IHEP-INFN medical applications

current collaborations and future perspectives

INFN - IHEP Annual Cooperative Meeting

Beijing - Rome July 7th - 8th, 2021

Istituto Nazionale di Fisica Nucleare

Manuel Da Rocha Rolo (INFN)

Outline

- **Ongoing activity on technology R&D for medical instruments**
  - CZT readout for gamma cameras
  - Pixel readout ASIC for photon counting
- **Items of interest for future joint developments**
  - Silicon strips and readout electronics
  - PET and time-of-flight technology
  - Boron Neutron Capture Therapy (BNCT)

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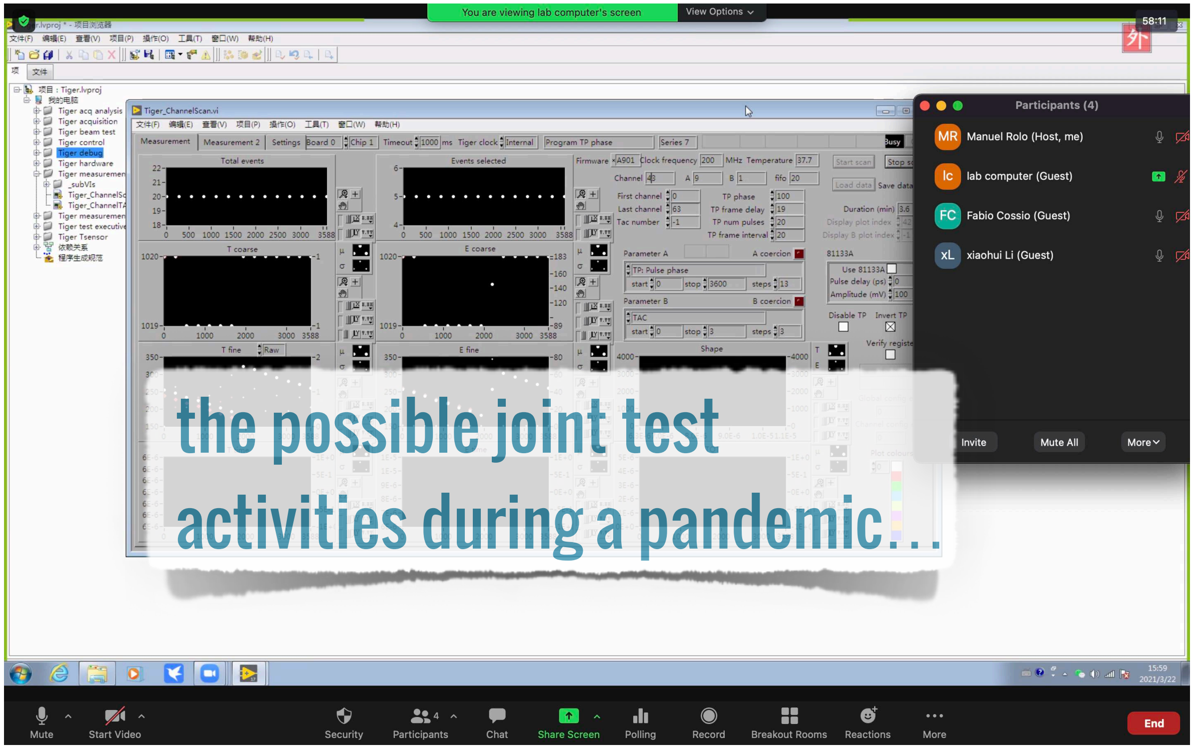
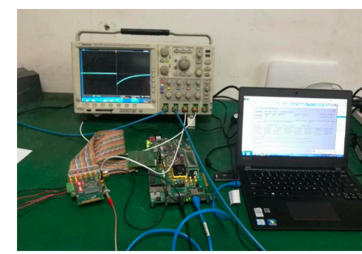
CZT Readout at IHEP with TIGER ASIC

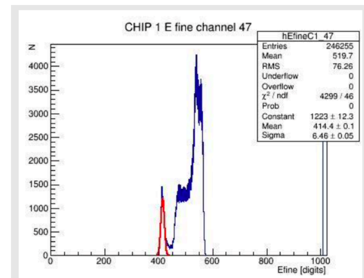
in collaboration with the Division of Nuclear Technology and Applications at IHEP

The **TIGER** ASIC was developed by the CGEM-IT collaboration for the upgrade of the BESIII Inner Tracker, in the framework of the H2020 **BESIIICGEM** project.



Horizon 2020 European Union Funding for Research & Innovation





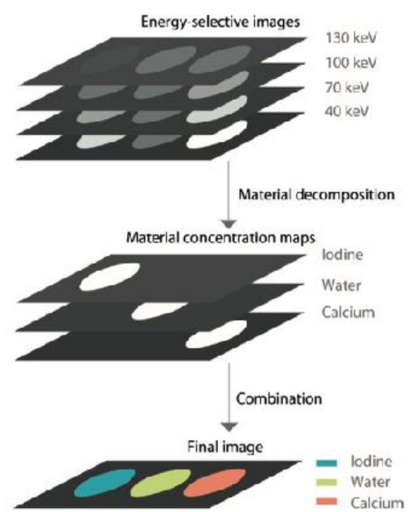
Tiger1 ~7%@662keV

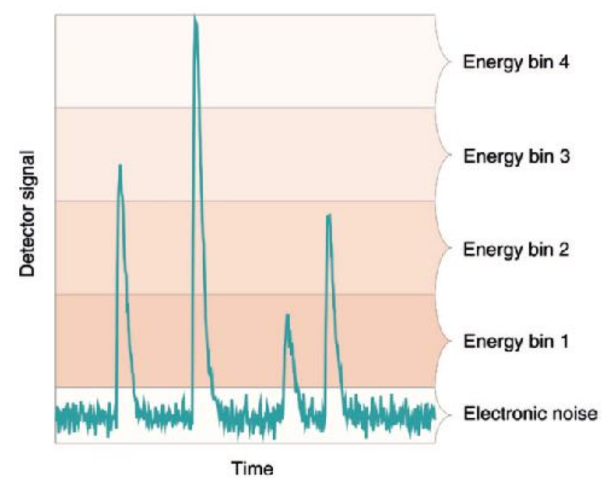
- A test stand for **TIGER** and CZT sensor was installed at IHEP. Remote test activities are working and allowing us to study the achievable performance with the current ASIC
- We will soon start the design of a new version with a lower-noise front-end. This activity is supported by the H2020 **FEST** project (WP3 and WP4)

Pixel Readout ASIC for photon-counting

in collaboration with the Division of Nuclear Technology and Applications at IHEP

- Photon counting CT: emerging technology, potential to dramatically improve clinical CT
- Requires energy-resolving x-ray detectors (instead of conventional energy-integrating detectors): counts the number of impinging photons to measure photon energy
  - ☑ higher contrast-to-noise ratio
  - ☑ improved spatial resolution
  - ☑ optimised spectral imaging
- **reduced radiation exposure**
- **higher resolution imaging**



