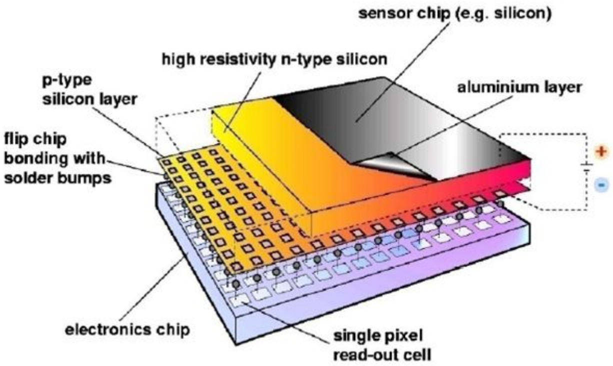


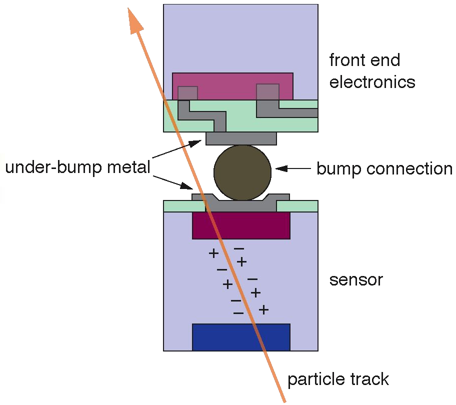
CCDs em astronomia
2010 - DAMIC

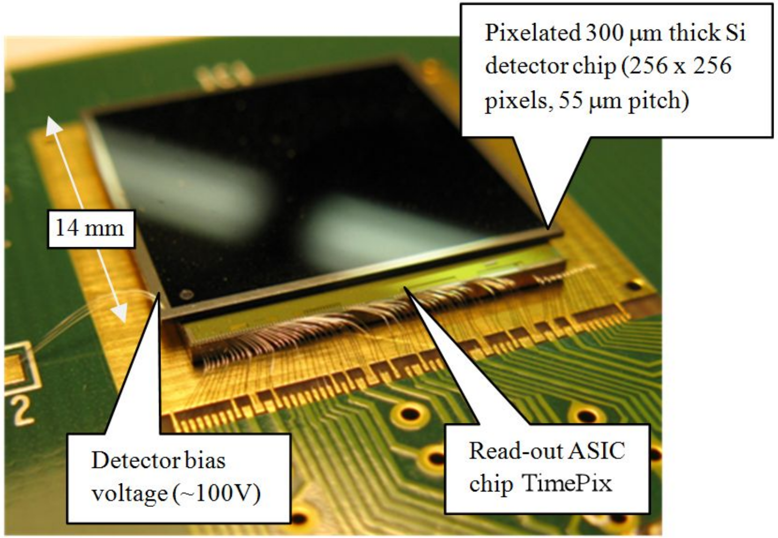


Aplicações

- Detectores semicondutores são desenvolvidos para a física de partículas e usados em várias áreas: imageamento médico, dosimetria, indústria aeroespacial…
- Um exemplo muito bem sucedido do detector híbrido de pixel Timepix3:







Cada pixel tem sua eletrônica analógica e digital
Bump-bonding entre sensor e ASIC chip
Pouco espaço morto
Possibilidade de usar variados sensores: Si, CdTe, GdAs, etc.

Desenvolvido no CERN
https://medipix.web.cern.ch

Aplicações

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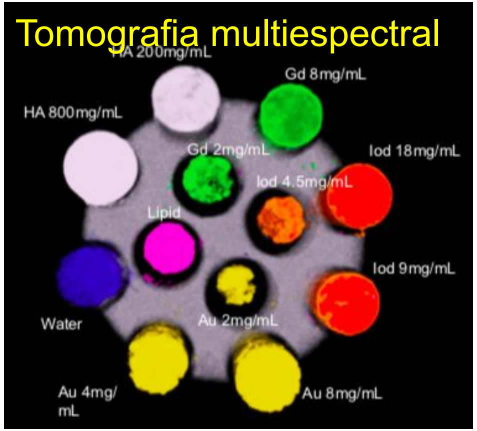
- Um exemplo muito bem sucedido do detector híbrido de pixel Timepix3:

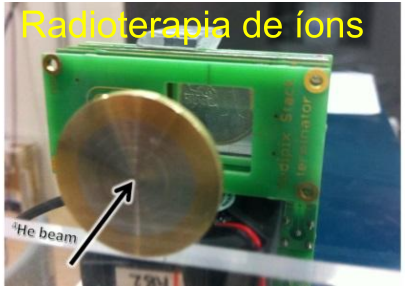

Velopix – upgrade I do LHCb


Estação Espacial Internacional – monitoramento de radiação

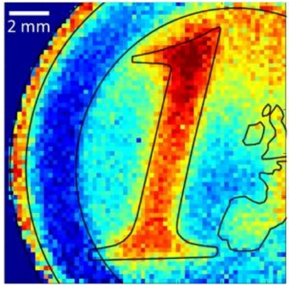


Tomografia multiespectral


Telescópio de reconstrução de traços



Radioterapia de íons



+ Dosimetria no ATLAS
+ Microscopia de elétrons
+ Imagens de raios-x
+ Câmeras óticas

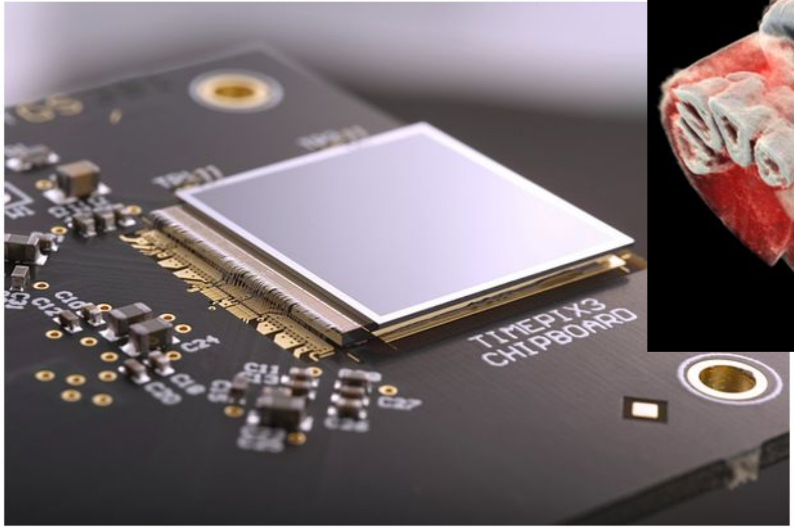
https://kt.cern/technologies/timepix3

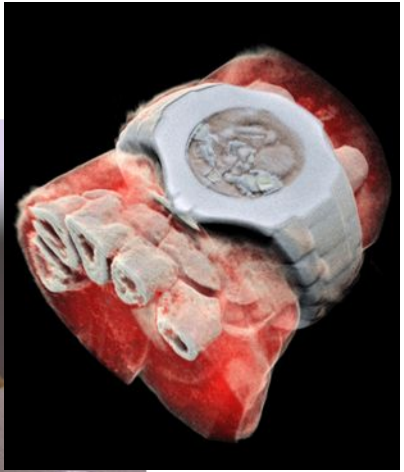
Aplicações

First 3D colour X-ray of a human using CERN technology

First human scanned with next-generation 3D colour scanner using CERN technology

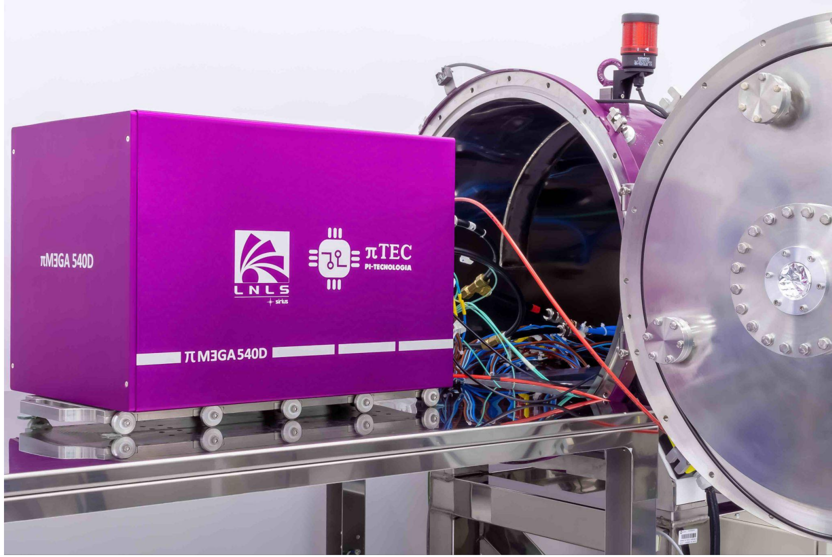
17 JULY, 2018 | By Romain Muller





Timepix3, one of the read-out chips of Medipix (Image: CERN)

Indústria brasileira: Pitec desenvolve detectores de raios-x baseados no Medipix3RX em colaboração com Sirius



