HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

Detector Technologies and Systems (DTS)
Summary

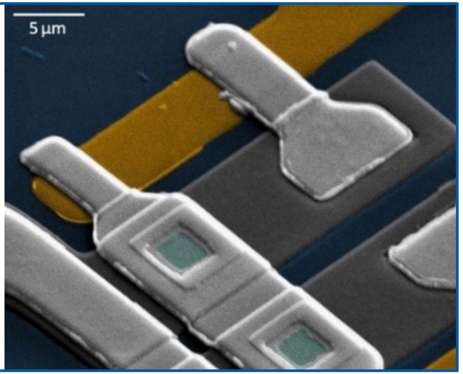
M. Weber, S. Masciocchi

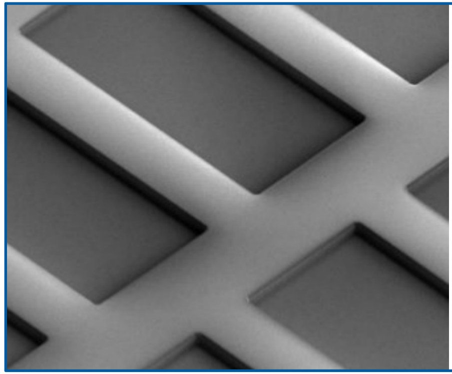
ST1 – Detection and Measurement

DTS excels in sensors and ASICs

Superconducting sensors

A mature technology with broad applications, ideal fit to Helmholtz



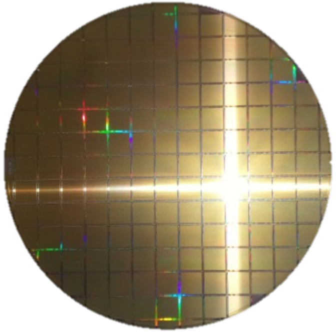


Post-processing silicon sensors

High quantum efficiency for soft X-rays, sensors tailored to specific application

High-Z semiconductor sensors

High quantum efficiency for hard X-rays



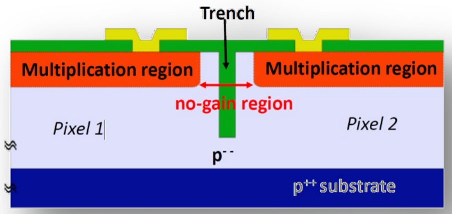
Innovative ASIC technology

Highest integration density, radiation-tolerance, speed

few technologies, many applications

ST1 – LGAD Hybrid Sensors

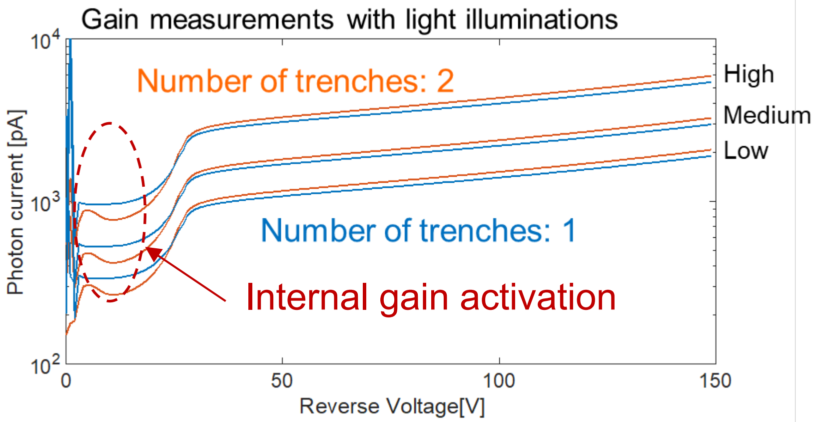
Silicon sensor for greater time, energy, and position resolution



Trench-isolated LGAD structure

- Development of segmented low-gain avalanche diodes (LGAD): small pixels, high fill-factor, time resolution down to tens of ps, edgeless design

- 18 wafers produced with different process and layout options
- Technology and layout design rules characterized

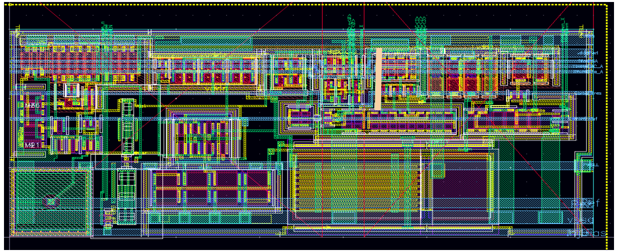


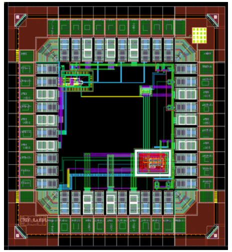
Poster session: M. Patil

- **Milestone DTS-2**: Establish availability of sensors with high spatial (20 µm) and time resolution (20 ps) for charged particles (2024)
- ***Ready for an engineering run***

ST1 – MAPS & CMOS Sensor Activities

Tangerine, H2M, dSiPM, passive CMOS Strips



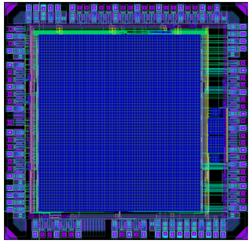


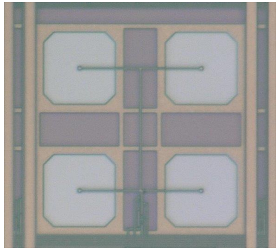
Status: 1st Prototype successfully tested, 2nd to be submitted

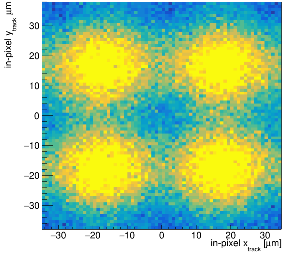
65-nm CIS from TPSCo foundry

- Charge-sensitive amplifier with Krummenacher feedback & discriminator, size: 35 x 15 μm² / 145 μV/e- / 35 e-
- H2M (CERN, DESY) & Tangerine (Helmholtz Innovation Pool)

DTS Talk: M. A. Del Rio Viera





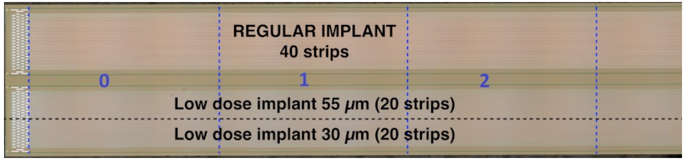


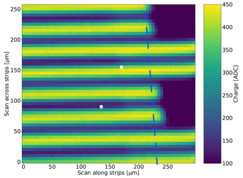
Status: Prototype successfully tested, evaluation in progress

150-nm CIS from LFoundry

- 32-by-32 pixel matrix with 4 SPADs each and global 12-bit TDC per quadrant
- 70 x 76 μm² / digital / kHz DCR / ~100 ps resolution
- Follow-up Project on DTS Common Fund 2014

DTS Talk: I. Diehl





Status: First batch tested, irradiation campaign ongoing

150-nm from LFoundry

- Sensor-only design with strips of different lengths
- Exercise stitching, evaluation of commercial CMOS process for HEP sensor production, irradiation study

ST1 – ALPIDE (Monolithic Active Pixel Sensor for the ALICE ITS3)

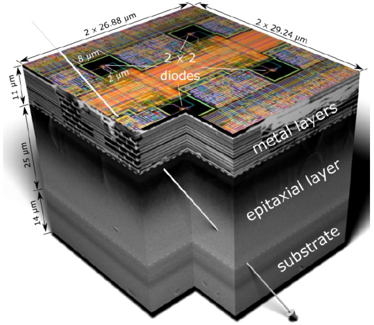
Test structures thoroughly investigated, including radiation hardness

