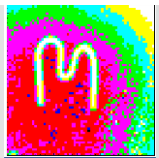
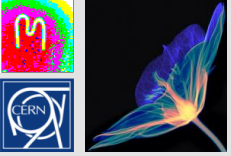


THE MEDIPIX AND TIMEPIX CHIPS: DESCRIPTION AND POSSIBLE USES FOR BEAM INSTRUMENTATION

M. Campbell[1], J. Alozy, R. Ballabriga, E.H.M. Heijne, I. Kremastiotis, X. Llopart, T. Poikela, E. Santin, V. Sriskaran, L.Tlustos and W.Wong

CERN, PH Department
1211 Geneva 23
Switzerland

[1] Honorary Professor at Glasgow University



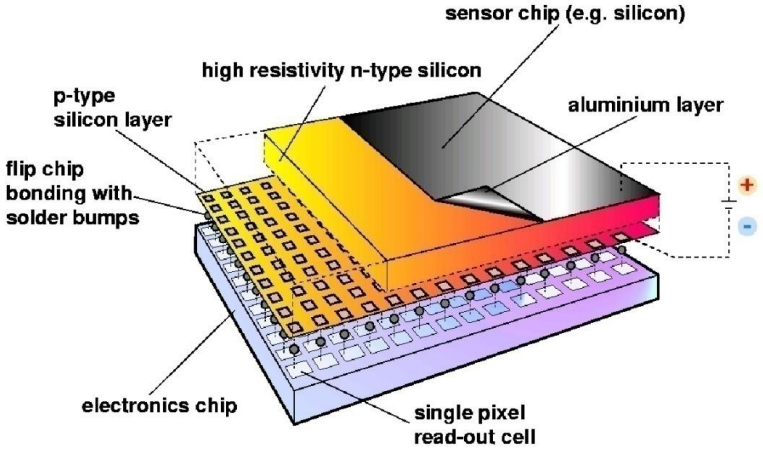
Medipix2 Collaboration

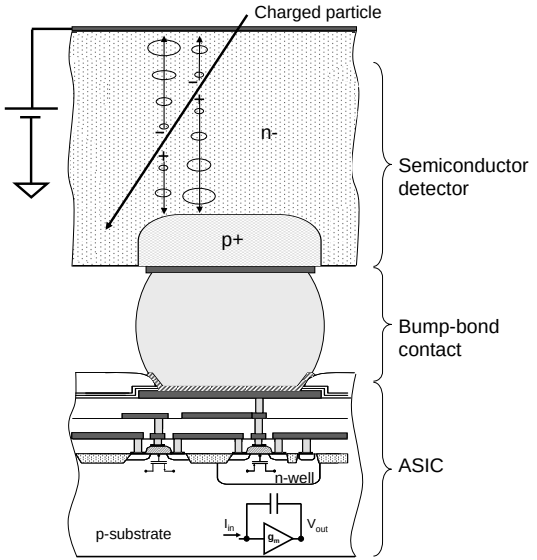
- University and INFN Cagliari, Italy
- CEA-LIST Saclay, France
- CERN, Geneva, Switzerland
- Friedrich-Alexander-University Erlangen-Nurnberg, Germany
- ESRF, Grenoble, France
- University of Freiburg, Germany
- University of Glasgow, UK
- IFAE Barcelona, Spain
- Mid-Sweden University, Sundsvall, Sweden
- MRC-LMB. Cambridge, UK
- University and INFN Napoli, Italy
- NIKHEF, Amsterdam, The Netherlands
- University and INFN Pisa, Italy
- FZU Czech Academy of Science, Prague, Czech Republic
- IEAP, Czech Technical University in Prague, Czech Republic
- Space Science Laboratory, UC Berkeley, USA


Medipix3 Collaboration

- University of Canterbury, Christchurch, New Zealand
- CEA, Paris, France
- CERN, Geneva, Switzerland,
- DESY-Hamburg, Germany
- Albert-Ludwigs-Universität Freiburg, Germany
- University of Glasgow, Scotland, UK
- Leiden University, The Netherlands
- NIKHEF, Amsterdam, The Netherlands
- Mid Sweden University, Sundsvall, Sweden
- IEAP, Czech Technical University, Prague, Czech Republic
- ESRF, Grenoble, France
- Universität Erlangen-Nurnberg, Erlangen, Germany
- University of California, Berkeley, USA
- VTT, Information Technology, Espoo, Finland
- KIT/ANKA, Forschungszentrum Karlsruhe, Germany
- University of Houston, USA
- Diamond Light Source, Oxfordshire, England, UK
- Universidad de los Andes, Bogota, Colombia
- University of Bonn, Germany
- AMOLF, Amsterdam, The Netherlands
- Technical University of Munich, Germany
- Brazilian Light Source, Campinas, Brazil

Hybrid Silicon Pixel Detectors





Standard CMOS can be used allowing on-pixel signal processing

Sensor material can be changed according to the application(Si, GaAs, CdTe..)

Gas detector readout - GEM

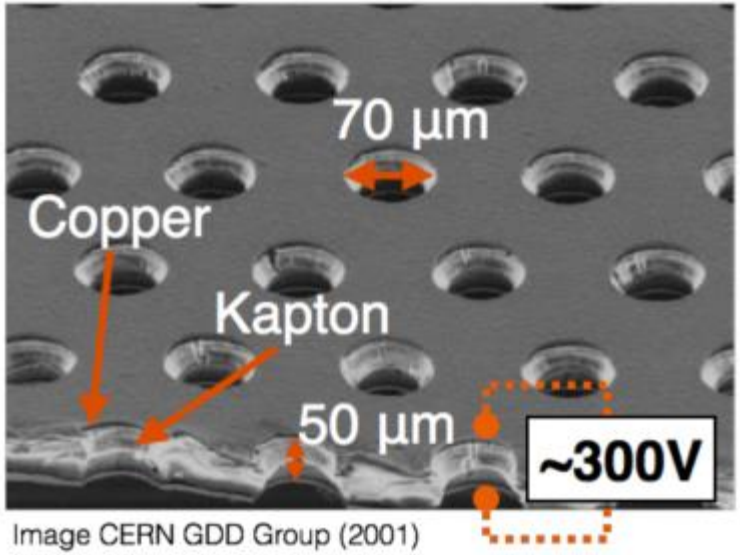
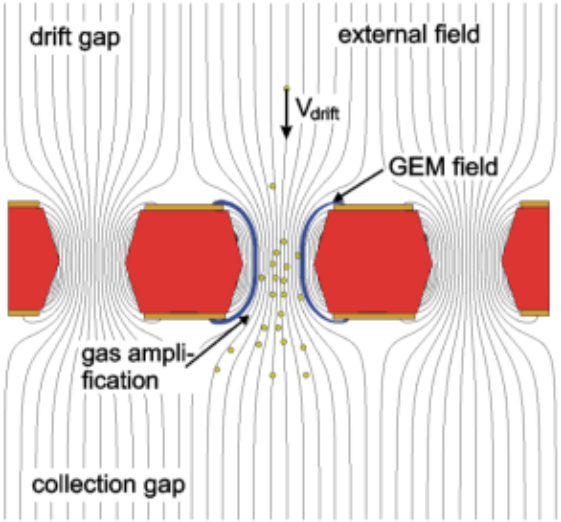
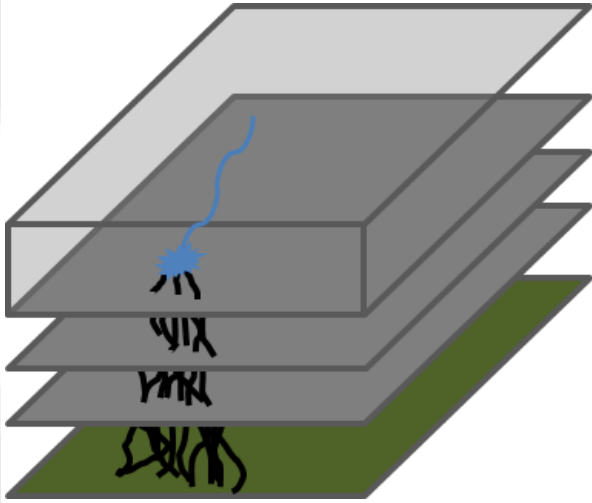


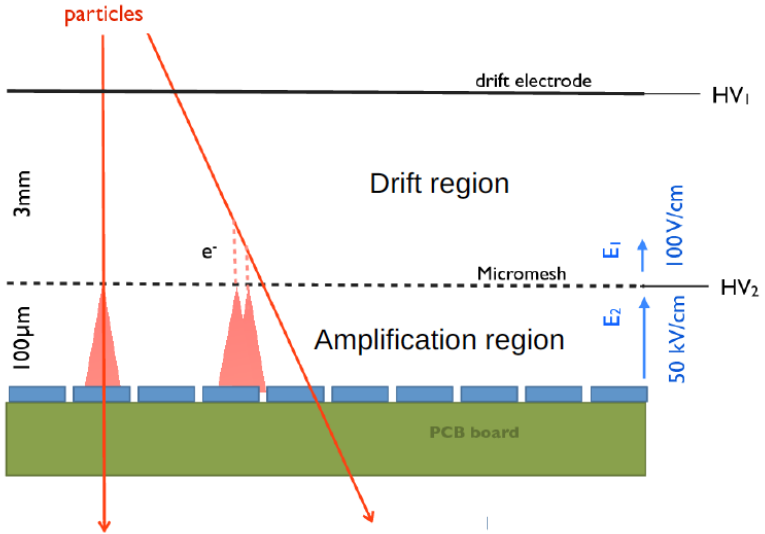
Image CERN GDD Group (2001)

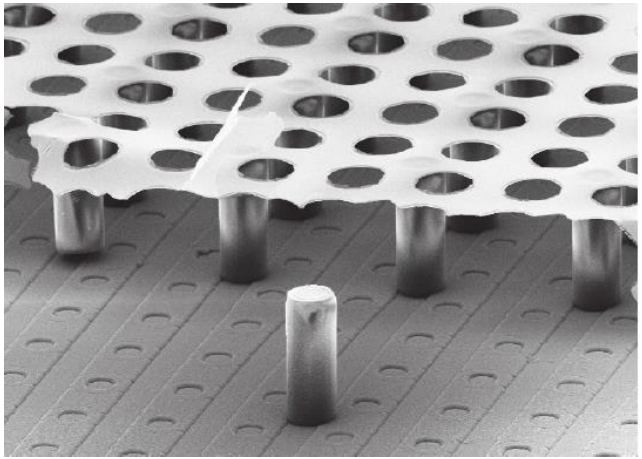




Naked pixel readout chip

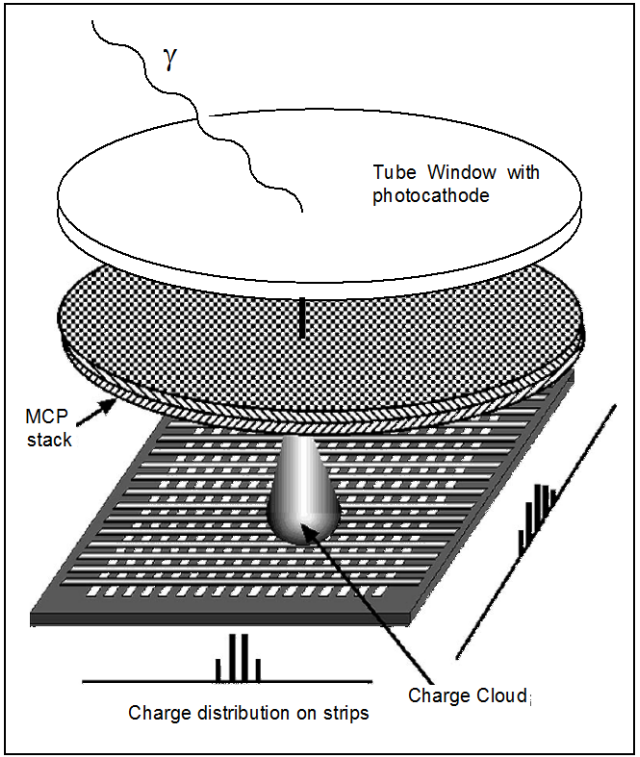
Gas detector readout - InGrid





Semiconductor detector is replaced with charge amplification grid
Permits lower energy events to be detected