Apresentação de Larissa Mendes RENAFAE 2022
https://indico.cern.ch/event/1124802/contributions/4834533/

Sensores para alta luminosidade

LHCb Phase I Upgrade | LHCb Phase II Upgrade

Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
$L = 2 \times 10^{33}$	HL-LHC Installation, ATLAS/CMS Phase 2 upgrades	$L_{int} \sim 50\ fb^{-1}$		$L = 1\text{-}2 \times 10^{34}$		$L_{int} \sim 300\ fb^{-1}$

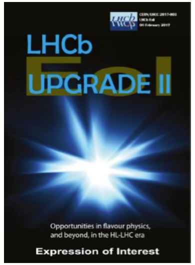
2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2040

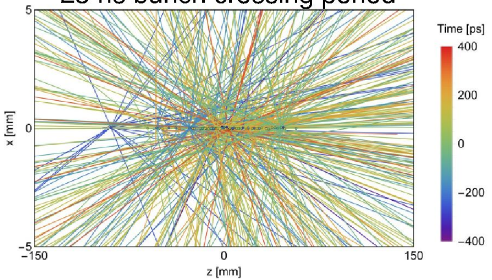
Grandes desafios experimentais para o futuro detector de vértices VELO do LHCb no LHC com alta luminosidade:

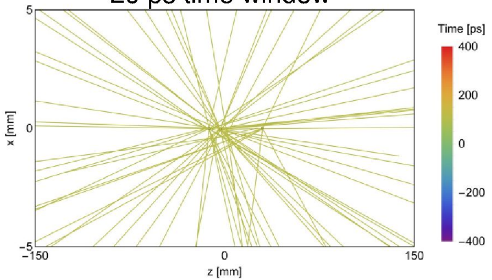
- Alta multiplicidade e densidade dos traços (50 pileup/colisão).
- Altas taxas dos dados (4.5×10^9 hits/s).
- Aumento nos danos de radiação (até $5 \times 10^{16}\ n_{eq}$ a r = 5 mm da colisão).
- Precisa manter a performance e resolução espacial.

=> Incluir medidas precisas do tempo (~30 ps resolução por traço)

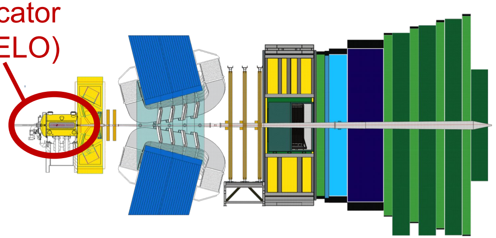
CERN-LHCC-2017-003







Vertex Locator (VELO)

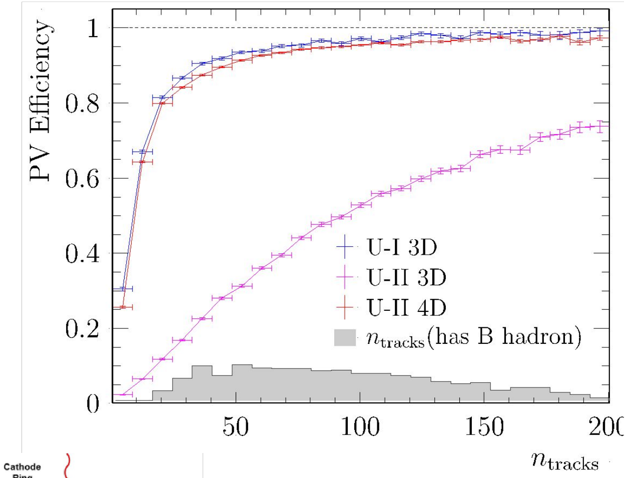


LHCb-TDR-023

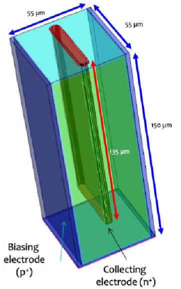
Novos sensores com reconstrução em 4D

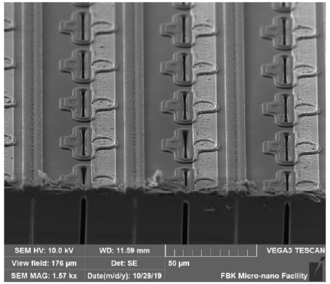
Busca por novas tecnologias de sensores e chips de leitura no LHCb:

- Timepix-4 tem resolução de 200 ps (Velopix2 ?).
- Sensores 3D TimeSpot (50 ps); ou sensores planos finos.
- Low-Gain Avalanche Detector LGAD (20 ps).
- Cenários considerados para o LHCb VELO: 4D tracking, afastar do ponto da colisão, ou planos de timing.
- Novas soluções em resfriamento (–30C).
- Temos até 2030 para o Upgrade 2 e o novo detector VELO.



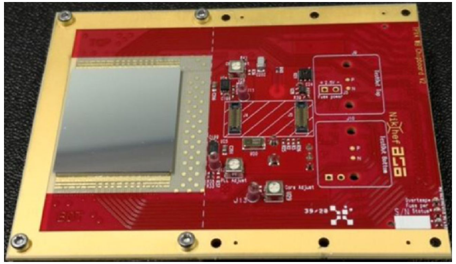
TimeSPOT

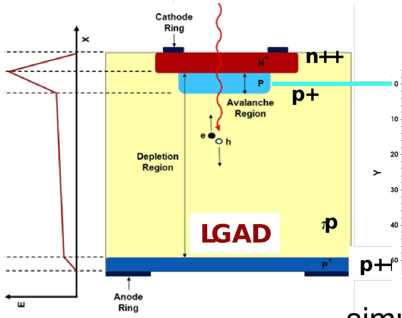


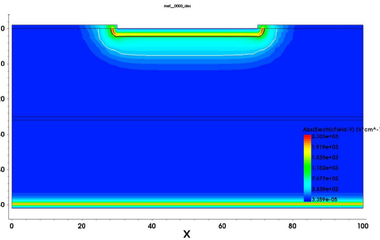


https://web.infn.it/timespot/

Timepix4

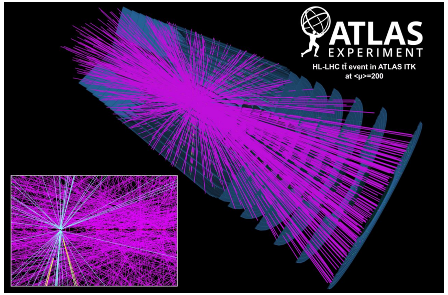




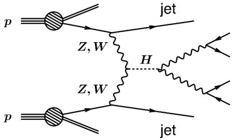


simulação de LGAD

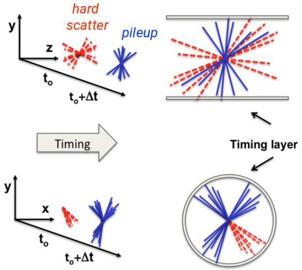
Ultra-fast timing is a key method for exploring HL-LHC physics



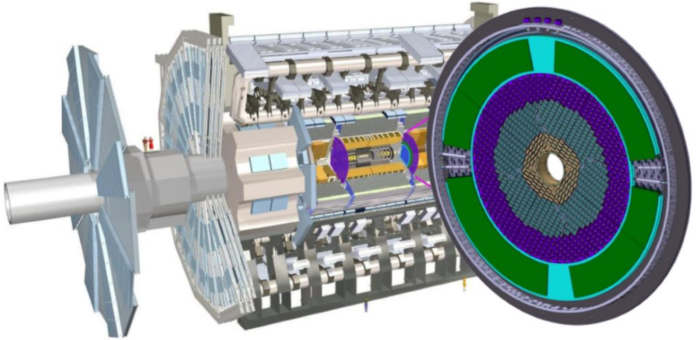
- ➔ most of LHC data are expected to come from HL-LHC phase (~$4ab^{-1}$)
- ➔ unprecedented 200 simultaneous p+p collisions at every 25 nanoseconds
- ➔ pile-up dominated environment
- ➔ very challenging track-vertex association during event reconstruction
- ➔ impossible for the central semiconductor tracker to achieve the necessary spatial resolution in forward region crucial for the precision measurements in the Higgs sector (e.g.VBF)



- ➔ introduce a 4th dimension (time) in the spatial track reconstruction
- ➔ must be capable of < 30 picosecond timing resolution
- ➔ high segmentation for track association

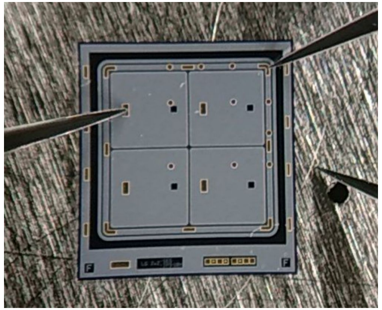


The High Granularity Timing Detector (HGTD)

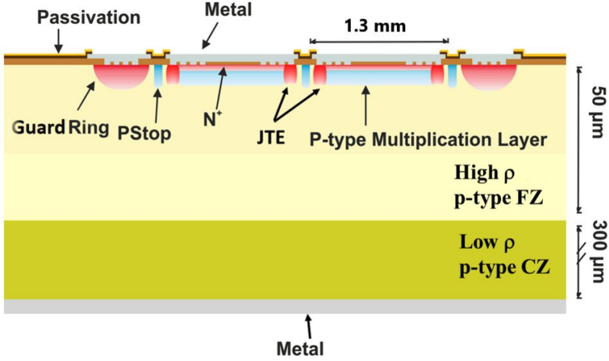


- ➔ 8 layers of ultrafast semiconductor sensors
- ➔ 16000 15x15 sensor arrays in 3 rings (3.4M channels)
- ➔ Total thickness ~ 12cm
- ➔ Total radius ~ 1.1m
- ➔ very radiation hard
- ➔ Needs very thin, very high timing resolution sensors !!