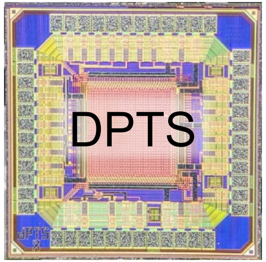
- Characterisation of neutron irradiated Digital Pixel Test Structures produced in 65 nm TPSCo CMOS process

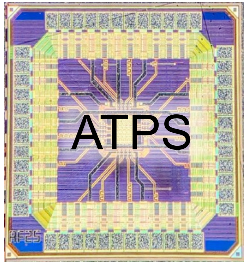
DTS Talk: P. Becht

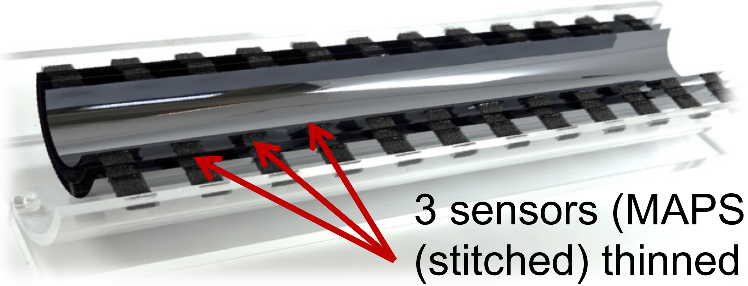
- Efficiency and spatial resolution of bent Monolithic Active Pixel Sensors measured with a 5.4 GeV electron beam

DTS Talk: B. Blidaru









3 sensors (MAPS) wafer-scale (stitched) thinned to O(20-40) µm bent to cylindrical shape

Pixel pitch: 10, 15, 20 and 25 µm

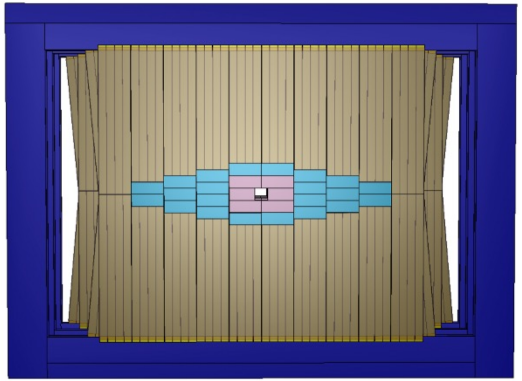
65-nm CIS from TPSCo

ST1 – MightyPix

An HV-CMOS pixel chip for LHCb’s Mighty Tracker

- Silicon sensors for inner part of proposed Mighty Tracker → radiation hard and good granularity
- First prototype **MightyPix1**
  - submitted to TSI in May 2022
  - Pixel matrix: 29 columns, 320 rows with 165 µm × 55 µm pixels
  - Simulations show MightyPix1 can already handle hit rate expected in hottest regions of Mighty Tracker

DTS Talk: S. Scherl



The Mighty Tracker: A hybrid of scintillating fibres (outer regions) and silicon sensors (inner regions)

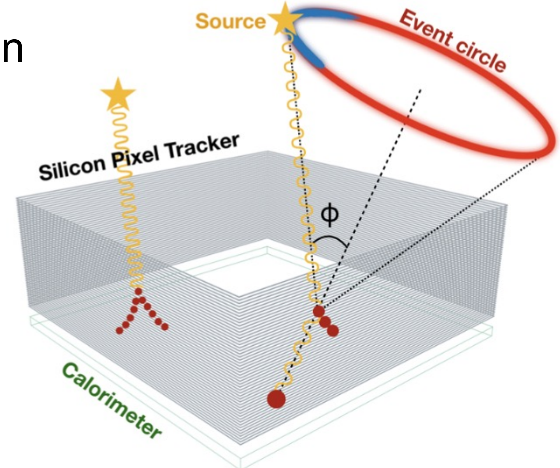
First prototype: MightyPix1

ST1 – AstroPix

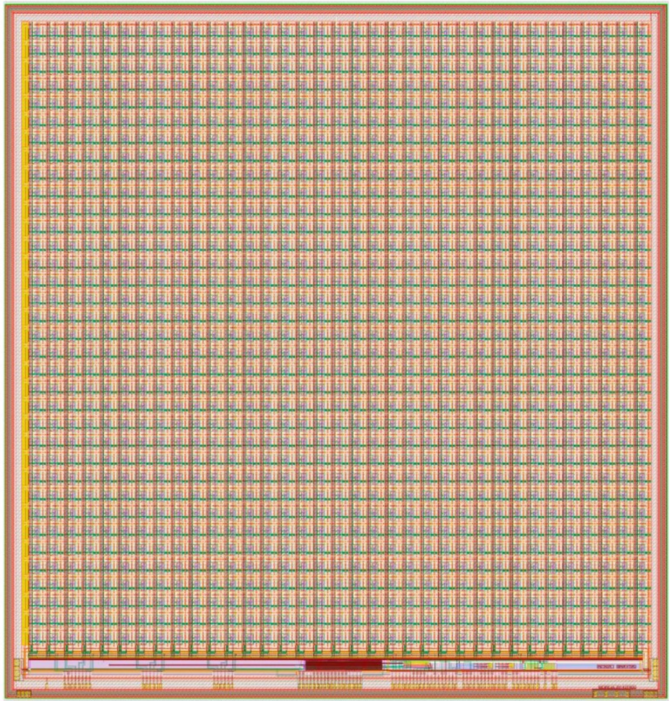
A novel HV-CMOS pixel sensor for experiments in space

- Silicon sensor for space Compton camera
- latest prototype: **AstroPix v3**
  - Full reticle size
  - 35 × 35 pixels
  - Low power consumption
  - High dynamic range

DTS Talk: N. Striebig



Schematic of Compton scattering and pair production for the silicon sensors



AstroPix v3

ST1 – Development of CoRDIA

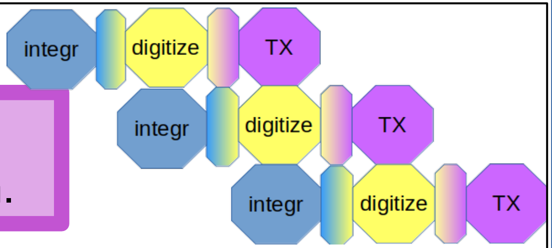
An Imaging Detector for next-generation Photon Science X-ray Sources

goal

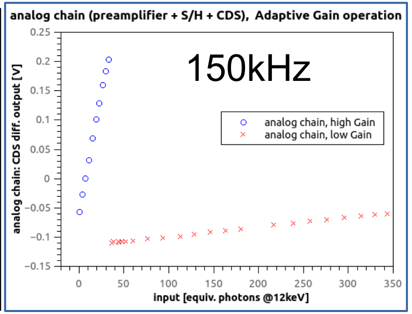
- > 100 kHz, continuous
- 100 µm pixel size
- compatible with high-Z & int.-amplification sensors
- 1-photon sensitive 12 keV
- 10k ph/pix/image (or more)

approach

Adaptive gain FE → ADCs 11b SAR → Timepix4 Gbit transm.



pipelined 3-stages architecture



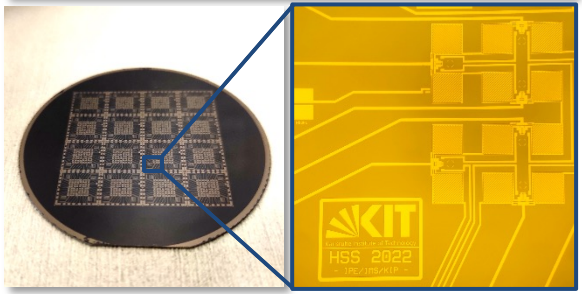
timeline

1. generation ASIC for start of Petra IV (~2027) will target mainly pixel pitch, continuous writing/reading, > 100 kHz continuous readout