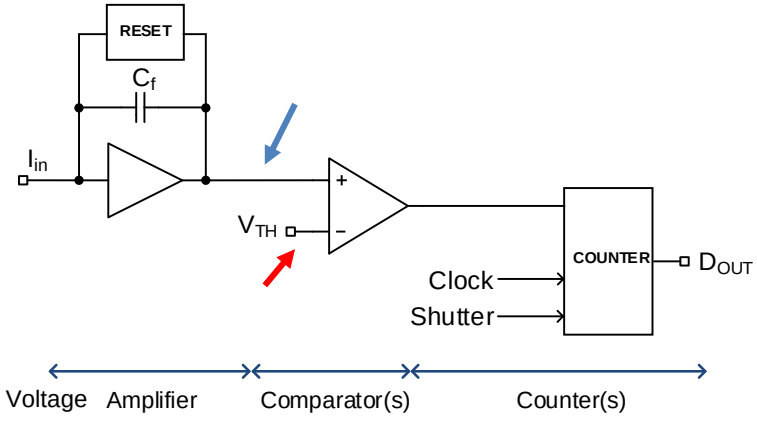
Micro-channel plate readout

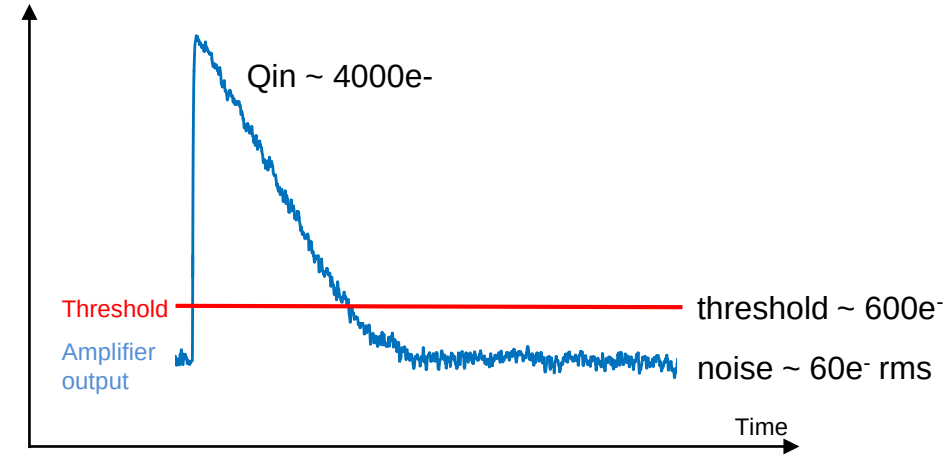


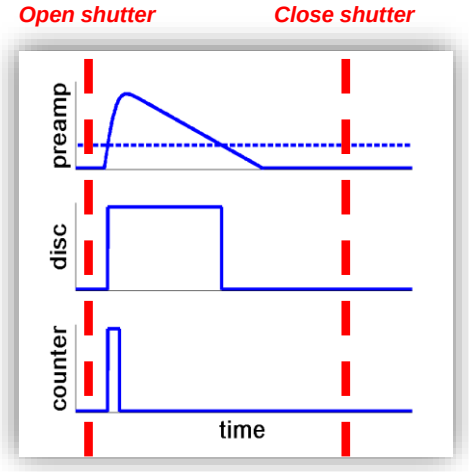
Gain of ~ 1000 to 10000 is enough for full sensitivity
--> improved lifetime

MCP can be used to detector electrons, ions or neutrons(when e.g. B doped)

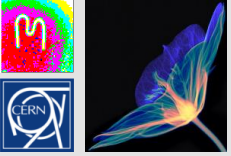
Hybrid Pixel Detector – Counting Electronics







→ Noise hit free imaging

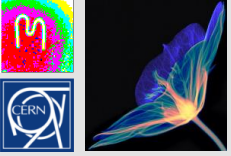


Hybrid pixel detectors

- Developed initially for LHC
- 3 large scale vertex detector systems (ALICE, ATLAS, CMS) operating smoothly
- One large RICH detector system (based on hybrid pixels in a photodetector tube) contributing to LHCb physics

- In the Medipix2 and Medipix3 Collaborations we have taken the technology into many new fields

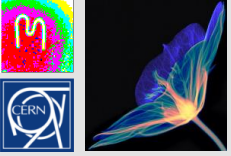
- This talk covers 2 readout chips and describes some applications in beam monitoring



Medipix chips since 2000

- Medipix2 (2002-2005)
  - First photon counting chip at 55μm pitch
  - Camera logic (shutter driven)
  - Window discriminator/pixel (one 15-bit counter)
  - Frame based readout (sequential read/write)

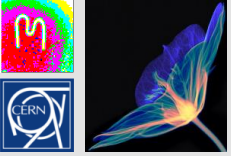
- Medipix3 (2009-2014)
  - Aimed at spectroscopic X-ray imaging
  - Readout pixel pitch of 55μm but sensor pixel pitch can be 55μm or 110μm
  - First photon counting chip with charge summing and allocation scheme
  - 2 counters per 55μm pixel
  - Frame-based readout but possibility of continuous read/write



Timepix chips

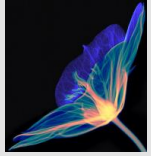
- Timepix (2006)
  - Arrival time measurement requested by EuDET Collab.
  - Readout compatible with Medipix2 (frame based)
  - One discriminator, one counter per pixel
  - Possibility to programme pixels in one of three modes:
    - Count hits (like Medipix2)
    - Measure arrival time (ToA)
    - Measure charge (ToT)

- Timepix3 (2014-2015)
  - Fully data driven architecture
  - For each hit pixel coordinates, amplitude (ToT) and arrival time (ToA) are sent off chip
  - Time stamp precision of 1.6ns possible
  - Can handle up to 80Mhits/sec



Outline

- The Timepix chip
  - Educational use
  - Space dosimetry and space weather
  - X-ray histology
  - Use in UA9
  - GEMpix if Hadron therapy Beam
- The Timepix3 chip
  - Silicon TPC
  - BGI system and results
- Medipix4 and Timepix4
- Conclusions



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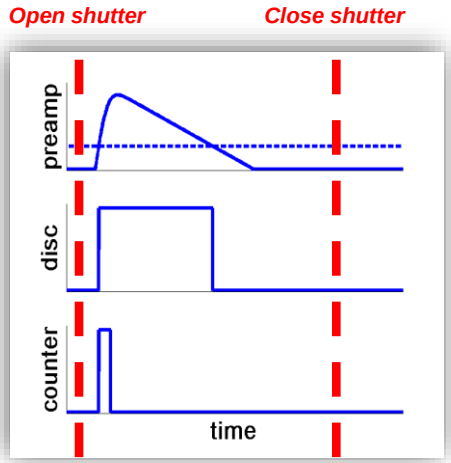
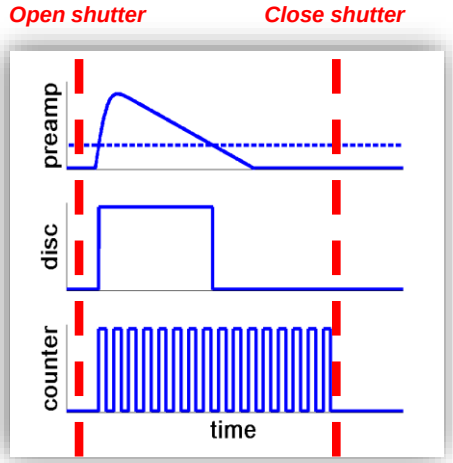
Timepix Pixel Operation Modes

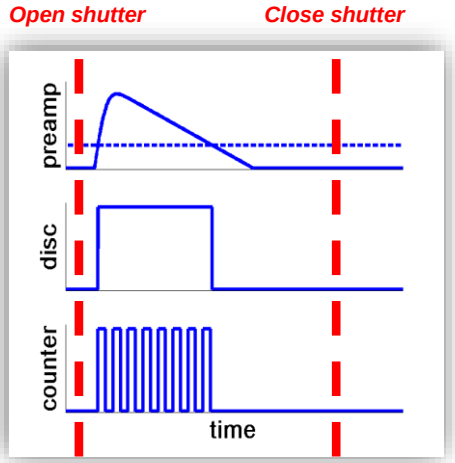
- Particle counting



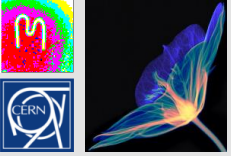
- Arrival Time*



- Time over threshold

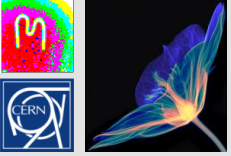


* Implemented at the request of the EUDet Collaboration



Timepix Specs

CMOS node	250nm
Pixel Array	256 x 256
Pixel pitch	55μm
Charge collection	e^-, h^+
Pixel functionality	PC (Particle Counting), TOT (Energy) or TOA (Arrival time)
Preamp Gain	~16.5mV/ke^-
ENC	~100e^-
FE Linearity	Up to 50ke^-
TOT linearity (resolution)	Up to 200ke^- (<5%)
TOA resolution	Up to 10ns (@ 100 MHz)
Time-walk	<50ns
Minimum detectable charge	~700e^- → 2.5 KeV (Si Sensor)
Counter Depth/Overflow	14-bits(11810)/Yes
Max Analog power (2.2V)	6.5μW/pix 190mA/chip
Static Digital Power (2.2V)	~500mW@100MHz/chip
Readout (@ 100 MHz)	Serial readout → 9.17 ms 32-bit Parallel readout → 287 μs



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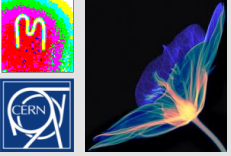

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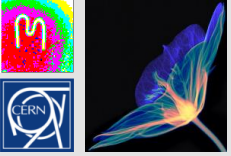

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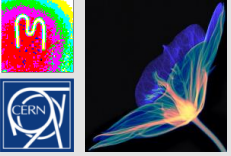

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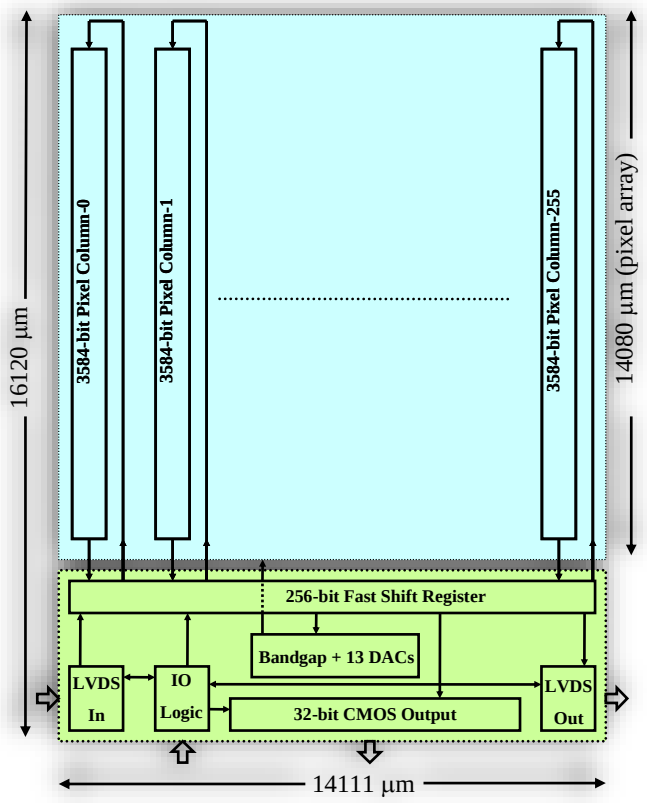
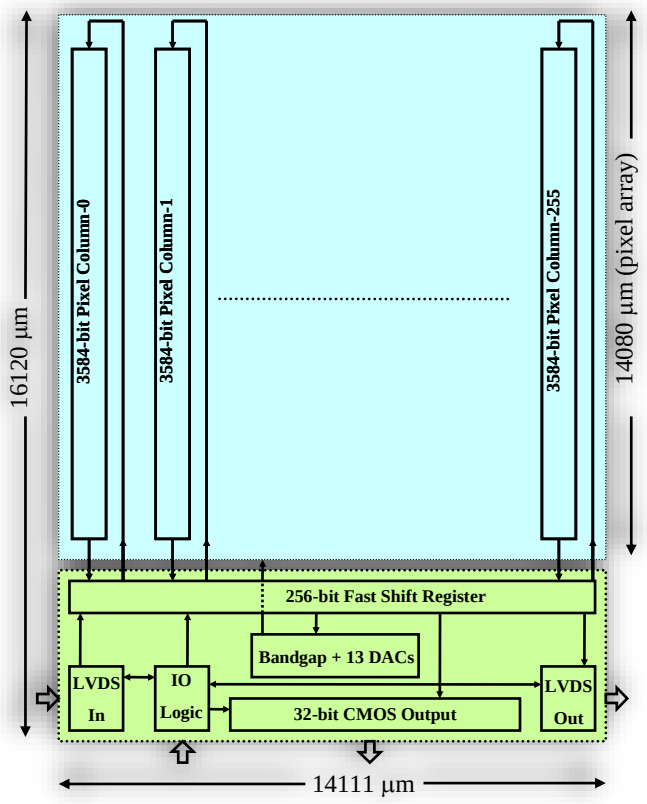
Timepix chip architecture



- 3-side Buttable floorplan
- In acquisition mode chip an external clock is used as a time reference (up to 100 MHz)
- 256x256 55µm square pixels
- Analog Power → 440mW
- Digital Power (Ref_Clk=50MHz) → 220mW
- > 36M Transistors
- System on chip design:
  - On-chip digital global biasing:
    - 14 DACs + Bandgap
  - Simple control logic
  - Serial readout (@100MHz) → 9.17 ms
  - Parallel readout (@100MHz) → 287 µs
  - Daisy-chain (serial only) for simple multiple chip readout