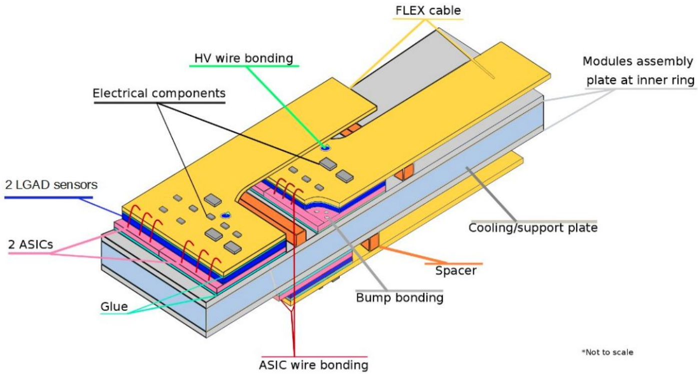
Ultra-fast semiconductor sensor (LGAD) is a key technology for ATLAS HGTD



- ➔ Low Gain Avalanche Detector (LGAD)
- ➔ state-of-the-art in ultra-fast timing (20-30 ps)
- ➔ n-on-p silicon
- ➔ highly doped p-layer under junction
- ➔ intrinsic charge multiplication, independent of thickness
- ➔ “simple” design
- ➔ 1.3x1.3mm2 (ATLAS HGTD), 1x3 mm2 (CMS MIP Timing Detector)
- ➔ can be fabricated very hadiation hard
- ➔ low material budget
- ➔ Production by CNM (Spain), Hamamatsu (Japan), FBK (Italy), Micron (UK), Brookhaven (US), IHEP (China)

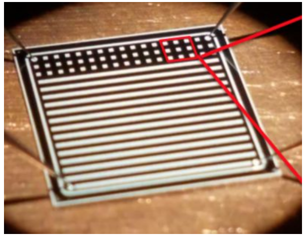


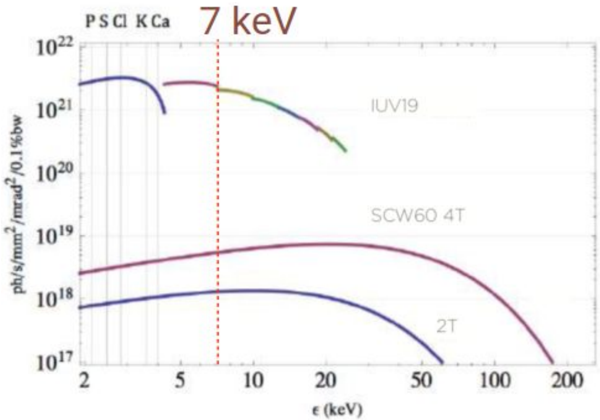
- ➔ custom ASIC readout
- ➔ flip-chip
- ➔ also provides instantaneous bunch by bunch luminosity information



Low Energy Applications

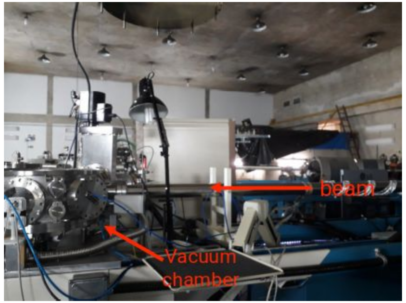
- ➔ AC-LGADs
- ➔ tens of microns spatial resolution
- ➔ sensitive to very low energy X-Rays
- ➔ rad hard, ultra fast response
- ➔ good energy resolution (S/N)

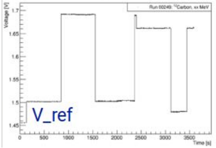


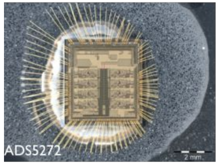


Local Irradiation facilities for Radiation Hard Semiconductor Sensors R&D

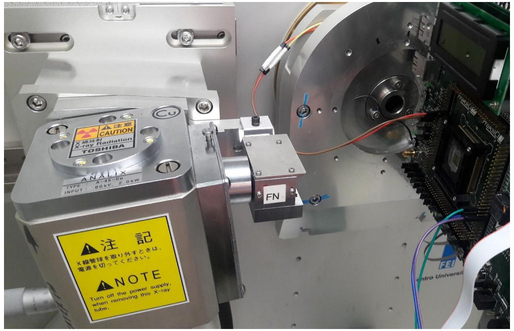
USP Pelletron accelerator: p (14 MeV) to Ag (110MeV)
Device can be tested while irradiated
Ex. COTS ADC tested for ATLAS





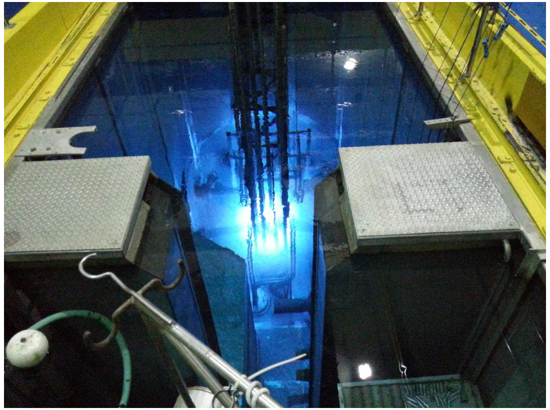


FEI x-Rays generator
Device can be tested while irradiated

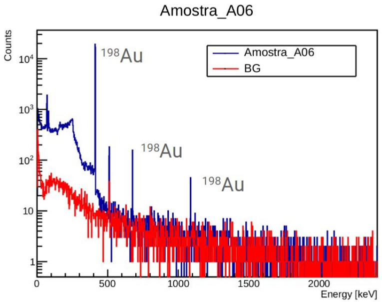


IeAV ^{60}Co source ~36 Gy/h collimated
Device can be tested while irradiated

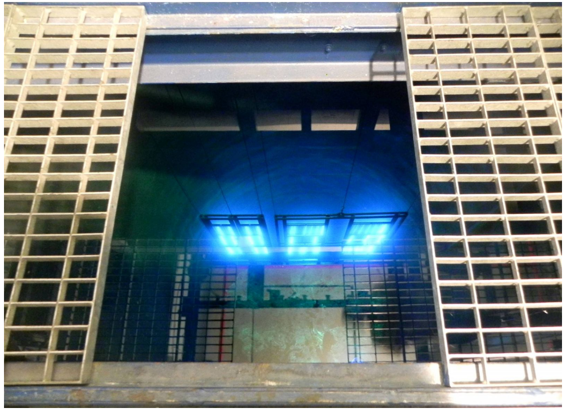
IPEN 5 MW research reactor
~10^{12} n_{eq}/cm^2s (up to 10^{13} near core)



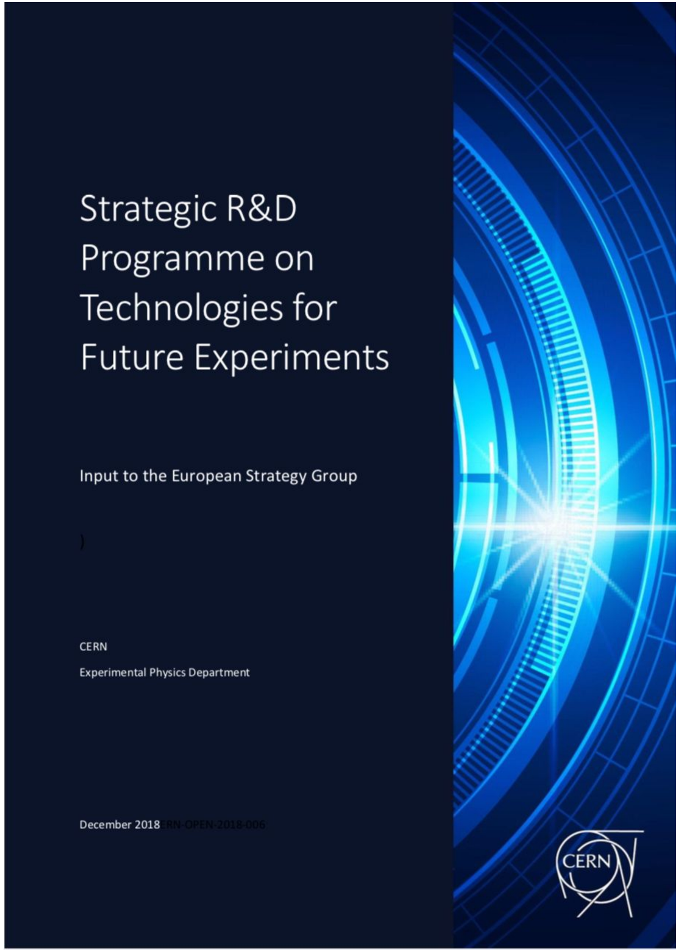
Some LGAD Sensors already irradiated @IPEN
γ spec. used to estimate dose and activation



IPEN 1 MCu industrial ^{60}Co irradiator



Ultra-fast semiconductor sensor is a key technology for future experiments and applications

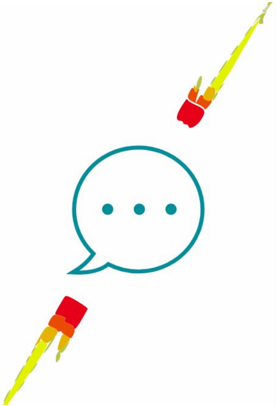


https://ep-dep.web.cern.ch/sites/default/files/Report%20final_0.pdf

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.