2. generation ASIC with extended dynamic range, minimum blind areas

Production and Development Center for High-resolution Superconducting Sensors

HSS SUPERCONDUCTING SENSORS



First superconducting niobium layer of a magnetic microcalorimeter array on a two-inch silicon wafer (fabricated with maskless aligner)

- Maskless Aligner „MLA150“ (Heidelberg Instruments GmbH)
  - **December 2021:** Delivery to KIT
  - **January 2022:** On-site acceptance and initial operation
  - **February 2022:** Regular use for R&D activities
- Etching system „Plasma Pro®100 Cobra“ (Oxford Instruments)
  - **August 2022:** Delivery to KIT
  - **Current status:** System installation by KIT staff
  - **October 2022 (planned):** On-site acceptance test
- Custom-built UHV-Sputtercluster (BESTEC GmbH)
  - **September / October 2022:** Design review + acceptance
  - **August 2023 (planned):** Factory acceptance test
  - **October 2023 (planned):** On-site acceptance test
- In parallel:
  - Process development on installed machines (supplemented by IMS deposition and etching systems)
  - Procurement preparation of remaining devices / machines

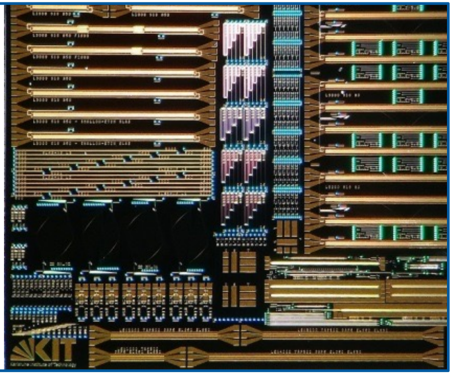
→ **HSS is on schedule, first sensors expected early 2024**

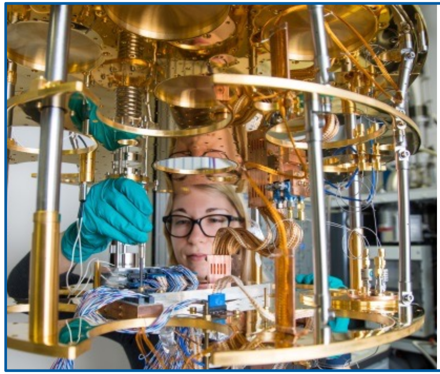
ST2 – System technologies

Critical technologies for coping with the data deluge

Silicon photonics

A game-changing technology,
enabling trigger-less detectors





Cryogenic readout

Enabling 1k-pixel sensors,
superconducting electronics
spin-off:
Quantum Computing

Real-time data acquisition

Scaling-up to Terabit/s,
advanced algorithms,
detector intelligence

Novel engineering techniques

High-density electronic integration, micro-fabrication, thermo-mechanical designs

ST2 – System Technologies

Key components for advanced detector systems

- **Core activities:**
  - Enabling optical communication for on-chip integration
  - High-performance and intelligent DAQ systems
  - Advancing packaging technologies
- **MT highlight:**
  - DAQ systems for Terabit per second data rates
  - Multiple high-performance boards have been developed by the Helmholtz centers

I/O rate of 6 TB/s with Serenity A2577 for various CMS applications

- **Next milestones:**
  - 2022 – Realize readout for cryogenic detectors with > 1000 channels
  - 2024 – packaging for hybrid non-Si materials and 3D structures

ST2 – DAQ for next generation particle physics

Managing highest data rates and trigger at Tb/s

- Existing prototypes being optimized for ‘production’ versions of the board (~500 units)
- Designing two flavors with 1 and 2 FPGAs (Xilinx VU13P) sharing the same management infrastructure
- Planned adoption in multiple CMS Phase-2 sub-systems (e.g. Tracker, HGCAL, MTD, RPC, Trigger and possibly BRIL)
- Currently thoroughly testing the Samtec Firefly 25 Gb/s optical transceivers

Serenity-A
ATCA Board

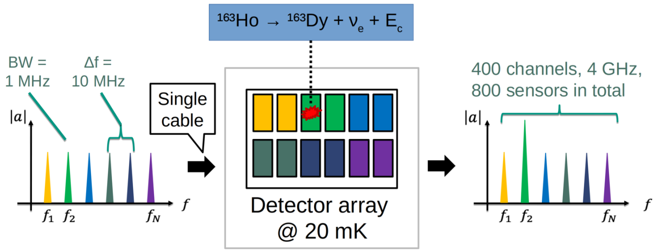
DTS Talk: T. Mehner
DTS Talk: M. Fuchs

ST2 – DAQ for ECHo neutrino mass experiment

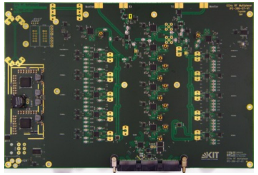
Electronics for readout of SQUID-multiplexed cryogenic sensors

- Successful operation of prototype with and w/o cryogenic sensors
- Full-scale hardware for processing of 800 sensors ready
  - Custom Converter-Board and RF-Frontend developed at KIT
  - Versatile FPGA-Board developed in **cooperation DESY & KIT**
- Ongoing topics and next steps:
  - Adaptation of the firmware to new hardware capabilities
  - Characterization and commissioning of hardware components
  - Improvement of measurement sensitivity

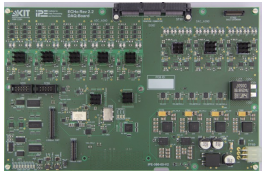
Multiplexing scheme



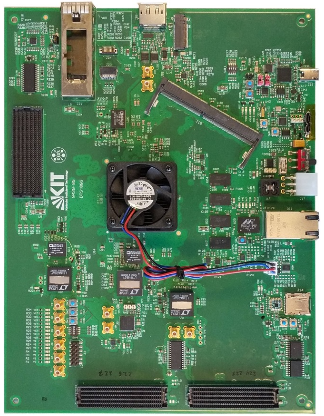
RF-Frontend



Converter board



FPGA board DTS-100G



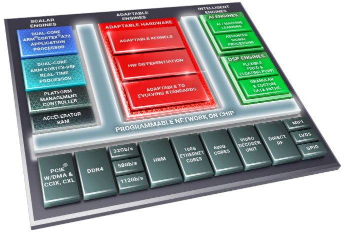
DTS Talk: T. Muscheid
DTS Talk: J. Salum

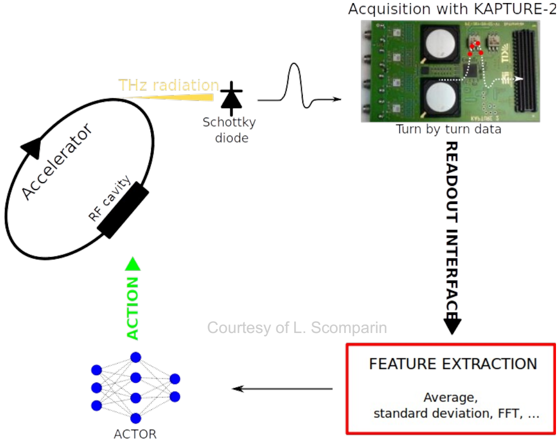
ST2 – Artificial Intelligence

New platforms and applications

Reinforcement Learning for autonomous particle accelerators

- Fast Neural Network inference (tens of μs latency comprising readout, inference and action)
- Novel Xilinx Versal ACAP platform
- ACCLAIM (Helmholtz Innovation Pool)
- ➔ Testing expected to start by end of year