Timepix chip architecture



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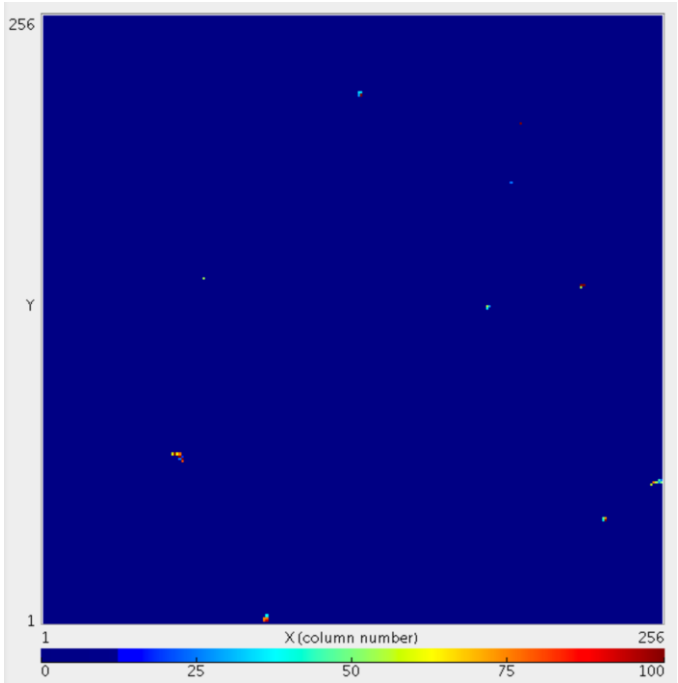
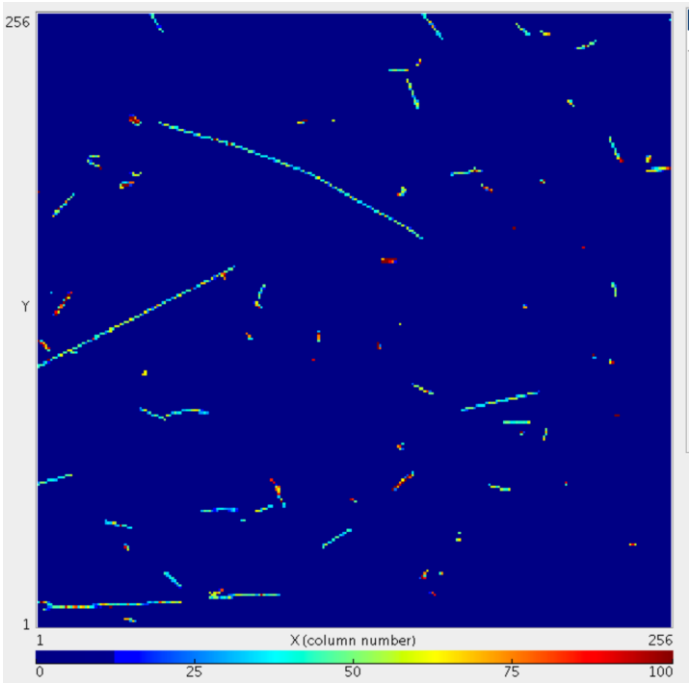
Timepix miniaturised readout

IEAP/CTU, Prague

Timepix chip – 60s exposures



Near sea level

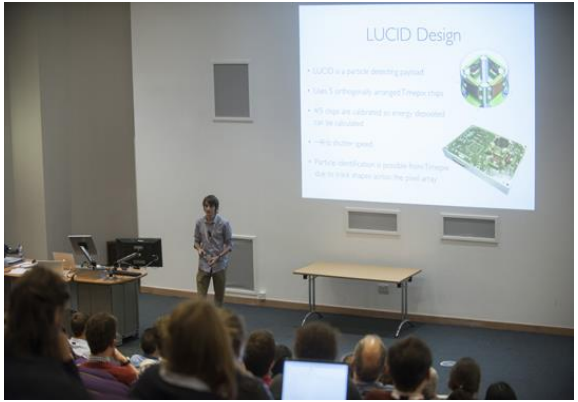


34 000 feet

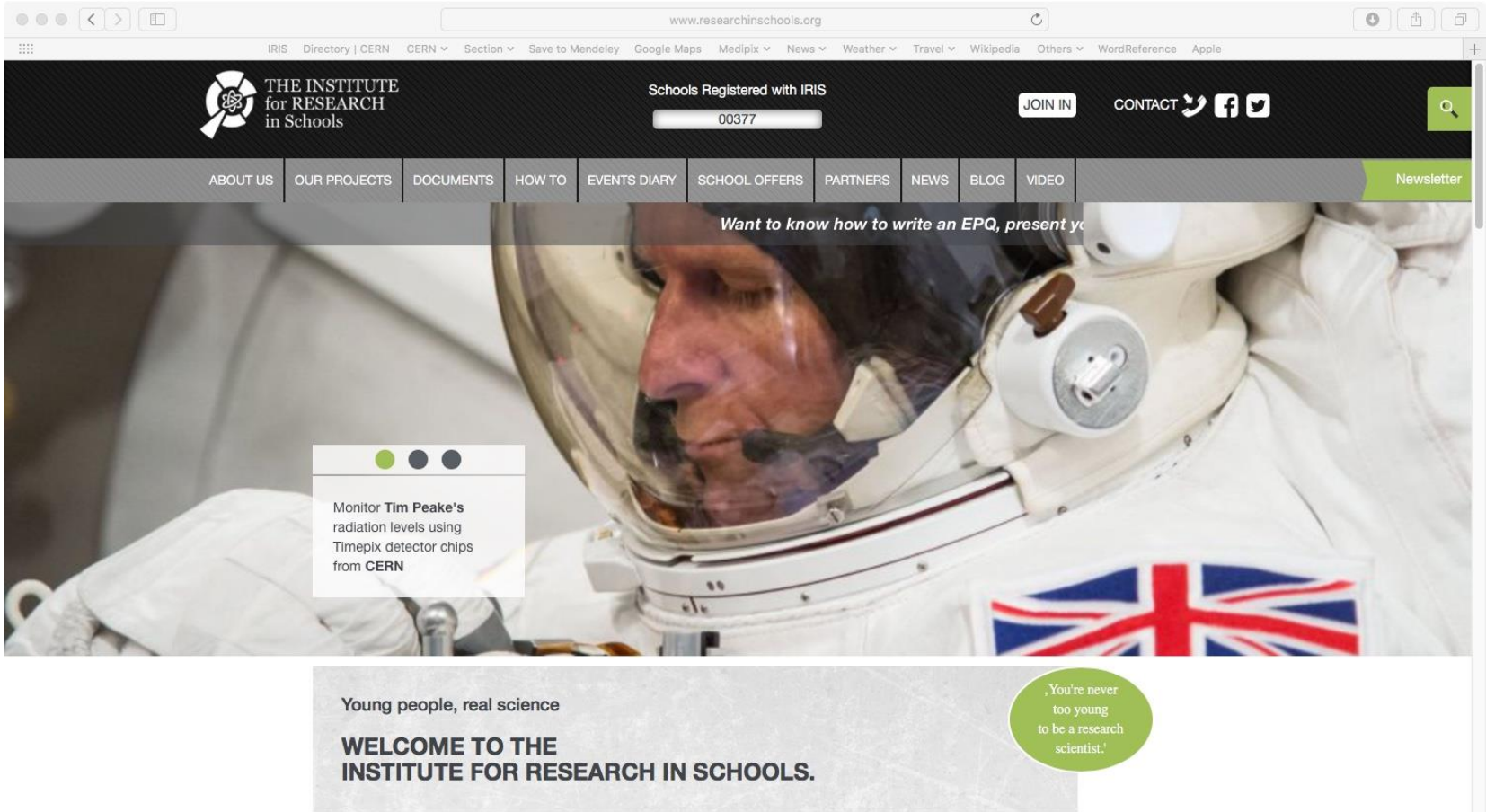
CERN@school

Simon Langton School, Canterbury, England

LUCID detector



Institute for Research in Schools



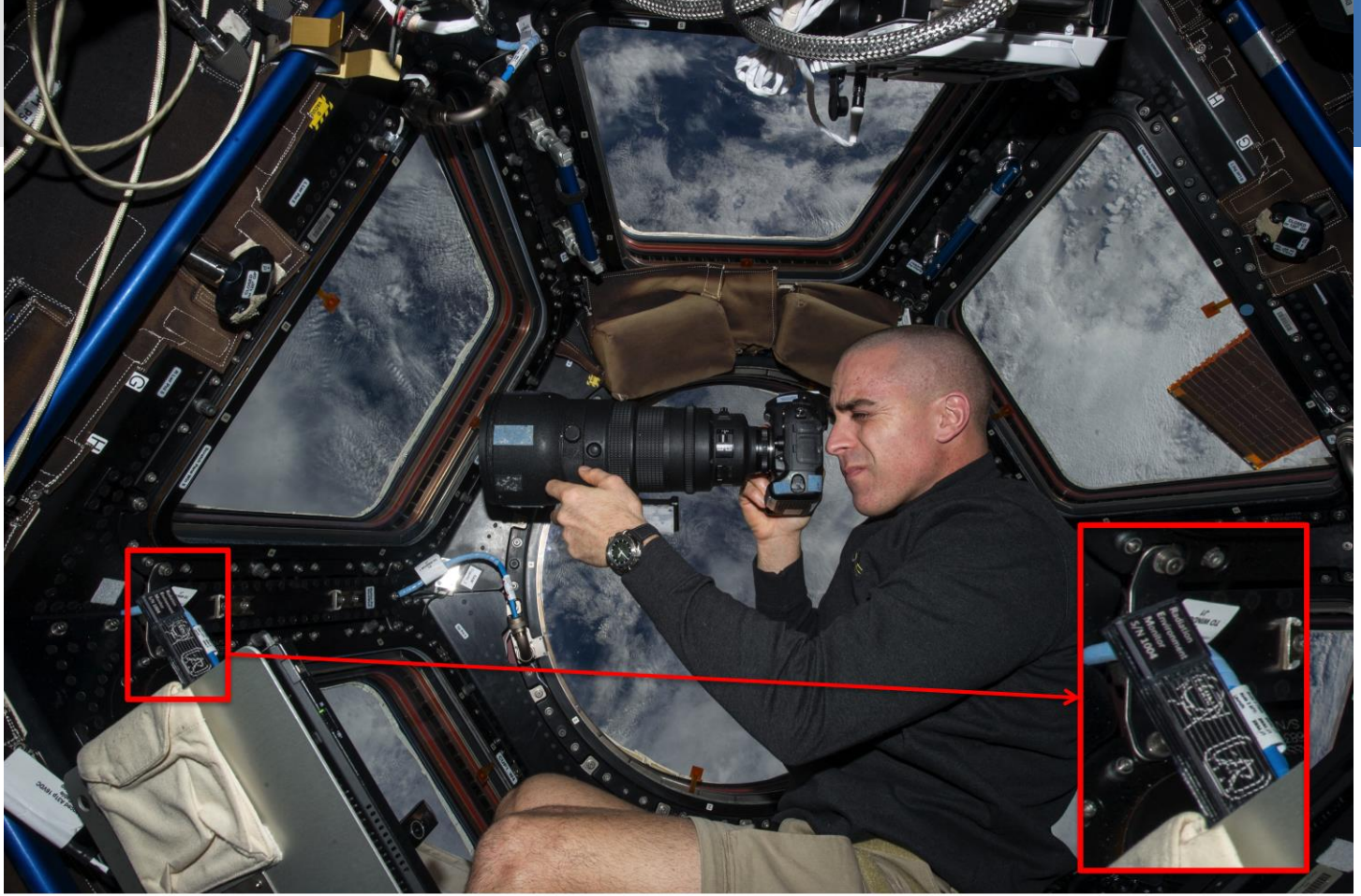
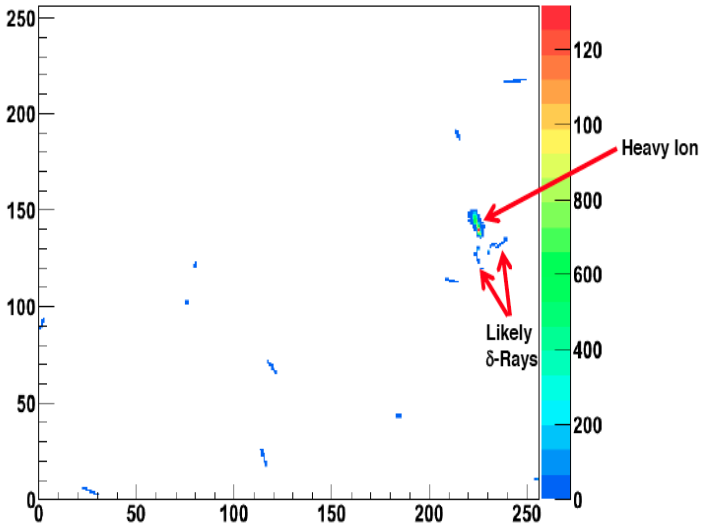
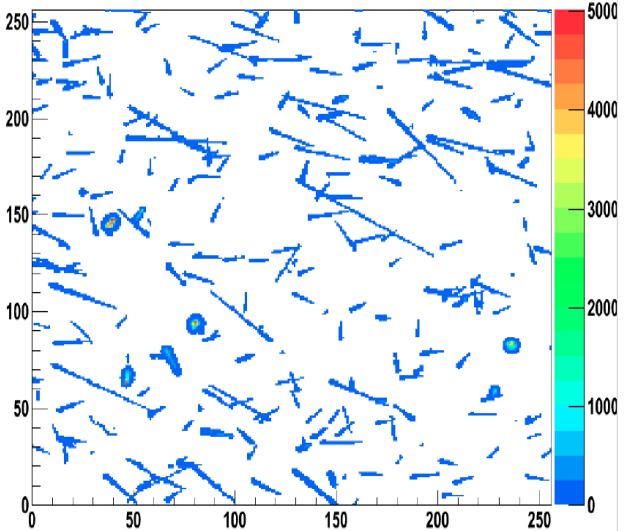


Image of the astronaut Chris Cassidy working near the Timepix USB on the International Space Station (Courtesy of NASA, photo ref. no. iss036e006175)