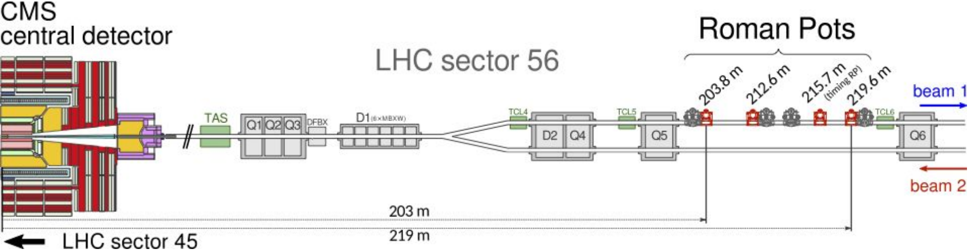
The 10 ps TOF-PET challenge

a step toward reconstruction-less TOF-PET

- a spur on the development of fast timing across disciplines and technologies
- an opportunity to collaborate as a community on a complex *final frontier* problem
- an incentive and opportunity to raise further funding
- a way to shed light on advanced nuclear instrumentation for medical imaging and beyond

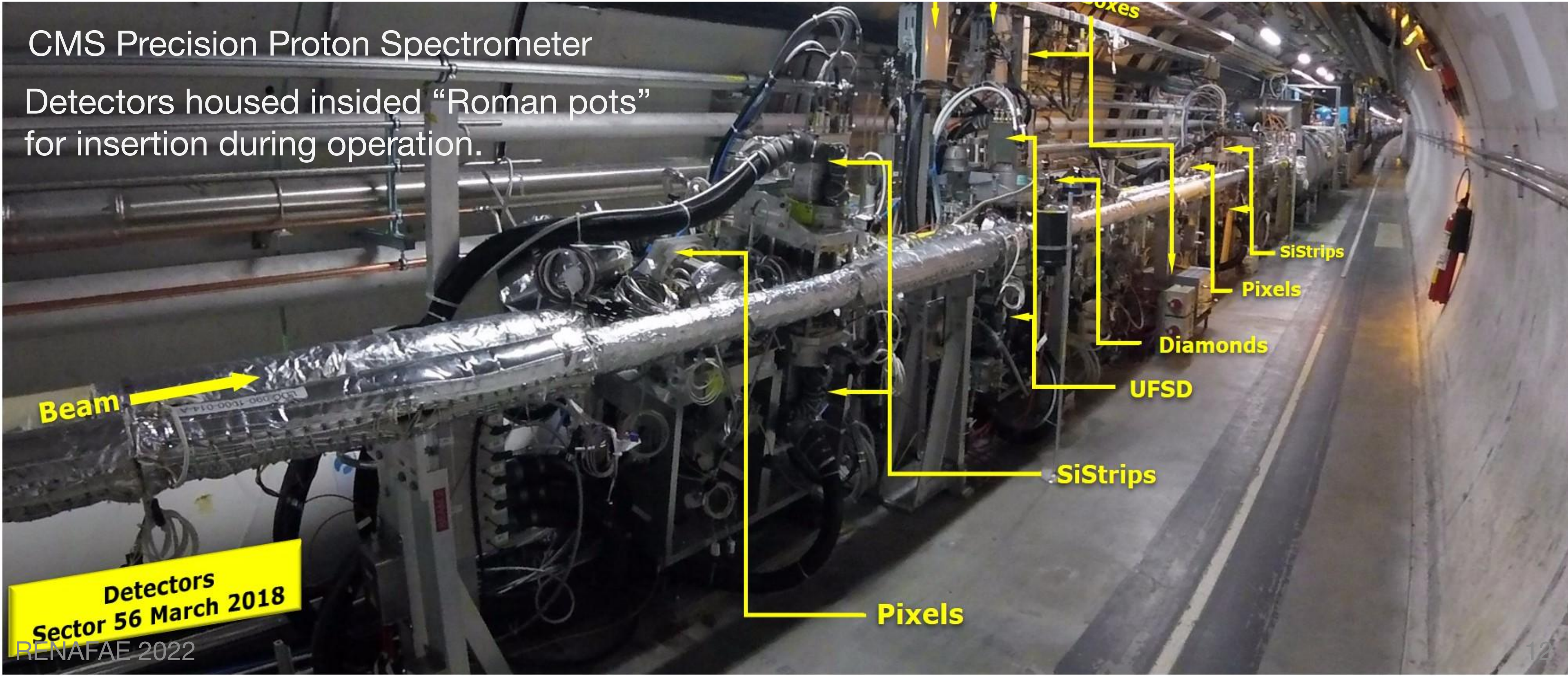
PDF version of motivations can be found here.

https://the10ps-challenge.org/

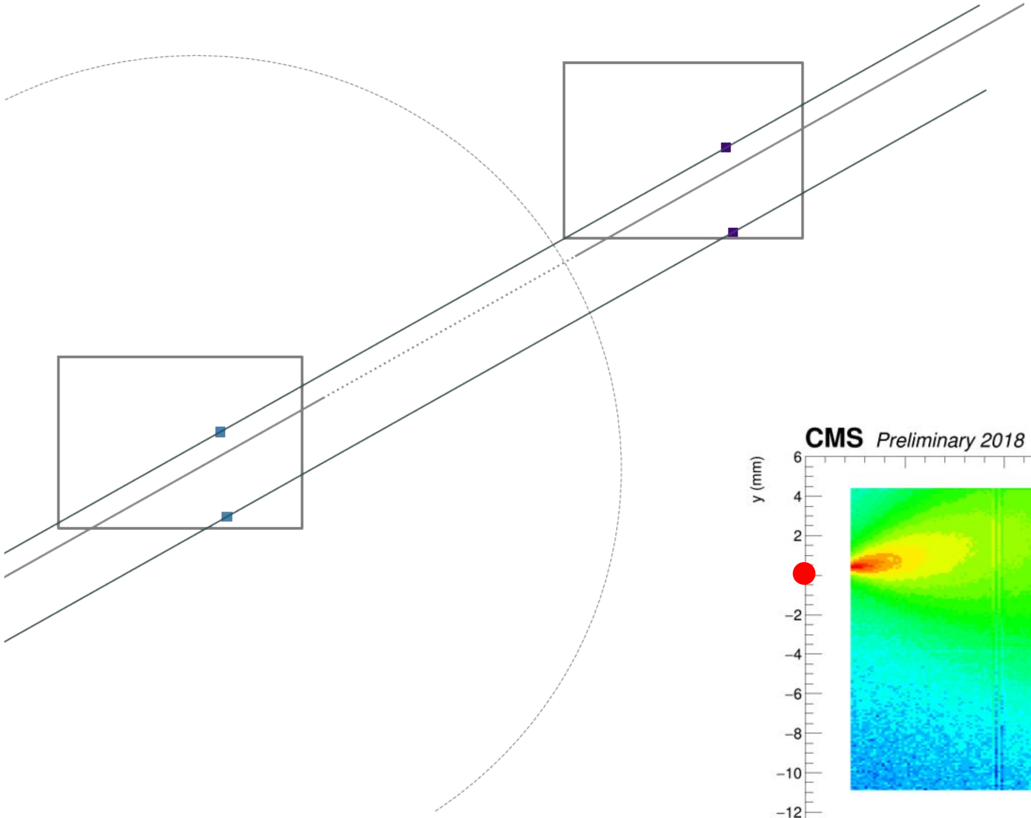


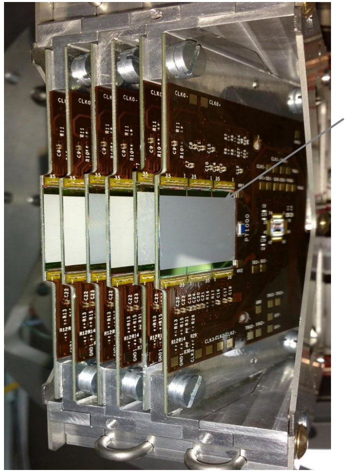
CMS Precision Proton Spectrometer

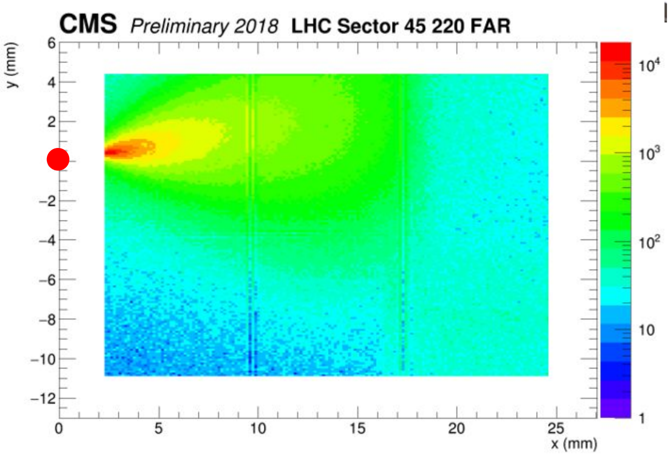
Detectors housed insided “Roman pots” for insertion during operation.