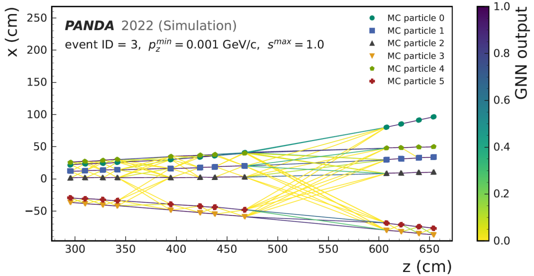




Poster session: L. Scomparin

Fast AI track reconstruction on FPGA for PANDA experiment

- Training of Interaction Networks for Graph classification
- Application to tracking in HEP detectors (e.g. PANDA)
- Tested performance of deployment on FPGA (collaboration with KIT-FZJ-GSI, master thesis of G. Heine)



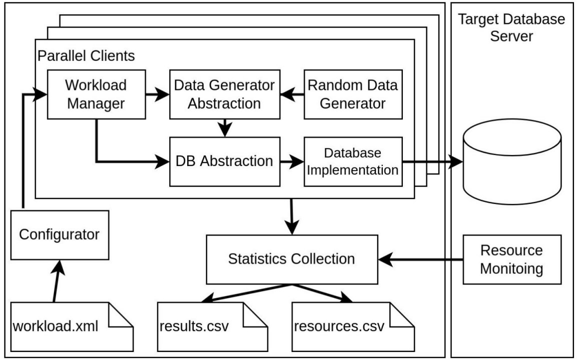
ST2 – Real-time data storage

SciTS – a tool to evaluation time-series databases (TSDB)

Goal: direct storage of DAQ data in database engines

- An evolution of TSDBs motivated by time-series special characteristics:
  - Indexed by its corresponding timestamps
  - Continuously expanding in size
  - Usually aggregated, down-sampled, and/or queried in ranges
  - has very write-intensive requirements
- **SciTS** is a benchmark for TSDBs in large-scale experiments and industrial IoT
  - Motivated by experiences in the KATRIN experiment
  - Parameterizable ingestion workloads & 5 practical query workloads based on our study of data management tools in scientific experiments

https://github.com/jalalmostafa/scits



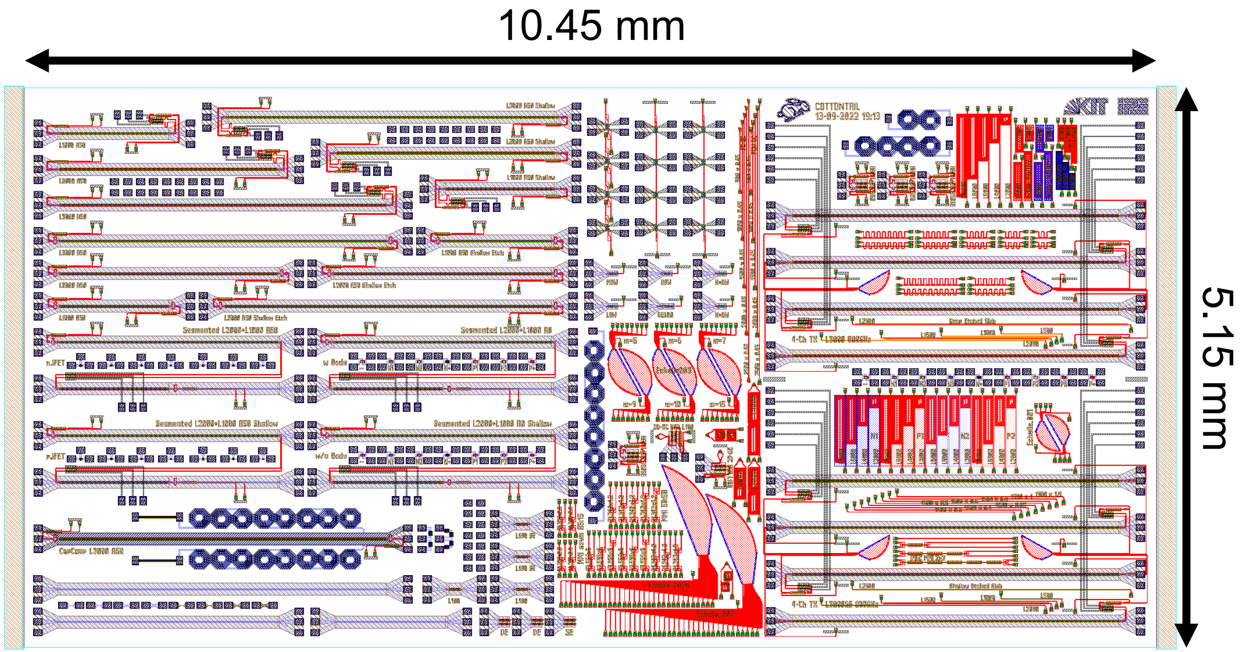
ST2 – Optical Communication

Silicon photonics

- New silicon photonic chip 'Cottontail':
  - Layout almost finished for fabrication at imec, Belgium
- Driver electronics:
  - GUI for easy and clear parameter setup under progress
- Fiber-chip coupling:
  - Recipe to prepare angle-polished, polarization-maintaining (PM) fibers formulated

Poster: M. Schneider

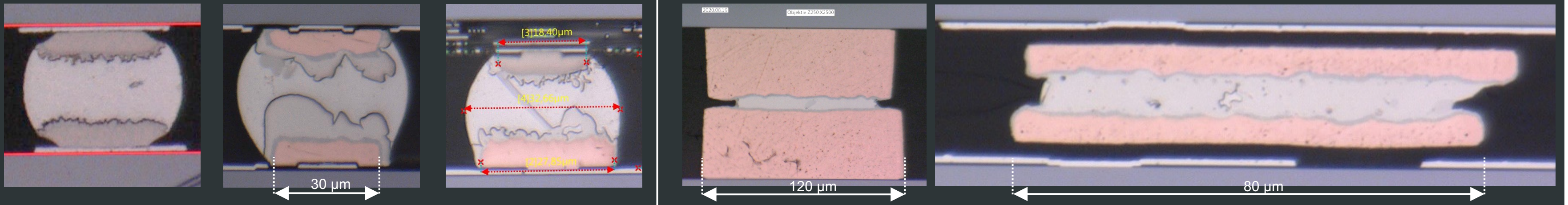
Cottontail: Chip for detector instrumentation with wavelength division multiplex



ST2 – Packaging Technologies at DESY

Cleaning, Bumping, Mounting & Reflow

Tiny Pads for 50-µm Pitch			Large Pads & Pillars for full Cu UBM	
Ni-Au	Cu	mixed	Cu Pillar	Cu Pad



To probe further: https://indico.scc.kit.edu/event/2678/contributions/10080/attachments/4931/7455/Flip_Chip_Packaging_DESY.pdf

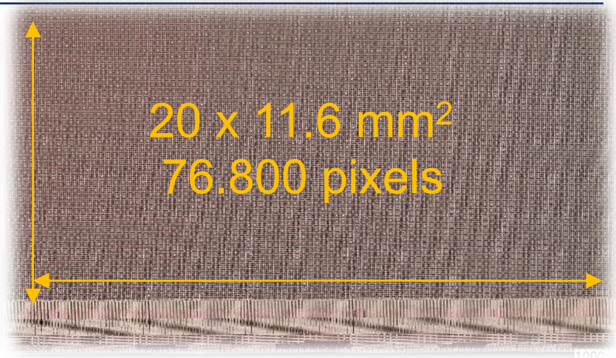
- CMS-Pixel Luminosity Telescope modules successfully mounted
- All processes for fast prototyping available in-house
- Paper with processes & results to be submitted to MDPI Materials