Timepix - 4s exposures



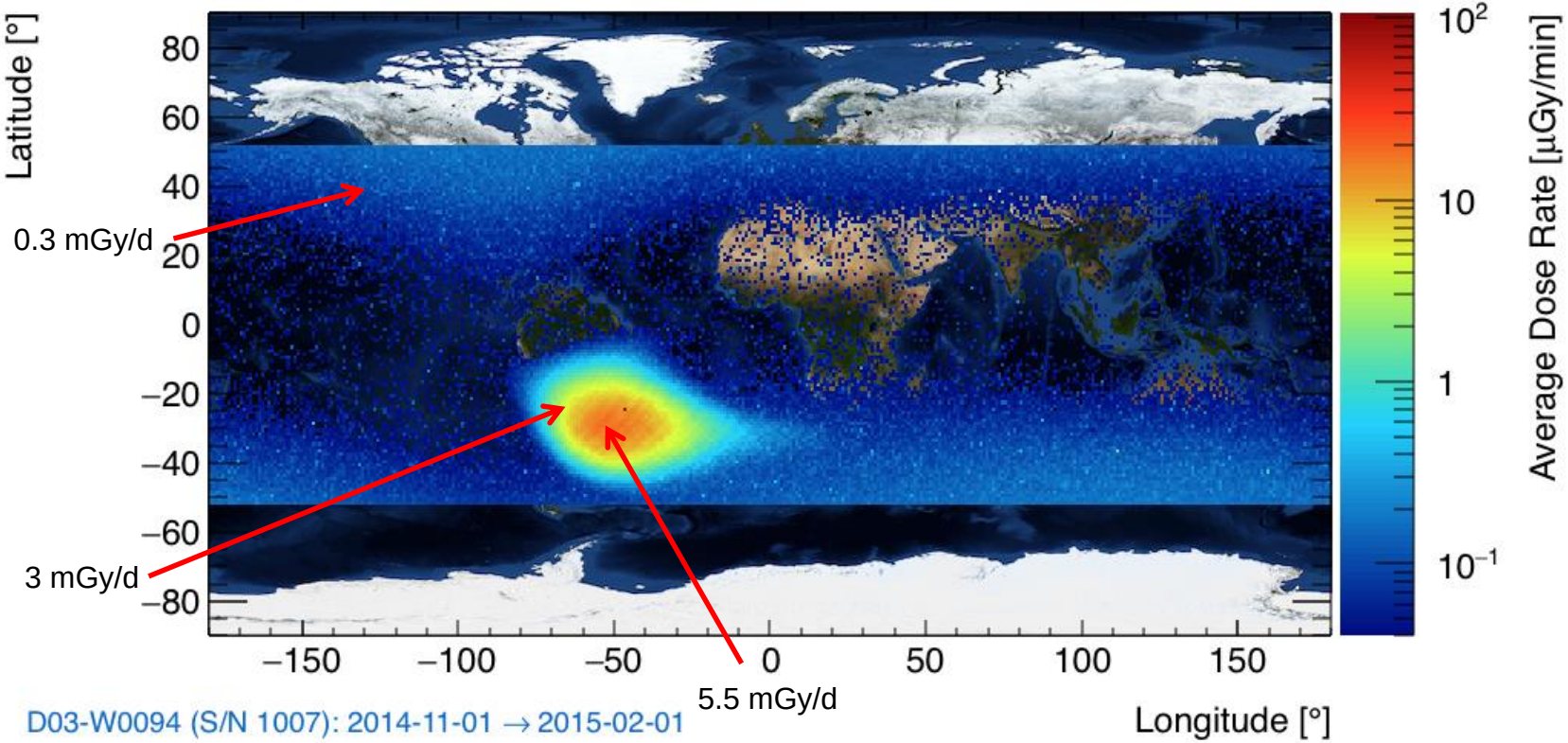
South China Sea



South Atlantic Anomaly

University of Houston, IEAP Prague, NASA

REM Dose Rate Data (μG/min)

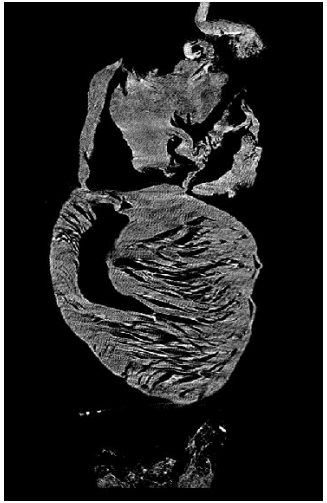


University of Houston, IEAP Prague, NASA

Large area detectors

WIDEPIX (now Advacam s.r.o.) is a spin-off of IEAP, Czech Technical University

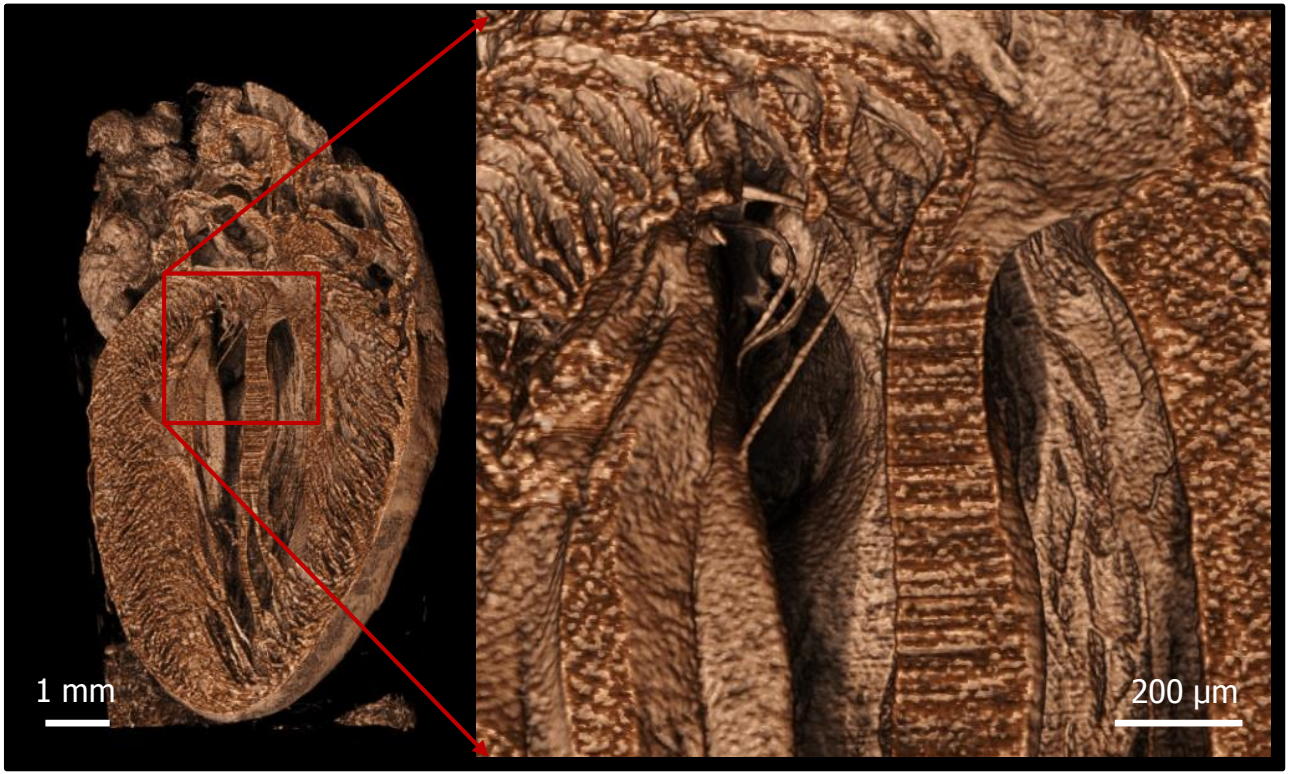
Micro-Computed Tomography scan of mouse heart



Ethanol-preserved mouse heart scanned using the WidePIX$_{10x5}$ detector
60 kVp tungsten spectrum
720 projections, 5 seconds per projection (one hours total)
Spatial resolution ca. 7 µm
Reconstructed using Volex, visualized using CTVox and Amide software

Slide courtesy of J. Dudak, IEAP, Czech Technical University

X-ray Histology



Slide courtesy of J. Dudak, IEAP, Czech Technical University

The UA9 detectors : Timepix

Based on silicon sensor 500 μm thick

About 20 readouts per seconds
- 200 μs with 20 ns resolution or
- 2 ms with 200 ns resolution

Cluster online reconstruction and data flow reduction

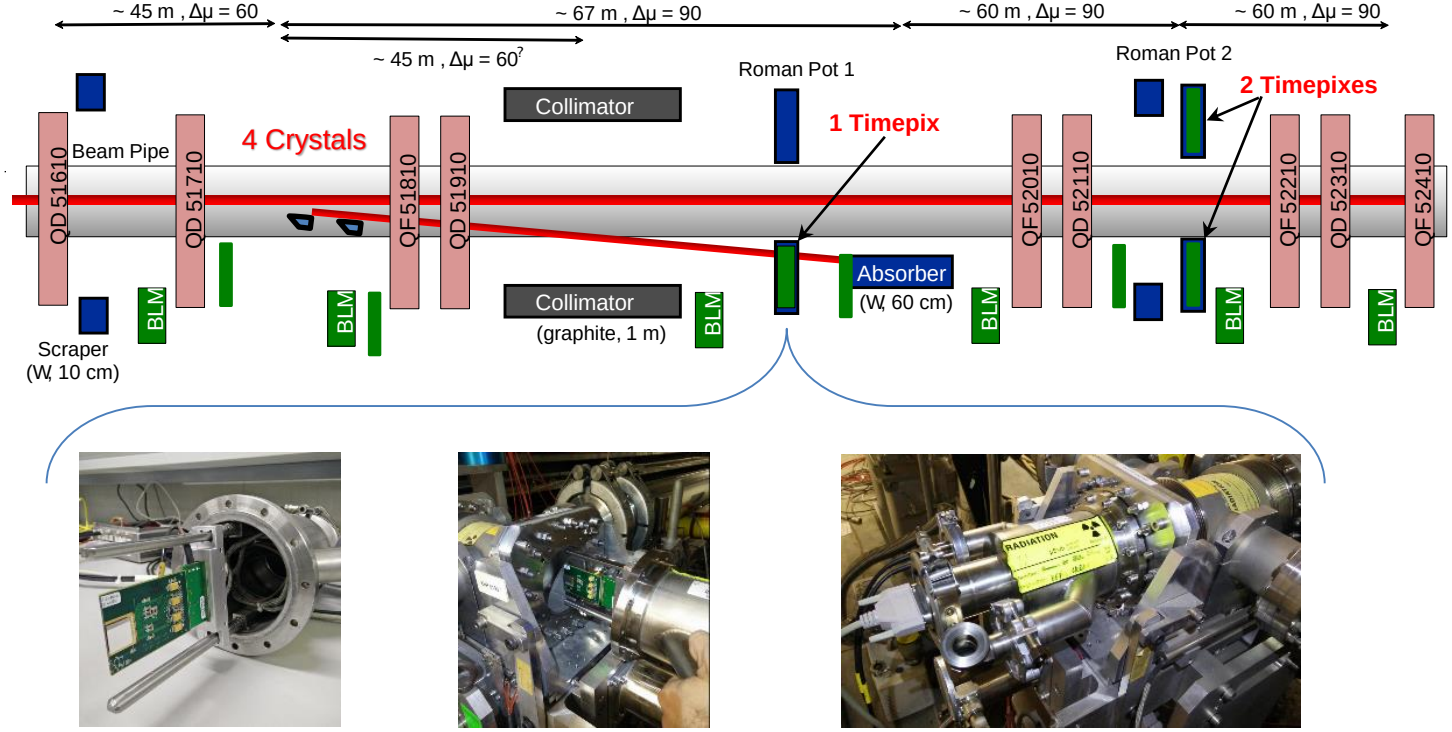
Synchronized readout with RF

We have three assemblies installed with 14x14 mm^2 active area (2 cm^2)
- 2 Timpixes on Roman pot #2 (dispersive area for extracted beam image)
- 1 Timepix on Roman pot #1 (image of the channeled beam)

The detector is read in ToA (Time of Arrival) to measure the particle flux versus time
This can compromise good flux measurement if the probability of two hits in the same pixel is high

F.Murtas, A. Natochi, W.Scandale UA9 Experiment

The UA9 SPS experimental setup



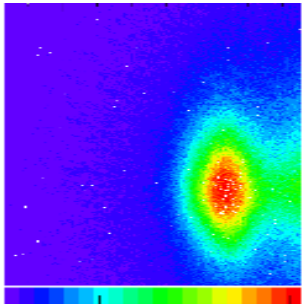
A third Medipix has been installed in the Roman Pot 1 on January 2017

F.Murtas, A. Natochi, W.Scandale UA9 Experiment

Channeled beam seen by Timepix

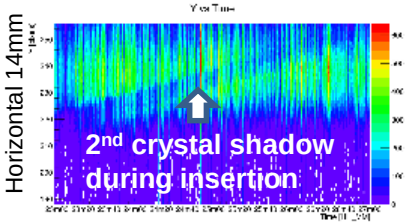
Characteristics of the beam:
→ Single bunch
→ Nominal intensity: 1.2 - 1.1 x 10^{11} p/bunch
→ p = 270 GeV/c
→ user LHCMD3: Qh = 20.13, Qv = 20.18

Vertical 14mm

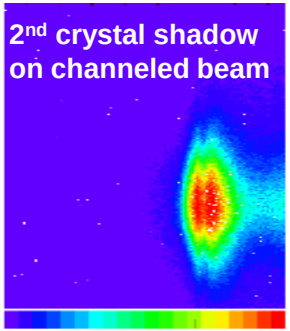


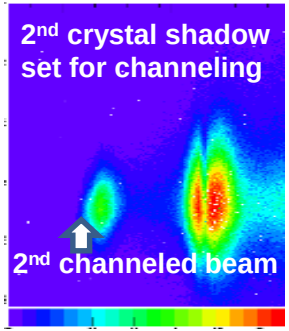
Horizontal 14mm

On October 17th double crystal experiment was performed



A second crystal was inserted in the channeled beam

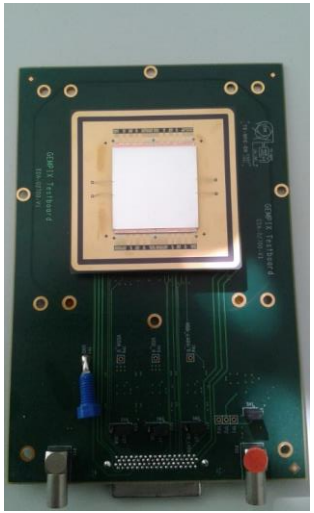




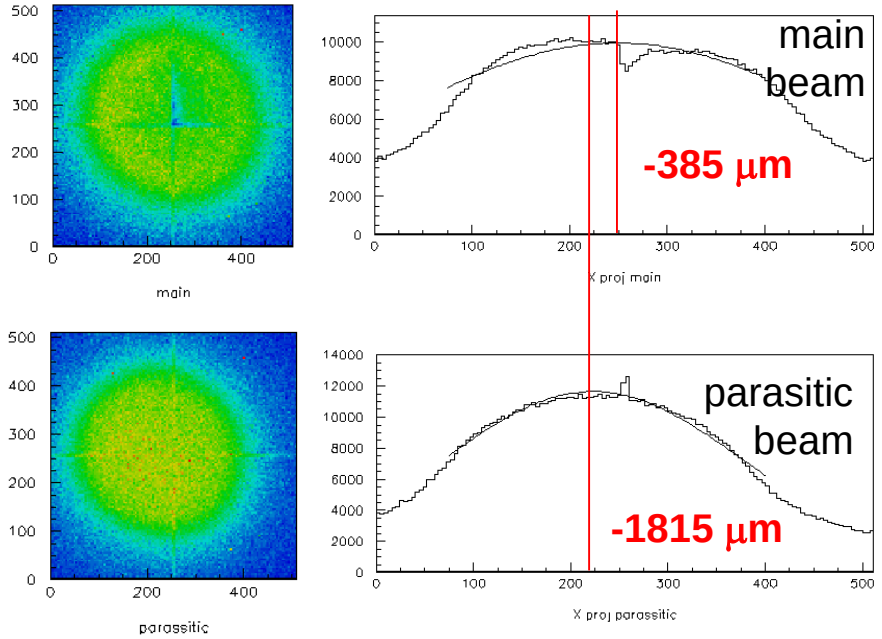
F.Murtas, A. Natochi, W.Scandale UA9 Experiment

Timepix-quad @NTOF

A Timpix-quad has been installed in the dump area of NTOF



Detector active area
28x28 mm^2

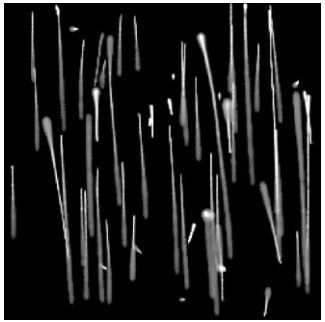


The position of the main and the parasitic beams differ horizontaly by 1.5 mm

F.Murtas

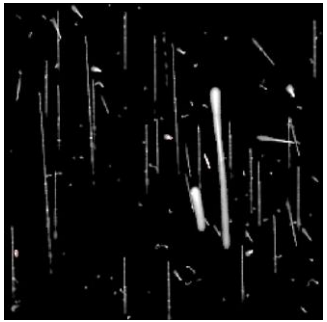
In-line images of a Hadron Therapy Beam

Protons 48 MeV



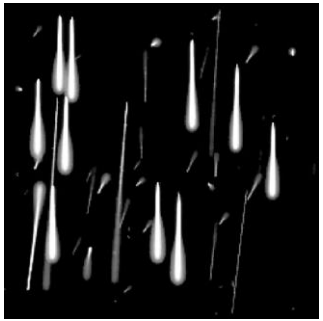
Only protons and their scattering, no secondaries.

Protons 221 MeV



Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u



Carbons and protons and their scattering, no secondaries.

Carbons 430 MeV/u

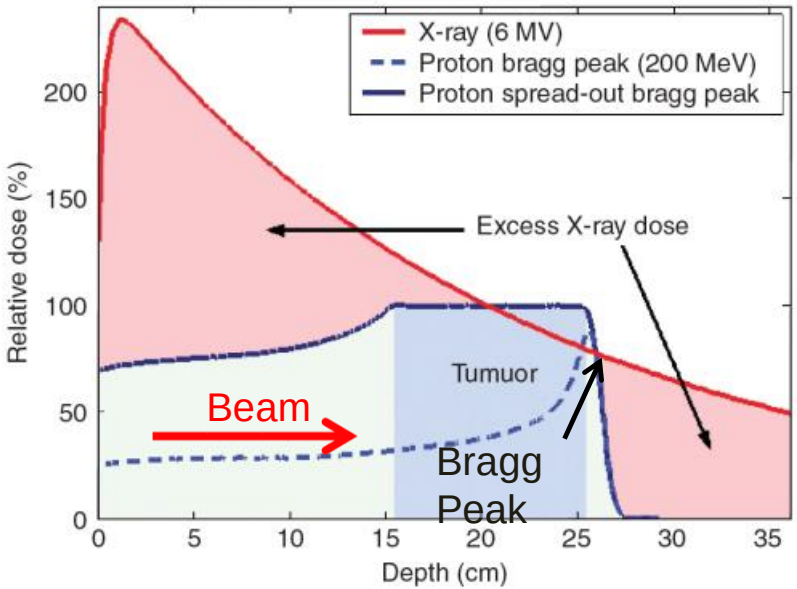
Carbons and many secondaries.

Timepix chip combined with Si detector

Jan Jakůbek
IEAP, Prague

Introduction: Radiation Therapy

- Cancer therapy:
  - Surgery
  - Chemotherapy
  - Radiation therapy
    - X-rays
    - Proton- / Hadrontherapy
- Need for quality assurance tools, beam monitors, …
- Typical system: water phantom + ion chamber
- New detectors needed for Proton- / Hadrontherapy!



→ GEMPix in water phantom

J. Leidner, F.Murtas, M. Silari

GEMPix: GEMs + Timepix

3 GEMs:

- Kapton foil with thin copper layers
- Gas amplification in holes (large field)
- Total gain of max 10^5

4 Timepix chips:

- 512 x 512 pixels
- each 55µm x 55 µm
- detection threshold per pixel of 1000 electrons

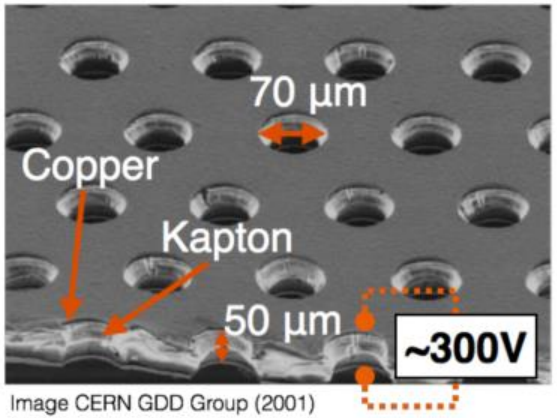
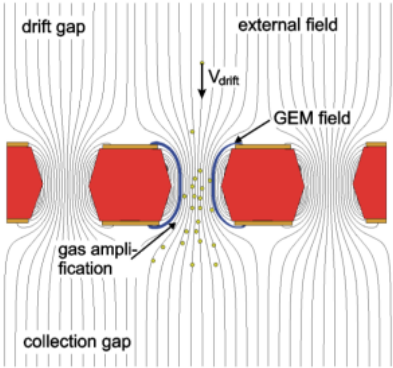
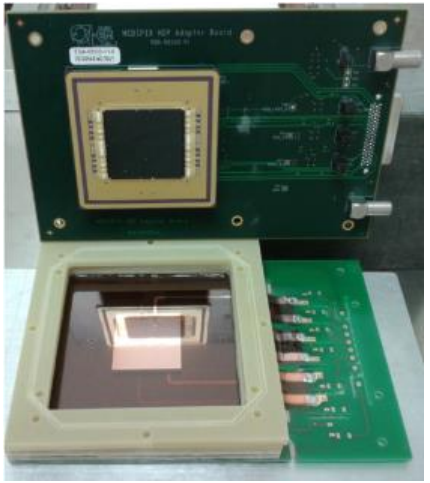


Image CERN GDD Group (2001)





J. Leidner, F.Murtas, M. Silari

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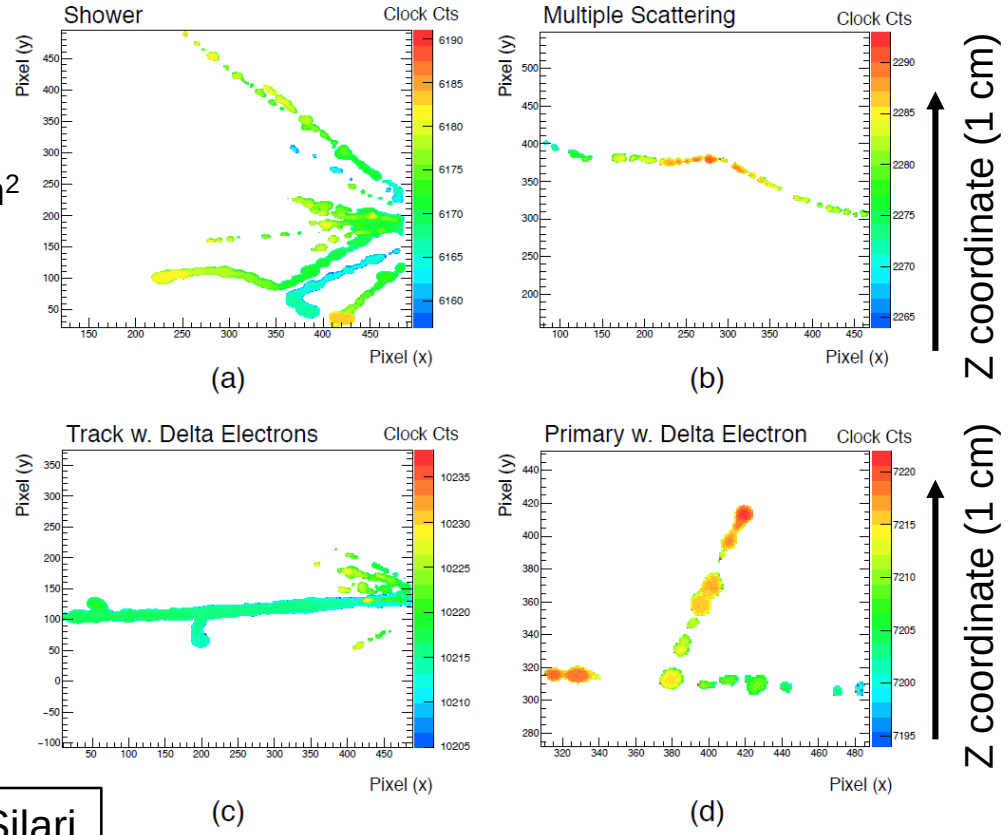
3D Track Reconstruction (TOA)

3x3 cm^2

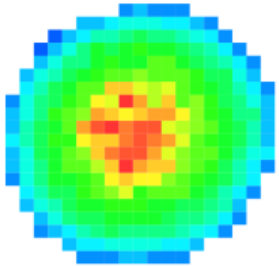


Possibility to study single particles
→ lateral measurements
→ secondaries

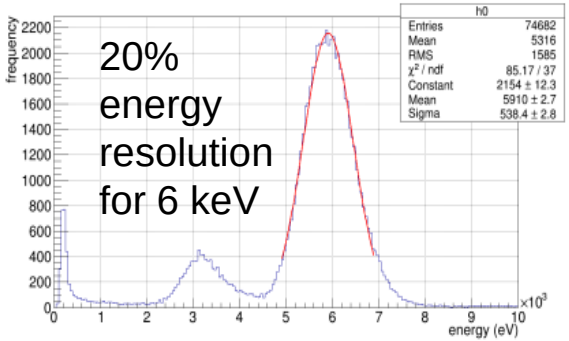
J. Leidner, F.Murtas, M. Silari

Charge Measurement (TOT)

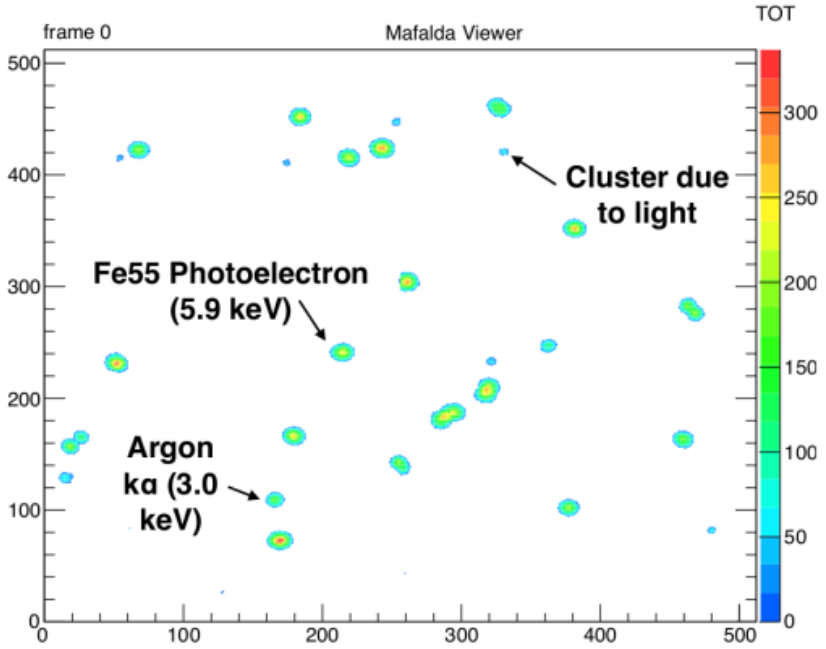
X-ray detection: 6 keV from ^{55}Fe (1s frame)