PPS tracking detectors: 3D pixels







Large and non-uniform radiation in region close to the beam.

Silicon 3D Pixels

Intrinsic radiation hardness: lifetime up to an integrated flux of 5×10^{15} p/cm^2 (100 fb^{-1})

Small inefficiency area at the edge of the sensor (slim edge ~200 μm, depending on bias voltage)

3D sensors in Run 2 (CNM):

- Double side, no passing-through columns

- Sensor thickness: 230 μm, Depth: 200 μm, Column diameter: 10 μm

- Pixel size: 100 x 150 μm^2

- 2E & 1E electrode configurations

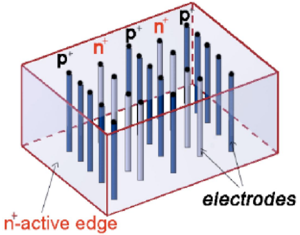
- Sensors tilted by ~18° for better spatial resolution (charge sharing)

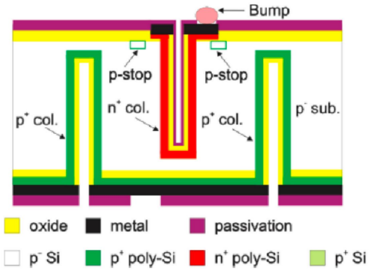
- Read-out chip: PSI46dig

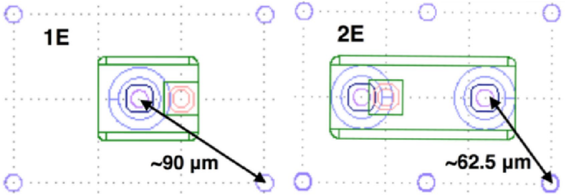
New 3D sensors for Run 3 (FBK):

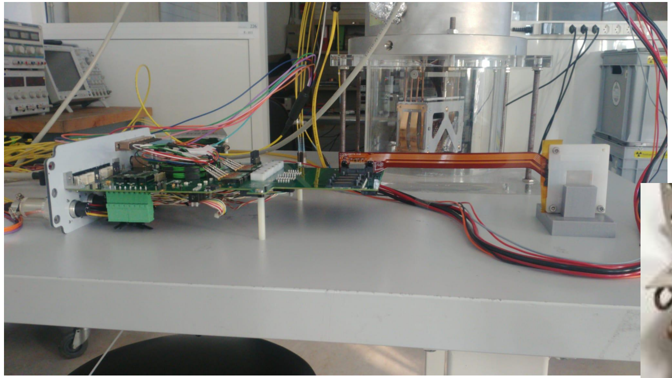
- Single side, 150 μm thickness, 2E electrode configuration

- Read-out: PROC600 (CMS Pixel Layer 1)







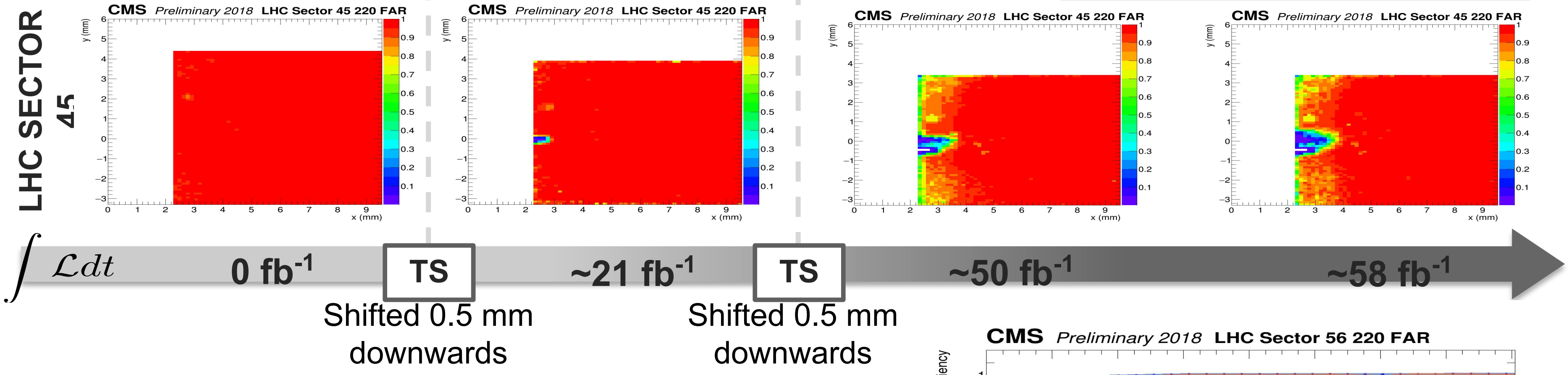


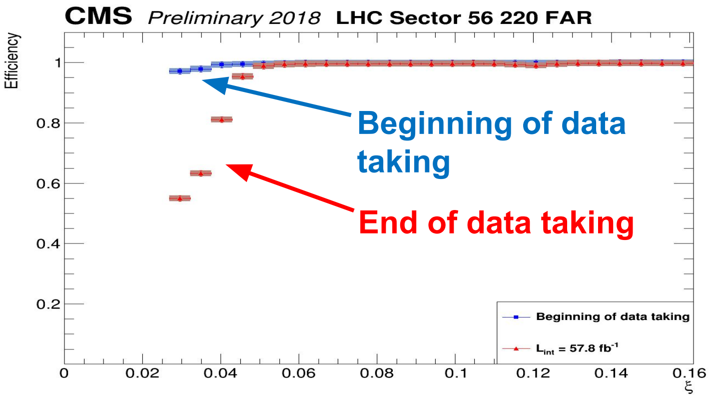
Para referência

Radiation damage in 3D pixel detectors

Efficiency (x,y) maps (in mm)

LHC SECTOR 45





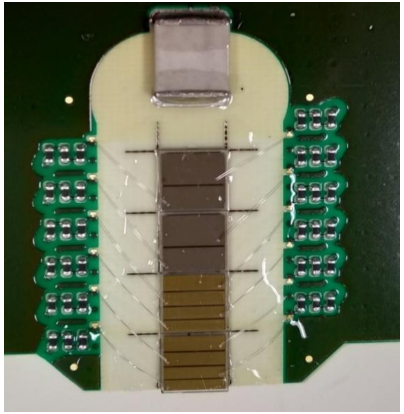
Drop in efficiency due to irradiation is clearly visible in the critical region. Recovery during Run 2 following manual vertical displacements.

<u>Pixel ROC (PSI46dig) not optimized for non-uniform radiation.</u> Highly irradiated pixels eventually above threshold in different bunch crossing window.

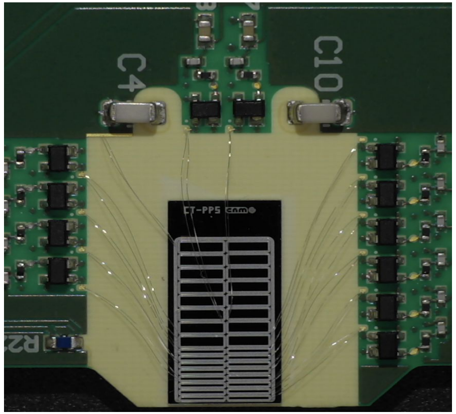
Average efficiency **outside radiation peak area**: > 95%.