ST2 – Bump-Bonding of CMS pixels for phase 2 upgrade

High-granularity and large-area bump-bonding technology

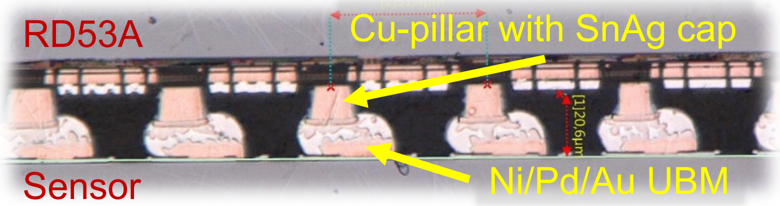
Toward to the production of the next pixel detector of CMS experiment

- Large active area and high-density technology with 33 kpixel/cm^2, pixel pitch of 50 µm
- Femto flip-chip bonder machine successfully upgraded to manage large devices

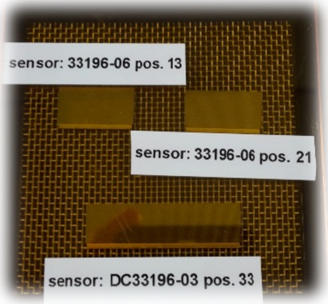


RD53A front-end ASIC (pre-production)

- Bonding process based on *solid-to-liquid* thermo-compression with *reflow* in-situ by formic acid



Cross-section of the bump-bonding connection



- **First delivery**: two singles and one-double assemblies sent to Hamburg for the electrical test and feedbacks

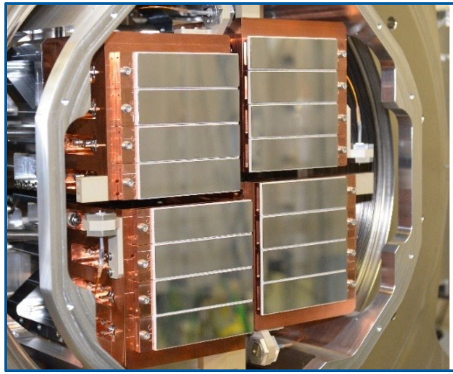
ST3 – Science systems

Build and characterize demonstrator systems ready for science

Particle physics

Ultra-low material silicon detectors with excellent time and spatial resolution

MU



Photon Science

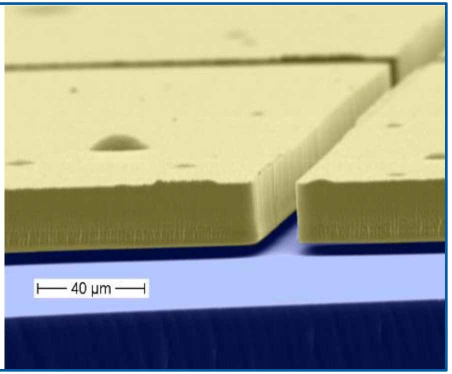
Megapixel detectors for soft X-rays, high-Z detectors,
MHz- frame rates

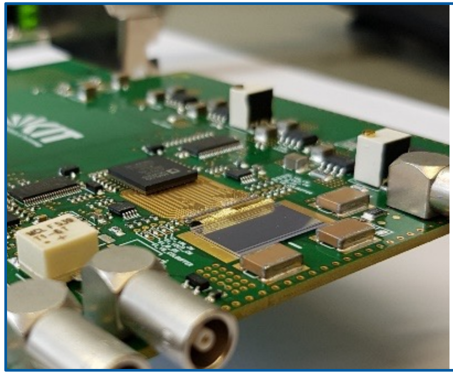
MML

Astroparticle physics

Cryogenic detectors of unique energy resolution for dark matter searches and neutrino physics

MU





Beam physics

Multi-spectral THz detectors for beam diagnostics,
6D THz camera

MT ARD

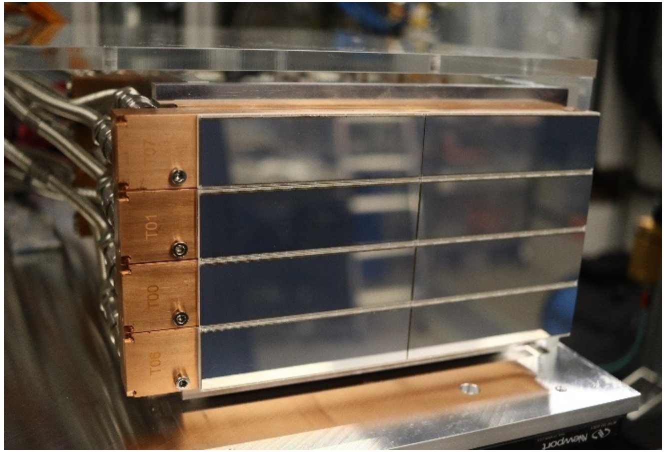
ST3 – Science Systems: Photon Science

AGIPD – Adaptive Gain Integrating Pixel Detector

- AGIPD 1.2 frontend modules in production for 1M channel systems at EuXFEL

  AGIPD1.2 ASIC fixes gain encoding of AGIPD 1.1

- Development of 2nd generation AGIPD systems
  - 0.5 Mpix prototype system in user operation at EuXFEL
  - Cooling system simulations completed and prototypes of core components successfully tested
  - new readout board in production
  - Electron-collecting version of AGIPD for high-Z sensors in production (AGIPD 1.3)

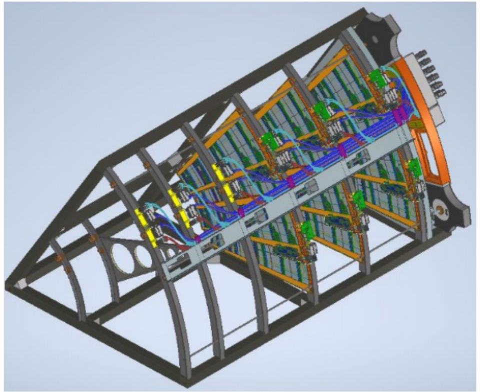


0.5 Mpix 2nd generation AGIPD prototype

ST3 – End Cap of ATLAS Inner Tracker (ITk)

System test a vital step towards detector production for LHC

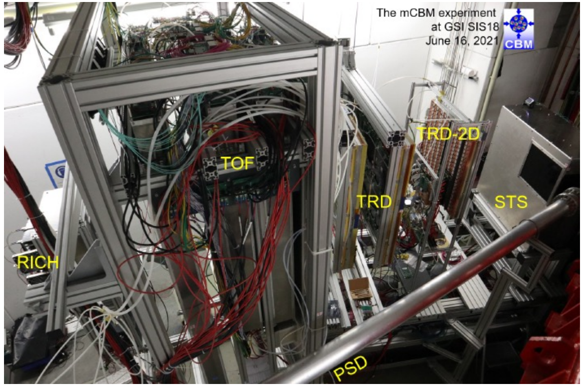
- segment of mechanical structure
- possiblility to test up to 12 petals
- all mechanics and services as in final experiment (power, cooling, control)
- structure is ready – installation in laboratory ongoing



ST3 – mSTS demonstrator for CBM experiment @ FAIR

Mini-Silicon Tracking System completed in 2021

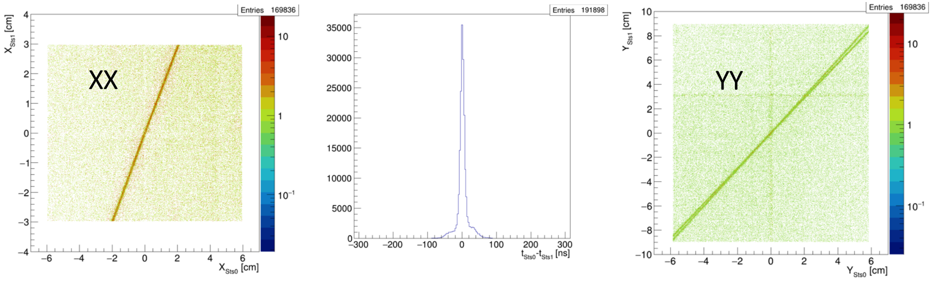
- prototype STS system of two tracking layers with 11 modules
- operation in O+Ni collisions at 2 AGeV @SIS19 (10^{10} ions per spill, ~ 500 kHz interaction rate)
- combined with other CBM demonstrator systems:
  mMUCH, mTRD, mTOF, mRICH, T0, free-stream DAQ to online Computing Center GreenCube