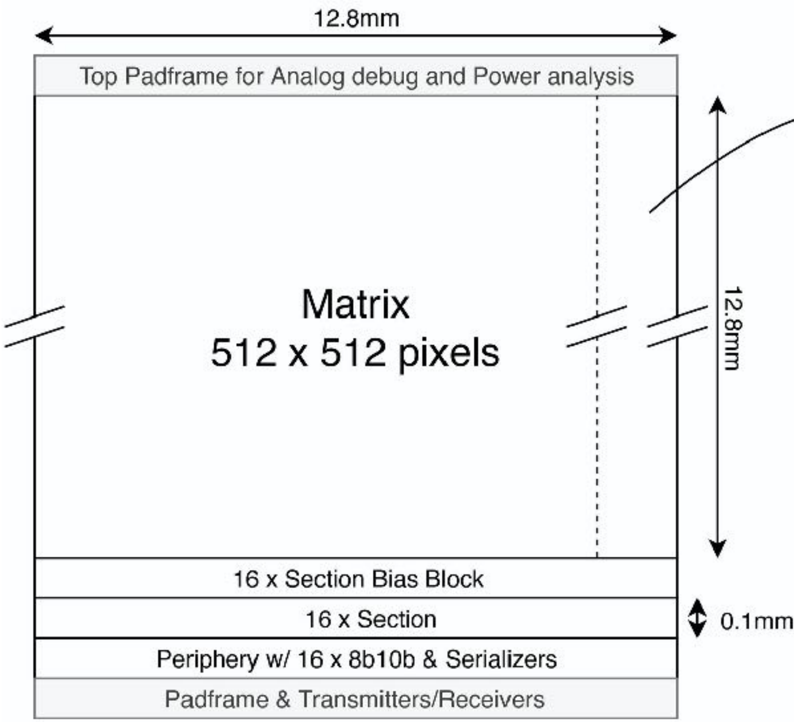


M J Willemink et al, Radiology: vol. 289, no. 2, Nov 2018

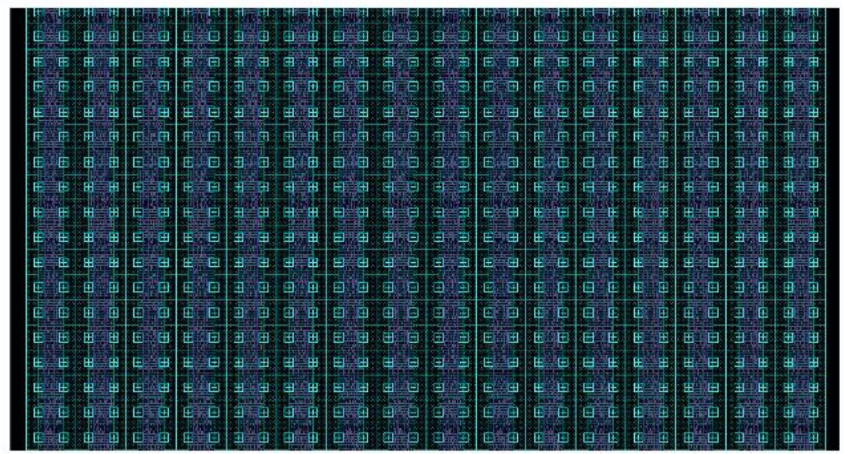
This activity is supported by the H2020 **FEST** project (WP4 Medical Applications)

Pixel Readout ASIC for photon-counting

in collaboration with the Division of Nuclear Technology and Applications at IHEP



Matrix (512x512 pixels)
Section (32x512 pixels)
Column (2x512)
Core (2x32)
Region (2x2) groups 4x 50 µm pixels



- Implementation of the sensor matrix for photon-counting ASIC using a 100 x 100 µm ARCADIA super-pixel
- Chip design and sensor simulations ongoing, silicon prototype production scheduled for 2022-Q2
- Final version should allow both a hybrid assembly of a CdTe detector and a fully-depleted silicon sensor
  - Synergic development within the framework of ARCADIA, with future support from H2020 FEST project

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中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

ARCADIA

Horizon 2020
European Union Funding
for Research & Innovation

Pixel Readout ASIC for photon-counting
Sensor and simulation setup

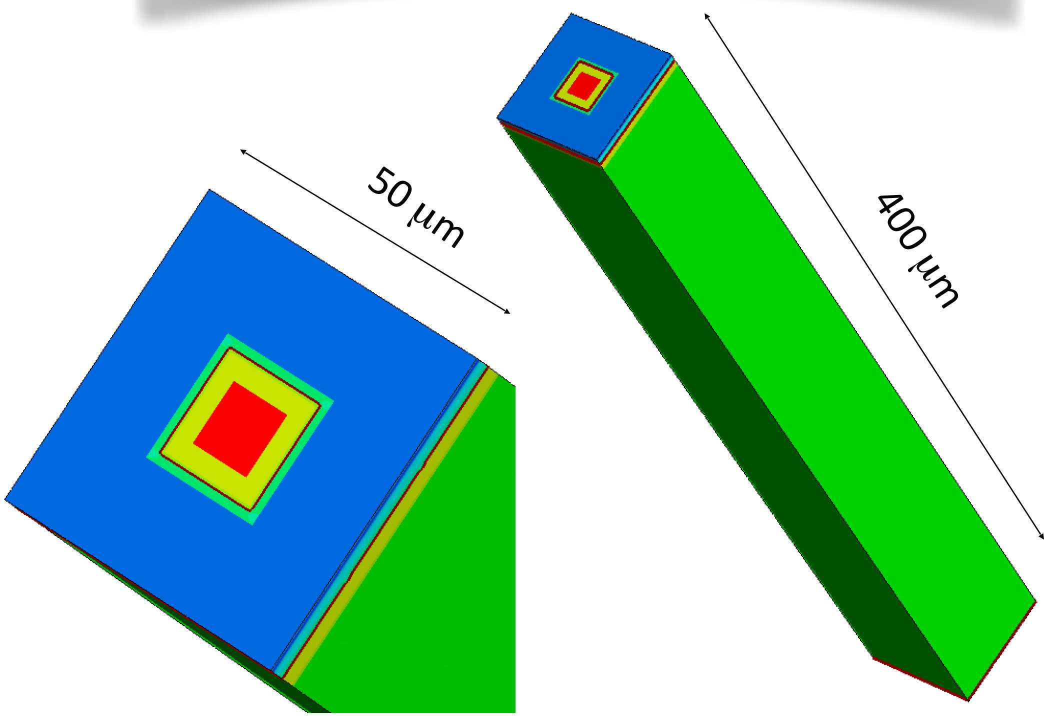
X-ray energy range: 10 - 100 keV, Photoelectric + Compton effects

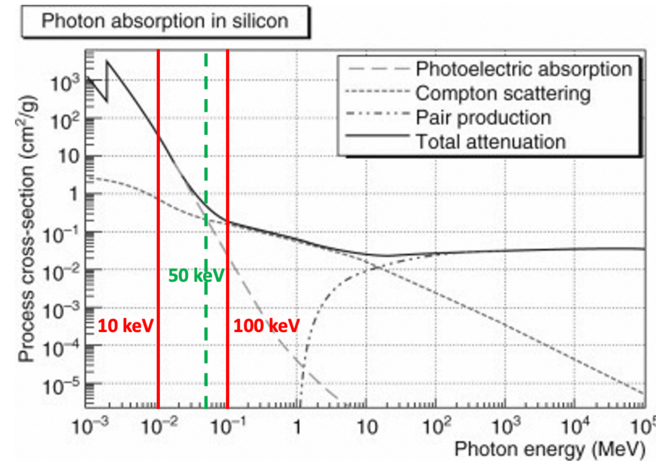
50 μm pitch, 400 μm thick ARCADIA pixel sensor