Single 6 keV X-Ray



20% energy resolution for 6 keV



20% energy resolution

J. Leidner, F.Murtas, M. Silari

Measurements at CNAO

- Carbon ions
- Energy: 280 or 332 MeV/n
- Scan along beam axis, ~30 positions
- Frames (pictures) of 20 ms taken, 5-10 frames per position
- TOT mode
- Total: 20 min per scan

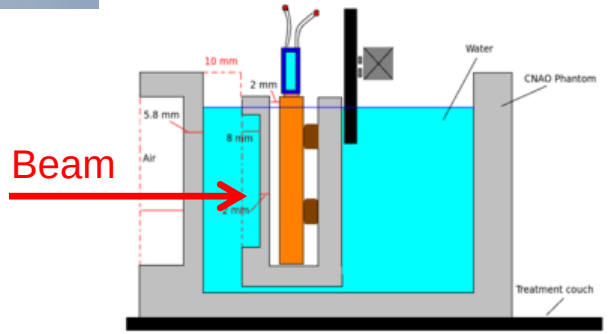
  → Frames provide beam monitoring

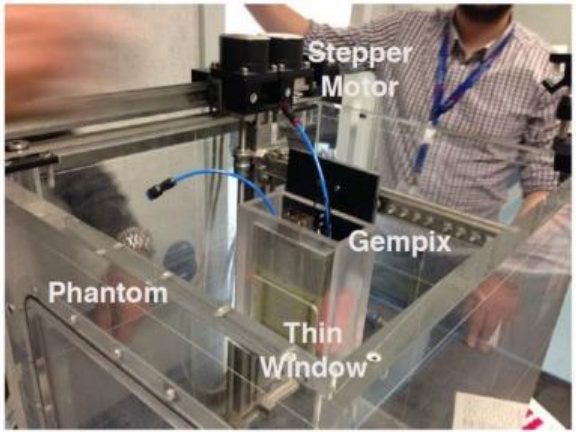
  → Integrated TOT counts per position provide Bragg Curve

  → 3D reconstruction of energy deposition

J. Leidner, F.Murtas, M. Silari

Setup at CNAO



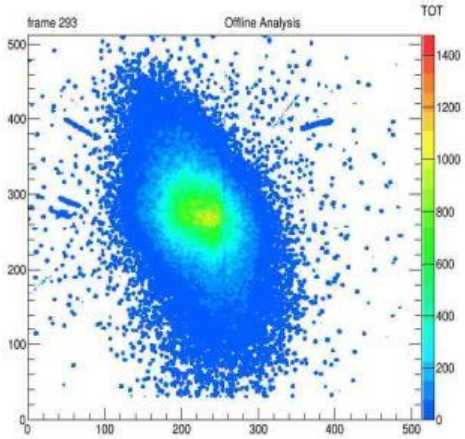


GEMPix inserted in a water phantom

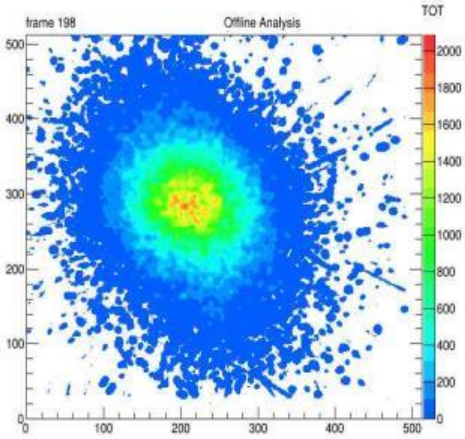
J. Leidner, F.Murtas, M. Silari

Beam Monitor

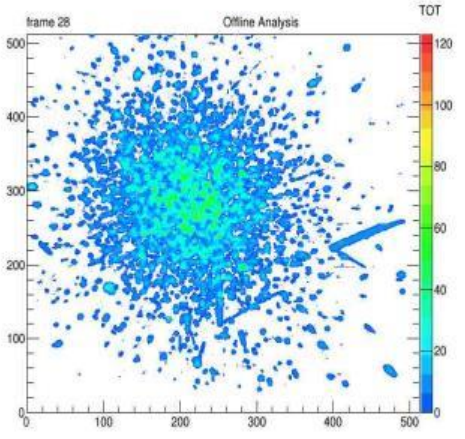
Plateau



Peak



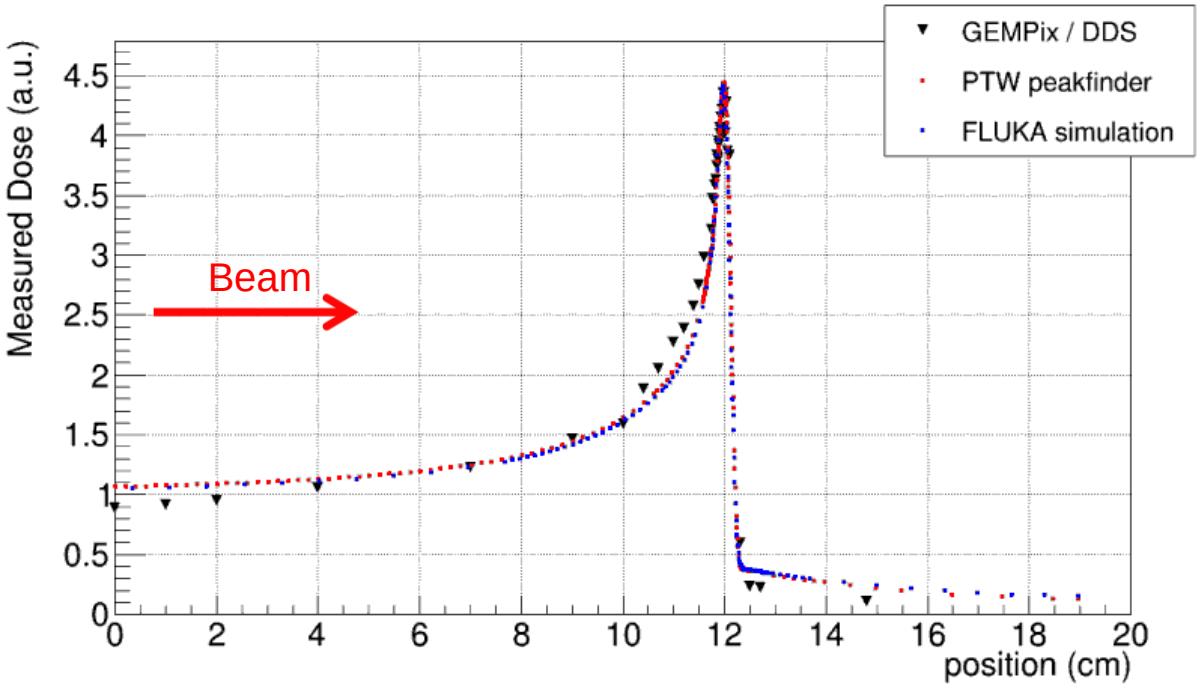
Tail



Beam spot taken on Plateau, Bragg Peak and Tail
Frame length: 20 ms / 100 ms (before / after the Bragg Peak)
Beam halo: single particle reconstruction

J. Leidner, F.Murtas, M. Silari

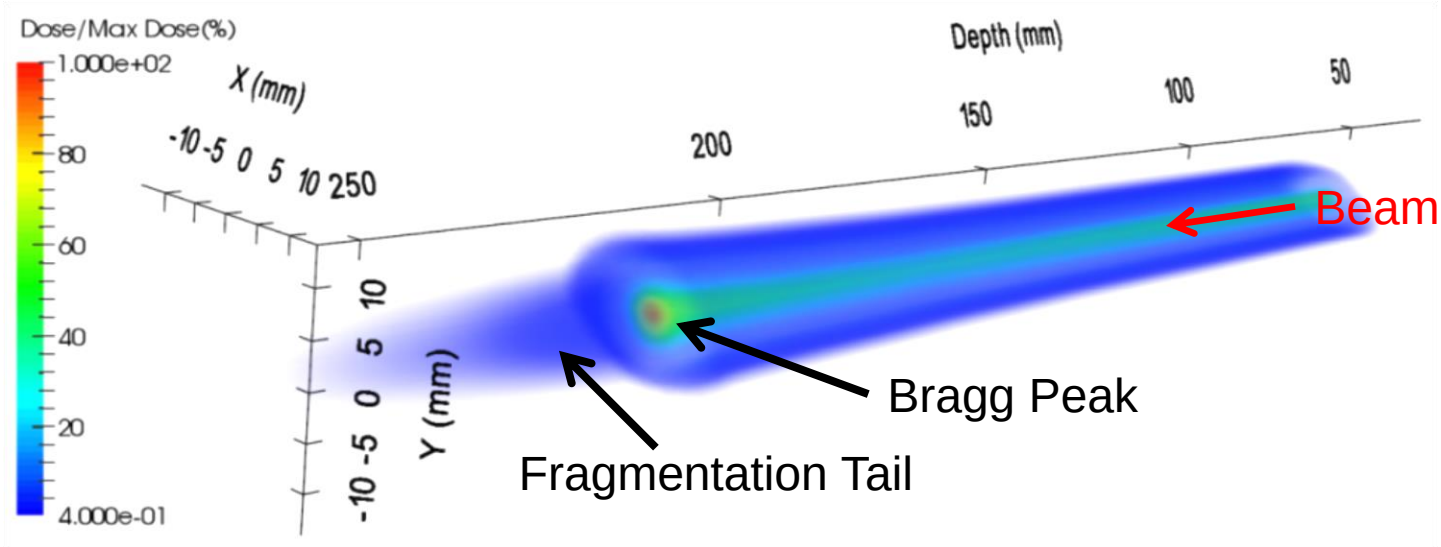
Depth Scan: Bragg Curve



In general: good agreement between reference measurements / simulation and GEMPix

J. Leidner, F.Murtas, M. Silari

3D Reconstruction



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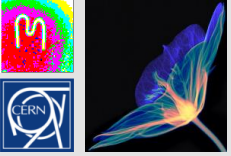
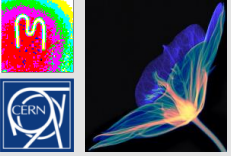


Outline

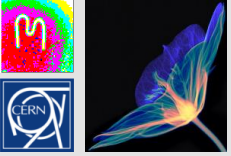
- The Timepix chip
  - Educational use
  - Space dosimetry and space weather
  - X-ray histology
  - Use in UA9 and NTOF
  - GEMpix if Hadron therapy Beam
- The Timepix3 chip
  - Silicon TPC
  - BGI system and results
- Medipix4 and Timepix4
- Conclusions



Timepix3 Specs

CMOS node	130nm
Pixel Array	256 x 256
Pixel pitch	55μm
Charge collection	e^-, h^+
Pixel functionality	TOT (Energy) and TOA (Arrival time)
Preamp Gain	~47mV/ke^-
ENC	~60e^-
FE Linearity	Up to 12ke^-
TOT linearity (resolution)	Up to 200ke^- (<5%)
TOA resolution*	Up to 1.6ns
Time-walk	<20ns
Minimum detectable charge	~500e^- → 2 KeV (Si Sensor)
Max Analog power (1.5V)	500 mA/chip
Digital Power (1.5V)	~400mA data driven
Maximum hit rate	80Mhits/sec (in data driven)
Readout	Data driven (44-bits/hit @ 5Gbps)

* Thanks to V. Gromov, et al. Nikhef, C. Brezina et al., Bonn



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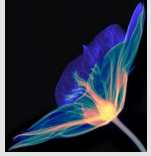

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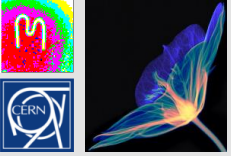

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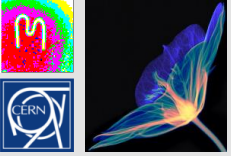

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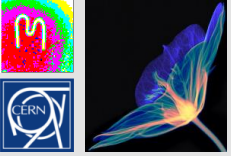

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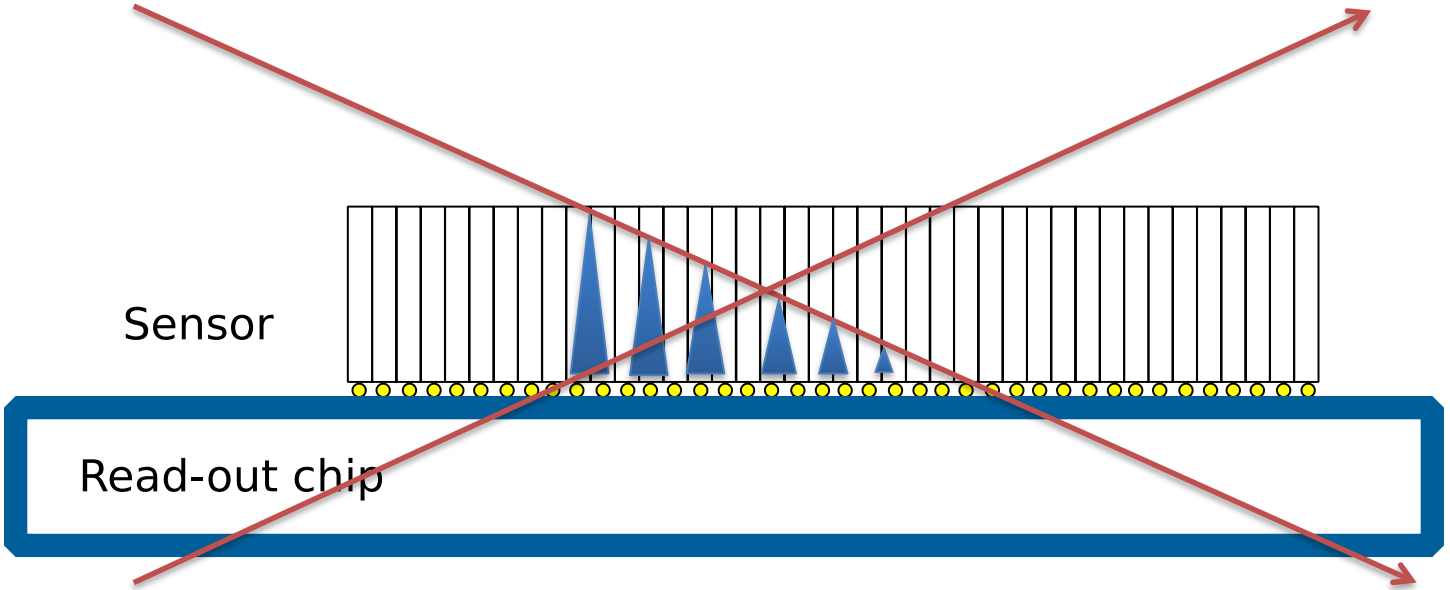
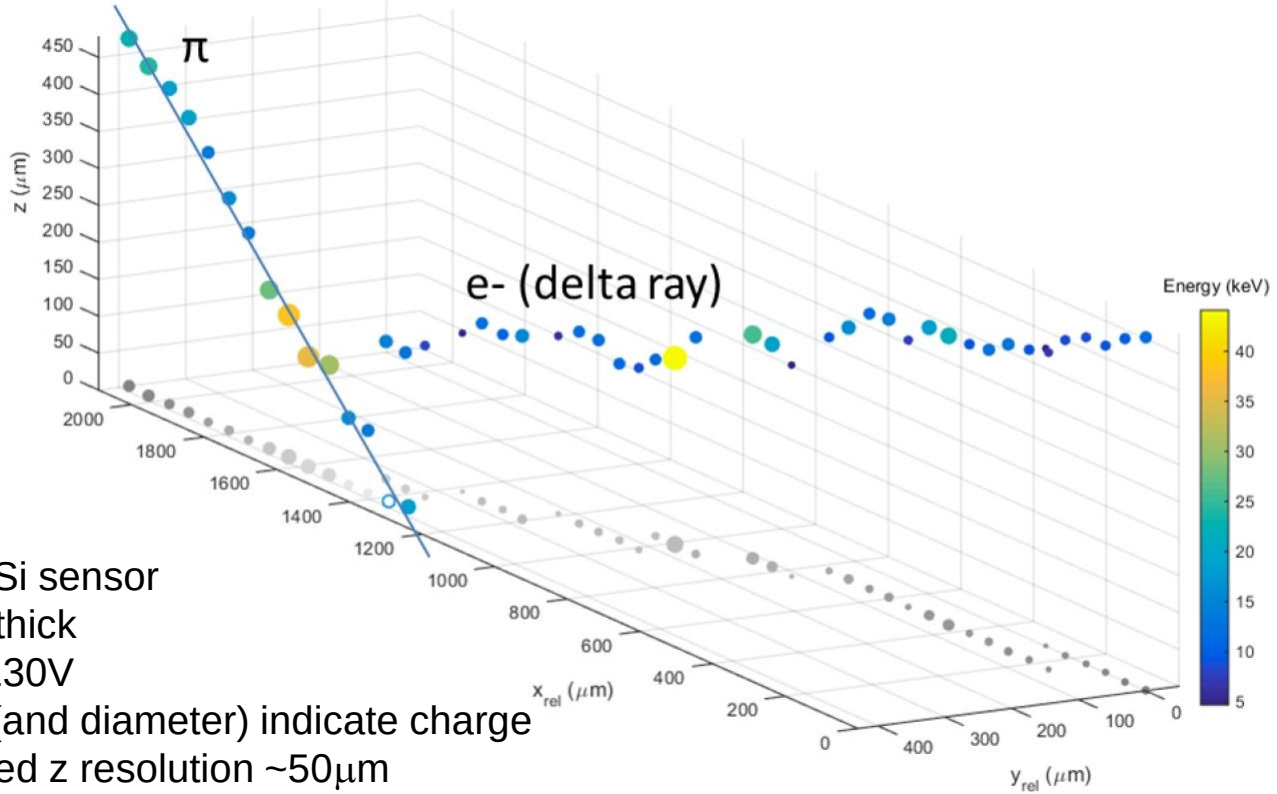
* Thanks to V. Gromov, et al. Nikhef, C. Brezina et al., Bonn

Tracking in a single Si layer

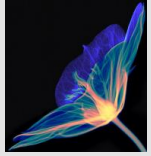


Test with 120GeV/c Pion Track



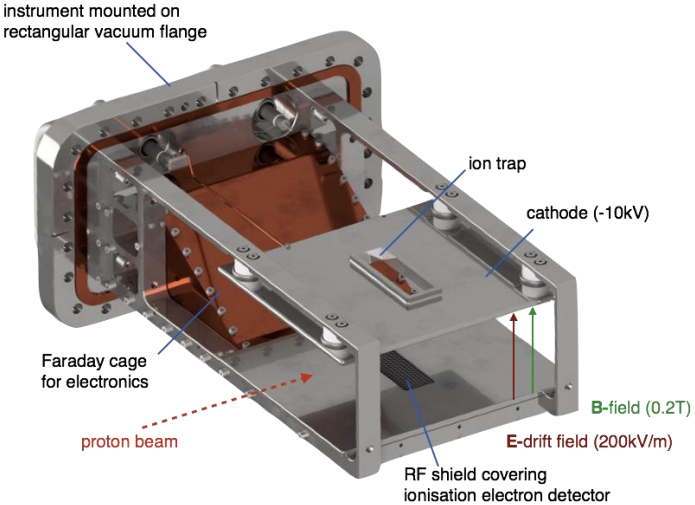
60 deg
p+ in n Si sensor
500μm thick
V_{bias} = 130V
Colour (and diameter) indicate charge
Measured z resolution ~50μm

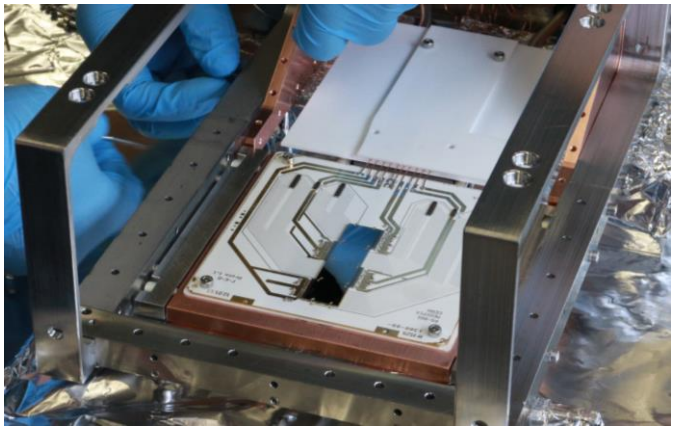
Slide courtesy of B. Bergmann, S. Pospisil, IEAP, CTU, Prague

Timepix3 miniaturised readout

PS-BGI Instrument

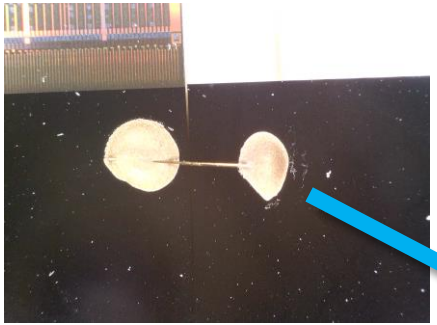




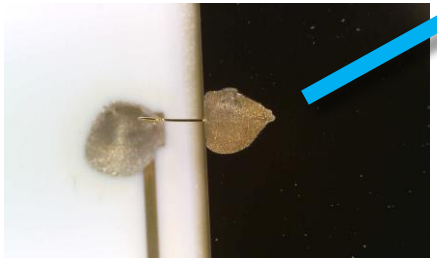
- Simplified explanation:
  - The beam ionize the rest gas, generating electron^{-}/ion^{+} pairs
  - An electric drift field accelerates the electrons down onto the pixel detectors
- Electronics for operation directly inside the ultra-high vacuum environment of the beam pipe
  - 4x Timepix3 with edgeless, p-on-n, non-metallized sensor mounted on a ceramic board
  - 3 out of 4 Timepix3 working

H. Sandberg et al., BE-BI-BL

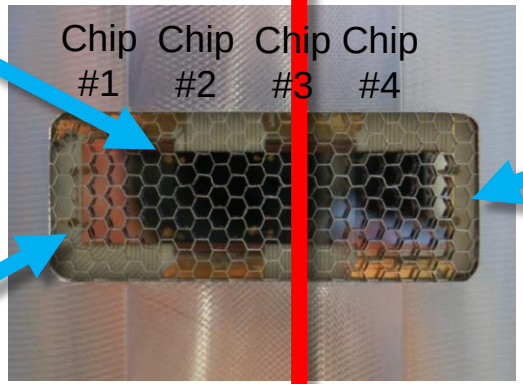
PS-BGI Instrument - Bias and honeycomb



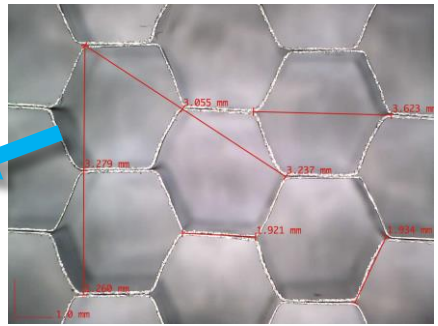
Bias wire between chips (conductive glue)



Bias wire from ceramic board to sensor (conductive glue)



Chip #3 is the non-functional chip



Honeycomb structured RF shield

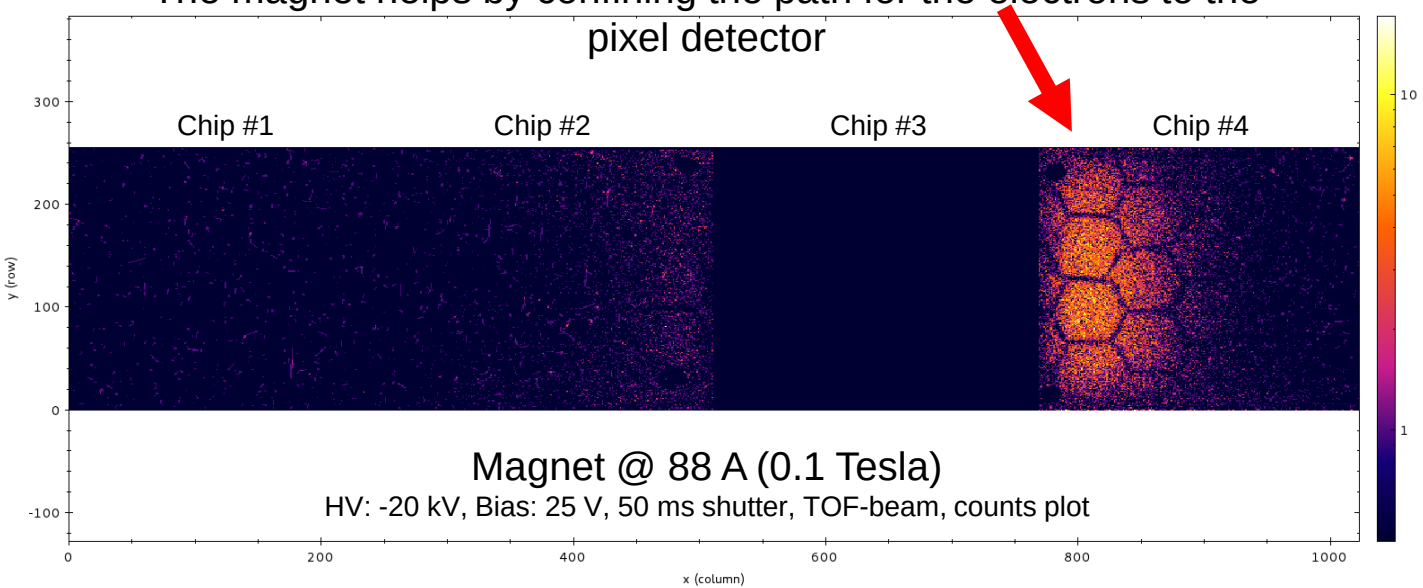
Beam passing over

H. Sandberg et al., BE-BI-BL

Turning on the magnet

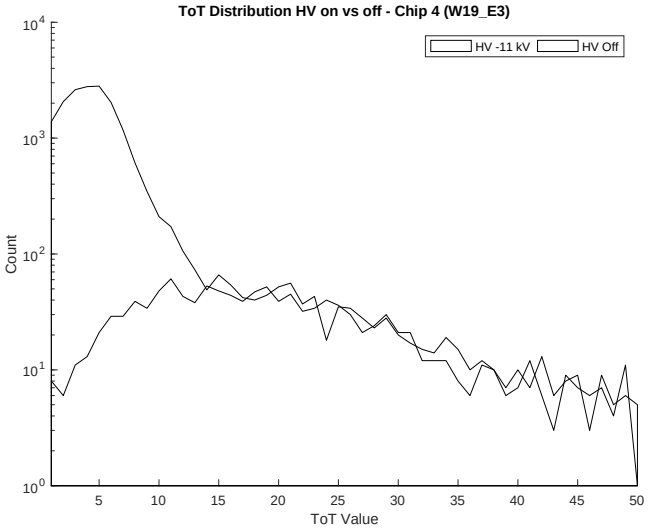
The electrons we have been looking for!

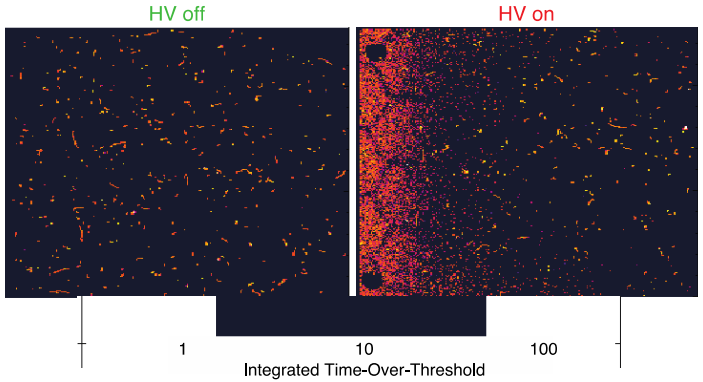
The magnet helps by confining the path for the electrons to the pixel detector



H. Sandberg et al., BE-BI-BL

Detection of ionization electrons

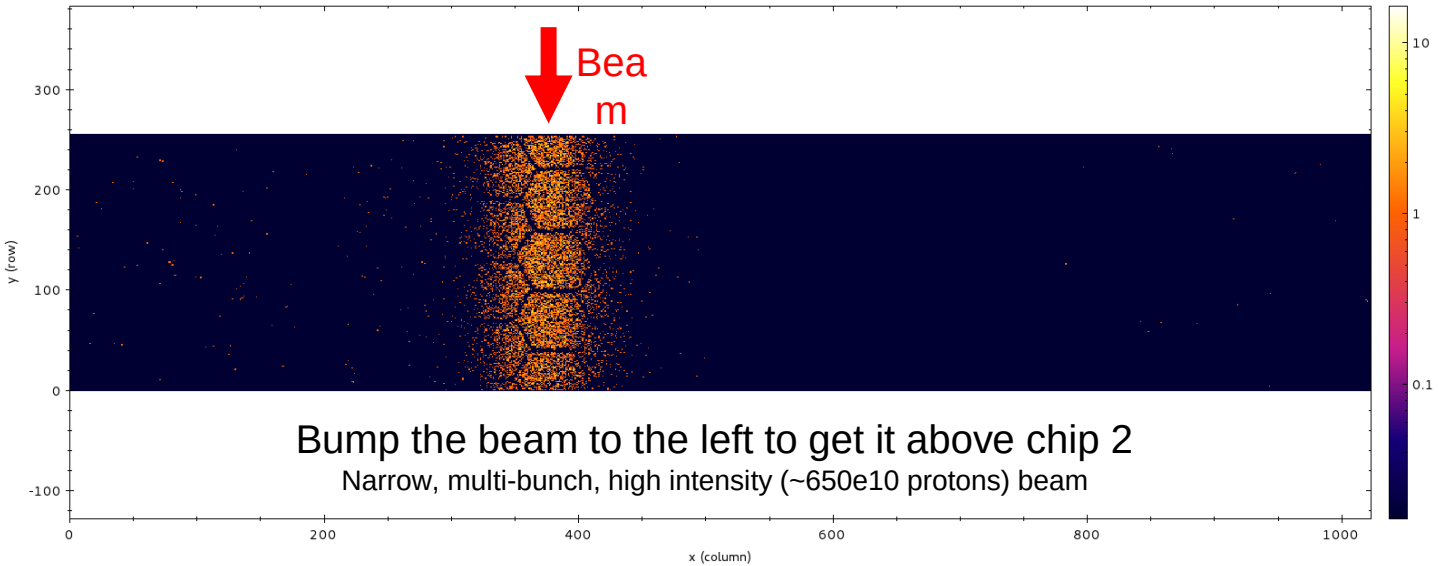




- A clear peak is visible with the HV on located at low ToT values
  - -> Ionization electrons
- For higher ToT values the distribution looks similar for HV on and off
  - Indicates a common background signal
- This enables us to apply a simple filter based on ToT to get a cleaner signal

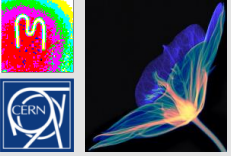
H. Sandberg et al., BE-BI-BL

Beam profile measurement



Magnet: 176 A (0.2 Tesla), HV: -13 kV, Bias: 30 V, 10 ms shutter, LHC 25ns 48-bunch beam, counts plot

H. Sandberg et al., BE-BI-BL



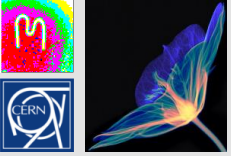
Other applications

- X-ray materials analysis
- X-ray non-destructive testing
- Large area synchrotron detectors
- X-ray imaging of cultural heritage items
- Dosepix chip development
- Gamma camera
- Compton camera
- Low Energy Electron Microscopy
- Transmission electron microscopy
- Dose deposition tracking in hadron therapy
- High resolution neutron imaging
- Single (visible) photon imaging
- Time-of-Flight mass spectrometry

} combined with MCP

Applications for CERN/Physics

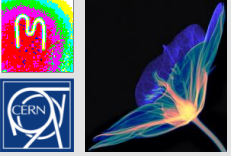
- LHCb VELOpix chip is directly derived from Timepix3
- LHCb Timepix3 telescope – 80 Mhits/sec
- Sensor studies for CLIC/LHCb
- Background radiation monitoring at ATLAS and CMS
- Beam monitoring in UA9
- Beam Gas Interaction monitor is operating at CERN PS
- ASACUSA experiment
- Beta particle channeling in ISOLDE
- Forward physics using Timepix3?
- Axion search at CAST (with InGrid)
- Large area TPC (with InGrid)
- Transition radiation measurements for ATLAS
- GEMPIX development for radiation therapy beam monitoring
- GEMPIX for ^{55}Fe waste management
- Developments for CLIC: CLICpix, CLICpix2, C3PD



Industrial licensing of Medipix/Timepix chips

- 2 Medium Sized Enterprises
  - PANalytical (The Netherlands)
  - Kromek (UK)

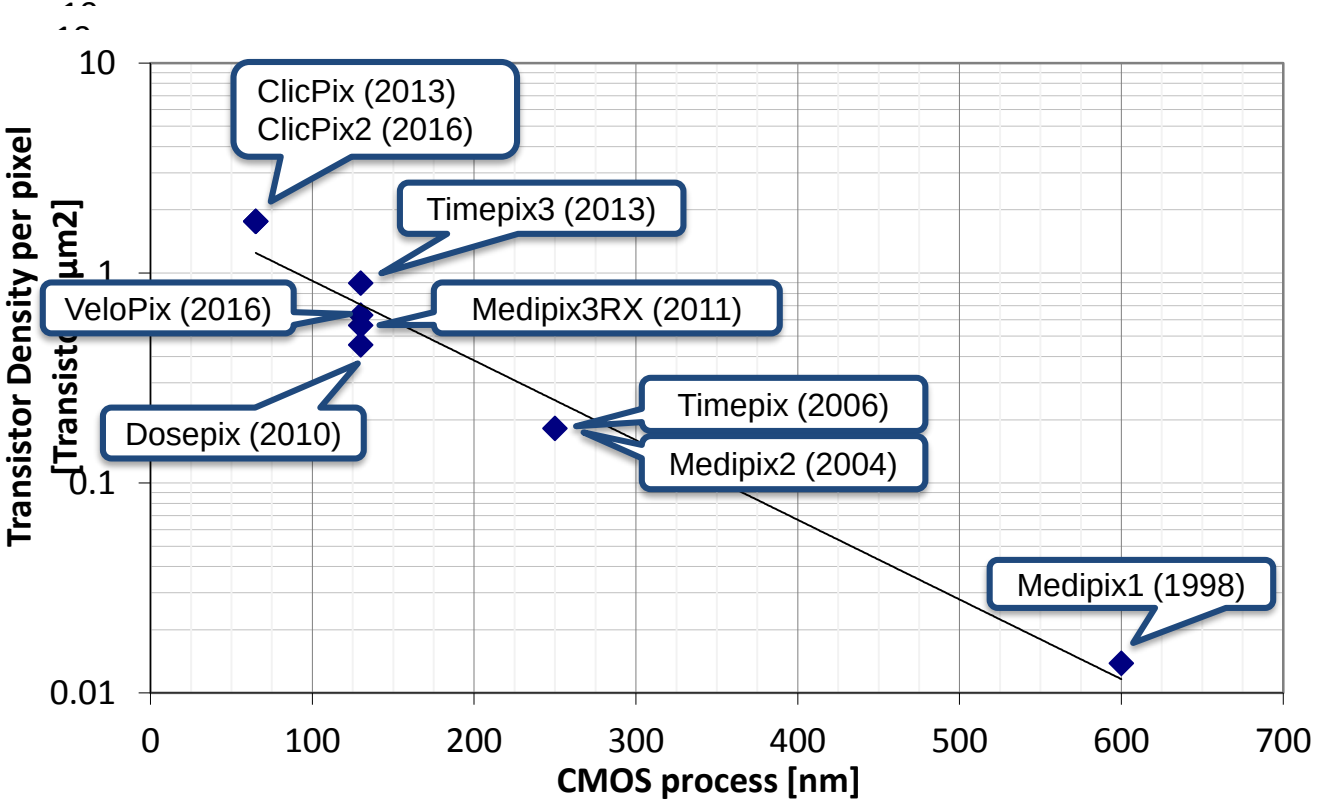
- 6 start-ups from Collaboration members:
  - Advacam s.r.o. (from IEAP, Czech Republic)
  - Amsterdam Scientific Instruments (from NIKHEF, The Netherlands)
  - MARS Bio-imaging (from University of Canterbury, New Zealand)
  - Quantum Detectors (from Diamond, UK)
  - X-ray Imaging Europe (from FMF, Germany)
  - X-Spectrum (from DESY, Germany)



Outline

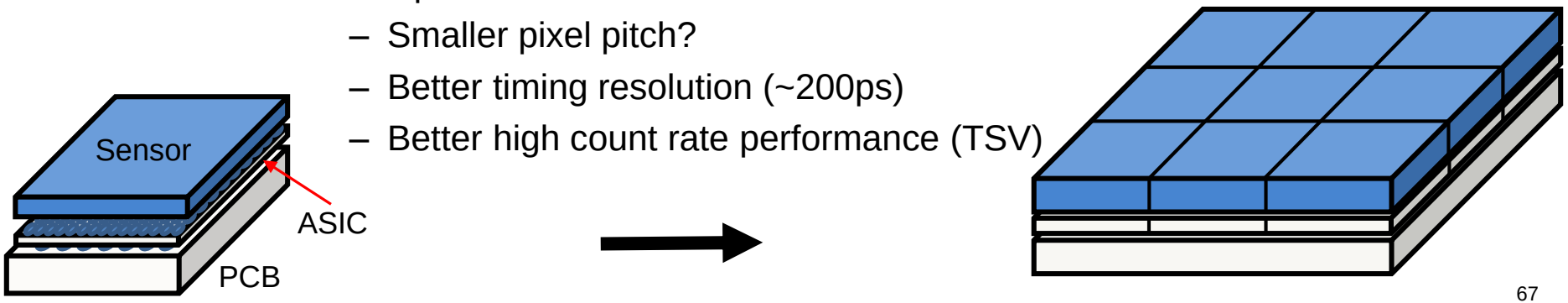
- The Timepix chip
  - Educational use
  - Space dosimetry and space weather
  - X-ray histology
  - Use in UA9
  - GEMpix if Hadron therapy Beam
- The Timepix3 chip
  - Silicon TPC
  - BGI system and results
- Medipix4 and Timepix4
- Conclusions

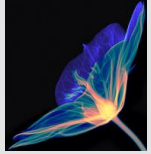
“Moore’s Law” of Medipix Family



What's next?

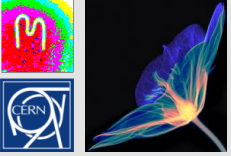
- The Medipix4 Collaboration was started in March 2016
- Chips to be fully tile-able on 4-sides – use of Through Silicon Vias (TSV) for I/O
- Medipix4 Photon counting spectrometric chip
  - Will use charge summing and allocation scheme
  - Multiple thresholds
  - Pixel pitch varied to match sensor material
  - Better high count rate performance (aimed at human CT)
- Timepix4
  - Smaller pixel pitch?
  - Better timing resolution (~200ps)
  - Better high count rate performance (TSV)





The Medipix4 Collaboration

- CEA, Paris, France
- CERN, Geneva, Switzerland,
- DESY-Hamburg, Germany
- Diamond Light Source, Oxfordshire, England, UK
- IEAP, Czech Technical University, Prague, Czech Republic
- IFAE, Barcelona, Spain
- JINR, Dubna, Russian Federation
- NIKHEF, Amsterdam, The Netherlands
- University of California, Berkeley, USA
- University of Houston, USA
- University of Maastricht, The Netherlands
- University of Canterbury, New Zealand
- University of Oxford, England, UK
- University of Geneva, Switzerland

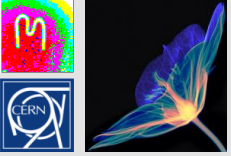


Conclusions

- Hybrid pixel detectors were developed as tracking detectors of LHC
- The Medipix2 and Medipix3 Collaborations have taken the technology into many other fields
- Timepix chips are actively detecting background radiation in school classrooms and in space
- Timepix has been used extensively in particle beam monitoring applications (in spite of some obvious limitations)
- Timepix3 is opening new possibilities with single layer tracking
- The next generation of readout chips will use Through Silicon Via technology permitting seamless tiling of large areas

Thank you for your attention!

Medipix3RX images: S. Procz et al.



Backup slide

Moore's uncertain future