ST3 – mSTS demonstrator

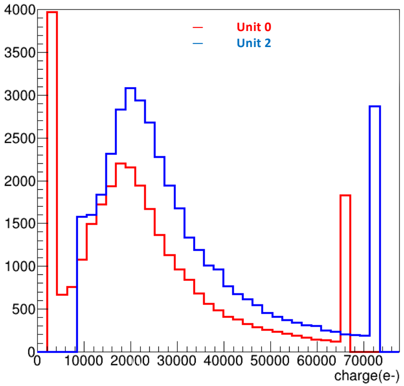
Demonstrator is fully operational

- Hit maps looking excellent, few r/o ASIC and individual channels missing
- first performance results match expectation … see [CBM Progress Report 2021]
- much more to come with data from mCBM campaign 2022

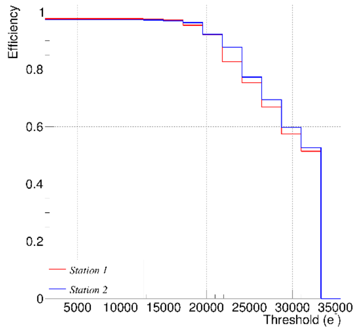


inside time window (-100, +100) ns

Correlations of hit pairs STS1:STS2 (hit time resolution 5 ns)



MIPS Charge calibration

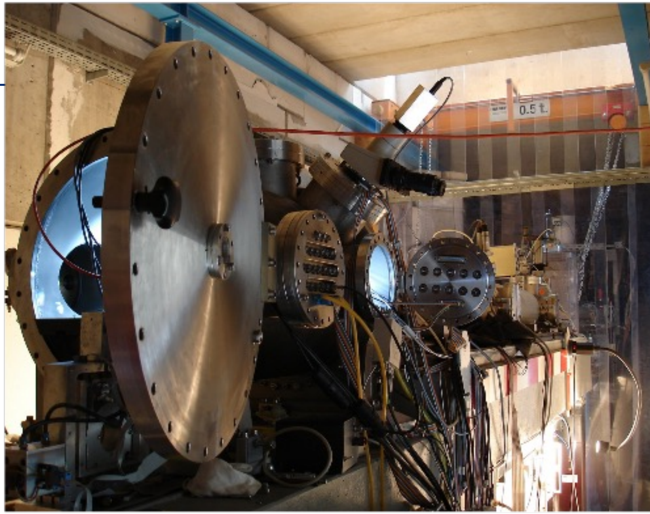


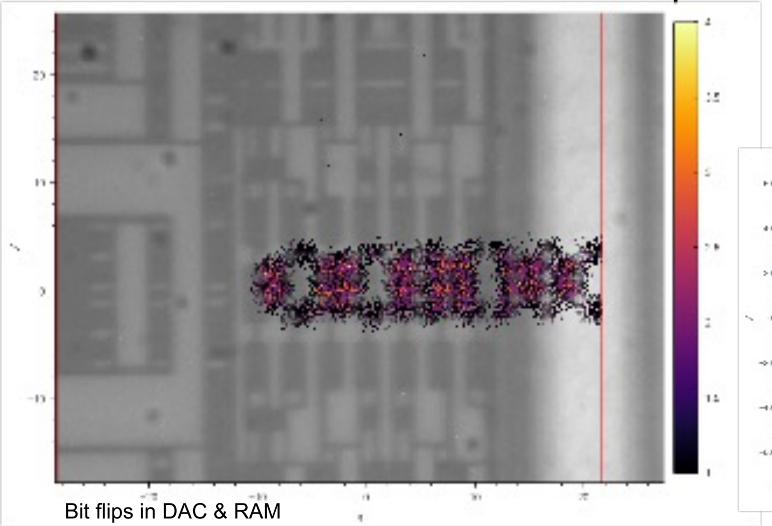
Hit reconstruction efficiency as function of r/o threshold

ST3 – CBM MIMOSIS-Sensor at the GSI Micro-Beam

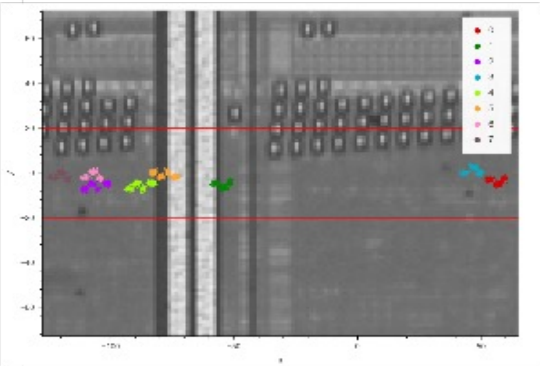
Single-event Effect Testing and Localization

- Bit flips in DAC & RAM
- Individual ion impact in vacuum with 3.6 to 11.4 MeV/u
- Beam focus 500 nm
- Pencil beam scan window 655 x 662 μm^2





Bit flips in DAC & RAM

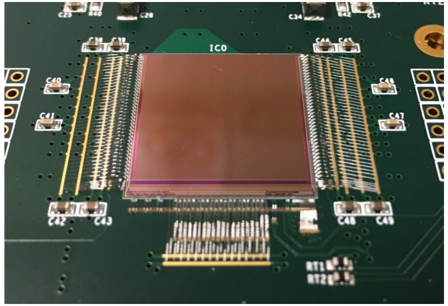


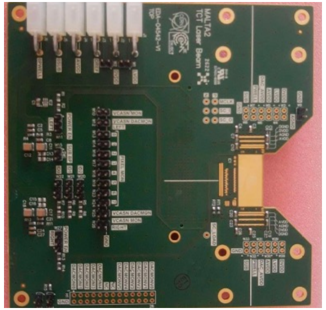
DTS Talk: O. Keller

ST3 – From Pixel Sensors to Systems

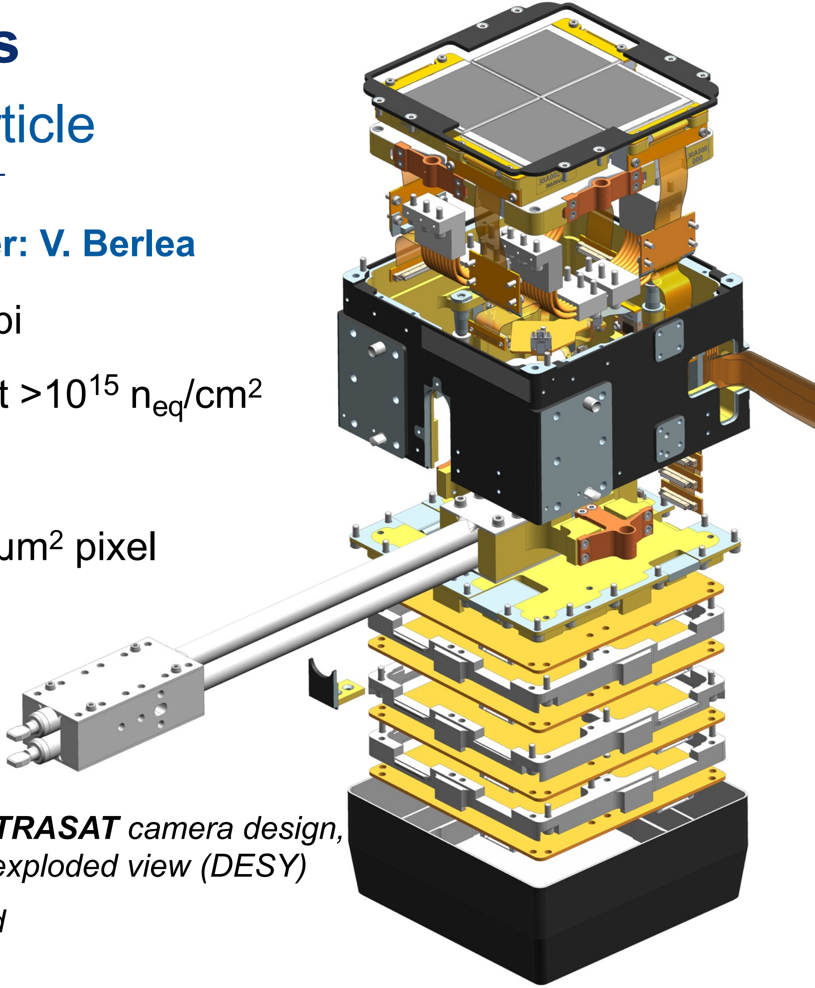
MAPS sensor R&D for particle and astroparticle

- MALTA2: MAPS sensor R&D **DTS Talk + Poster: V. Berlea**
  - Tower Semiconductor 180nm modified process w/ epi
  - tracking/vertexing, 36.4 x 36.4 μm^2 pixel, rad tolerant $>10^{15}\ n_{eq}/cm^2$
- ULTRASAT: UV MAPS satellite camera system
  - stitched 4.7x5 cm^2 backside-illuminated sensor, 9.5 μm^2 pixel
  - 90 Mpixel array w/ custom mechanics and readout





***MALTA2** sensor and Edge-TCT readout*

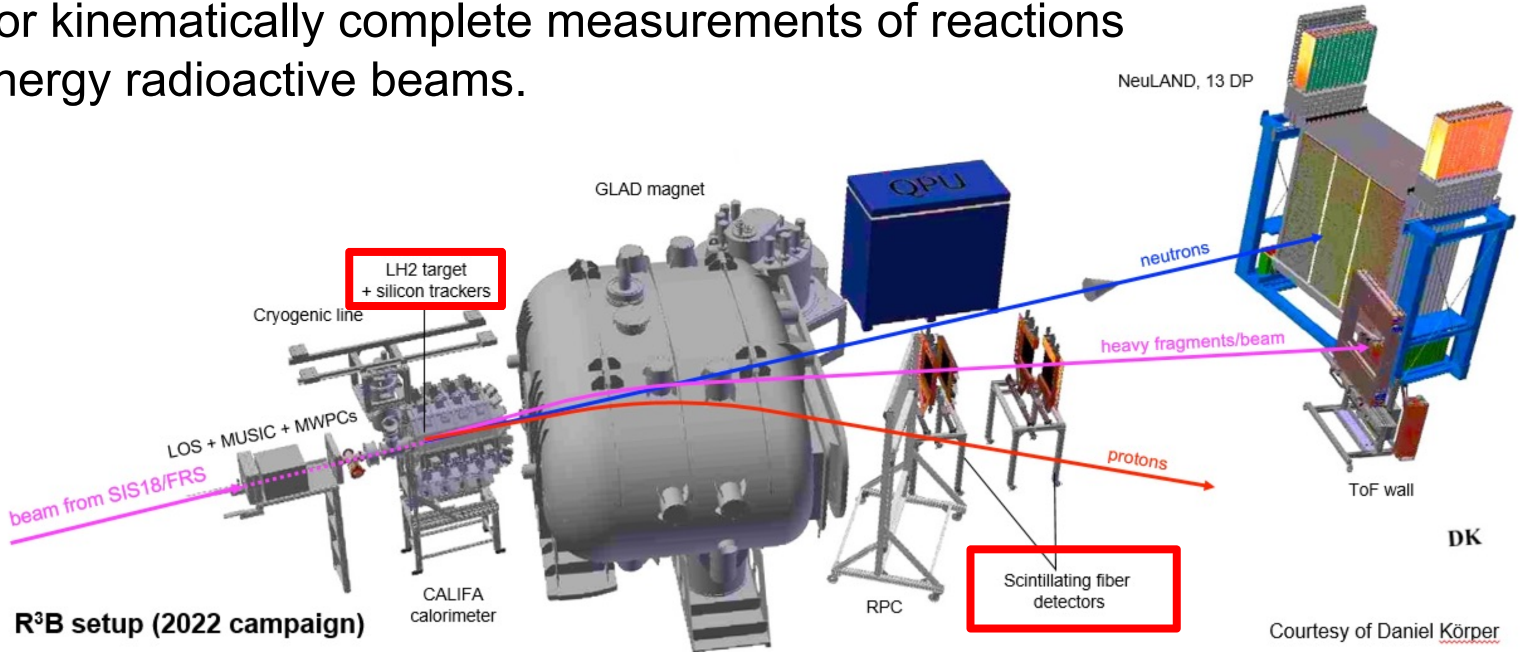


***ULTRASAT** camera design, exploded view (DESY)*

ST3 – New Detector Systems @ R³B

Experimental setup for studies of Reactions with Relativistic Radioactive Beams

- A versatile reaction setup with high efficiency, acceptance and resolution for kinematically complete measurements of reactions with high-energy radioactive beams.



R³B setup (2022 campaign)

Courtesy of Daniel Körper

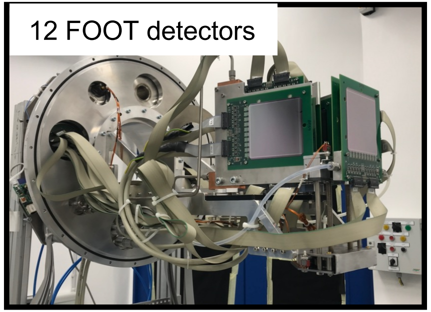
ST3 – New Silicon Tracker @ R³B

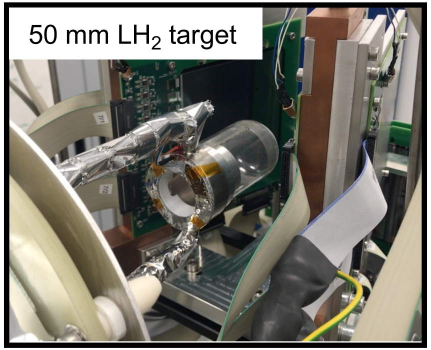
FragmentatioOn Of Target Experiment (FOOT)

Two-arm FOOT configuration in 2022 experiments:

- Tracking recoil protons from target e.g. from (p,2p) reactions and heavy fragments
- HAMAMATSU single-sided sensors, 50 µm strip pitch, 150 µm thick, 640 channels

- Original development of FE and DAQ by INFN group from Perugia
- FE board contains:
  - 10 charge-sensitive ASICs IDE1140 (IDEAS, Norway)
  - AC-coupled, pulse height proportional to the input charge
  - 64 strips bonded to a single ASIC
  - Buffer amplifiers
- First prototypes at GSI: June 2021
- First beam test in Jülich: October 2021





ST3 – Scintillating Fiber Systems @ R3B

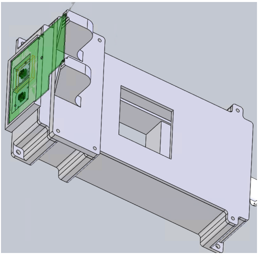
Detector Production

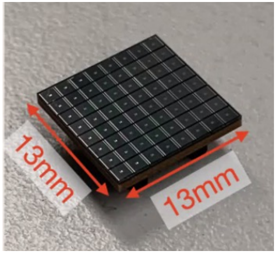
- First prototypes started in 2017
- First series in 2019, so far all with MAPMT