CMS DP 2019/036
CMS PRO-21-001

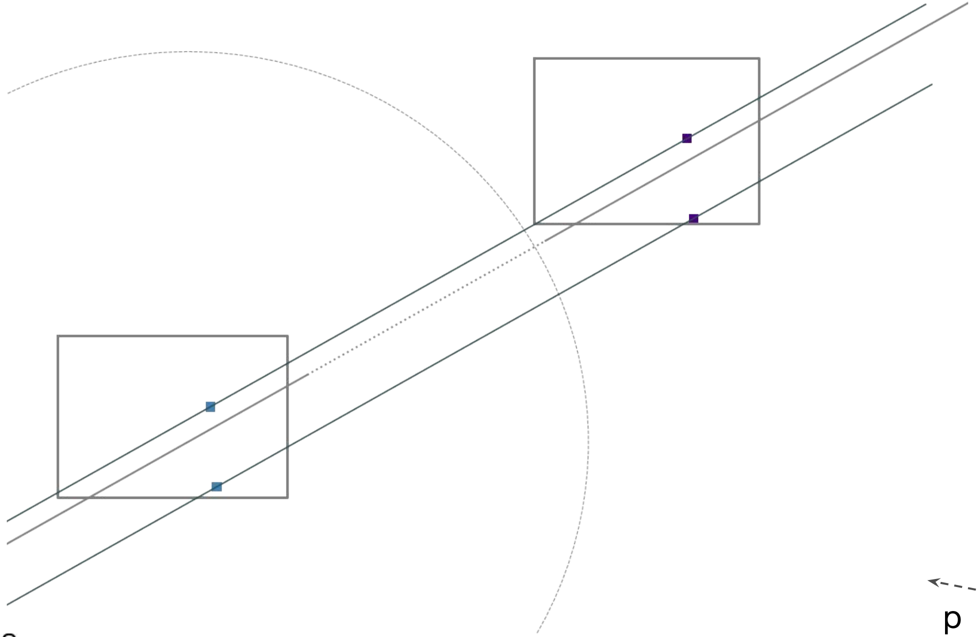
PPS timing detectors

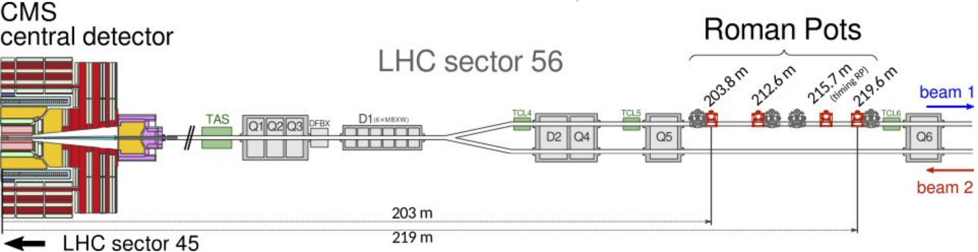


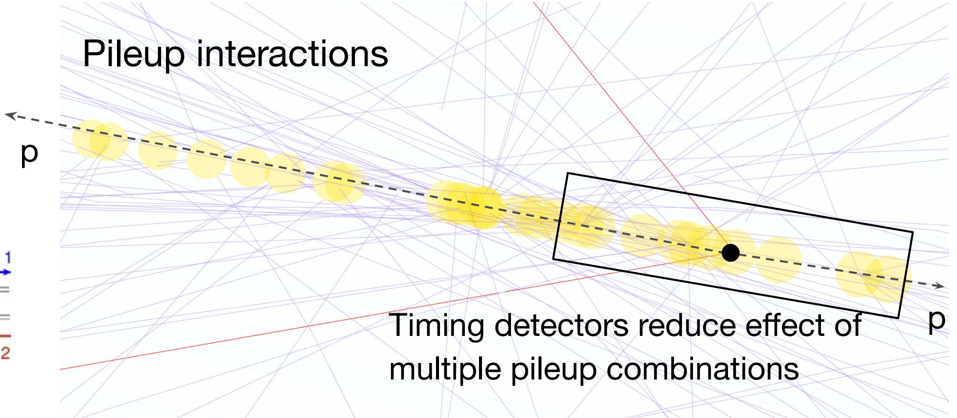
Artificial Diamond (scCVD)



Ultra-fast silicon detectors (LGAD)







Artificial diamonds

Ultra pure single crystal CVD Diamonds. Dimensions per crystal: 4.5 x 4.5 x 0.5 mm.

Detector segmentation introduced in metallization phase (Cr 50nm + Au 150nm or TiW 100 nm).

Pads directly connected to pre-amplifier (~0.2 pF with 0.25 μm bonding wire diameter). Coating in sensitive areas to reduce HV discharges (> 500V).

Read-out: NINO (discriminator ASIC) + HPTDC (digitizer board)

<u>Degradation of detector performance during Run 2 due to:</u>

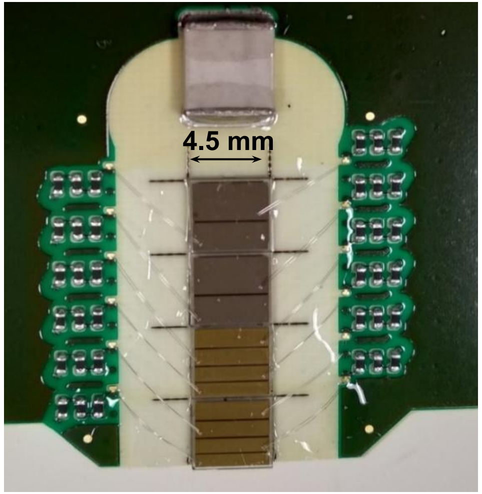
- RF noise pickup inside RP (reduced amplifier gain).

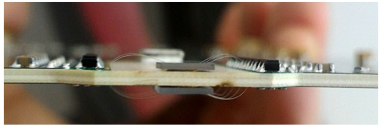
- Beam-induced HV discharges (reduced bias voltage).

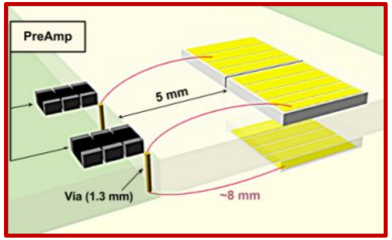
<u>Updates for Run 3:</u>

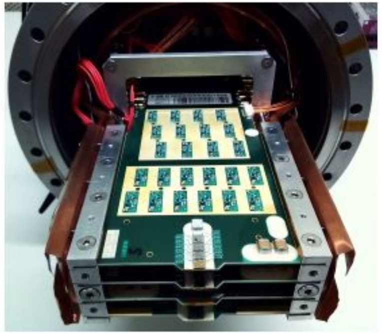
- New hybrid board: increased distance of amplifier from irradiation peak, improved RF shielding and HV isolation, optimization of pre-amplifier stage. Remote control of the amplifiers gain. Secondary readout with SAMPIC chip (fast sampler @7.8 Gsa/s) for commissioning.

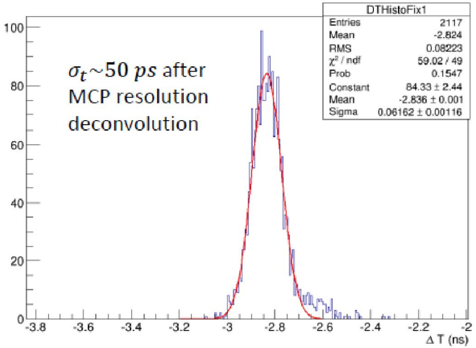
- Each station equipped with 4 double-diamond planes (2SD+2DD in 2018): <u>8 DD planes in each sector + 70 ps/plane (including digitization):</u> **<u>25 ps/sector.</u>**











Time difference distribution between DD and reference MCP ($\sigma_{t,MCP}$~40 ps)

JINST 12 (2017) no.03, P03026

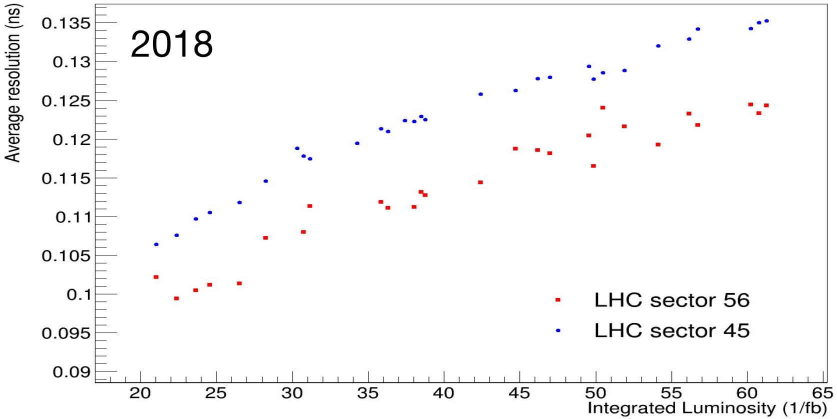
Para referência

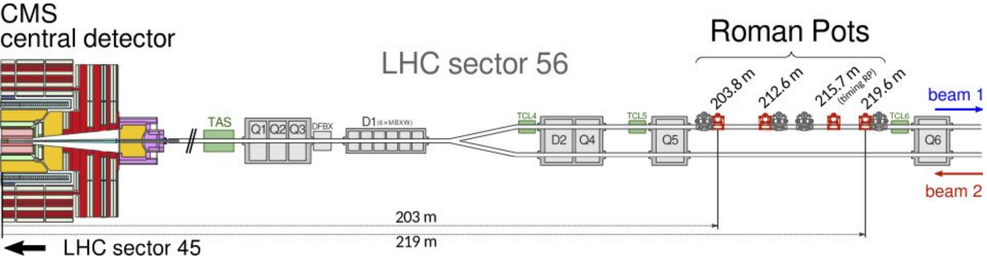
Timing resolution (Diamond)