Punch through onset V_{pt} = -363.6 V

Capacitance @ V_{pt} = 12.8 fF

Voltage at collection electrode = 0.8 V





Scope:

- study charge sharing
- charge collection time < shaping time ~ 100 ns

Sentaurus TCAD

- electric and weighting field maps

Allpix2

- Monte Carlo signal generation
- 5x5 pixel matrix

TCAD: L. De Cilladi (INFN/Unito)

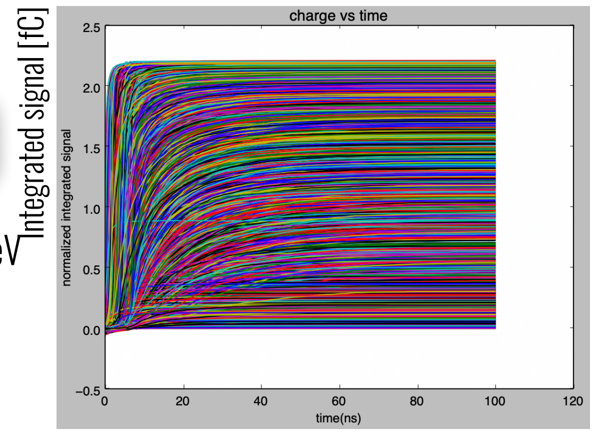
Pixel Readout ASIC for photon-counting
Signal simulation for 50 keV photons

Compton scattering

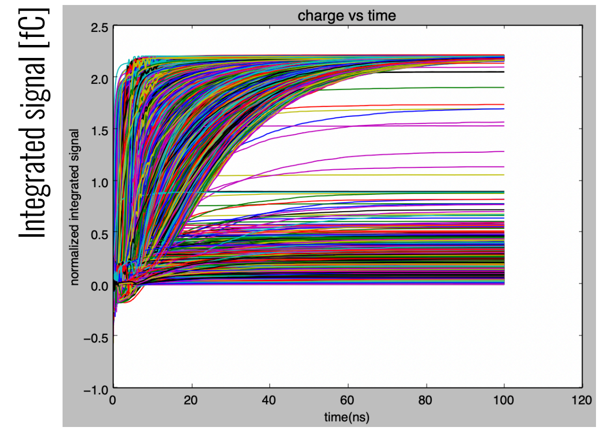
- Fraction of energy transferred to recoil electron: 9% mean, 17% max
- Charge deposit: 0.2 fC mean, 0.38 fC max

Photoelectric absorption

- K-shell 1s electron binding energy = 1.839 keV
- Kinetic energy of K-shell 1s photoelectrons
- = 50 keV – 1.839 keV
- Charge deposit: 2.14 fC



Central pixel signal only



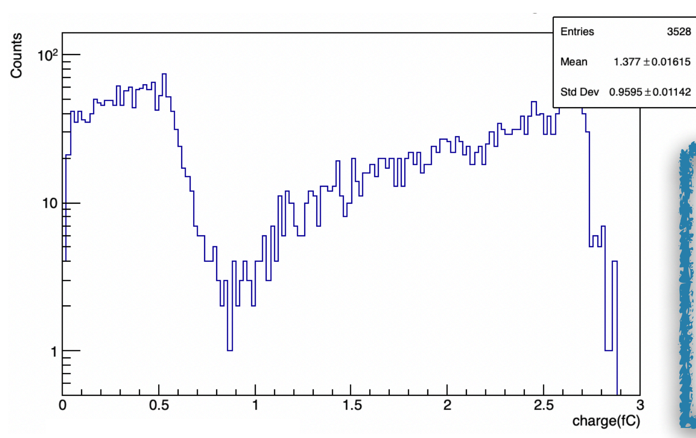
Full 5x5 matrix signal

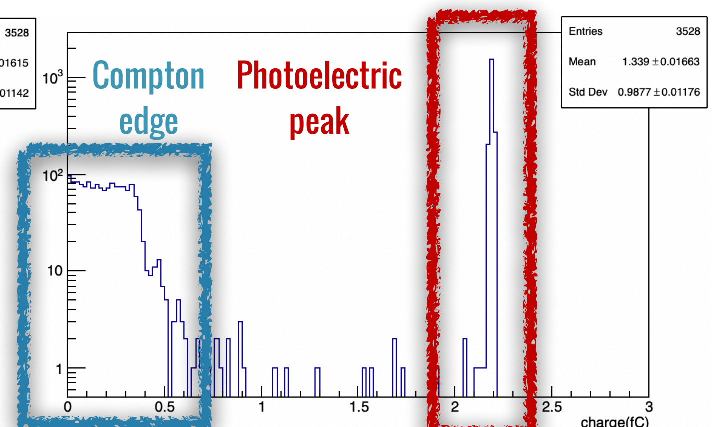
Monte Carlo simulation

- 100k incoming photons
- Perpendicular incidence
- Random incidence point over the CENTRAL pixel of the 5x5 matrix

Detected photons (Compton + photoelectric, no threshold) = 3528

Detection efficiency = ~4%





Collected charge [fC]

TCAD: L. De Cilladi (INFN/Unito)

Pixel Readout ASIC for photon-counting Architecture and Chip Design

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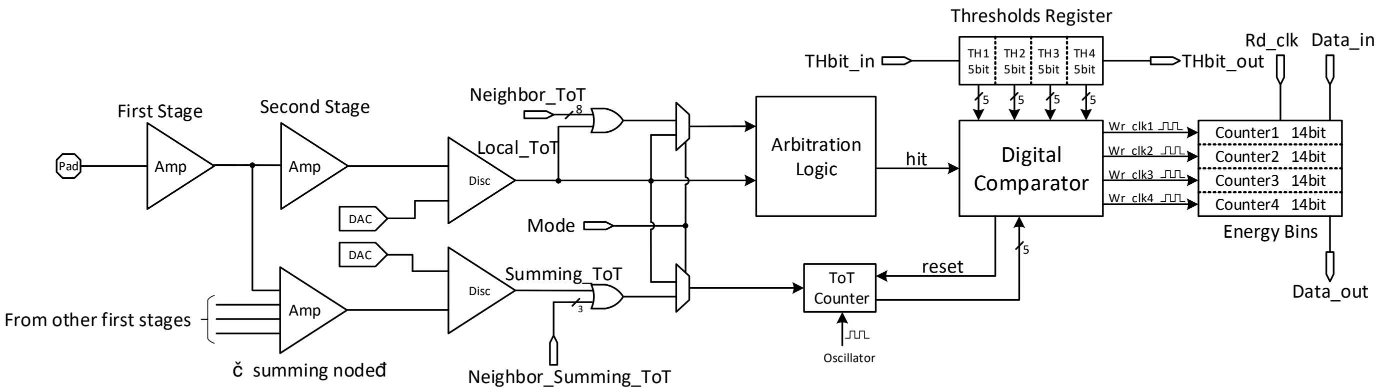
ARCADIA



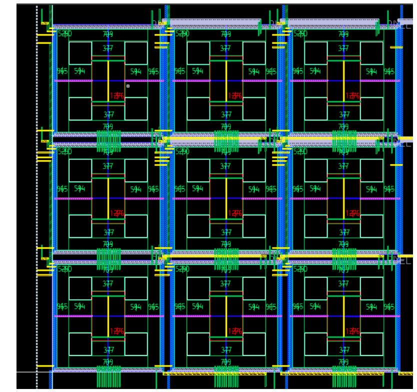
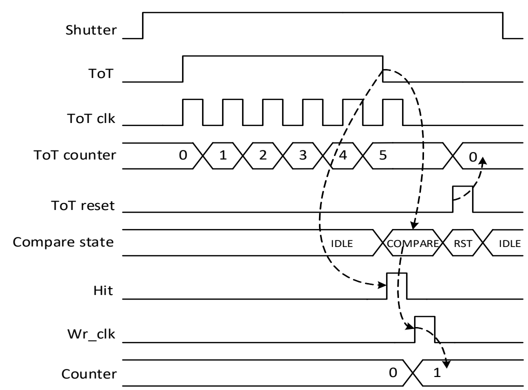
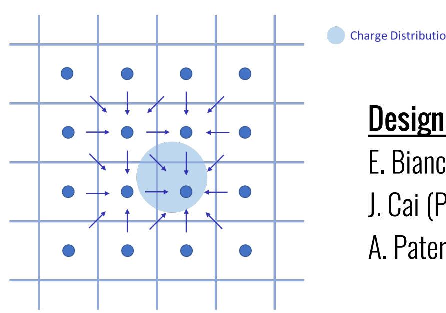


Figure: top routing of a 3x3 pixel region (each pixel is built with 2x2 50 µm cores



- ✓ The arbitration logic module compares local ToT with 8 neighbour ToTs to decide if local pixel has the largest read of the generated charge and then the hit signal is pulled up high
- ✓ The deposited energy is obtained by the ToT counter in which the numbers of cycles of oscillator clock is recorded
- ✓ A digital comparator assigns an energy bin to the event
- ✓ Pixel logic implementation on a 50x100 µm area complete, post-layout simulations with 9 pixels done, end of column (data/configuration) logic design ongoing; analogue front-end design started



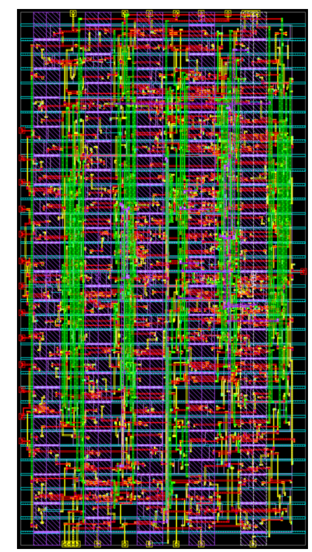


Figure: Pixel logic implementation on a 50x100 µm area

Designers:

E. Bianco (PhD INFN/Polito)

J. Cai (PhD IHEP/Polito)

A. Paternò (Post-doc INFN CSN5)

Pixel Readout ASIC for photon-counting

in collaboration with the Division of Nuclear Technology and Applications at IHEP

中国科学院高能物理研究所
Institute of High Energy Physics
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- **Phase 0**: First demonstrator of X-ray detector built on the CMOS MAPS developed in framework of ARCADIA: 512x512 25 μm pixel matrix, demonstrated 400 μm thickness of fully-depleted silicon. Tapeout late 2020, silicon and associated DAQ at IHEP by Q1 end 2021. Test stand can be of interest for synergic activities on R&D for CepC. Engineers at DNTA will work on a dedicated DAQ for X-ray detector instruments, starting from a system integration perspective.

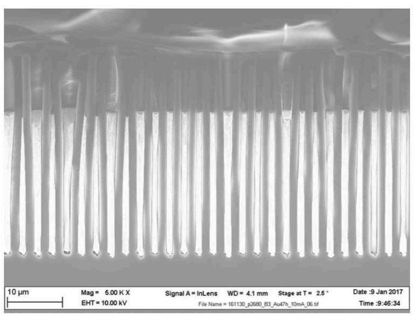
- **Phase 1**: Started from the chip integration flow of ARCADIA-MD1 to implement a 100x100 μm pixel for photon counting, featuring the clustering algorithms and a multi-energy binning. We will send to production a matrix of 128x128 or 128x16 pixels, to be decided as a function of the advancement of the design. First tapeout by mid-2022, fully-depleted CMOS sensors available at IHEP by the end of 2022. The pixel implements a physical connection of the input to a top metal layer, allowing for a flip-chip assembly of a CdTe sensor.

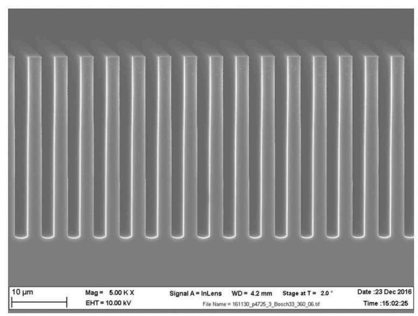
- **Phase 2**: Verification of architecture, data readout, functional parameters, front-end and pixel logic. If results OK, proceed with CdTe assembly and test on a medical instrument at IHEP during 2023.

This activity is supported by INFN CSN5 **ARCADIA** and the H2020 **FEST** project (WP4 Medical Applications)

Phase contrast X-ray imaging with photon counting detectors

- we might have a common interest on the development of X-ray dynamic imaging with phase contrast, based on interferometry with reticles
- particular interest on soft tissue imaging, but potential to become an enabling technique for X-ray imaging with exceptional signal-to-noise ratio

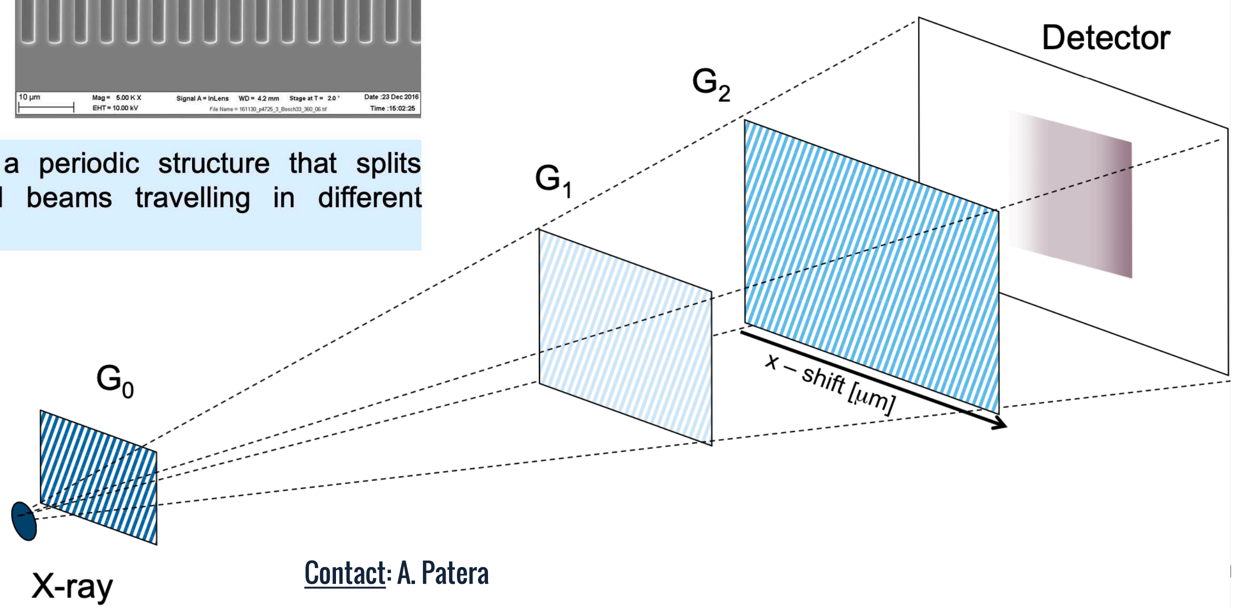




Grating: Optical component with a periodic structure that splits and diffracts X-rays into several beams travelling in different directions.

TALBOT-LAU

G_0: Source Grating, period p_0
G_1: Phase Grating, period p_1
G_2: Analyzer Grating, period p_2



Contact: A. Patera

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IHEP and INFN-TO Collaboration on Medical Physics and Instrumentation: 1st Online Workshop 17-19 May 2021

INFN

Welcome and Institutional address	Manuel Dionisio Da Rocha Rolo	https://infn-it.zoom.us/j/5948111880, Zoom	09:00 - 09:30
The readout electronic system for nuclear imaging equipment	Xiaohui Li	https://infn-it.zoom.us/j/5948111880, Zoom	09:30 - 09:40
The development of detector technique based on CZT	Xiaopan Jiang	https://infn-it.zoom.us/j/5948111880, Zoom	09:42 - 09:52
The R&D of PET Imaging system at IHEP	Xianchao Huang	https://infn-it.zoom.us/j/5948111880, Zoom	09:54 - 10:04
The readout ASIC for hybrid X-ray photon counting detector with charge sharing correction	Jiale Cai	https://infn-it.zoom.us/j/5948111880, Zoom	10:06 - 10:16
CT image reconstruction algorithms	Baodong Liu	https://infn-it.zoom.us/j/5948111880, Zoom	10:18 - 10:28
Q&A		https://infn-it.zoom.us/j/5948111880, Zoom	10:30 - 10:45
Phase contrast X-ray imaging	Alessandra Patera	https://infn-it.zoom.us/j/5948111880, Zoom	10:45 - 10:55
Innovative detectors for beam monitoring in particle therapy	Roberto Sacchi	https://infn-it.zoom.us/j/5948111880, Zoom	10:57 - 11:07
Fast dose recalculation for online treatment verification in particle therapy	Simona Giordanengo	https://infn-it.zoom.us/j/5948111880, Zoom	11:09 - 11:19
PET detectors for range verification in particle therapy	Elisa Fiorina	https://infn-it.zoom.us/j/5948111880, Zoom	11:21 - 11:31
Image reconstruction, analysis and simulation software	Veronica Ferrero	https://infn-it.zoom.us/j/5948111880, Zoom	11:33 - 11:43
Q&A		https://infn-it.zoom.us/j/5948111880, Zoom	11:45 - 12:00

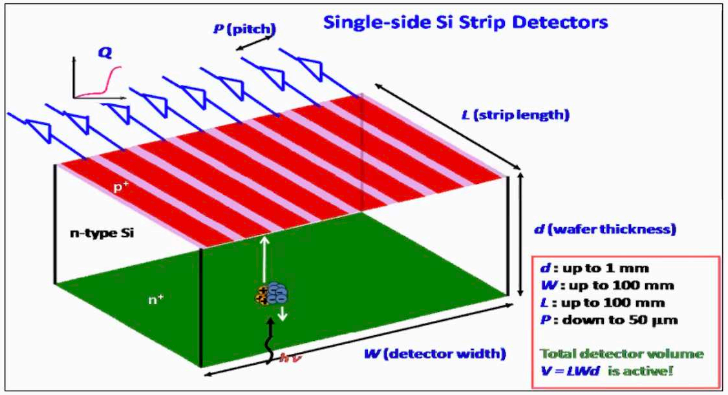
First operative workshop held this year for the exploration of new joint activities and collaboration opportunities

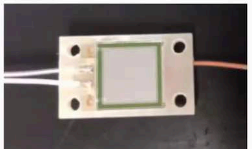
- 43 participants, a lot of ideas and brainstorming
- A seed for further IHEP-INFN collaboration in medical applications, looking forward to a **2nd "Real" Workshop on 2022**!

Collaboration proposals (IHEP)	Dr Xiaohui Li	https://infn-it.zoom.us/j/5948111880, Zoom	09:00 - 09:45
Collaboration proposals (INFN)	Manuel Dionisio Da Rocha Rolo	https://infn-it.zoom.us/j/5948111880, Zoom	09:45 - 10:30
Open Discussion and Meeting Wrap-up		https://infn-it.zoom.us/j/5948111880, Zoom	10:30 - 12:00

Si-strip detector for X-ray diffraction

① **Silicon Micro-strip detector(by IHEP)**





Detector Specifications

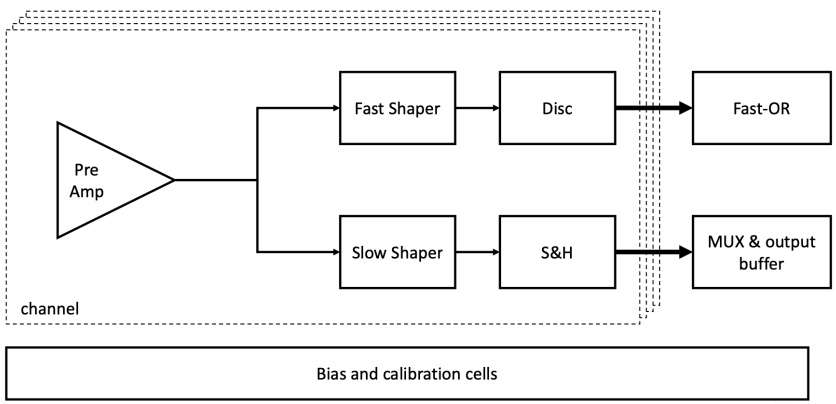
Entry	Specifications
application object	X-ray diffraction
Strips	128 strips, 50μm pitch
Length of the strips	8mm
Global count rate	$\geq 1\times10^8$ cps
Energy resolution	< 380ev @ 8Kev
Sensor Thickness	500μm
Frame Rate	4.2KHz

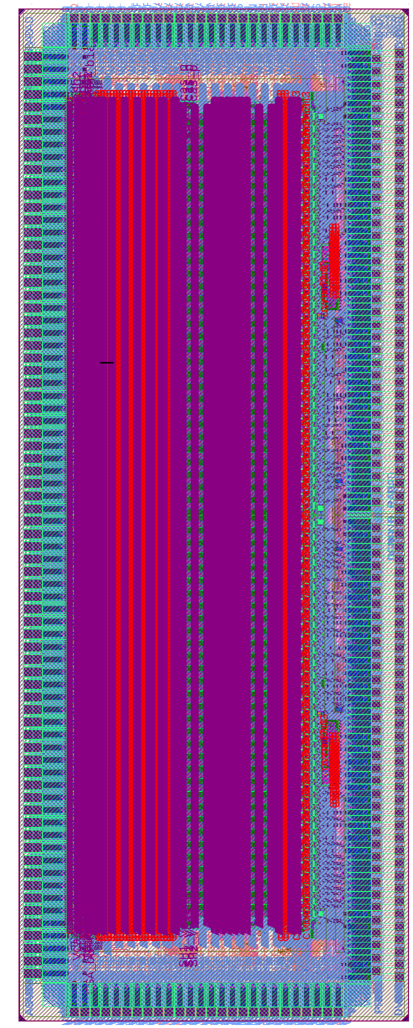
Used for X-ray diffractometer

- IHEP develops technology for silicon micro-strip detectors and X-ray diffractometers
- We will explore the use of **ASTRA** for the performance evaluation with Si-strips and CZT: a test stand with hardware and data acquisition to be installed at IHEP during 2022-Q1
- the proposed activities and collaboration framework could pave the way for the co- development of future X-ray photon detectors for the High Energy Photon Source (HEPS)

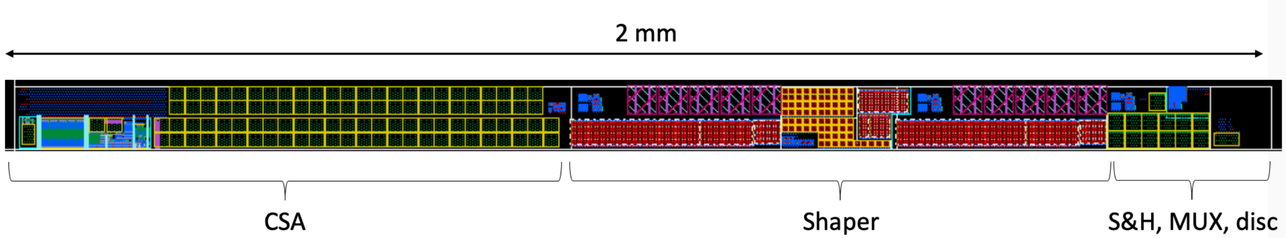
ASTRA: Adaptable Space sTrip Readout ASIC
An ARCADIA - HERD Joint Development

- Chip area=3x3.5mm^2
- 32 channels (100 µm pitch), layout with scalability to 64 channels (and 50 µm pitch)
- Front-End compatible for both polarities
- Programmable peaking time (1.5-8.5 µs)
- Configurable gain to make it suitable for different sensors topologies (i.e. 150-300 µm thickness sensors)
- ENC = 800 e- @ C_{in} = 100 pF and T_p = 6.5µs
- Power consumption < 0.6 mW/ch





Figures:
(mid) architecture and
(bot) layout of the channel;
(right) CAD layout of the 64-channel embodiment



CMOS Embedded Si-strip and readout

- Design and Production of continuous and "pixelised" strips, range 10 - 100μm pitch
- Proof-of-concept: **CMOS monolithic strip block and readout electronics**

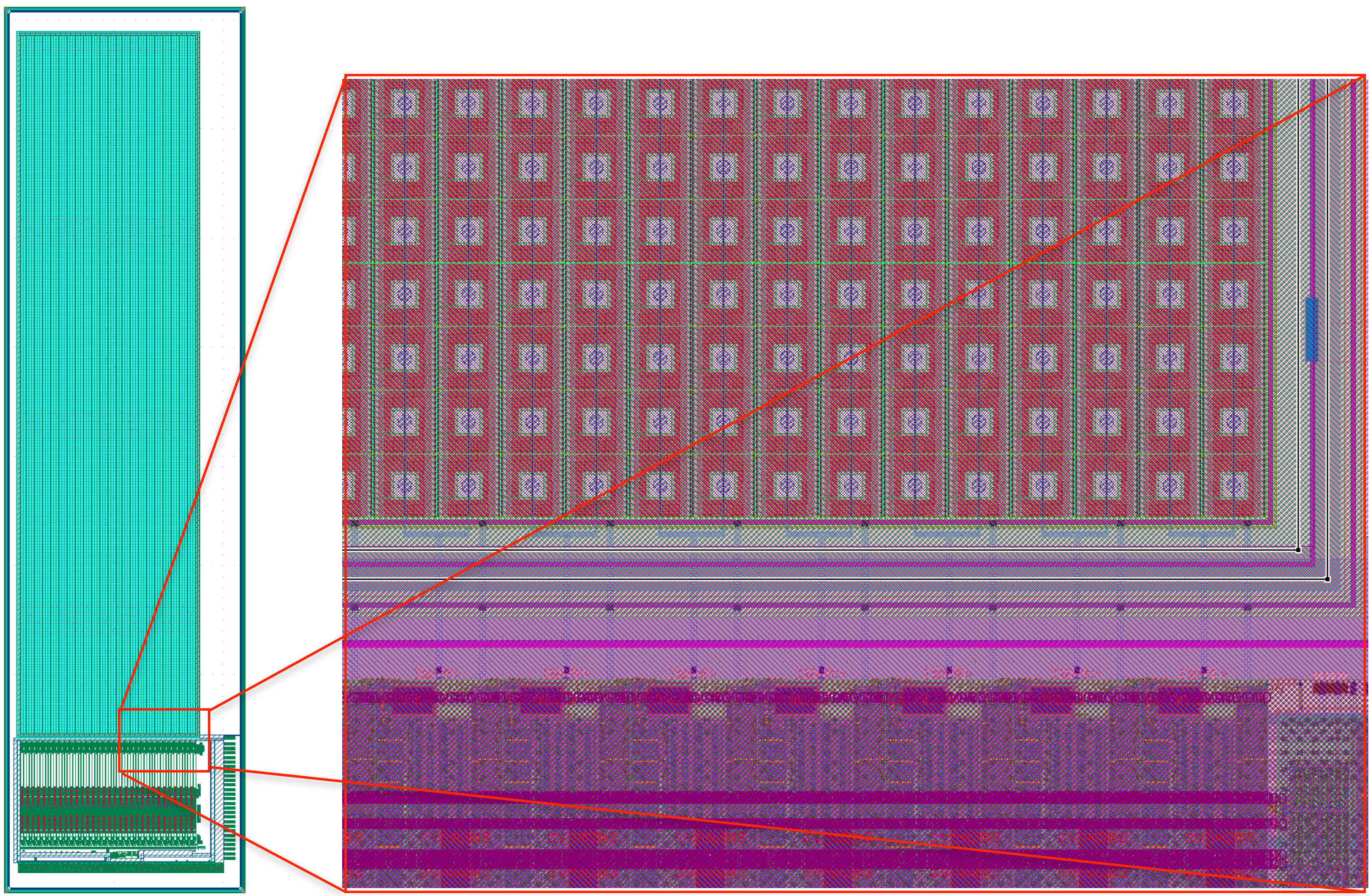


Figure: CAD Layout of 2x32x50μm pixelised strips

Figure: (top) detail of 2x32x50μm pixelised strips and (bottom) 32-channel custom readout

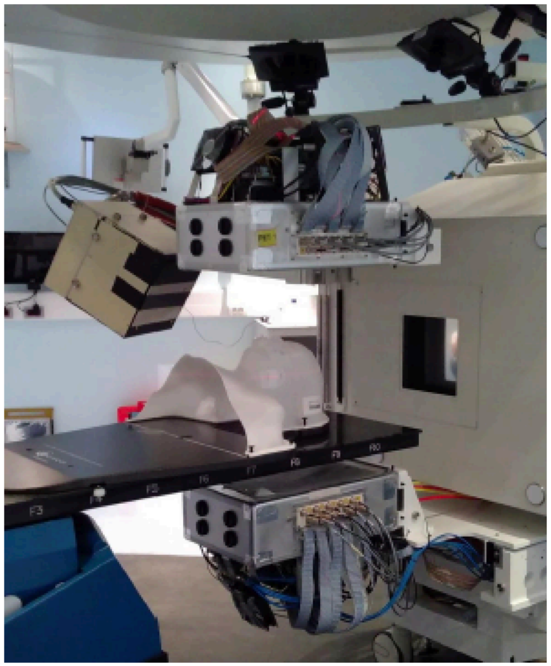
R&D for PET imaging at INFN

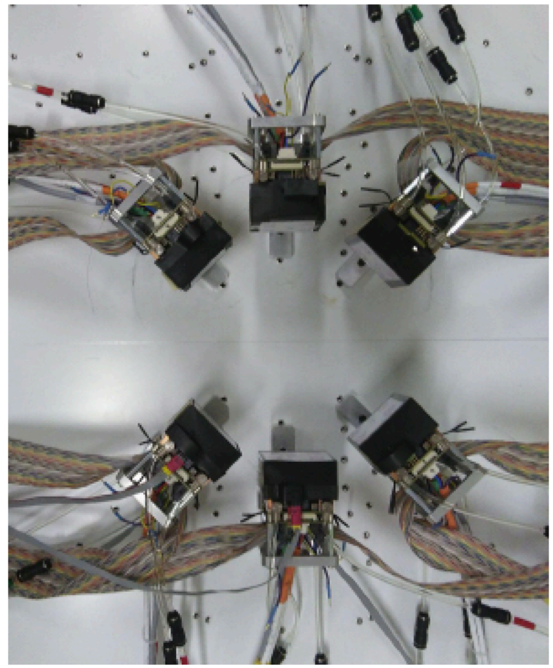
INFN

InSide

I3PET

PET
MR
EEG
TRImage





Simulations
ASIC / FPGA / DAQ
Mechanics
Cooling

+ Detectors
Reconstruction
Analysis

+ EM shielding

Current projects at INFN focus on PET as online range verification and beam monitoring systems in Particle Therapy

Technology for PET imaging

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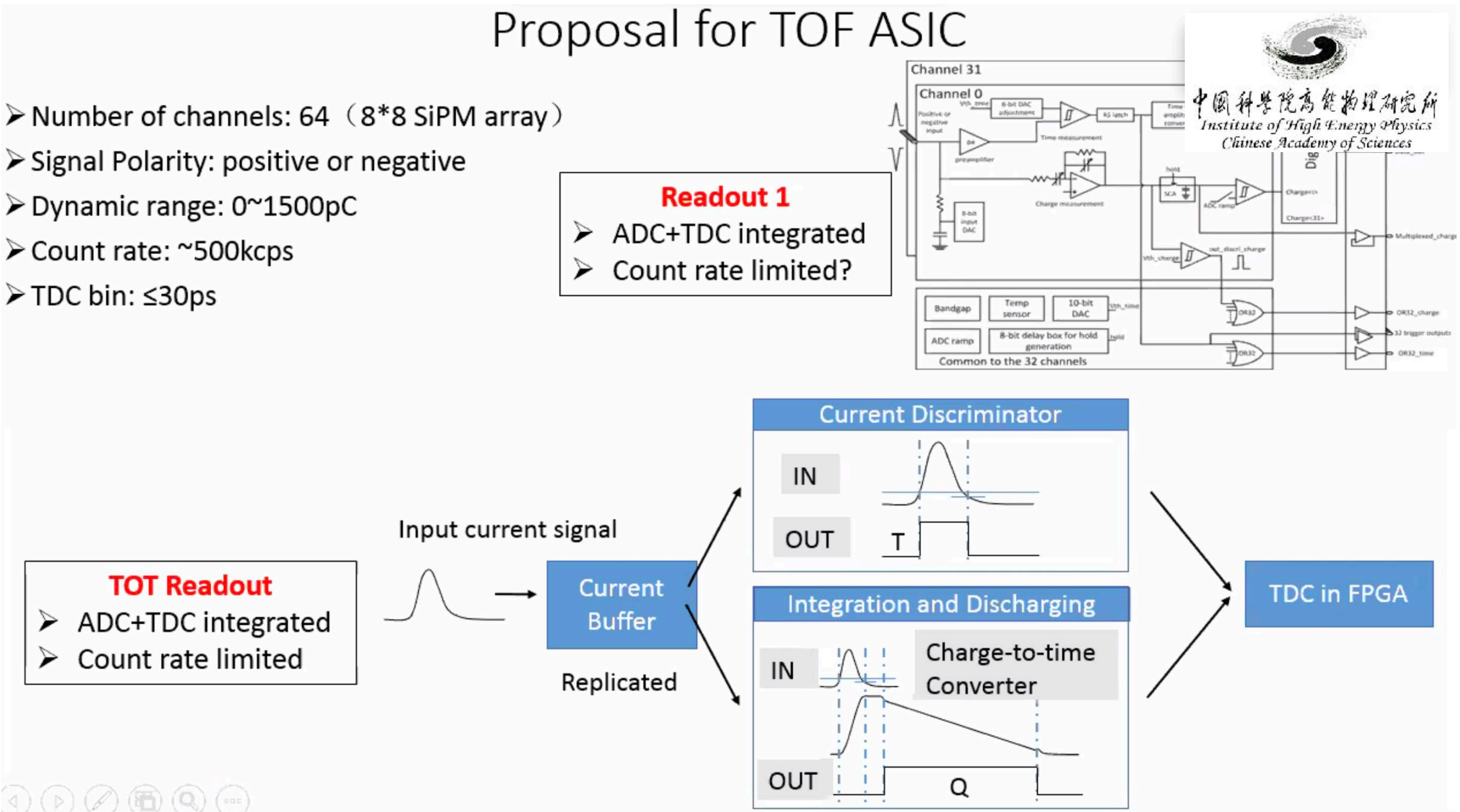
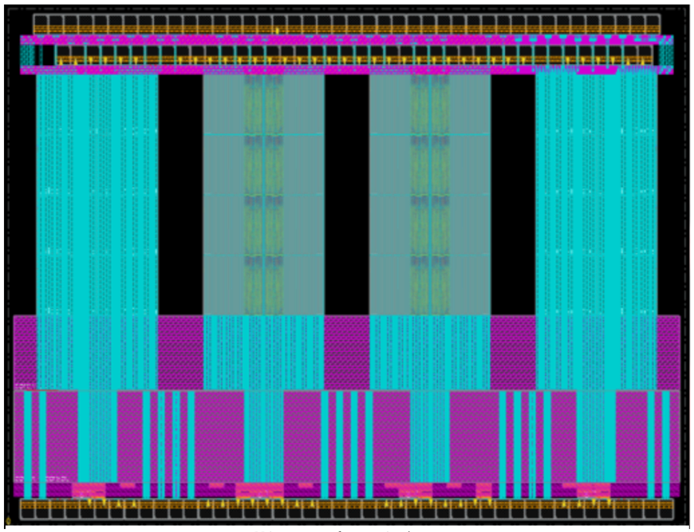
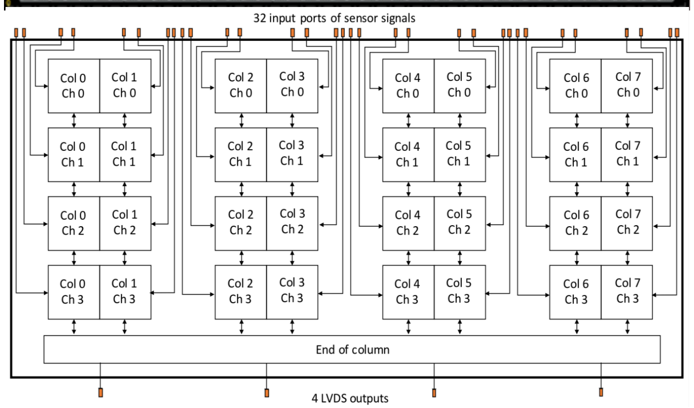
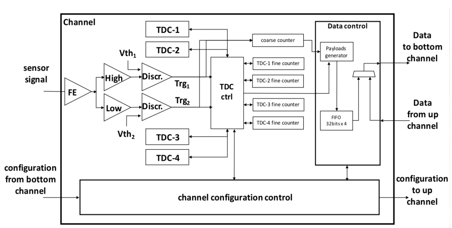


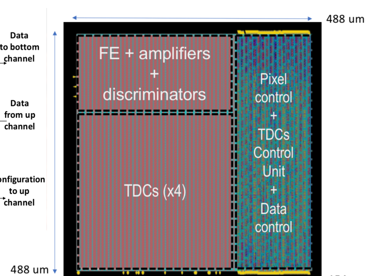
- IHEP is working on the development of technology for whole-body PET and small animal PET scanners with TOF capability, and applying for funding on PET-MRI (brain imaging)
- Upgrades or new developments with SiPMs require fast integrated readout electronics.

ASICs for fast-timing with SiPMs



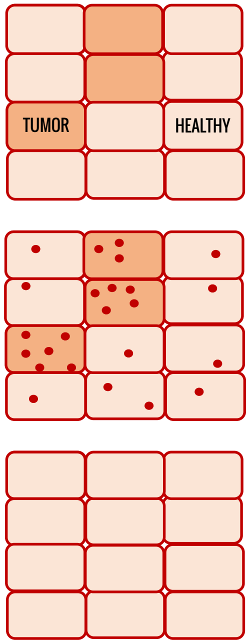




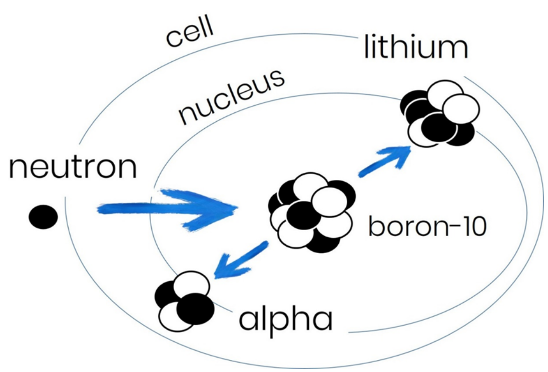


- towards a 3D a-SiPM "digital tile"
- Developed by INFN (CSN2) for the readout of SiPMs at 77K, cold tests ok, characterisation with SiPMs ongoing
- 32-pixel matrix mixed signal ASIC
- the chip performs amplification, signal conditioning and event digitisation, and features fully digital I/O
- Single-photon time tagging mode or time and charge measurement
- 64-bit (32-bit on time tagging mode) event and status data is generated on-pixel and propagated down the column
- 4 LVDS TX data links, SPI configuration
- operation up to 320 MHz (TDC binning down to 50 ps)
- Hardware and DAQ can be installed at IHEP

Boron Neutron Capture Therapy (BNCT)

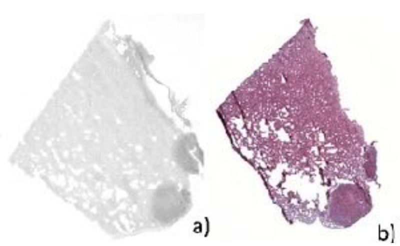


- BNCT is an experimental radiotherapy based on the administration of ^{10}B and low-energy neutron irradiation
- neutrons are captured in ^{10}B and release 2 high-LET short-ranged charged particles in the tumour cells

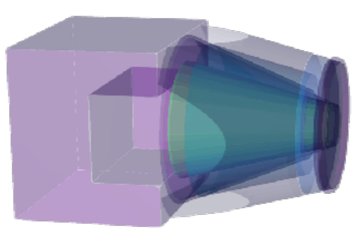


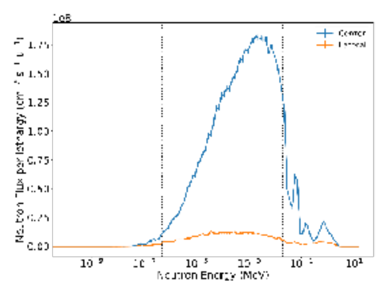
Selectivity due to boron distribution

BNCT for metastases, infiltrated and non-operable tumours

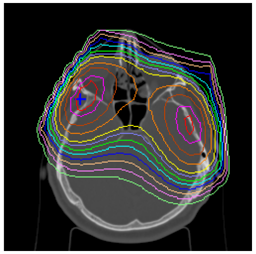


Boron quantification





Neutron beam design and therapeutic potential evaluation



Treatment Planning & dosimetry

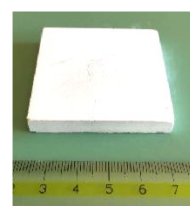
Research in BNCT with Chinese partners

- Design of clinical irradiation facilities
- Projects and dosimetric evaluations of neutron beams (Xiamen BNCT centre)
- Test of Treatment Planning System
- Test of new boronated drugs
- Production and characterisation of new materials for neutron moderation through sintering process (with Dept. of Chemistry – University of Pavia)
- Capability of creating targets for production of radioisotopes

Scientific Collaboration agreement signed June-2020 between INFN-PV and Nanjing University of Aeronautics and Astronautics, first step towards the **International Joint Laboratory for Advanced Particle Therapy (JLAB-APT)**

BNCT clinical centre @ Xiamen

Coupling of Cu and V for target construction



Densified AlF_3 and AlF_3+ 2% LiF
High density (~ 100%)

Sintering machine @ INFN Pavia

Outlook and perspective

- Good progress over the last 3 years on joint development of technology for medical instruments (ASICs for gamma cameras, design of X-ray single-photon counters).
- The first point-to-point workshop for brainstorming demonstrated the potential to foster and expand the framework of the collaboration for medical physics between INFN and IHEP.
- Planned activities for microelectronics (Si-strips, TOF-PET), developments of technology for PET-MRI (EM shielding) and X-ray imaging, eventually work together on detector design for HEPS. Growing activity on BNCT could also open new opportunities.
- The H2020 **FEST** project can provide support to these activities (WP4 Medical Applications)
- A lot of people thinking together generate a lot of ideas… which will in turn require a lot of manpower to put them into practice: Proposal for a framework that allows for the exchange of PhD students in medical physics?

IHEP-INFN medical applications

current collaborations and future perspectives

Istituto Nazionale di Fisica Nucleare

Thank You for your time!

感謝諸位的時間