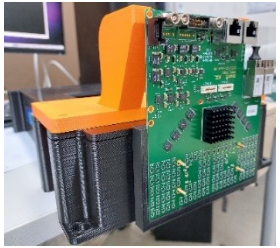
- For 2021 beamtimes we improved:
  - fiber ribbon production
  - mechanical design
  - dedicated readout

C. Caesar, D. Savran, M. Heil, H. Heggen for the R3B collaboration

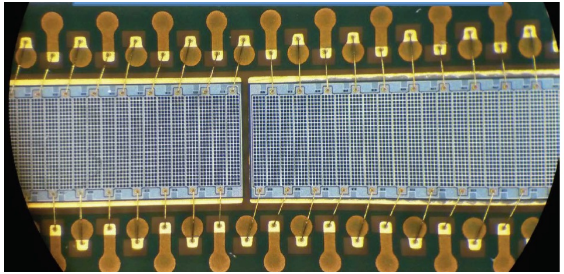
ongoing: development using „SiPMs“ 1d array and Matrix







prototype with 128 channel FPGA TDC tested succesfully in GSI beam time in 2022



Sitzung der FIS-Kommission am 21./22. Februar 2022

Vorstellung des Investitionsantrages

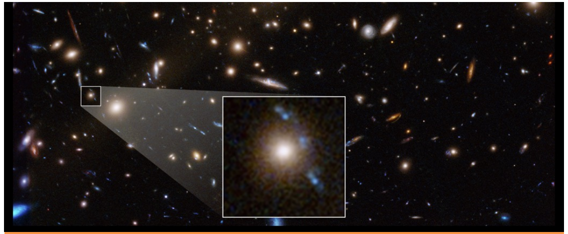
DDL- Helmholtz Distributed Detector Laboratory

- Intense preparation by DDL team
- Inspired talk by Heinz Graafsma

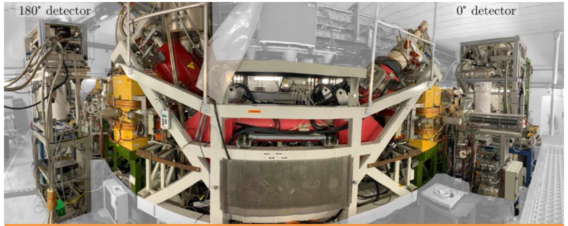
DDL für Helmholtz und Gesellschaft

Beispiel: Kryogene Sensoren und SQUIDs (KIT)

Forschung mit extrem empfindlichen Detektoren



Dunkle Materie



Präzisionsspektroskopie

- eV Energieauflösung
- ns Timing
- einzelne Quanten
- Megapixel

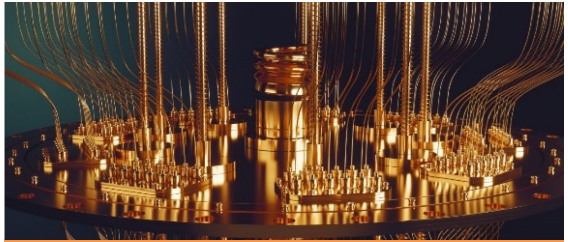
DDL-Infrastrukturen

Reinrauminfrastruktur

Mikrostrukturierungstechnik

Breite Anwendungen

- Metrologie
- Rohstoffsuche
- Medizintechnik
- Quantentechnologien

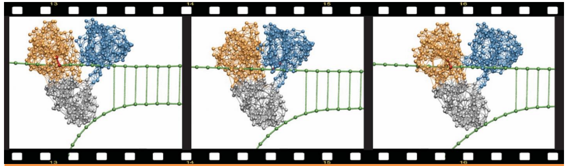


Quantentechnologien

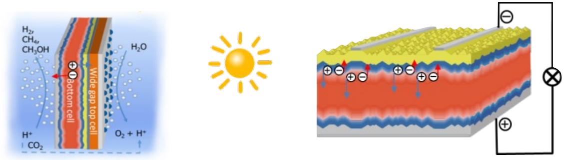
DDL für Helmholtz und Gesellschaft

Beispiel: Silicon post-processing (DESY)

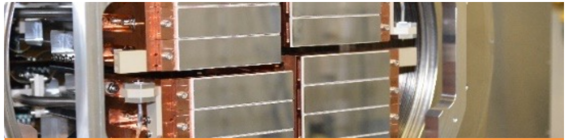
Forschung bei niedrigen Photon Energien



Biologische Materialien



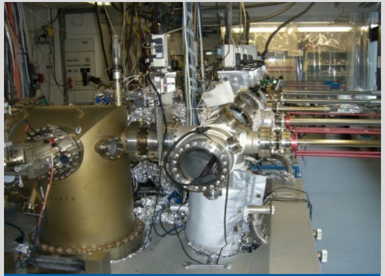
Energiematerialien



Grundlagenforschung

- < 500 eV Röntgen
- 100 Megapixel
- Quantensprung in Sensitivität

DDL-Infrastrukturen

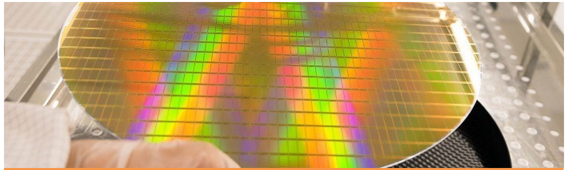


Silicon post-processing

Breite Anwendungen

- Medizin
- Gesellschaft
- Sicherheit

Bildgebung



Mikroelektronik

#	Milestone	ST	Year	Center
7	Realize scalable readout technologies for pixelated cryogenic detector systems with > 1000 channels	2	2022	KIT
11	Evaluate the performance of a Compton detector in the high keV-low MeV regime	3	2022	DESY, GSI, KIT
8	Validate integrated microchannel cooling structures	2	2023	DESY, GSI
2	Establish availability of sensors with high spatial (20 μm) and time resolution (20 ps) for charged particles	1	2024	DESY, GSI, KIT
3	Develop a readout ASIC family for combined space, time, and energy measurement	1	2024	DESY, KIT
9	Establish packaging technologies for hybrid detectors with non-Si materials and 3D structures	2	2024	DESY, GSI, KIT
12	Assemble silicon beam telescope system demonstrating at the same time ultrafast timing, high spatial resolution, and ultra-low X/X_0	3	2024	DESY, GSI, KIT
1	Establish and commission the Distributed Detector Laboratory	1-3	2025	DESY, GSI, KIT
4	Develop a high-rate pixel readout ASIC for diffraction-limited synchrotron sources and future FELs	1	2025	DESY
5	Establish silicon photonics system components for optical data transmission	1,2	2025	DESY, KIT
13	Operate routinely a 1k-pixel cryogenic MMC sensor array for precision QED tests at CRYRING	3	2025	GSI, KIT
14	Provide pixelated THz detector combining spectral, space and time measurement for beam diagnostics	3	2025	KIT
6	Establish availability of high-performance sensors covering the entire X-ray spectrum	1	2026	DESY, KIT
15	Bring into operation a highly granular 5D (position, time, energy) calorimeter prototype with SiPM readout	3	2026	DESY, KIT
10	Assemble an intelligent terabit data acquisition and processing platform for advanced algorithms	2	2027	DESY, KIT
16	Demonstrate hybrid pixel system capable of matching CW-FEL bunch rates with advanced (optical) data transmission	3	2027	DESY, KIT

Summary

- It is so great to see you all in person again!
- We need more of these meetings, even if our way of working has changed.
- Again, there is a wealth of results and huge progress.

- Next evaluation will largely be based on our work in the next 2.5 years:
  completion of milestones, delivery of projects, collaboration and vision for the future.

- The DDL proposal is waiting for the final decision of the Helmholtz Senate in October

Thank you!!