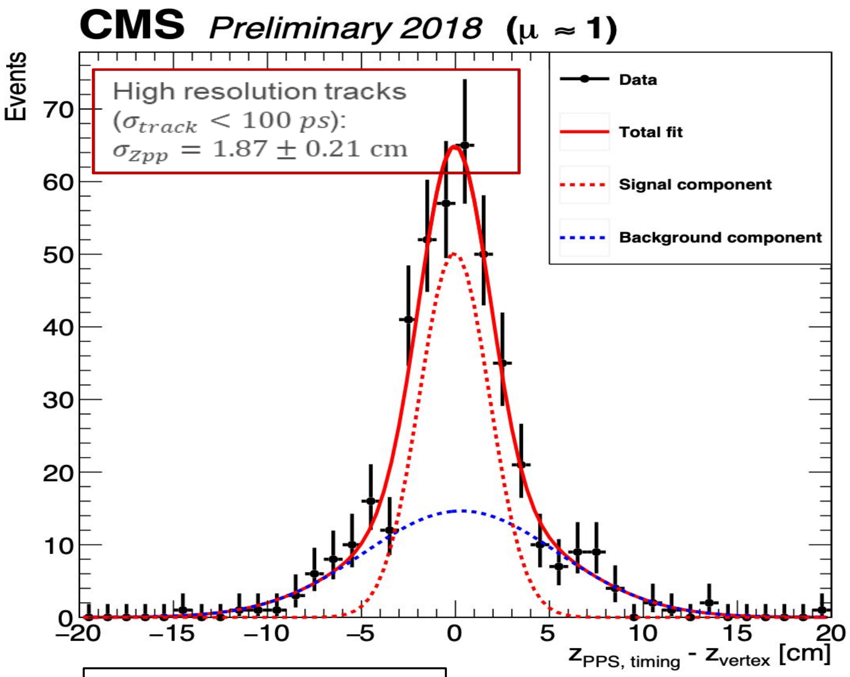
$$Z_{\text{pps}} - Z_{\text{vertex}} = \frac{c}{2}.\Delta t_{\text{pps}} - Z_{\text{vertex}}$$

Measurement of the full timing station resolution (2 single + 2 double planes) taking into consideration the full read-out chain (sensor + amplifier + digitization + timing calibration + reconstruction)

CMS DP 2019/034



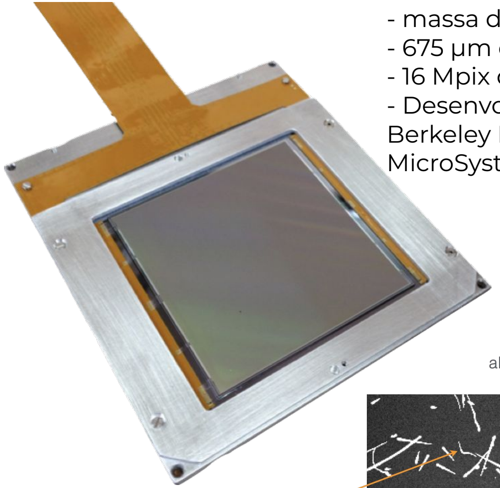




CMS DP 2020/046
CMS PRO-21-001

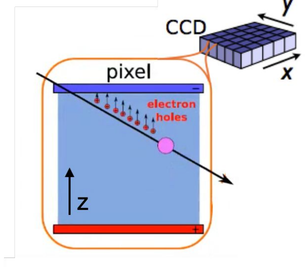
CCD – Charge Coupled Devices

- Detectores originalmente desenvolvidos para fazer imagens em grandes telescópios
- Também utilizados em física de partículas: detecção de neutrinos e matéria escura (baixíssimo limiar ~ 50 eV)

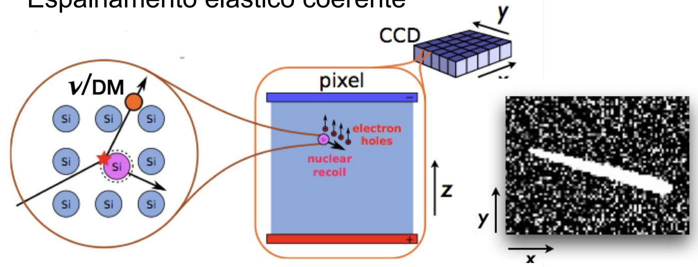


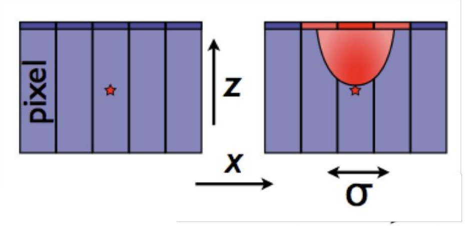
- massa de 6 g
- 675 µm de espessura
- 16 Mpix de 15 µm x 15 µm
- Desenvolvidas por Lawrence Berkeley National Laboratory MicroSystems Lab

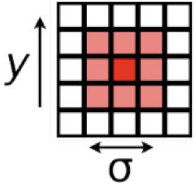
Partícula ionizante

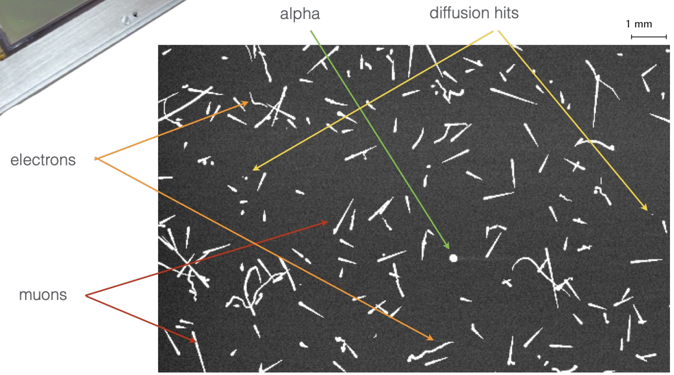


Espalhamento elástico coerente









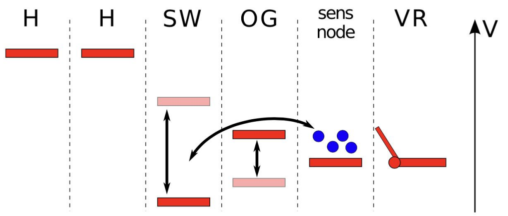
Vantagem:
- O alvo é o próprio detector
- Limiar de detecção baixo
- Resolução espacial muito boa

Desafios:
- Pequenas energias de ionização
- Eficiência de ionização nunca medida (fator de extinção)

Skipper CCD

Nova tecnologia

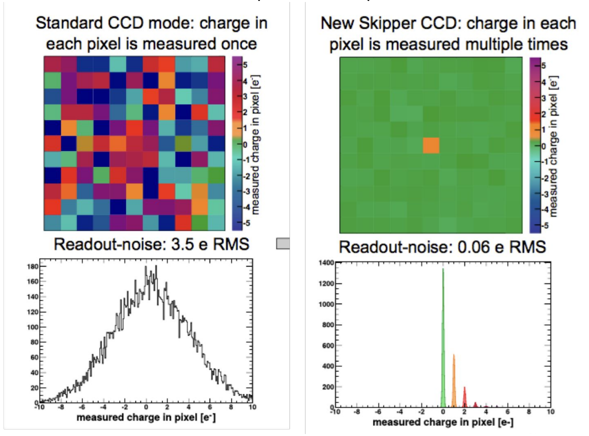
Permite baixar o limiar de detecção a ~ 10 eV



Múltiplas leituras da carga do mesmo pixel

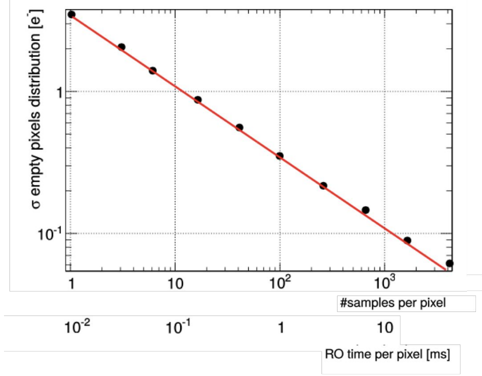
J. Tiffenberg et al, PRL 119 (2017)
using a detector designed by Stephen Holland (LBNL)
PRL 125, 171802 (2020)
SENSEI DM experiment currently using skipper CCDs

- Contando electrons (0, 1, 2, ...)

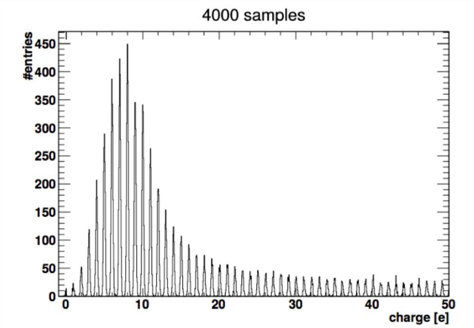


$N_{\text{readouts}} = 1$ $\quad$ $N_{\text{readouts}} = 4000$

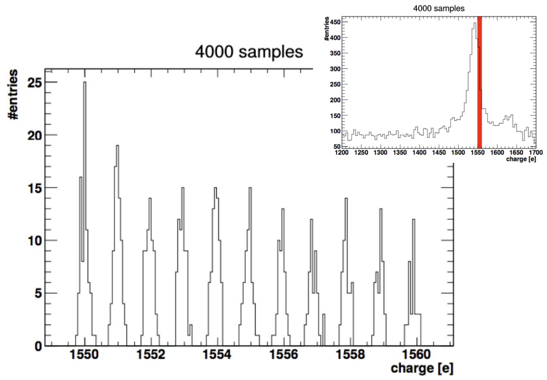
$\sigma = 3.5e^-$ $\quad$ $\sigma = \frac{3.5e^-}{\sqrt{4000}} = 0.06e^-$



- Contando electrons (..., 48, 49, 50, ...)

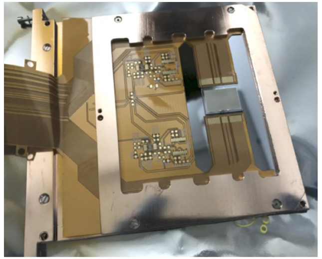


- Contando electrons (..., 1550, 1551, ...)

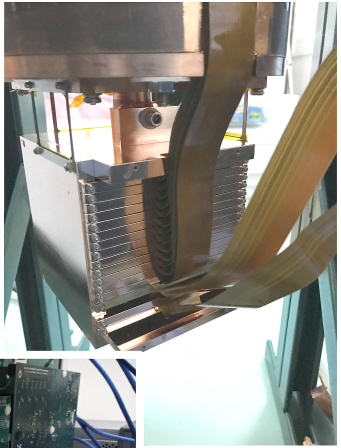


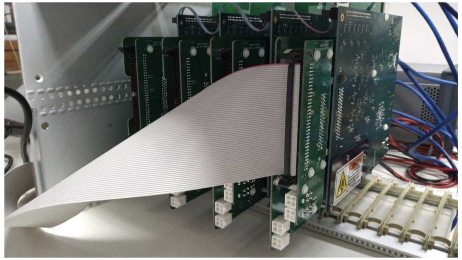
Skipper CCD @ CONNIE e aplicações

@CONNIE para detecção de neutrinos do reator de Angra 2 (a nível do mar)

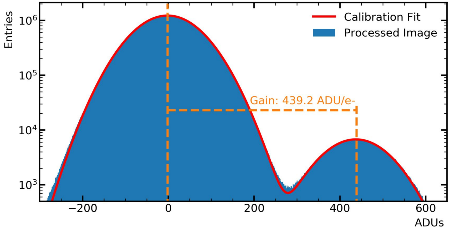


2 Skipper-CCDs de 1022 x 682 pixels



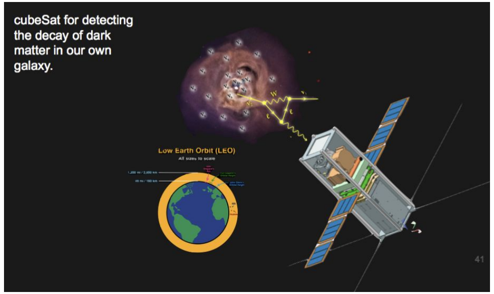


Electrônica de baixo limiar de detecção (LTA)

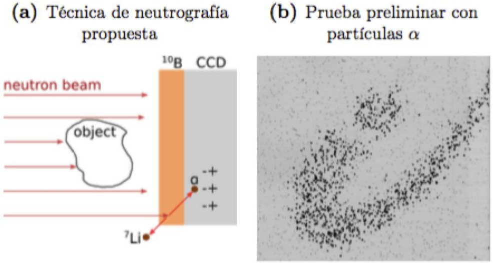


Calibração e medida de elétrons individuais

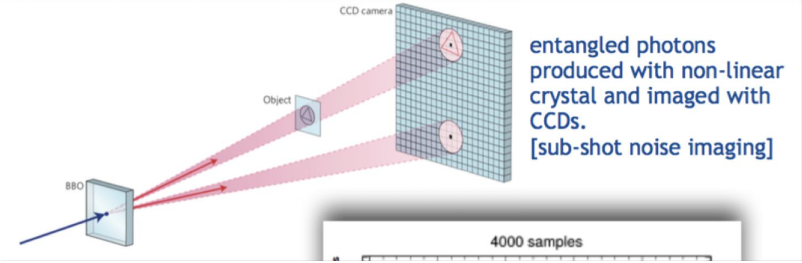
- No espaço (detecção do decaimento da DM)



- Neutrografia

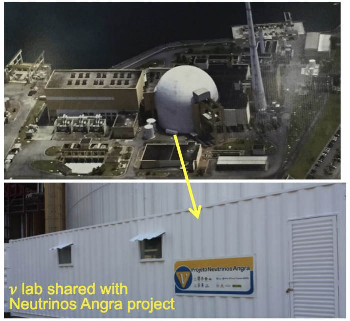


- Quantum imaging

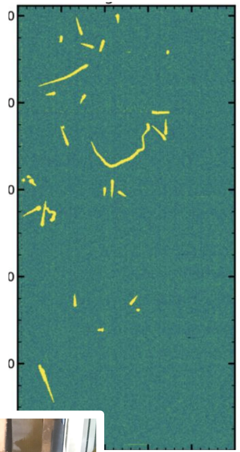


Skipper CCD - No Brasil

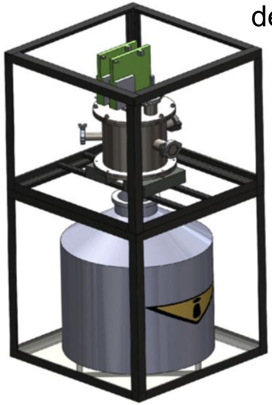
@CONNIE para detecção de neutrinos do reator de Angra 2
@CBPF & UFRJ para o desenvolvimento de instrumentação e novas iniciativas



@ Angra 2 - primeiro no mundo

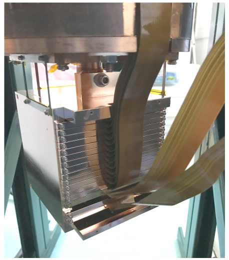


Armazenamento e processamento de datos @ CHE–CBPF

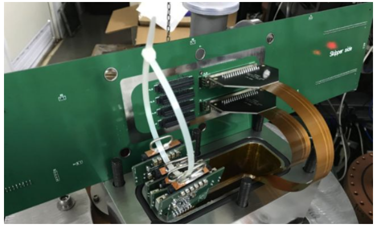


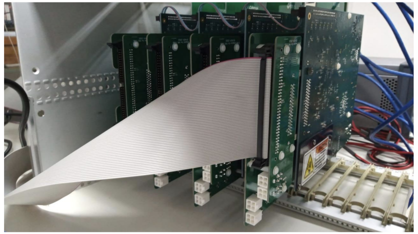
Bancada com câmara de vácuo para Skipper CCDs @ UFRJ

Desenvolvimento e integração de eletrônica @ CBPF



Instalação Skipper - CCDs





Possível estrutura do texto do projeto sobre detectores semicondutores

- Breve introdução a detectores semicondutores
- Breve introdução aos projetos com envolvimento brasileiro que usam detectores semicondutores
- Projetos com envolvimento brasileiro usando LGAD:
    - ATLAS
    - CMS
- Projetos com envolvimento brasileiro usando sensores 3D pixel e Diamond:
    - CMS
- Projetos com envolvimento brasileiro usando detectores híbridos de pixel:
    - LHCb
- Projetos com envolvimento brasileiro usando sensores Skipper CCD:
    - CONNIE
- Possíveis aplicações da tecnologia (vantagens e desvantagens) e envolvimento de empresas e instituições
    - Detecção de matéria escura, neutrinos, fótons, partículas carregadas
    - Imageamento médico
    - Medidas de nêutrons, física nuclear, dosimetria
    - Ótica quântica
    - Indústria aeroespacial
    - …

Para referência

Tipos de detectores de silício

Pixel: 3D, Diamante, LGAD, Híbridos, …

Skipper CCD

Grupos Brasileiros envolvidos

UERJ
UFRJ
USP
CBPF

Experimentos

ATLAS	- CERN	- Altas energias
CMS		
LHCb		
CONNIE	- Brasil	- Baixas energias

Desafios tecnológicos

Medidas ultrarrápidas do tempo
Eletrônica de leitura rápida
Resistência à radiação
Baixo ruído (detector quântico)
Variadas espessuras
Resolução espacial e geometria
Resfriamento eficiente …

Aplicações

Aceleradores, Neutrinos, Matéria escura, Física médica, Física nuclear, Dosimetria, Ótica quântica, Indústria aeroespacial…

Financiamento brasileiro

FAPESP

FAPERJ
Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico