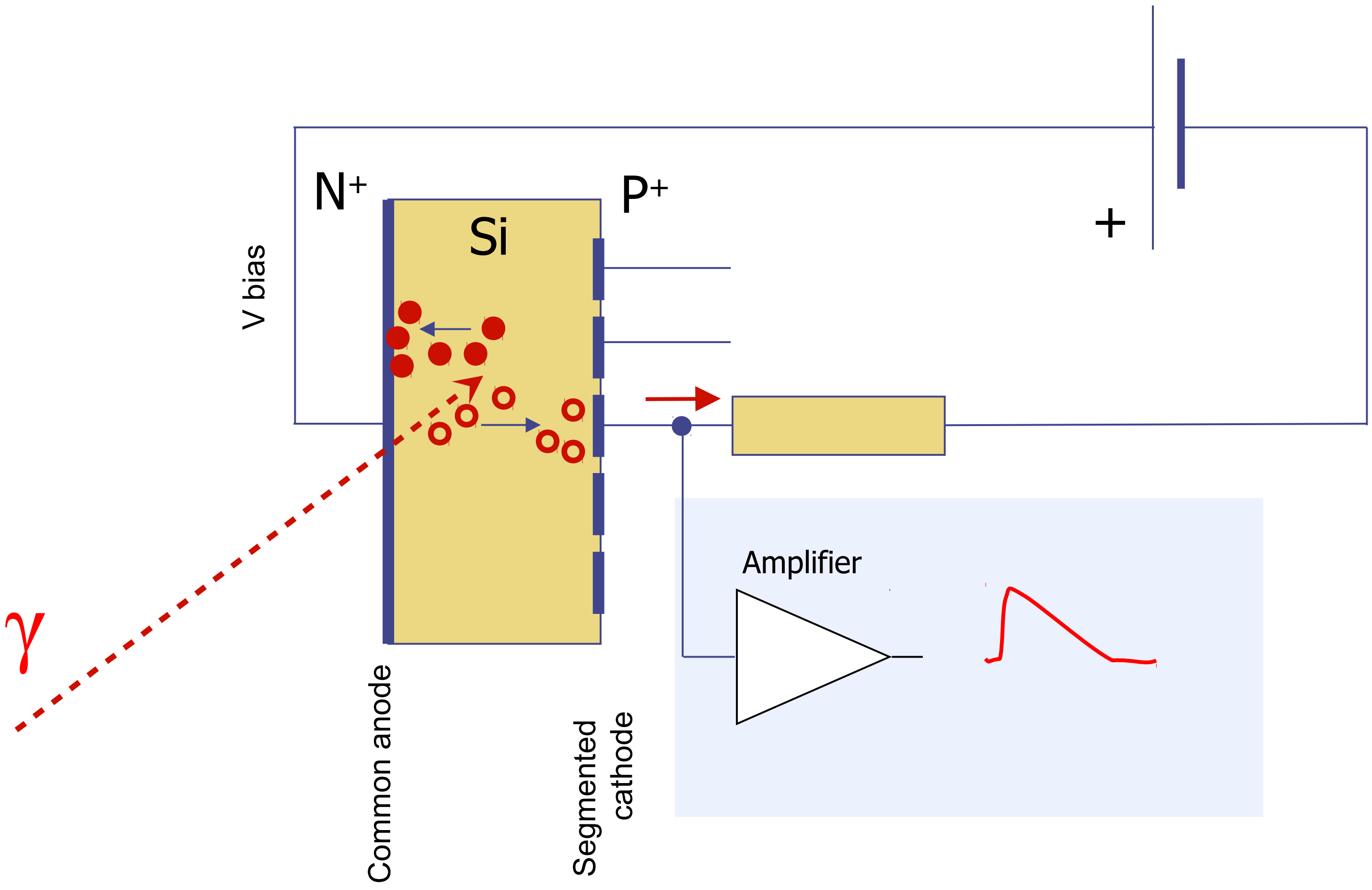
Детекторы Medipix на основе новых материалов для фундаментальных и прикладных исследований

отчет о выполнении проекта и предложение по продлению

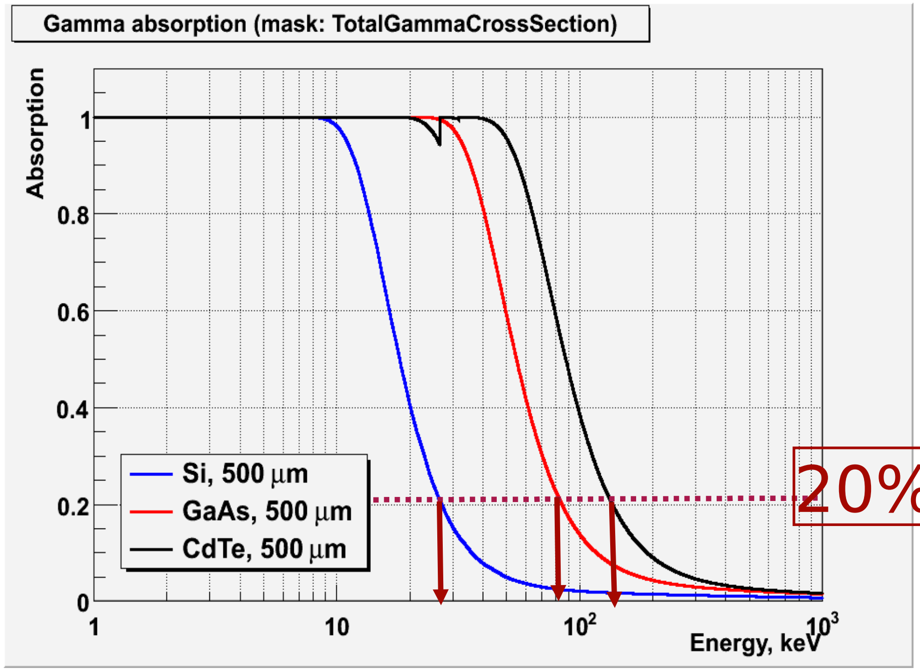
A. Zhemchugov

Physics of a semiconductor detector



Gallium arsenide as a detector material

- GaAs is a well-known semiconductor, second widespread after silicon
- Limited use in particle detection because of low resistivity, low CCE and high intrinsic noise
- New modification of GaAs, compensated by Cr (GaAs:Cr), has been invented in Tomsk State University in 2000-2005
  - suitable for detector construction
  - radiation hard
  - Z(GaAs)~ 32 vs Z(Si)=14 → higher photon detection efficiency



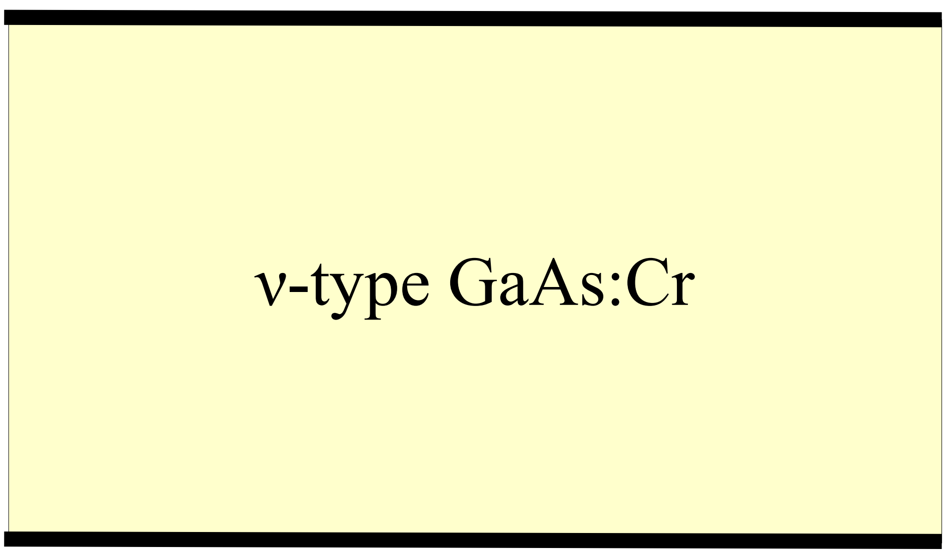
Material	main charge carriers	electron drift length	bulk resistivity	active sensor thickness	intrinsic noise
LEC SI-GaAs	holes	0.3-0.5 mm	$<2*10^8$ Ω*cm	<300 μm	high
GaAs:Cr	electrons	0.7 - 2 mm	$\sim 10^9$ Ω*cm	up to 1 mm	low

The idea of Tomsk GaAs:Cr

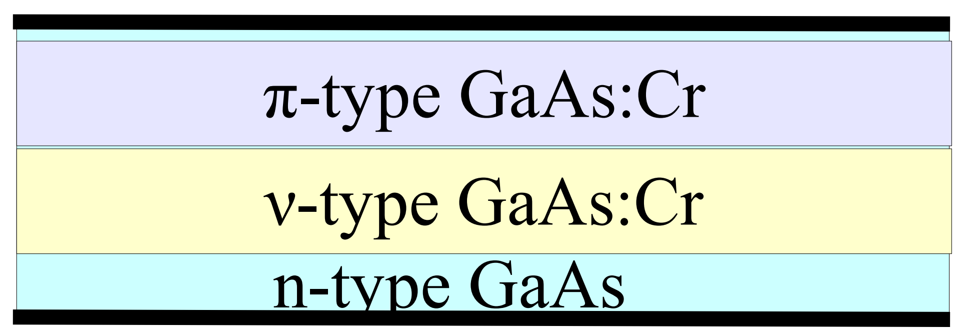
- **LEC SI-GaAs — commercially available**
  - difficult to control the impurities at low level
  - EL2 centers capture the electrons (τ~0.2 ns)
- **n-type SI-GaAs = LEC Si-GaAs doped with Nd~10^{17} donors (Sn or Te) – also commercially available**
  - EL2 centers are compensated
  - n-type, low resistivity
- **Compensated GaAs = n-type SI-GaAs compensated with Cr (or Fe)**
  - high resistivity (=low free carrier concentration)
  - type depends on Cr concentration: p-type (π-type) if $N_{Cr}>N_d$ and n-type (ν-type) if $N_{Cr}<N_d$
  - N_{Cr} and N_d are 'macroscopic': it is possible to control the material properties in wide range

Two types of GaAs:Cr detectors

- 'Resistive' GaAs:Cr
  - resistivity ~10^9 Om*cm
  - active thickness up to 1 mm
  - electron drift length up to 2 mm



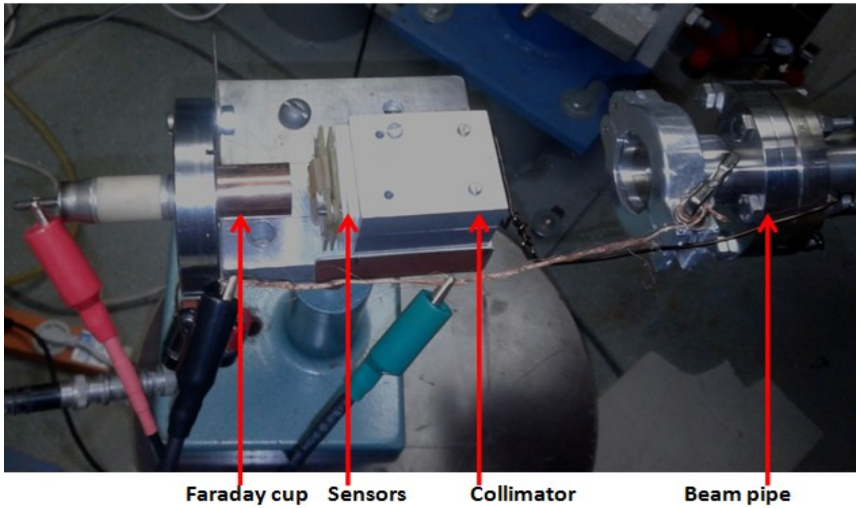
- πν junction structure
  - active thickness is determined by πν junction (~0.1-0.2 mm depending on Ubias)
  - resistivity and CCE is Ok



Radiation hardness studies

Linac-200 at JINR

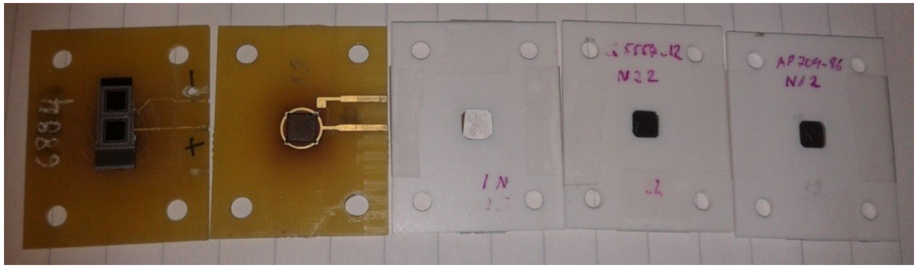
Part of refurbished 800 MeV linac MEA from NIKHEF

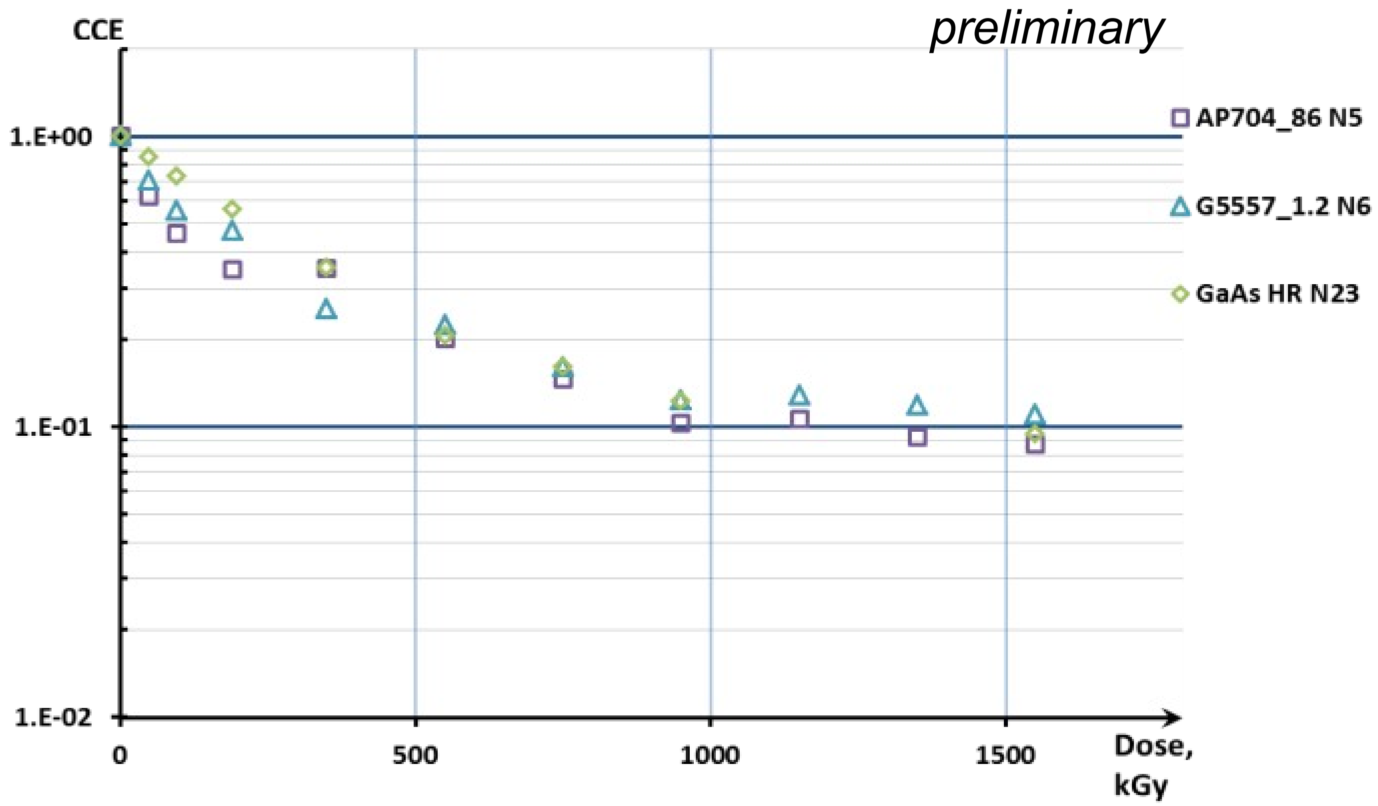


- 22 MeV electrons
- Current in bunch 15 μA
- Bunch width 2 μs
- Bunch frequency 10-250 Hz
- Focal spot ~ 1 mm, can be defocused up to 20 mm
- Estimated doserate for GaAs ~ 600 kGy/hour

We thank Dr. V. Kobets and his team

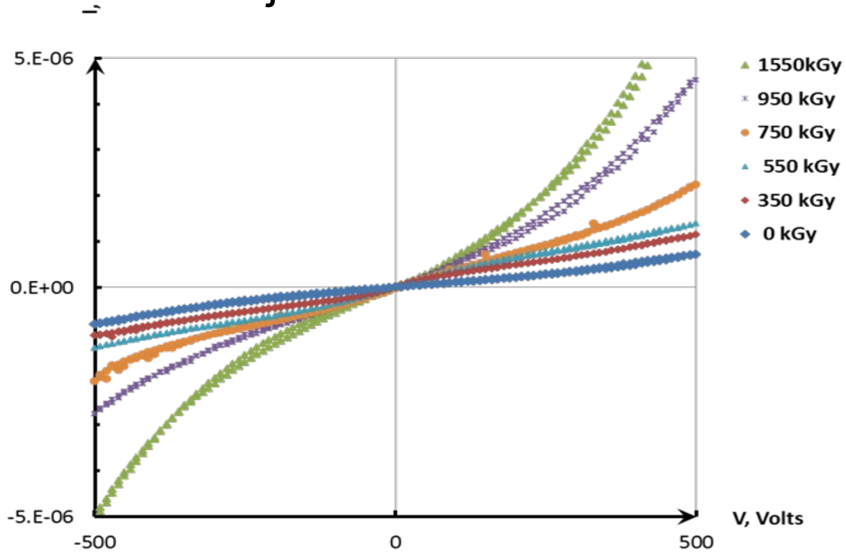
CCE vs Dose



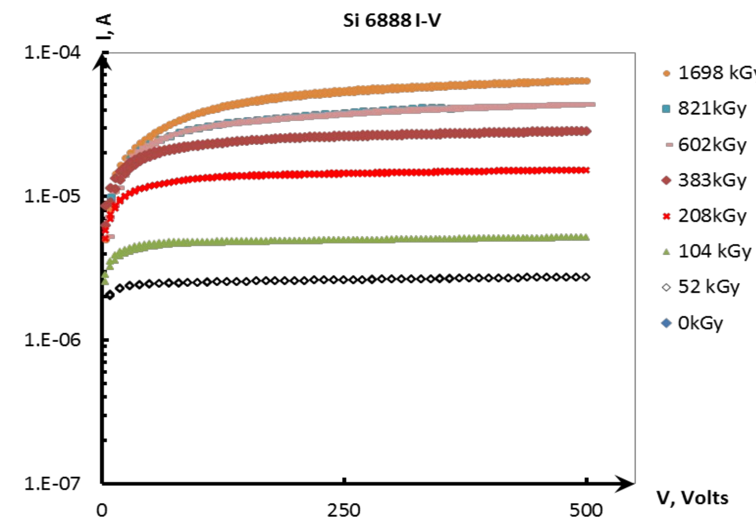

CCE
preliminary
1.E+00
1.E-01
1.E-02
0
500
1000
1500
Dose, kGy
AP704_86 N5
G5557_1.2 N6
GaAs HR N23

I-V measurements

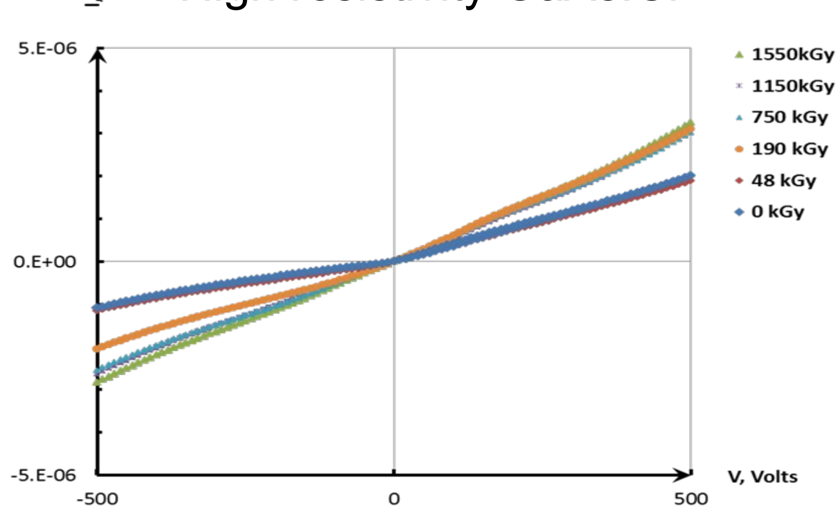
$\pi\nu$ junction GaAs:Cr



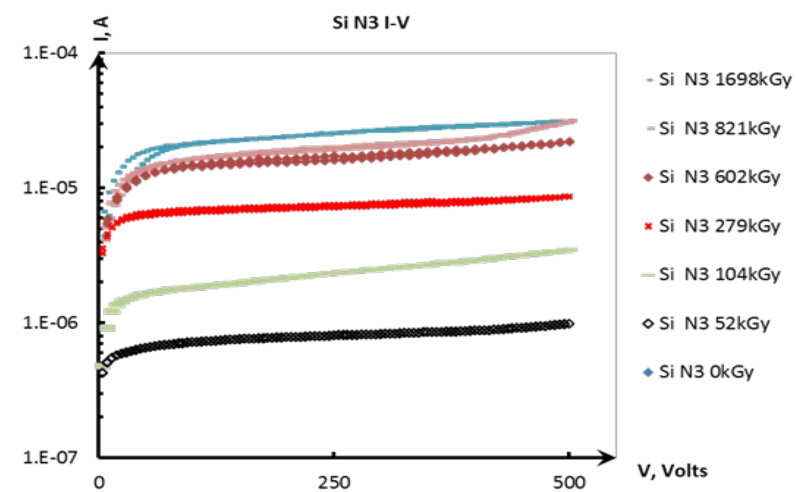
Si from SLAC



High resistivity GaAs:Cr

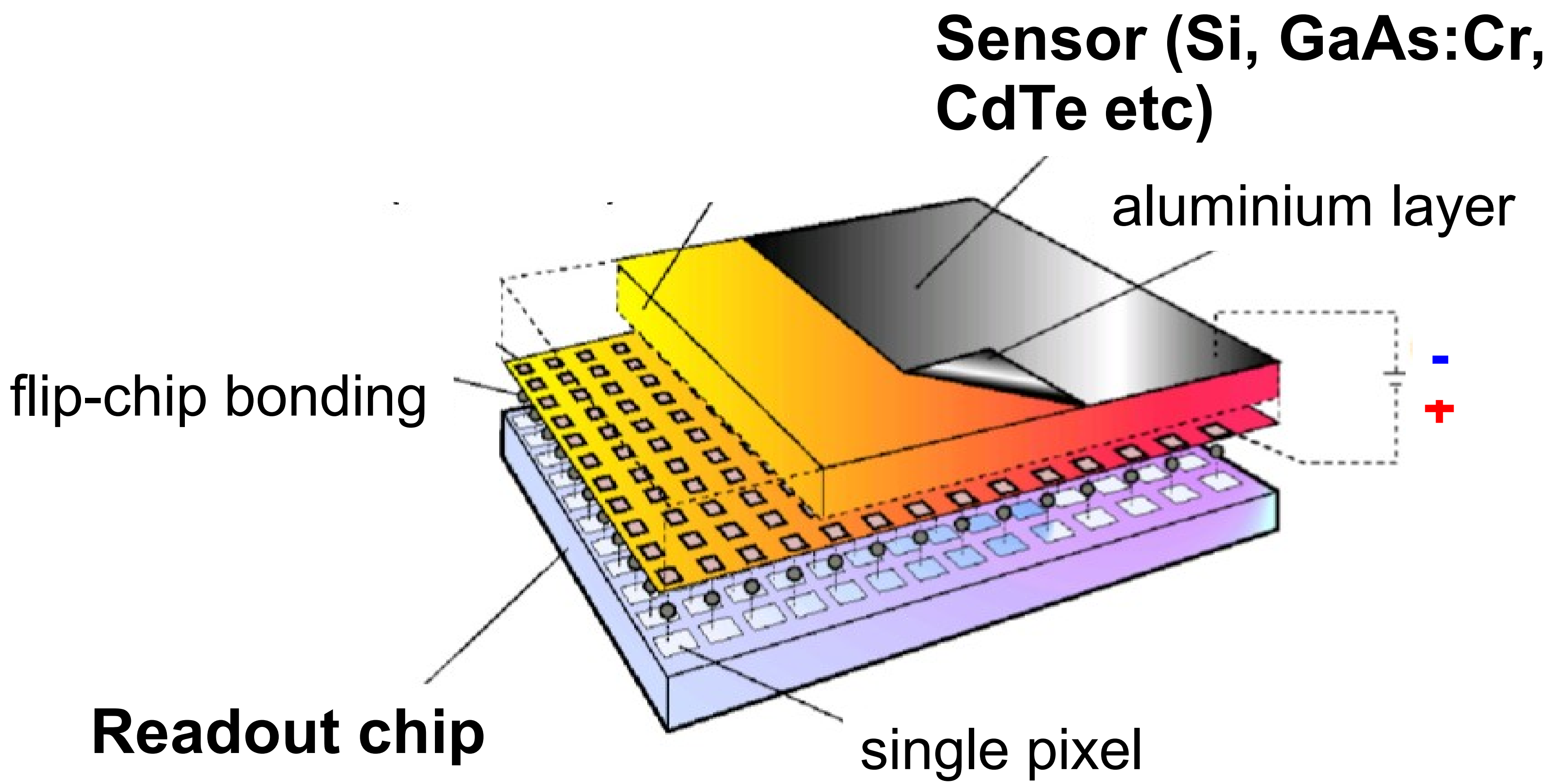


Si from Dr.Zamyatin's group

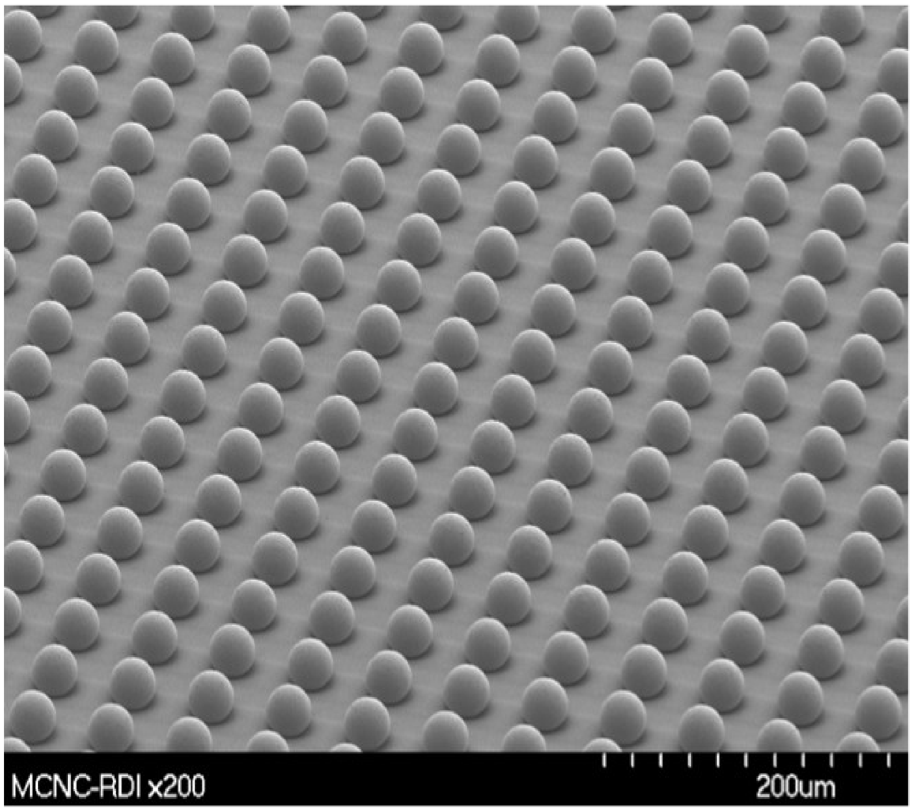


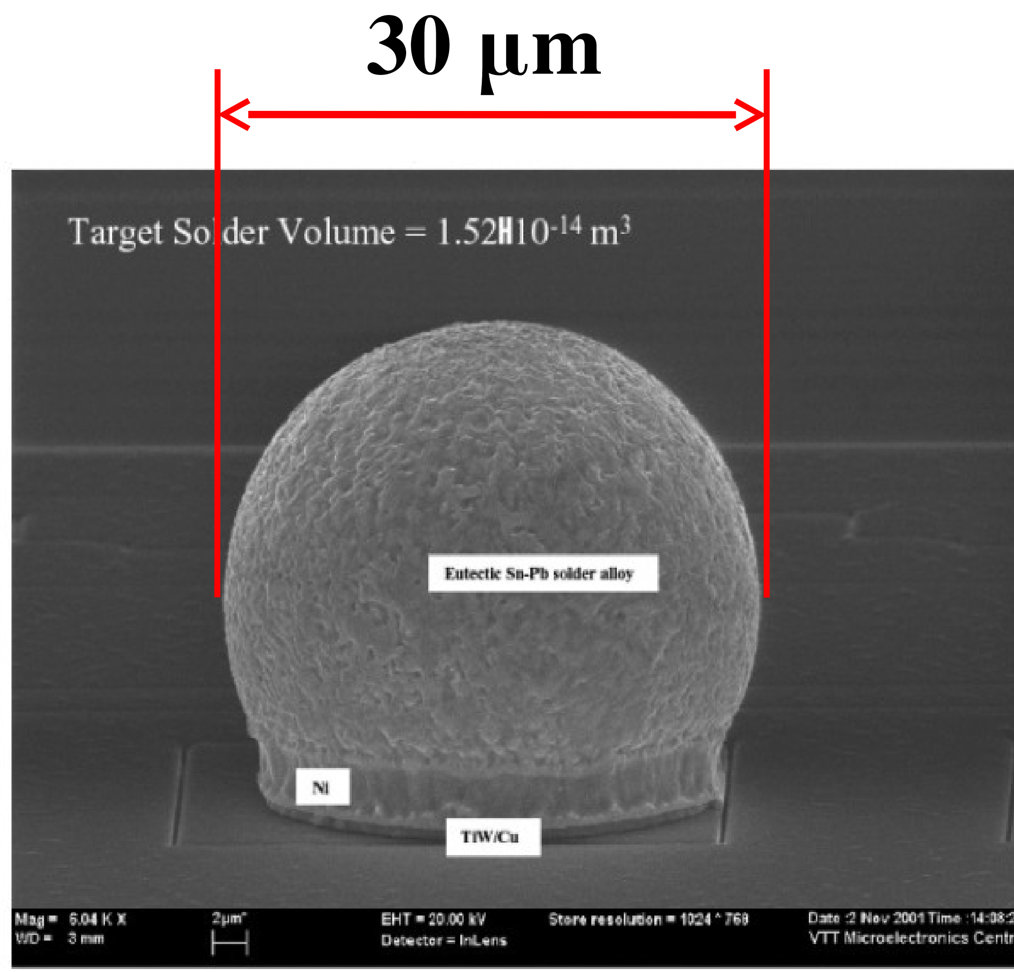
GaAs:Cr based Medipix detectors

Hybrid pixel detectors



Flip-chip bonding



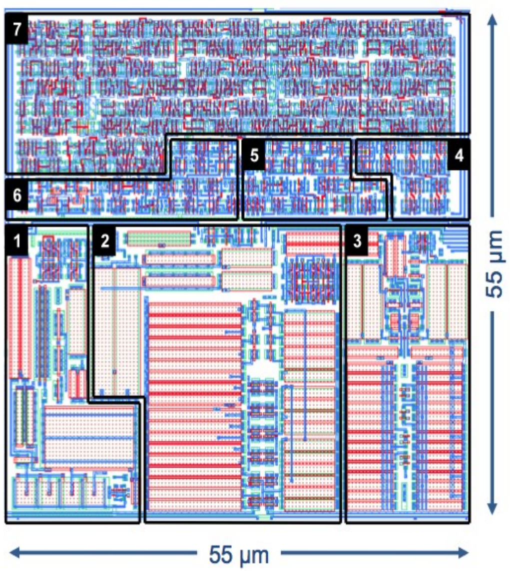


Medipix readout chip

- Family of single photon counting readout chips. Two discriminator thresholds in each pixel. Recent version support charge summing mode
- 256x256 pixels 55x55 μm^2 each (14.1x14.1 mm)
- Developed by the Medipix collaboration based at CERN

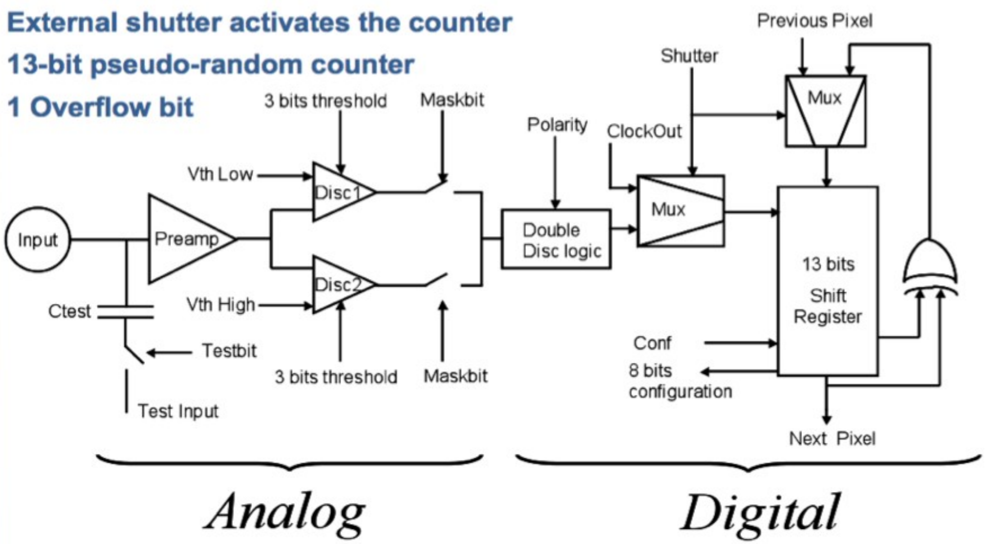
- Fully exploit the available 130 nm CMOS technology
- ~1600 transistors per pixel

1. Preamplifier
2. Shaper
3. Two discriminators with 5-bit threshold adjustment
4. Pixel memory (13-bits)
5. Arbitration logic for charge allocation
6. Control logic
7. Configurable counter



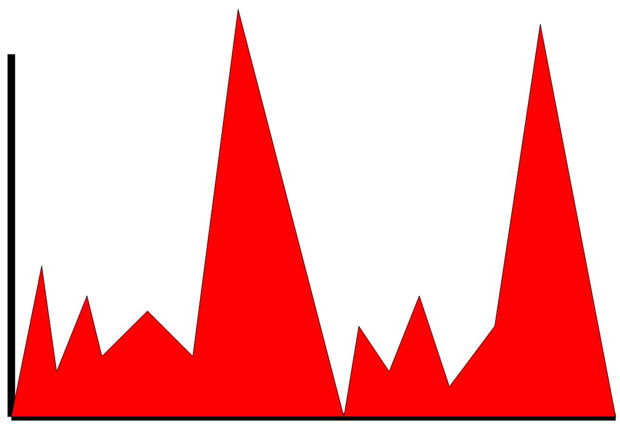
Circuit inside a single Medipix pixel

Charge sensitive preamplifier with individual leakage current compensation
2 discriminators with globally adjustable threshold
3-bit local fine tuning of the threshold per discriminator
1 test and1 mask bit
External shutter activates the counter
13-bit pseudo-random counter
1 Overflow bit



Single photon counting

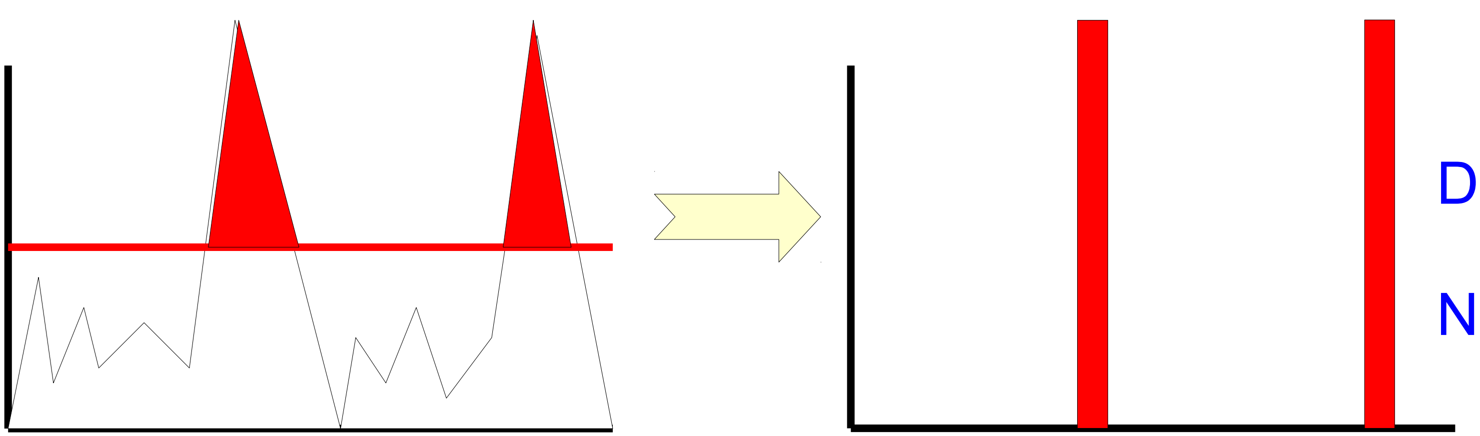
- Integration



Analog signal

Noise is integrated and inherent in signal

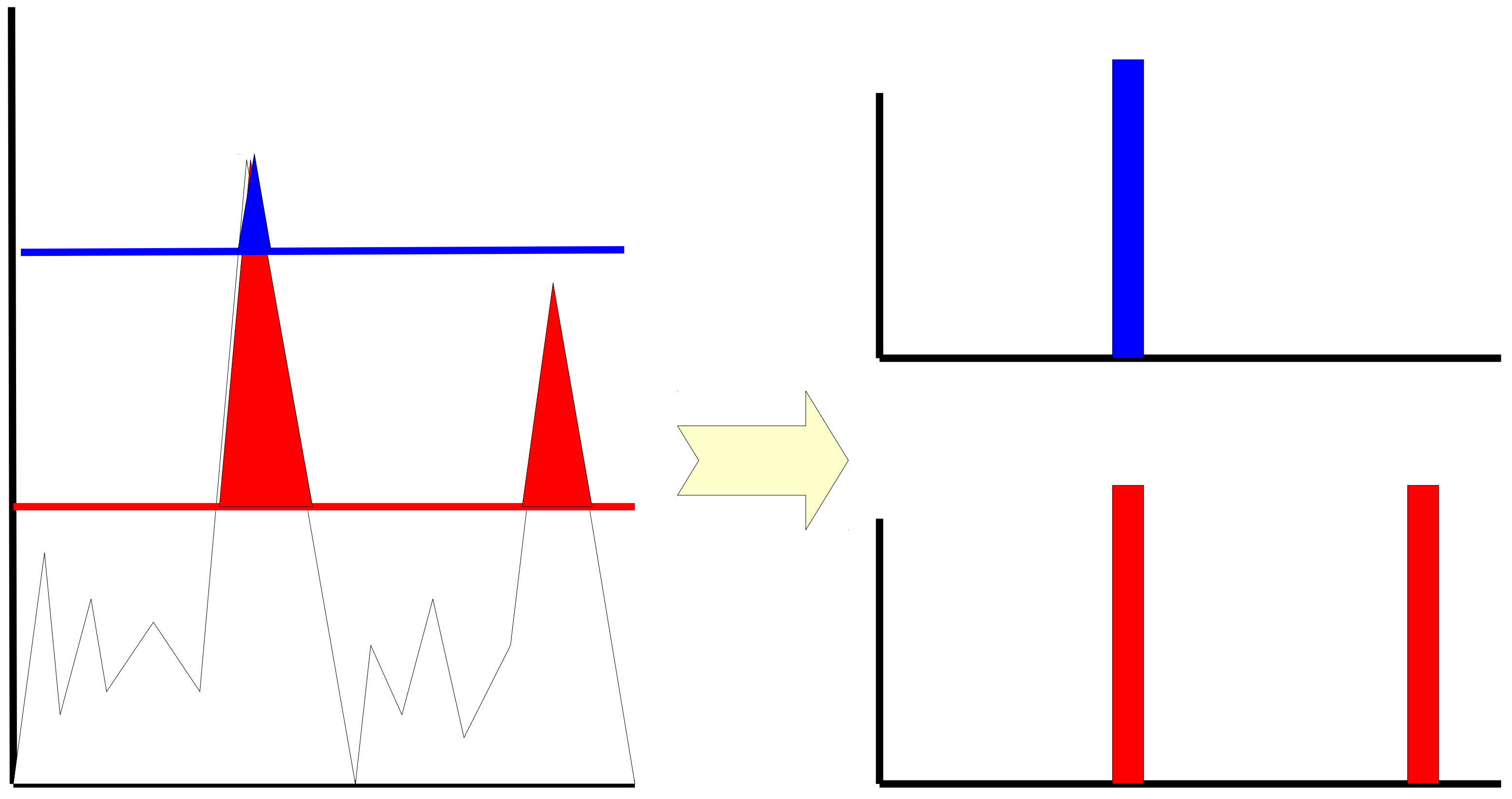
- Single photon counting



Digital signal

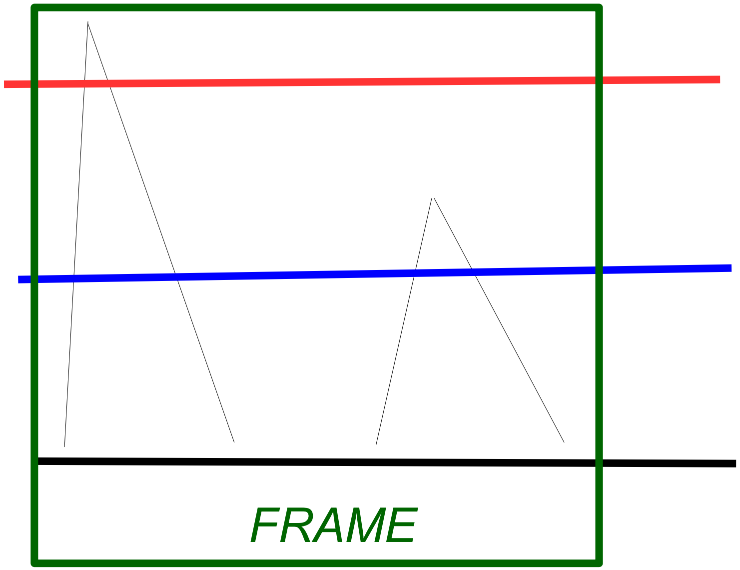
Noise is removed

Energy discrimination



Medipix and Timepix

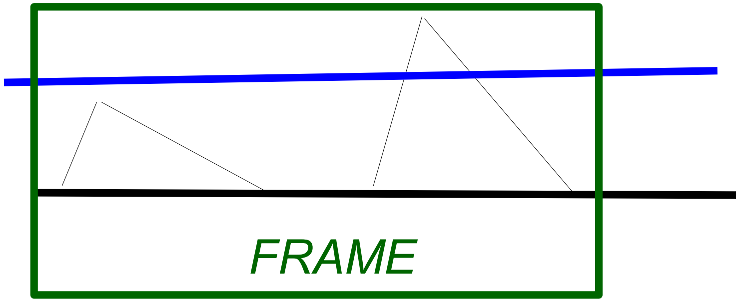
Medipix



COUNT1

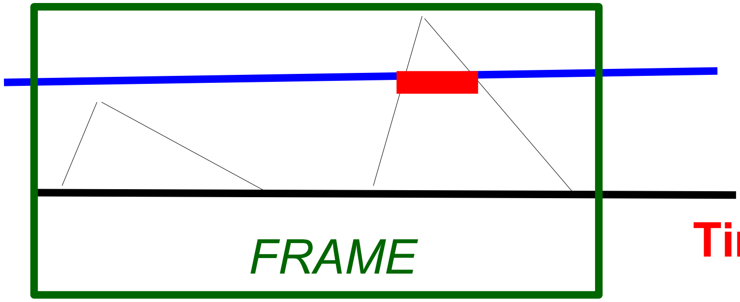
COUNT2

Timepix



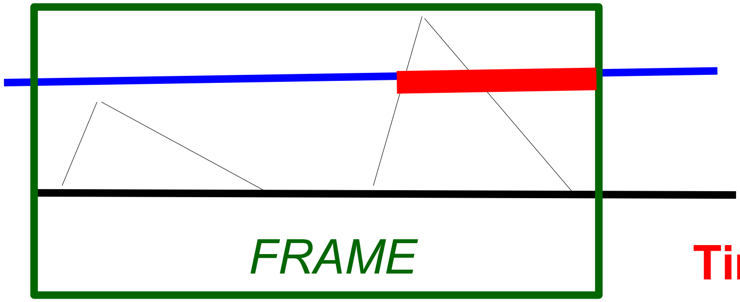
MEDIPIX Mode

COUNT



TOT Mode

Time Over Threshold

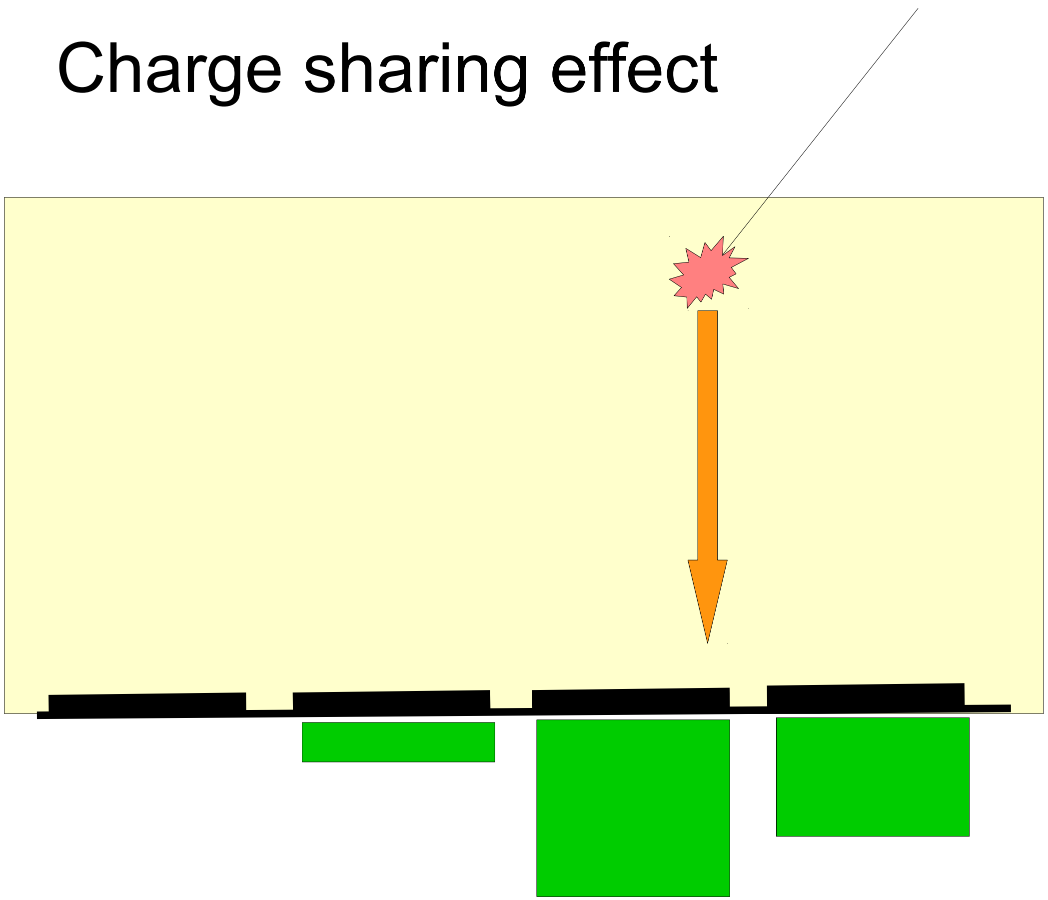


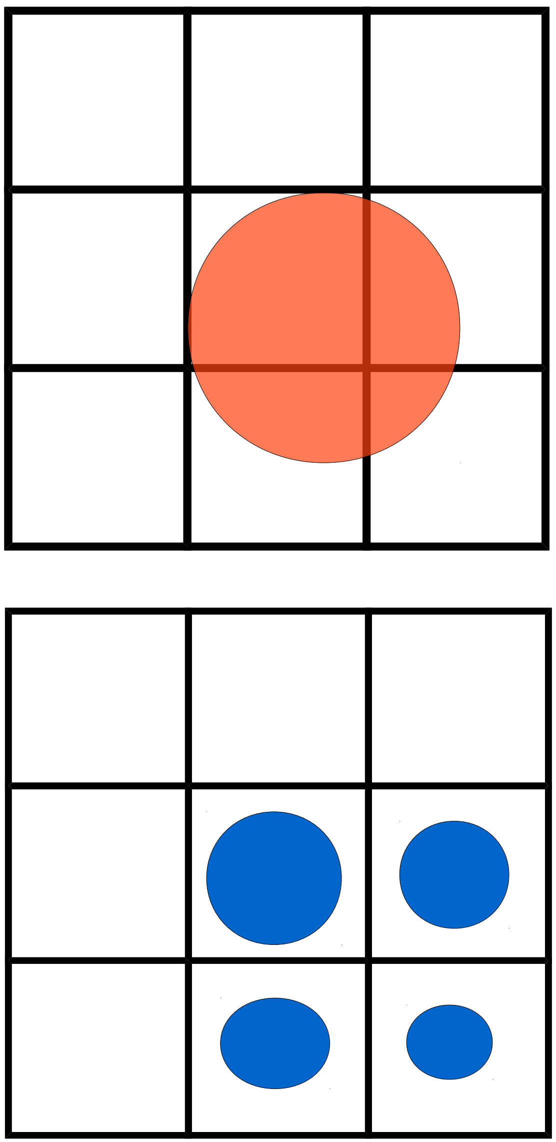
TOA Mode

Time Of Arrival

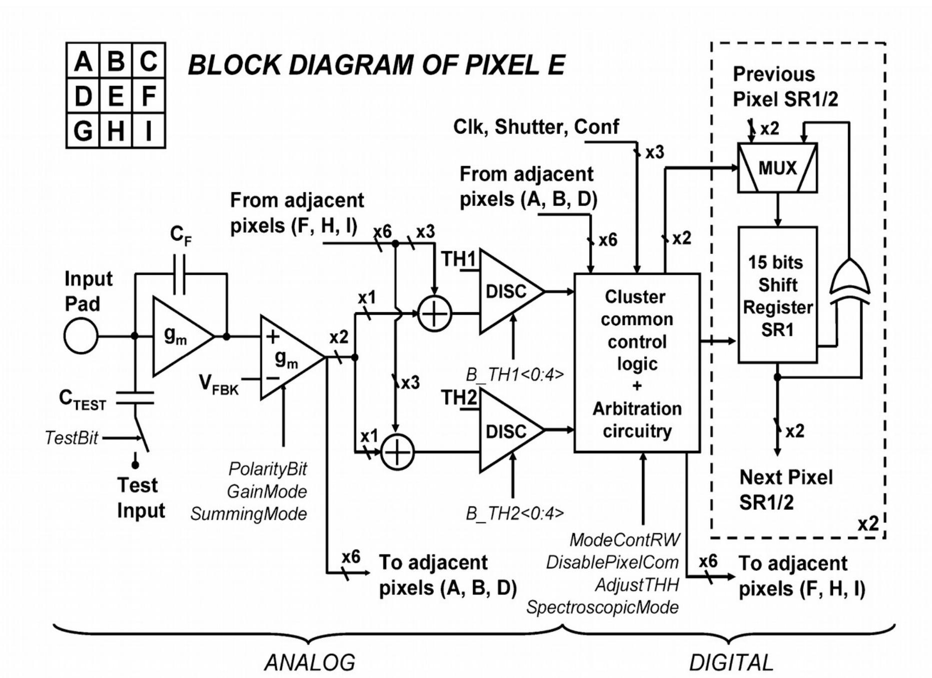
Charge summing in Medipix3

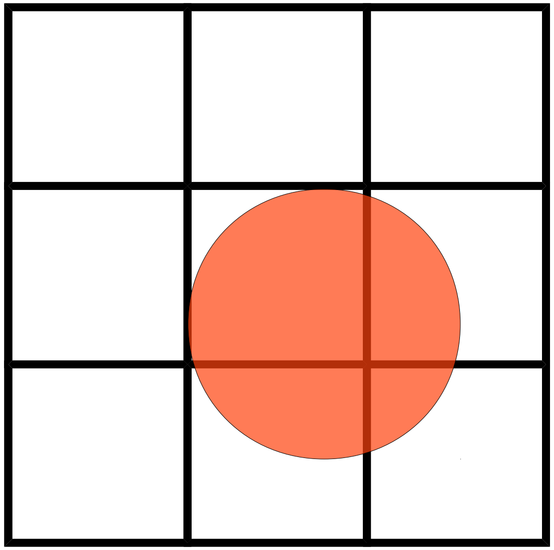
Charge sharing effect

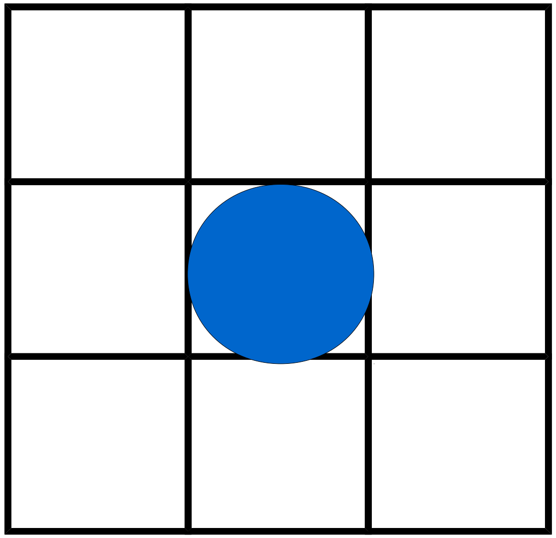




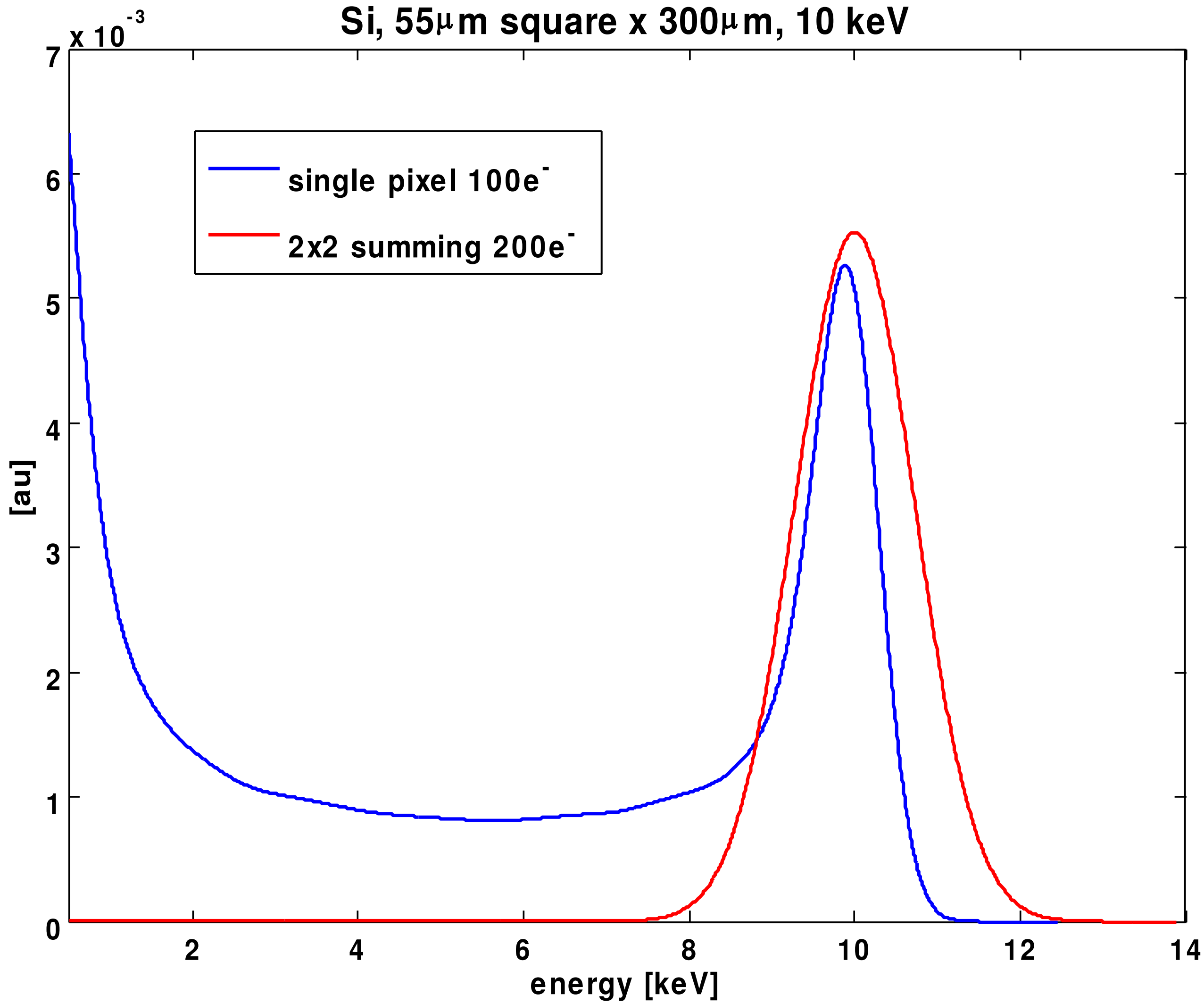
Charge summing in Medipix3







Charge summing in Medipix3 (simulation)



- ***Simulated Data***
- ***Si 300μm, 55μm pixel***
- ***10keV monochromatic photon beam***
- ***In the new architecture charge sharing tail is eliminated***

Simulation: L. Tlustos
R.Ballabriga

Charge summing in Medipix3 (experiment)

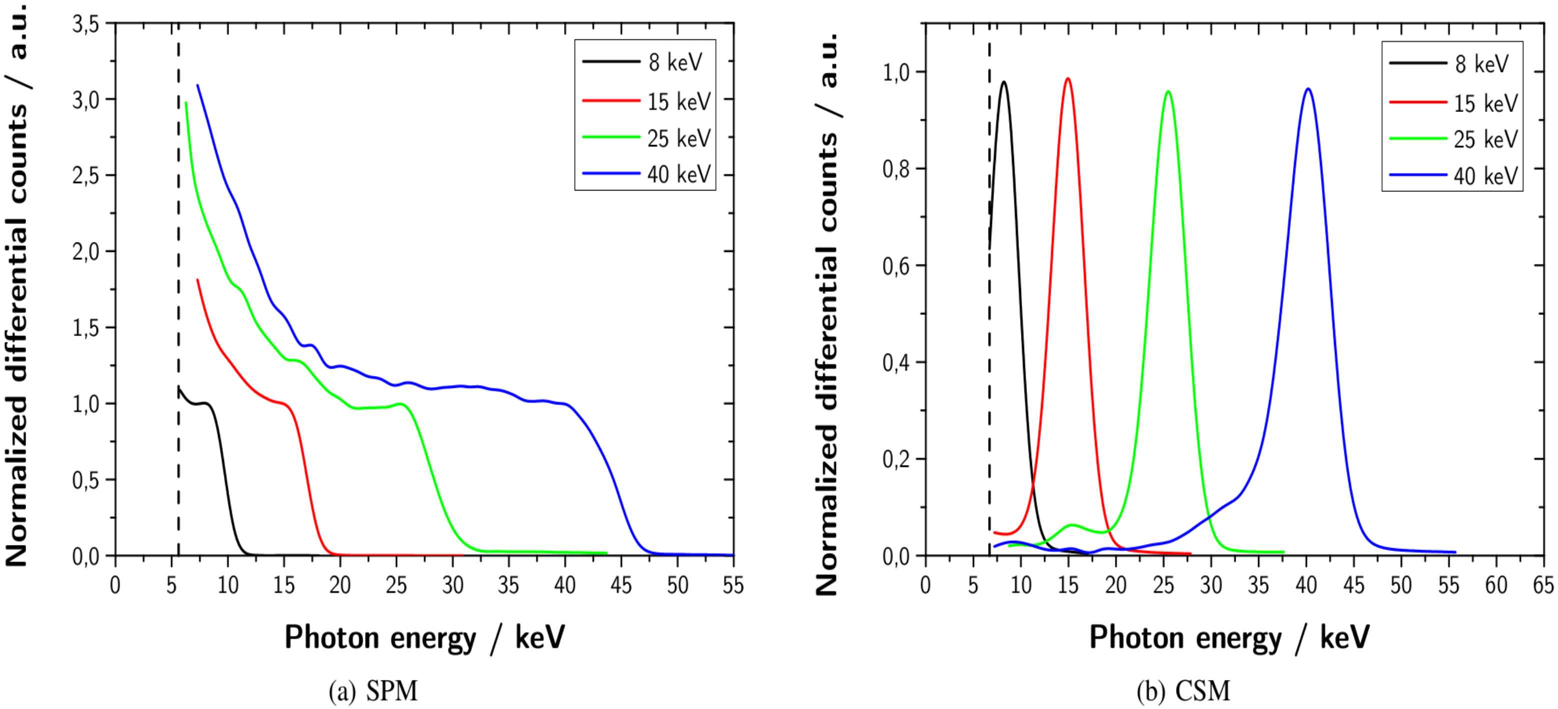


Fig. 5. Energy response functions in SPM (a) and CSM (b) for monochromatic synchrotron radiation of 8 keV, 15 keV, 25 keV and 40 keV. Shown are spline interpolations. The levels of the electronic noise are indicated by the dashed black lines.

Medipix chip evolution

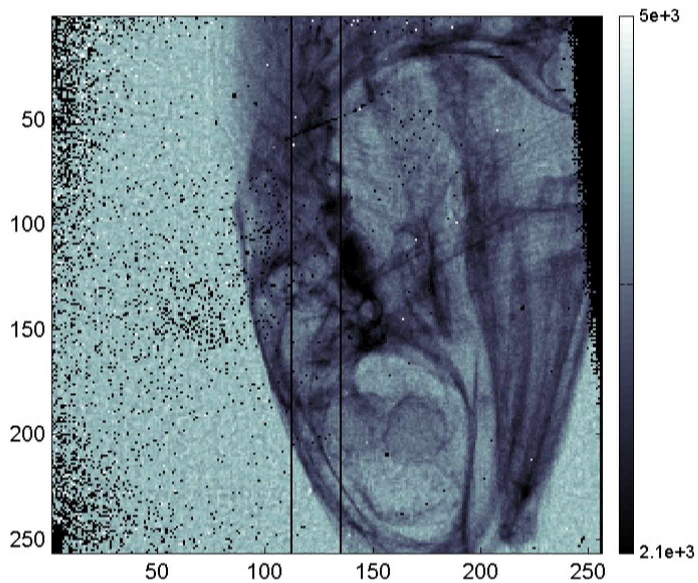
	Medipix2	Timepix	Medipix3	Timepix3	Medipix4	Timepix4
Pixel side (μm)	55	55	55/110	55	x/2x/3x	y
Technology (nm)	250	250	130	130	65	65
# pixels in x and y	256	256	256/128	256	512/256/128	512
Readout architecture	Frame based Sequential RW	Frame based Sequential RW	Frame based Continuous RW	Data driven/ frame based	Frame based Continuous RW	Data driven/ frame based
Charge summing and allocation mode (CSM)	No	No	Yes	No	Yes	No
# thresholds	2 (window discriminator)	1	2/4/8 Seq RW 1/4 Cont RW	1	?	1
ToT/ToA	No	ToT (14 bit) OR ToA (14 bit, 10ns precision)	No	ToT (10 bit) AND ToA (14 bit, 1.56ns precision)	No	ToT AND ToA
Front end noise (e$^-$ rms)	110	100	80(SPM) 174(CSM)	62	≤ 80 (SPM) ≤ 174 (CSM)	≤ 62
Peaking time (ns)	150	100	120	30	$\ll$120	$\ll$30
Max count rate (Mc/mm^2/s)*	826	-	826 (SPM 55μm) 164 (CSM 55μm) 376 (SPM 110μm) 28 (CSM 110μm)	0.43 (data driven)	x5 Medipix3	x10 Timepix3
Number of sides available for tiling	3	3	3	3	4	4

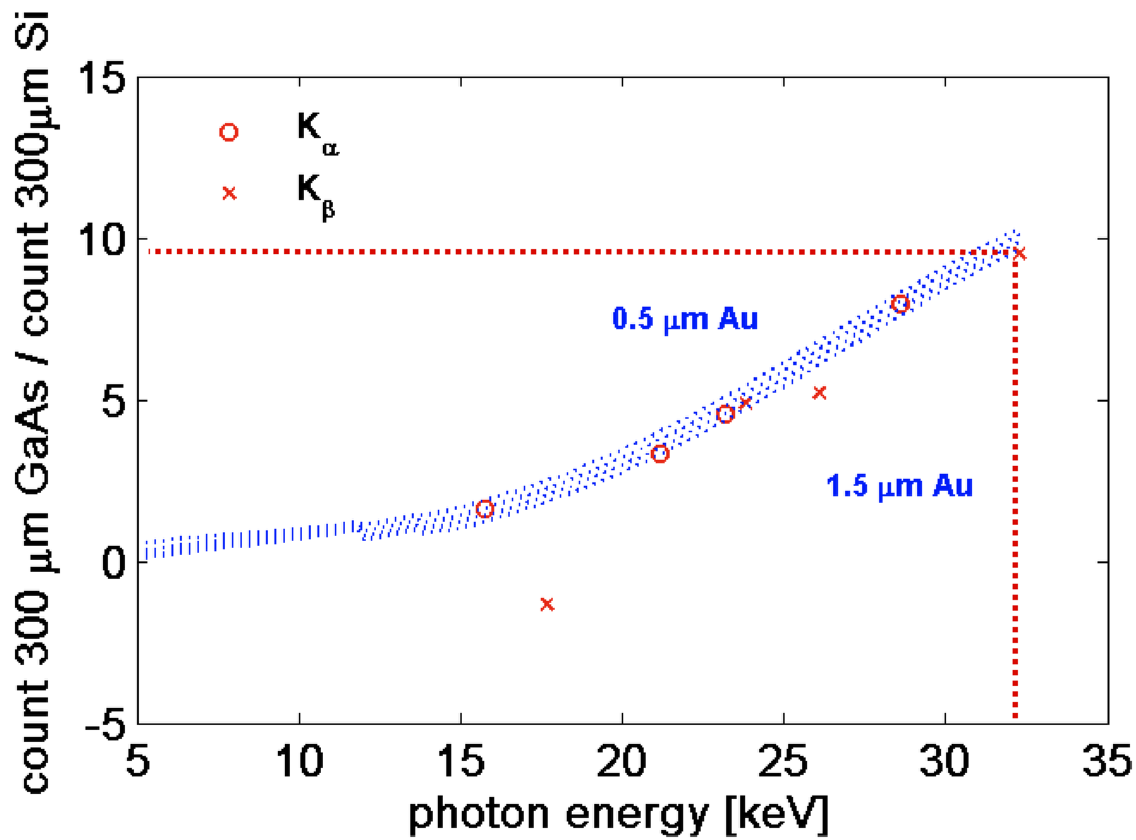
JINR is a member of Medipix collaboration since 2015

Characterisation of GaAs:Cr based Timepix detectors

First Medipix+GaAs:Cr detector

Developed in 2008 by the collaboration of JINR, Tomsk and CERN

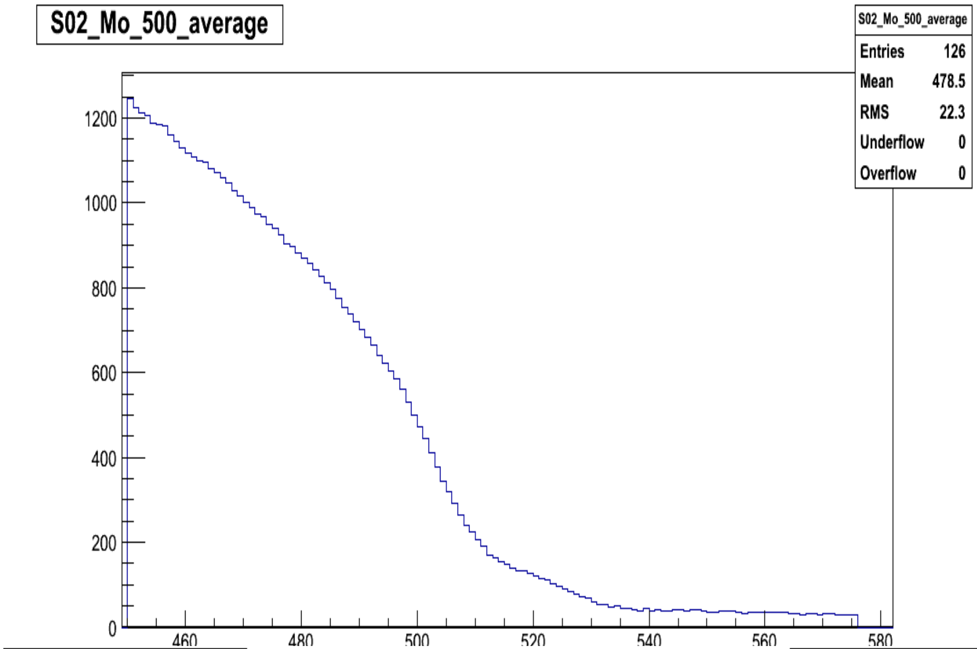


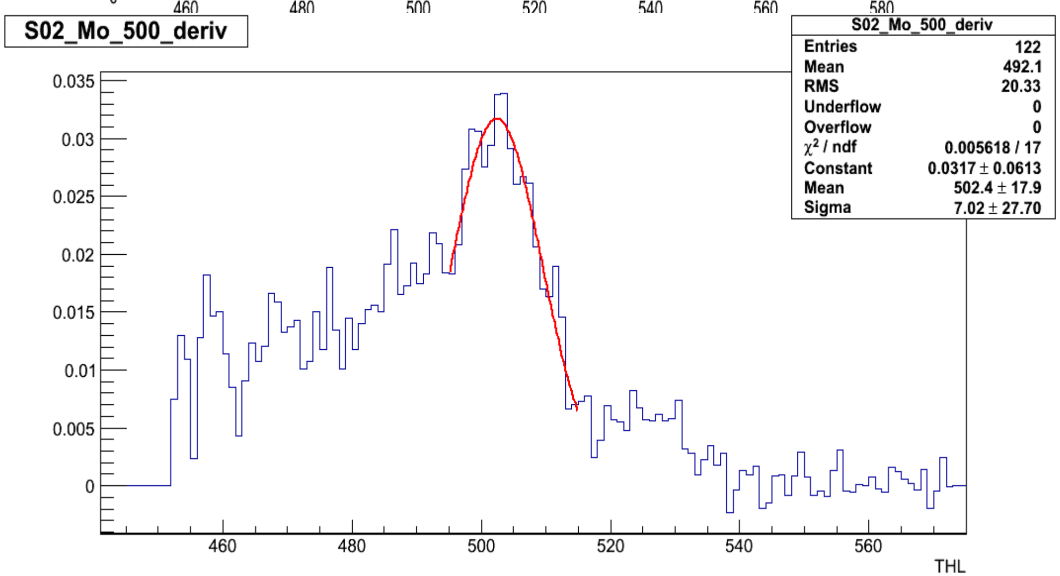


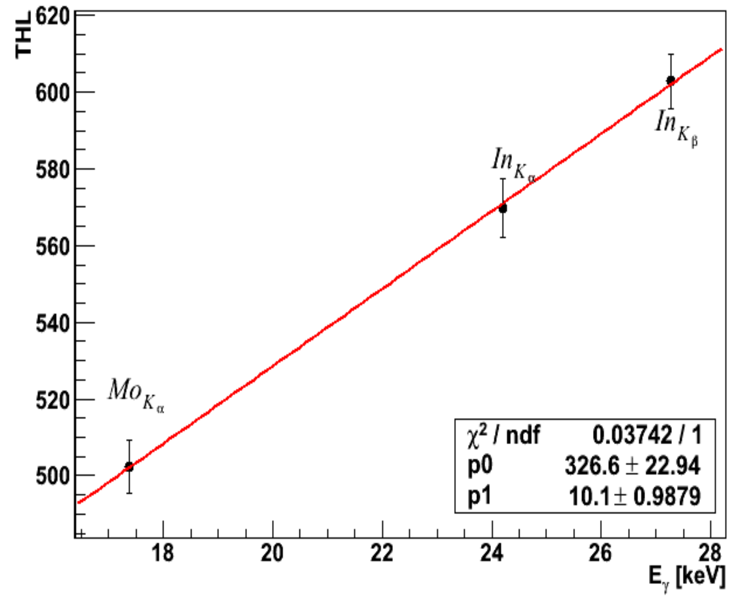
G.Shelkov, L.Tlustos, O.Tolbanov, "Chracterisation of GaAs(Cr) Medipix2 Hybrid Pixel Detectors" NIM A663 (2011) S103-S107

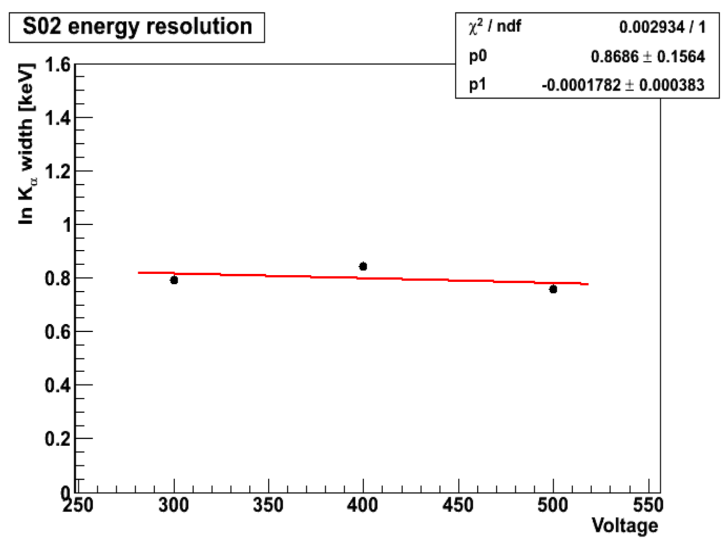
Energy resolution (GaAs+Timepix)

S02: 300 um GaAs+Timepix (Medipix mode), S02 500V Ubias = -500 V ***2012***





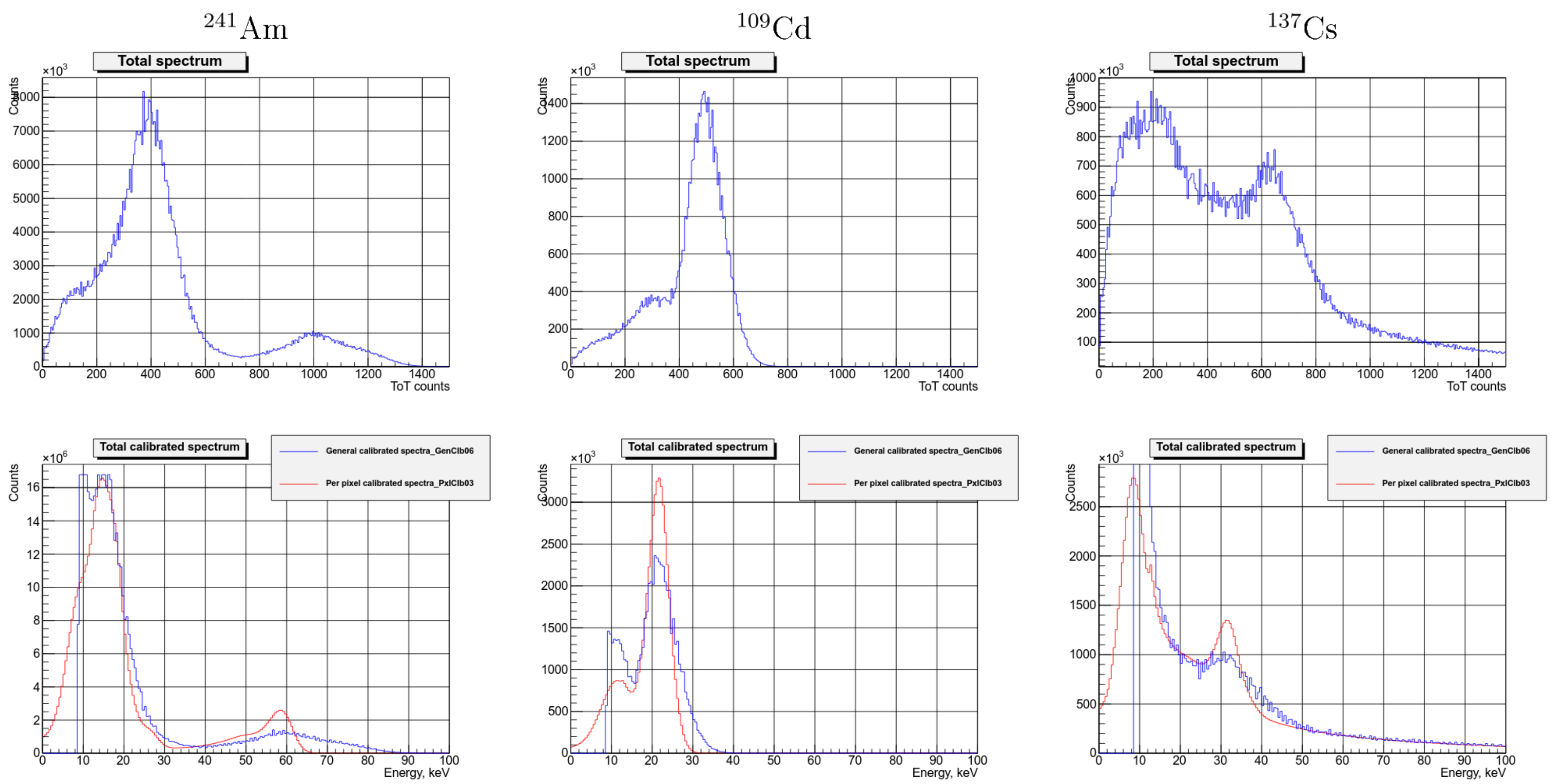




Energy resolution (GaAs+Timepix TOT)

Суммарные спектры до и после обобщенной и попиксельной калибровки. ^{241}Am, ^{109}Cd, ^{137}Cs

2013



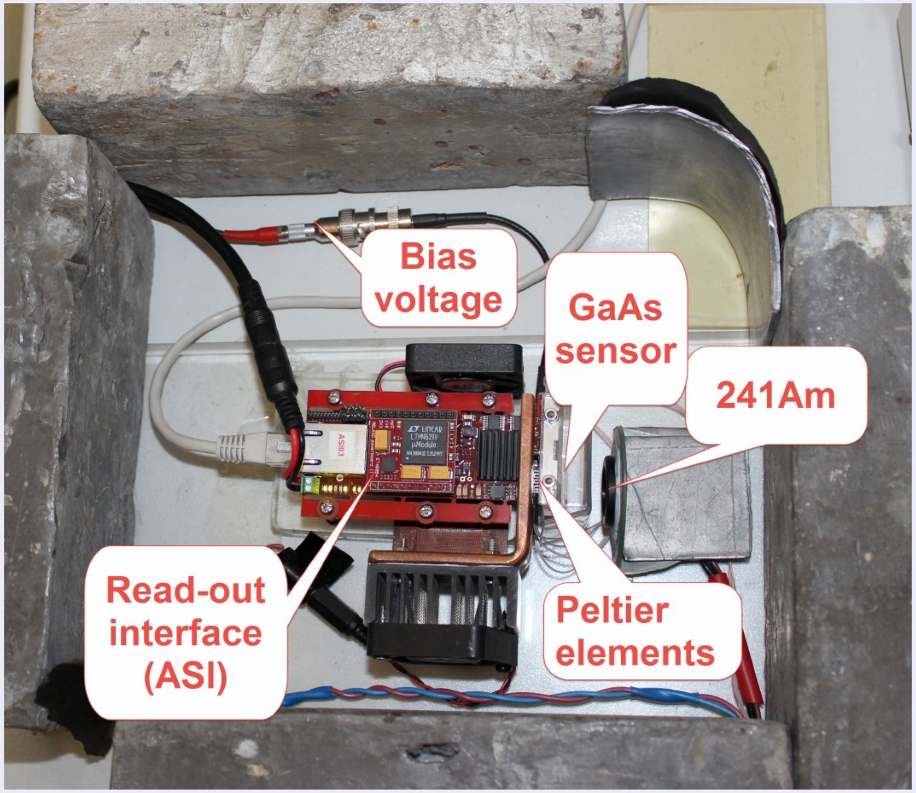
Энергетическое разрешение по суммарным спектрам

GaAs+Timepix (TOT mode), 2013

Энергия, кэВ кэВ	Разрешение без калибровки,%	Разрешение после обобщ. калибр.,%	Разрешение после попикс. калибр.,%
16.6 (Zr)	18.6	18.7	17.4
18.4 (Mo)	15.1	21.9	15.7
21.3 (Rh)	14.7	18.9	15
22.0 (^{109}Cd)	13.4	18	12.3
24.5 (Cd)	14.4	19.3	11.9
25.6 (In)	13.6	19.4	12.5
26.7 (Sn)	13.5	18	10.9
32.0 (^{137}Cs)	17.6	18.3	12
59.5 (^{241}Am)	11	13.8	5.5

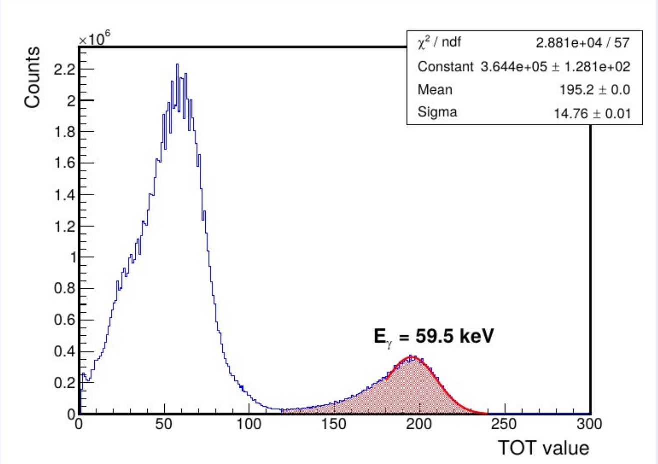
Long term stability measurements

Photo of setup



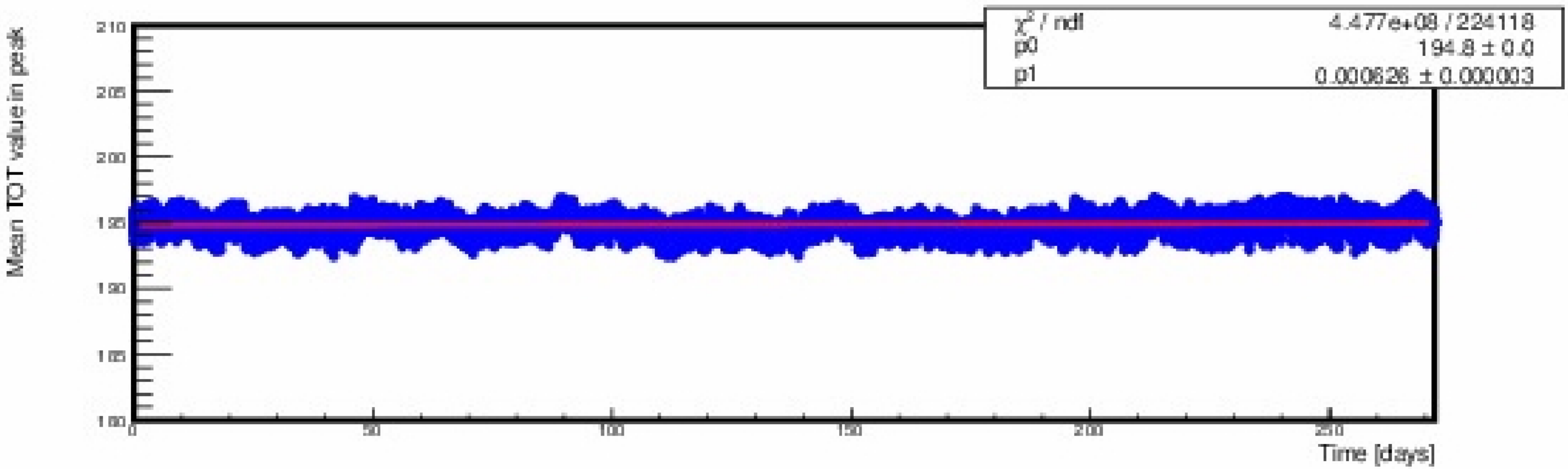
- Timepix + GaAs:Cr sensor (1000 μm) thermostabilized at $T_{stab} = 20 \pm 0.2^0 C$ operates in TOT mode
- RelaxD read-out (by ASI) + SoPhy v.1.1.3
- irradiation by ^{241}Am source and looking for changing position of E_γ=59.5 keV peak in time
- 10 month of almost continuous measurements

Measured ^{241}Am spectrum



Long term stability measurements

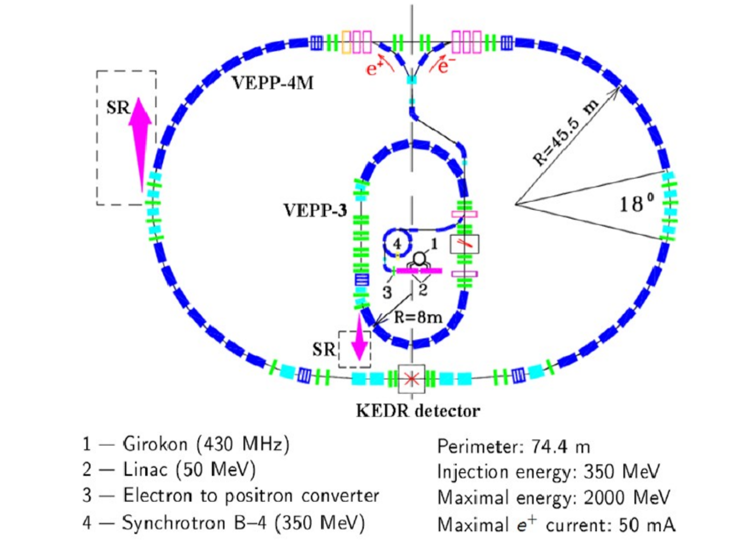
^{241}Am peak position during time



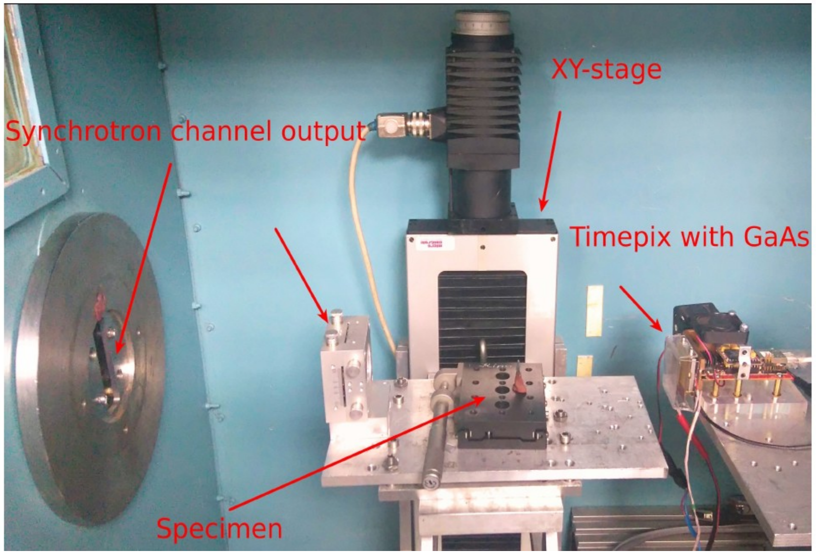
- Mean value of peak changed less than promile per year
- From 28 $\rightarrow$ 61 'dead' pixels after 10 month of operation

Beam tests at synchrotron radiation facility in Novosibirsk

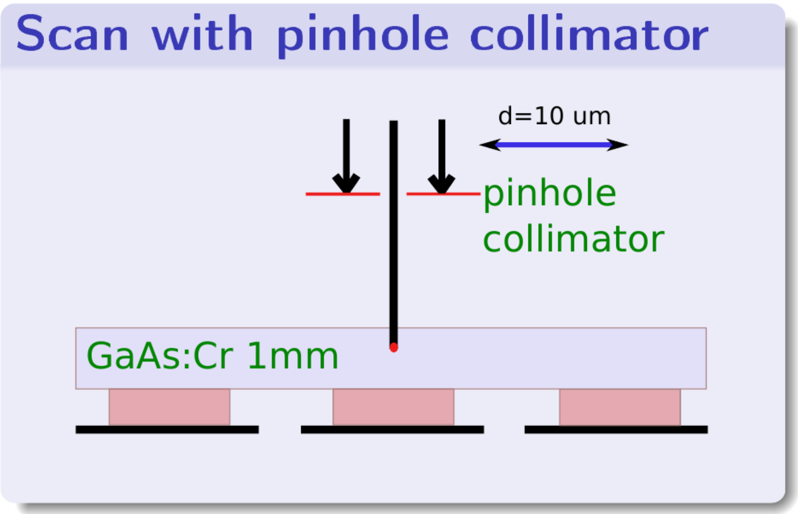
- Measurements were done at electron-positron storage rings VEPP-3M and VEPP-4M, serving as sources of synchrotron radiation
- VEPP-3M:
  - Electron beam energy: 2 GeV
  - Beam current up to 100 mA
  - Bunch length: 1 ns
  - Period: 125 ns
  - Flux up to: $6 * 10^{10}\ ph/mm^2/s$
- SR station "X-ray microscopy and microtomography":
  - Energy range of monochromatic radiation: 6 - 44 keV
  - Monochromated SR beam size: 2 mm x 40 mm
  - Collimator down to 10 x 10 μm



Timepix with 1 mm GaAs:Cr in MPX mode

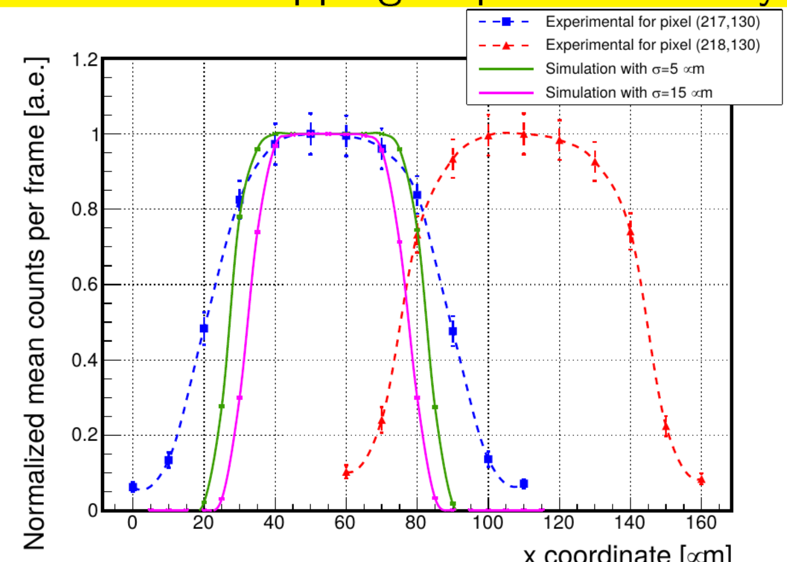


Beam tests at synchrotron radiation facility in Novosibirsk

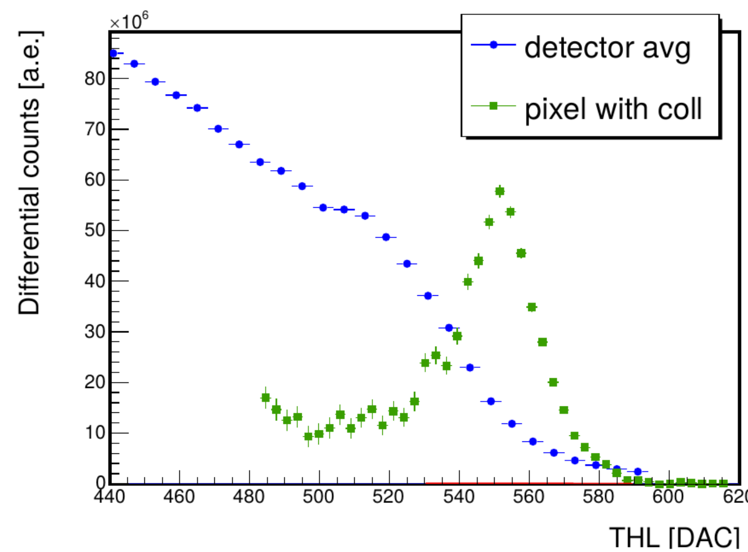


- Several pixels of the detector have been scanned with step of 10 μm using a monochromatic collimated photon beam of 10 x 10 μm^2 (12 - 40 keV)
- Pixel response was obtained for various beam positions - geometrical mapping of pixel sensitivity
- Energy resolution of a single pixel was measured: **4.5** % @ 18 keV

Geometrical mapping of pixel sensitivity



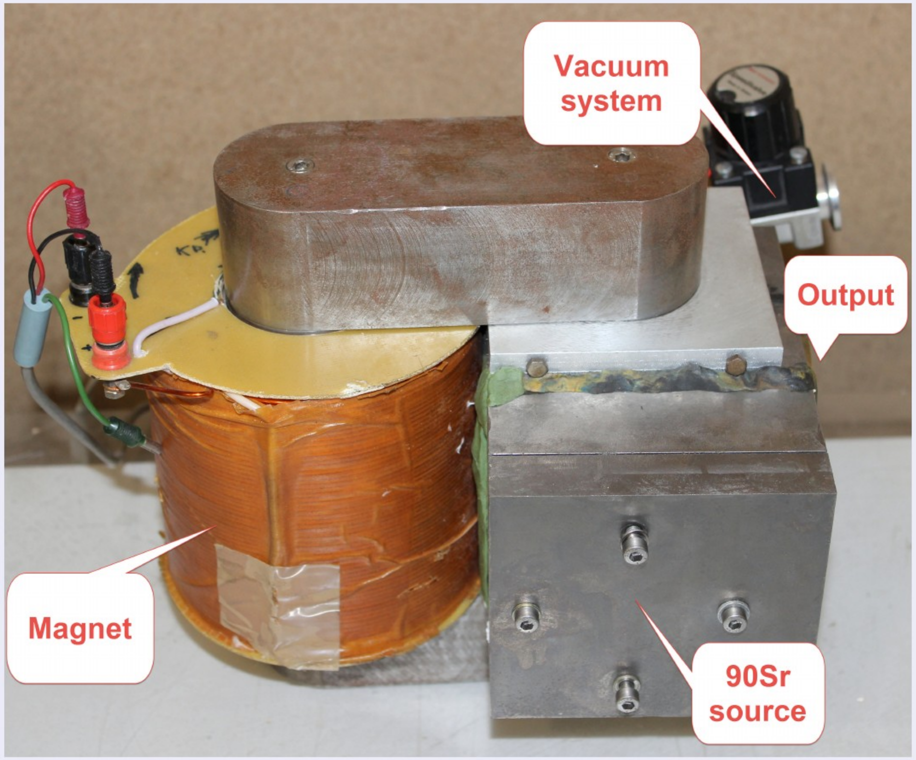
ERF of a single pixel and ERF of whole detector



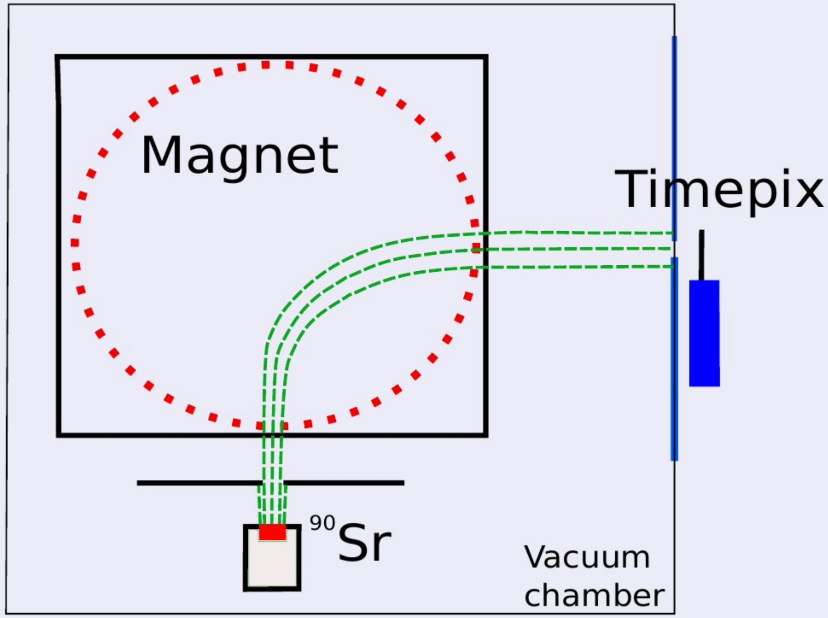
Separator of monoenergetic electrons

Source ^{90}Sr, $E_e \in$ [80,2000] keV

Photo of separator



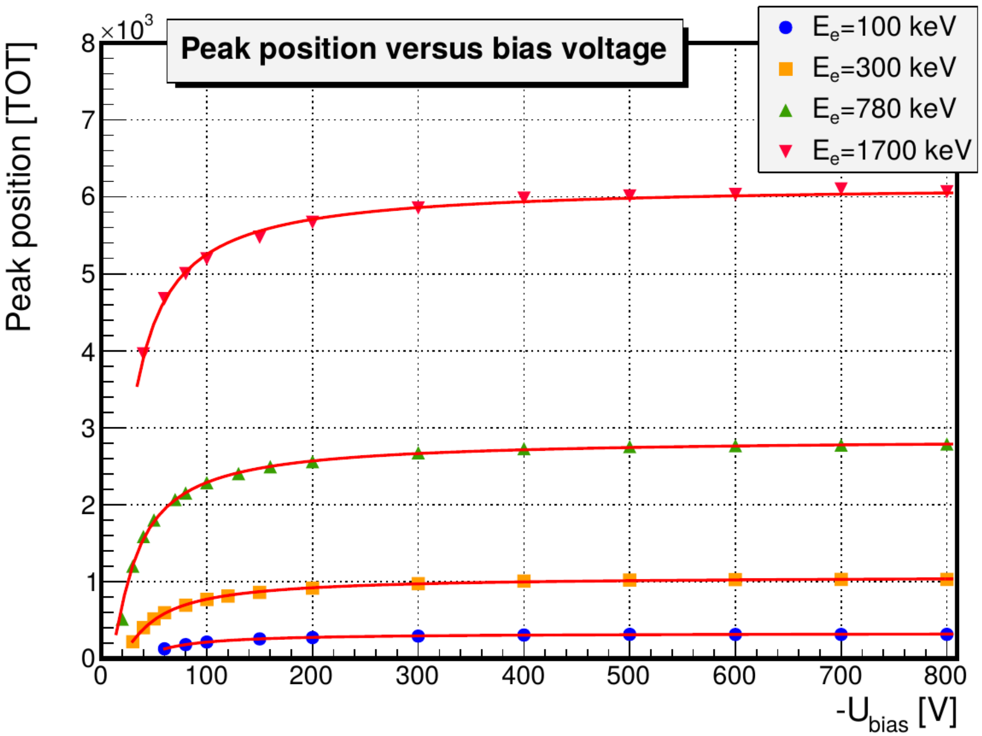
Schema of separator



μτ vs depth

For Timepix with GaAs:Cr sensor of 900 μm thickness:

- it is shown that collected charge is maximal for various electron energies
- fit by Hecht equation -> $\mu_e\tau_e$ values are obtained

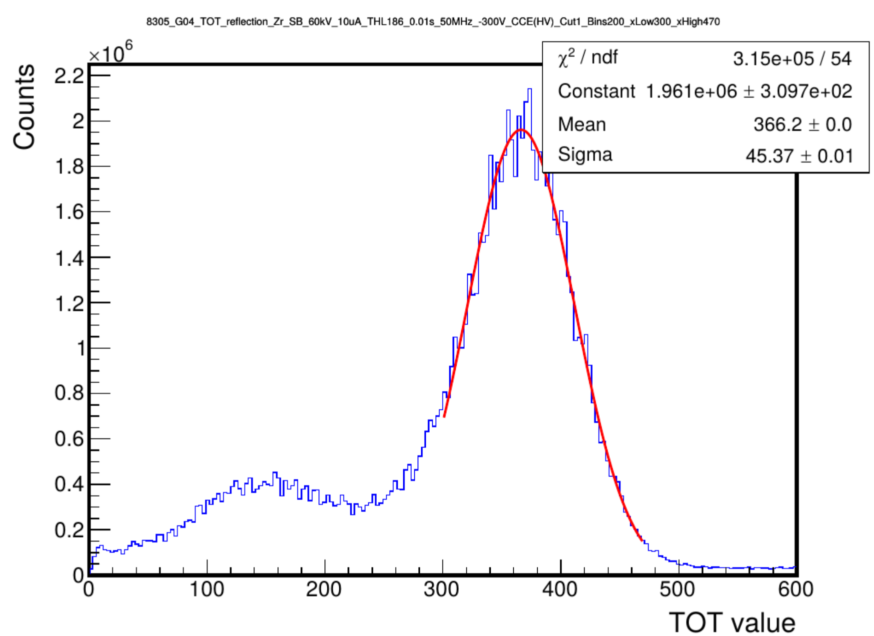


E_e [keV]	Range [μm]	$\mu_e\tau_e$ $[cm^2/V]$
100	24	(1.2 ± 0.05)x10^{-4}
300	143	(1.4 ± 0.05)x10^{-4}
780	450	(1.9 ± 0.02)x10^{-4}
1700	881	(2.7 ± 0.06)x10^{-4}

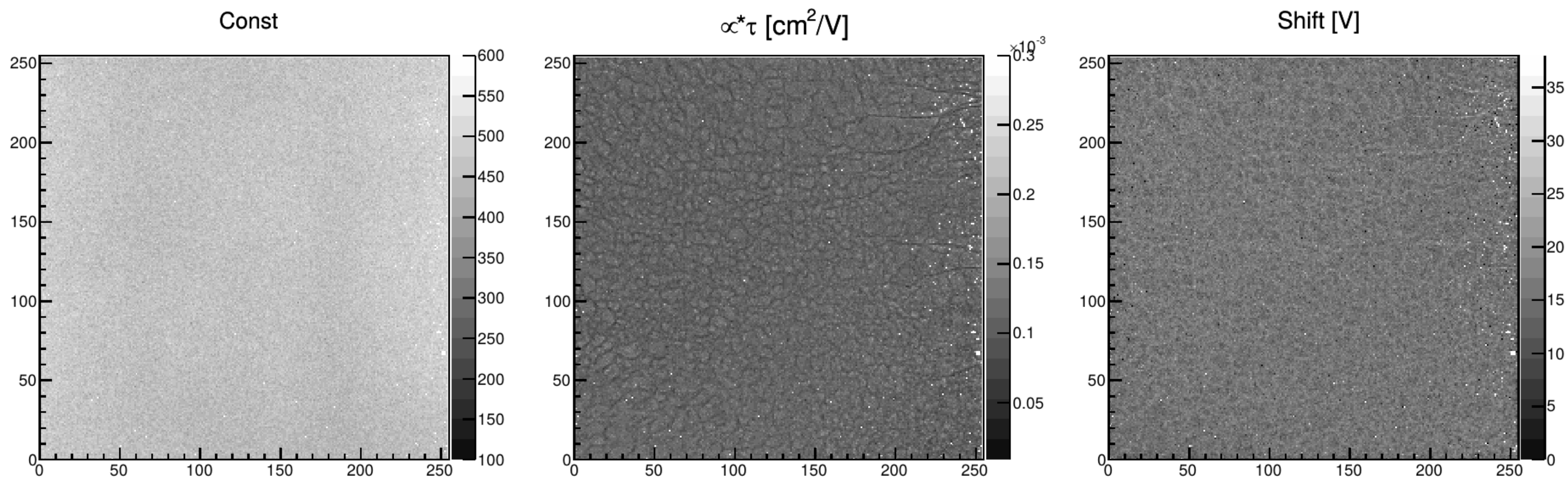
- Peak from 100 keV electrons is observable $\rightarrow$ dead layer (if exists) is less 20 μm

Electron charge transport in GaAs:Cr based Timepix detectors

- DUT: Timepix L05-W0203 with sensor AG-892№59-1 (500 um)
- X-ray characteristic spectra of a Zr foil were collected at varying bias voltages
- Photons corresponding to Zr K_α= 15.7 keV have a mean free range in GaAs less 25 μm -> the majority of interactions will occur close to cathode
- Mean value of 15.7 keV photo peak was calculated for each pixel at different bias voltages - only single pixel events are evaluated
- Obtained dependencies "Peak position vs bias voltage" for each pixel were fitted using modified Hecht equation for case of small pixels [arxiv:1701.03459]

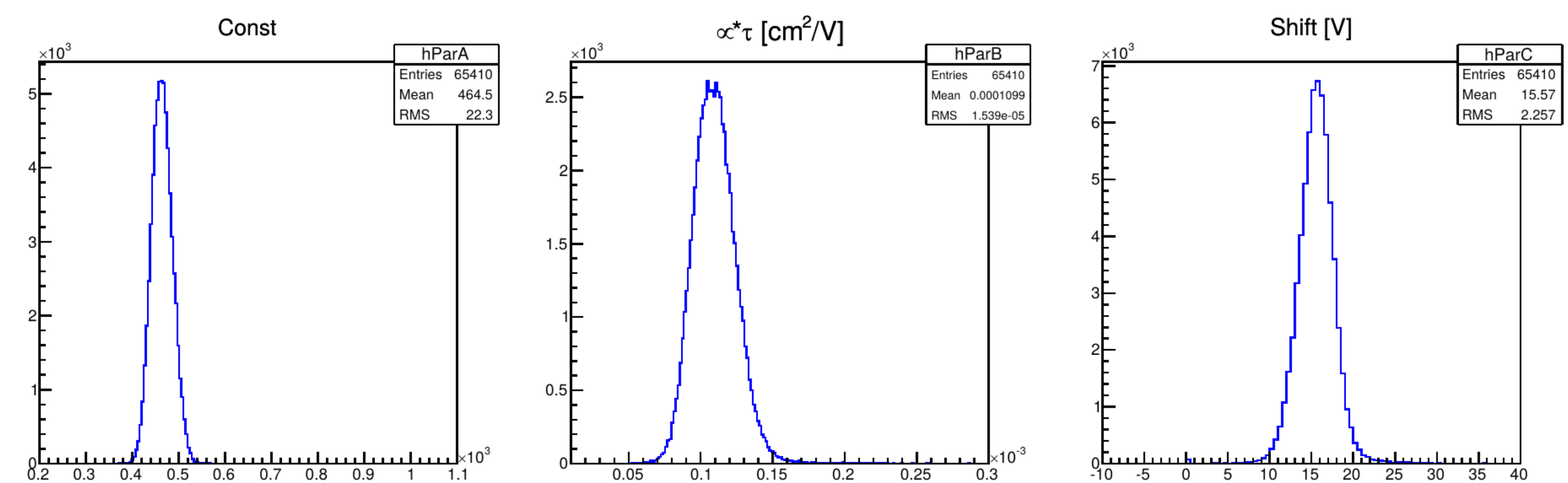


Electron charge transport in GaAs:Cr based Timepix detectors



$$Q(U) = Q_0 \cdot \frac{d}{\mu\tau\cdot(U-U_0)} \cdot \int_0^d w(x) \cdot e^{-\frac{-x\cdot d}{\mu\tau\cdot(U-U_0)}} dx + e^{-\frac{d^2}{\mu\tau\cdot(U-U_0)}}$$

$$\mu_e\tau_e = 1.1 \cdot 10^{-4}\ [cm^2/V]$$

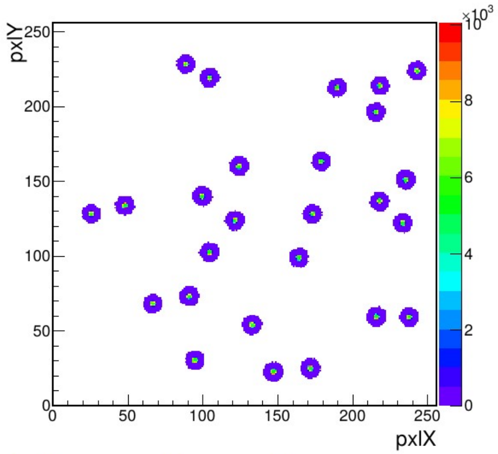


Irradiation by heavy ions

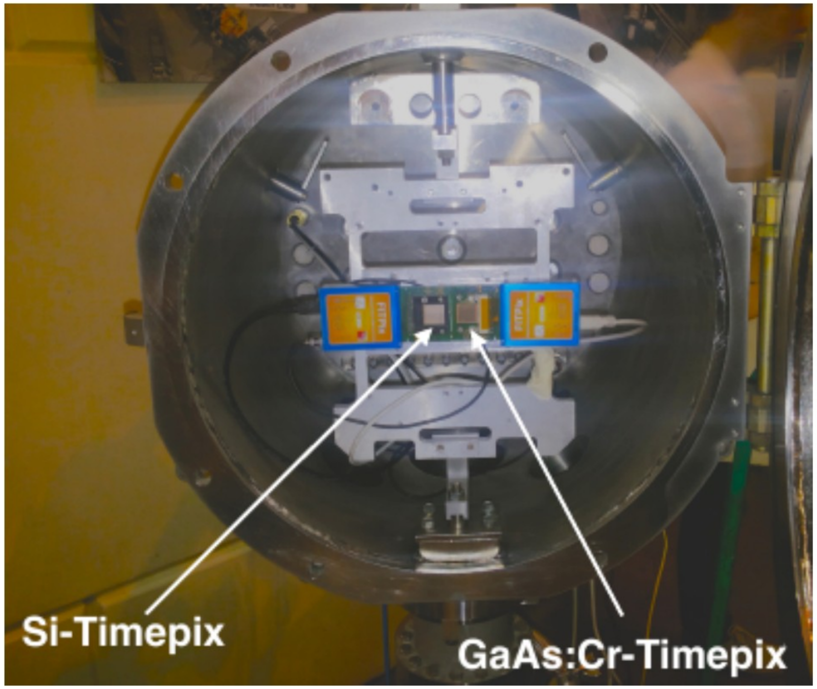
Several irradiation test-beams of GaAs:Cr and Si detectors with different ions were carried out using the JINR cyclotron U-400M:

- ^{22}Ne
- ^{40}Ar
- ^{84}Kr
- ^{132}Xe

Kinetic energy from 30 MeV to 2.9 GeV.



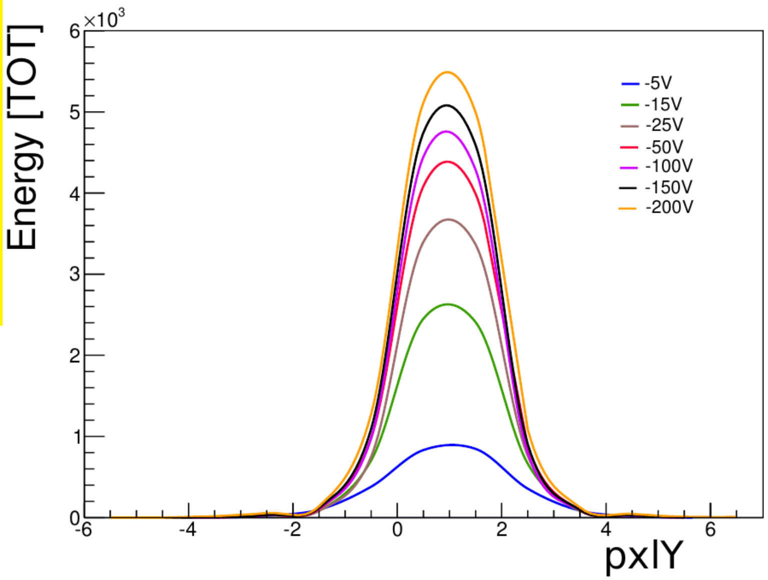
Typical frame from ions



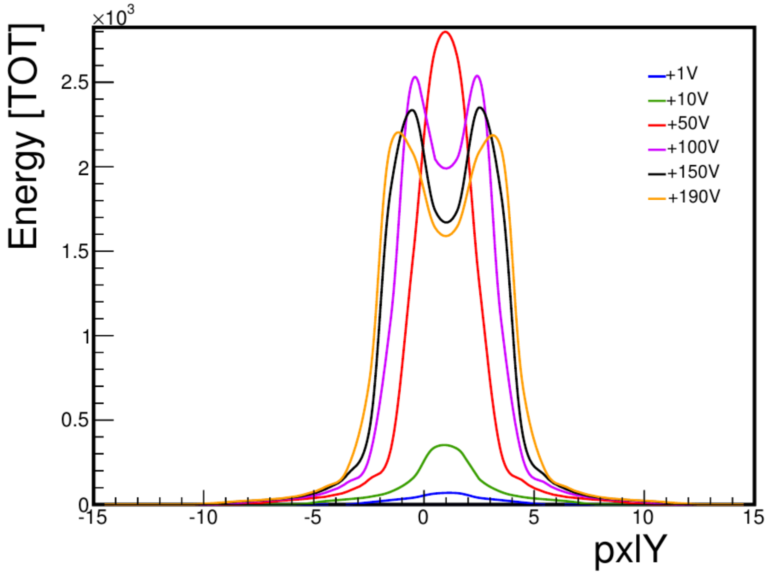
Irradiation by heavy ions

Profile of cluster

77 MeV



2378 MeV



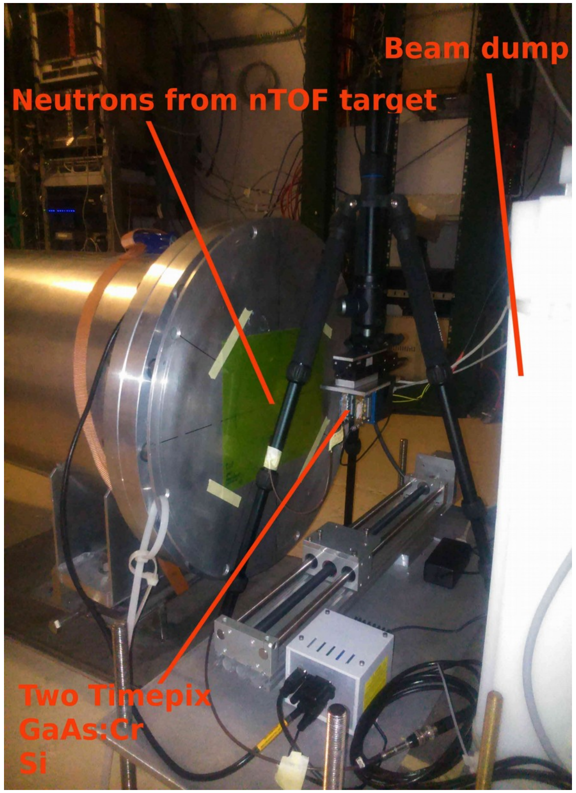
e^- collection mode

h^+ collection mode

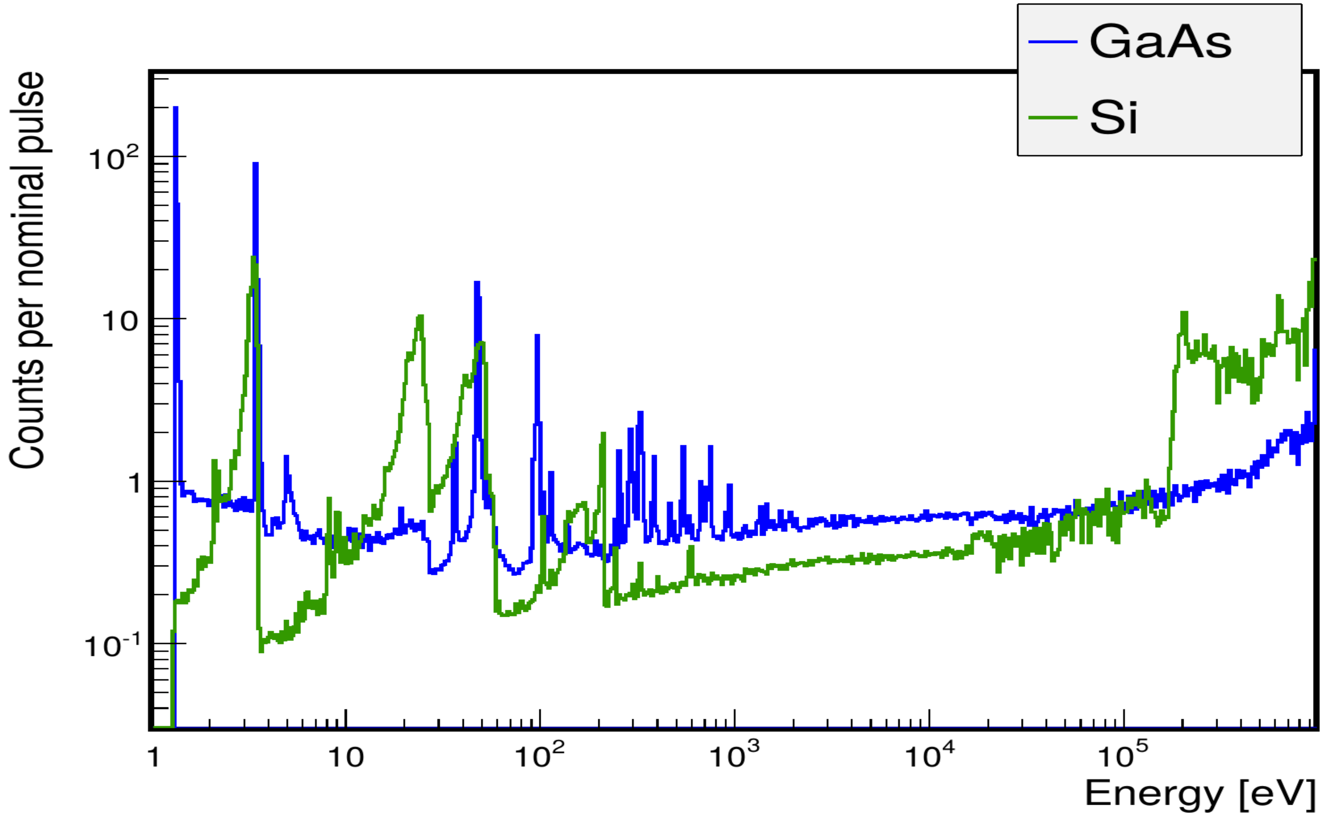
- More detailed information: S.M. Abu Al Azm et.al. Response of Timepix Detector with GaAs:Cr and Si Sensor to Heavy Ions. Physics of Particles and Nuclei Letters, 2016, Vol. 13, No. 3, pp. 363–369.

Irradiation by neutrons

n-TOF @ CERN
October 2015

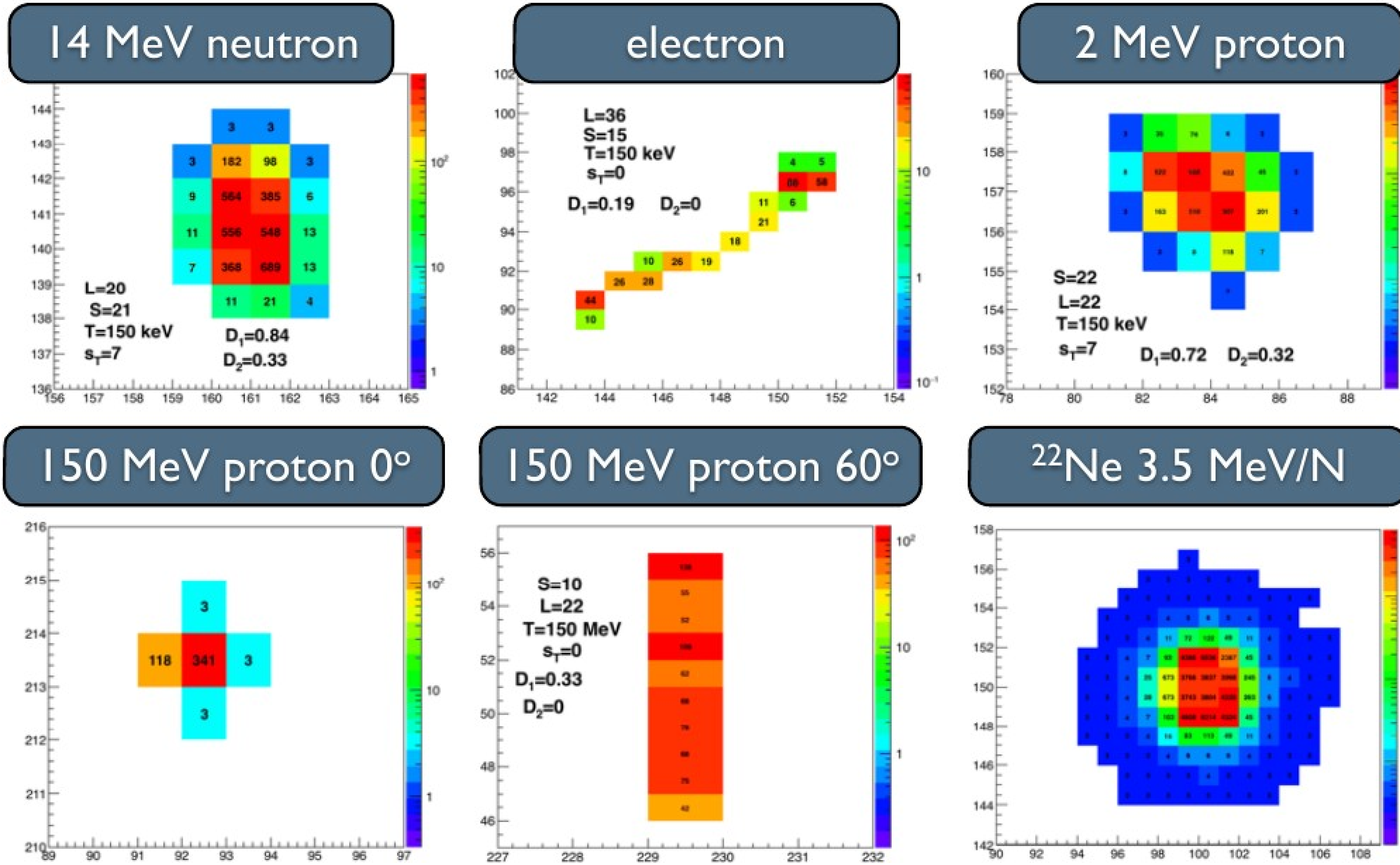


Neutron spectrum measured by Timeix detector

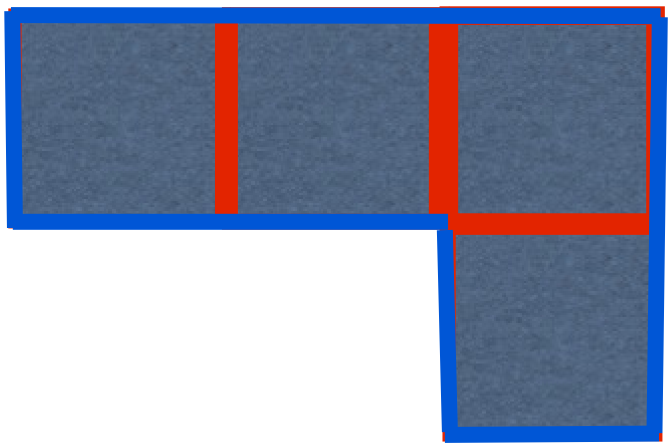


Nominal pulse = 7×10^{12} protons

Particle identification?



Discriminator 1



$$D_1 = 16\ S/L^2$$

$$0 < D_1 \leq 1$$

S=4 - square of the cluster

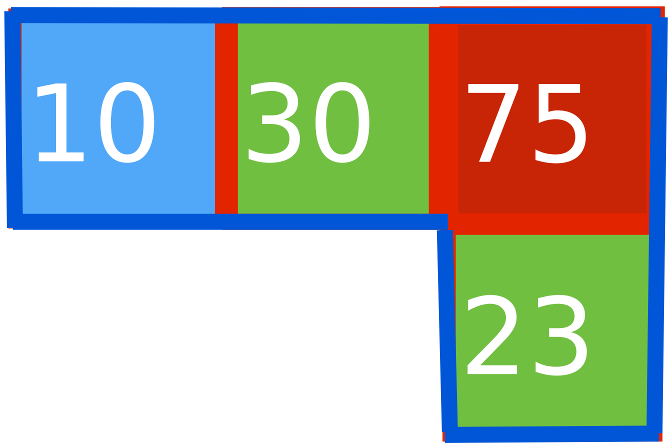
L=10 - perimeter

D_1=0.64

D_1 characterises the shape of the cluster.

In pixel geometry D_1 is maximal for square: D_1=1

Discriminator 2



$$D_2 = s_T/S$$

$$0 \leq D_2 \leq 1$$

S=4 - square of the cluster

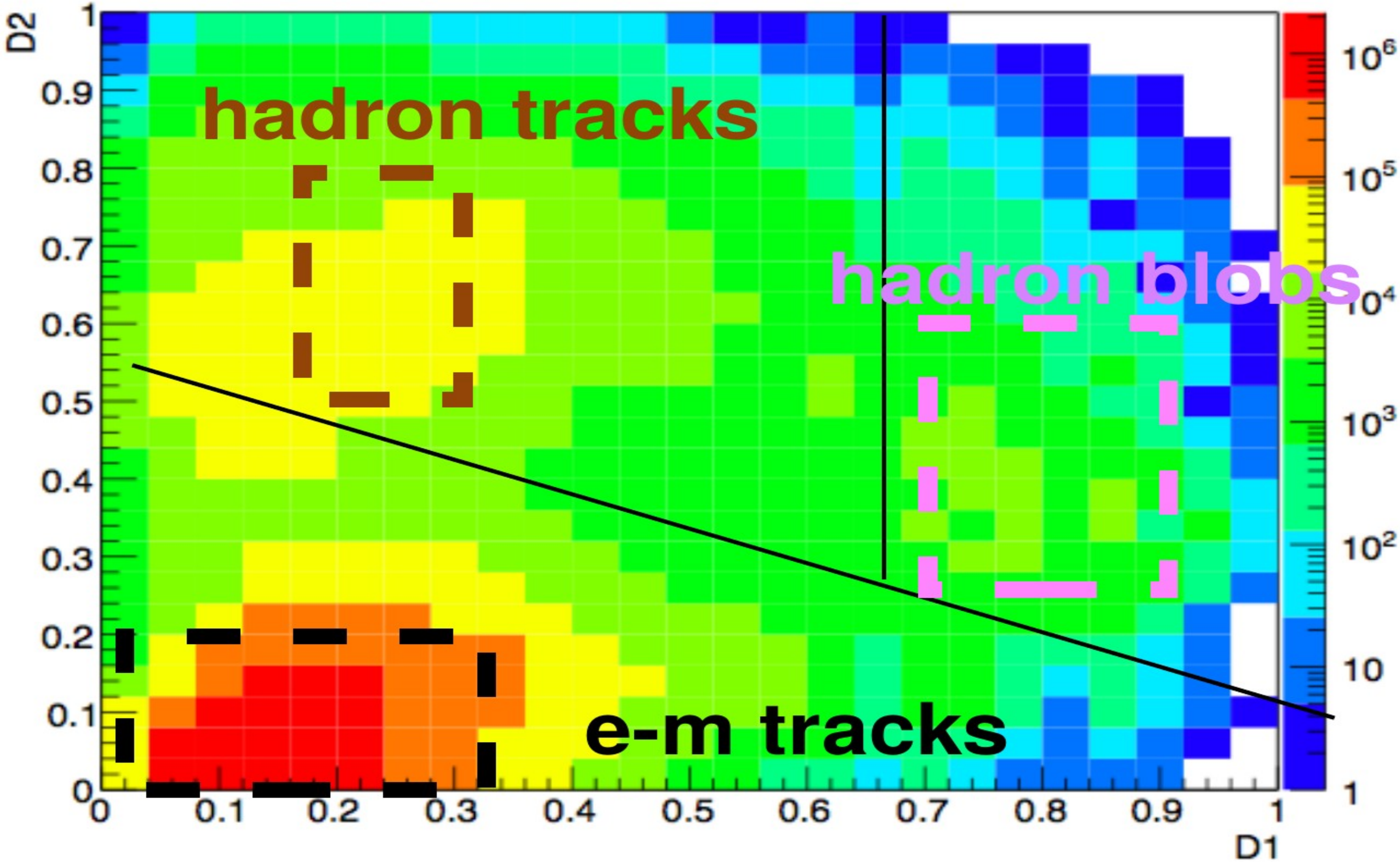
T=20 - threshold

s_T=3 - square of the cluster above the threshold T

D_2=0.75

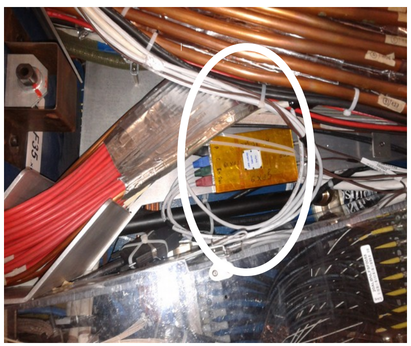
D_2 characterises energy distribution over the pixels

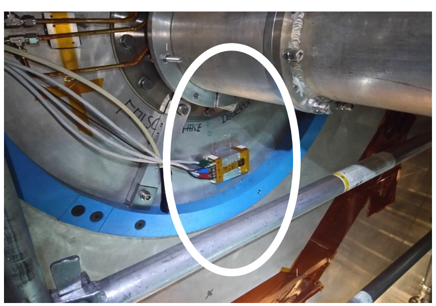
Particle identification

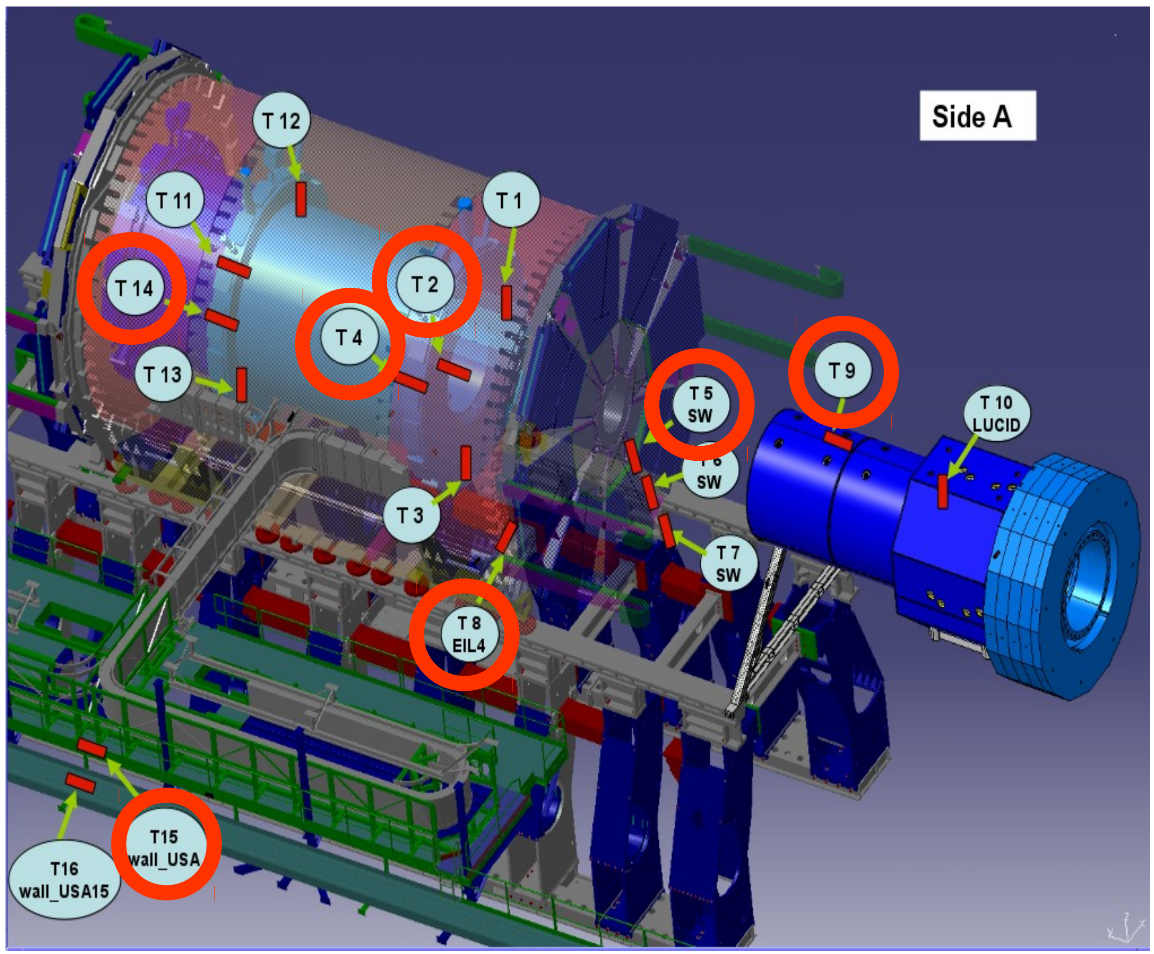


ATLAS GaAsPix

15 GasAs:Cr based Timepix detectors were installed in the ATLAS pit in 2016-2017 to monitor the radiation background

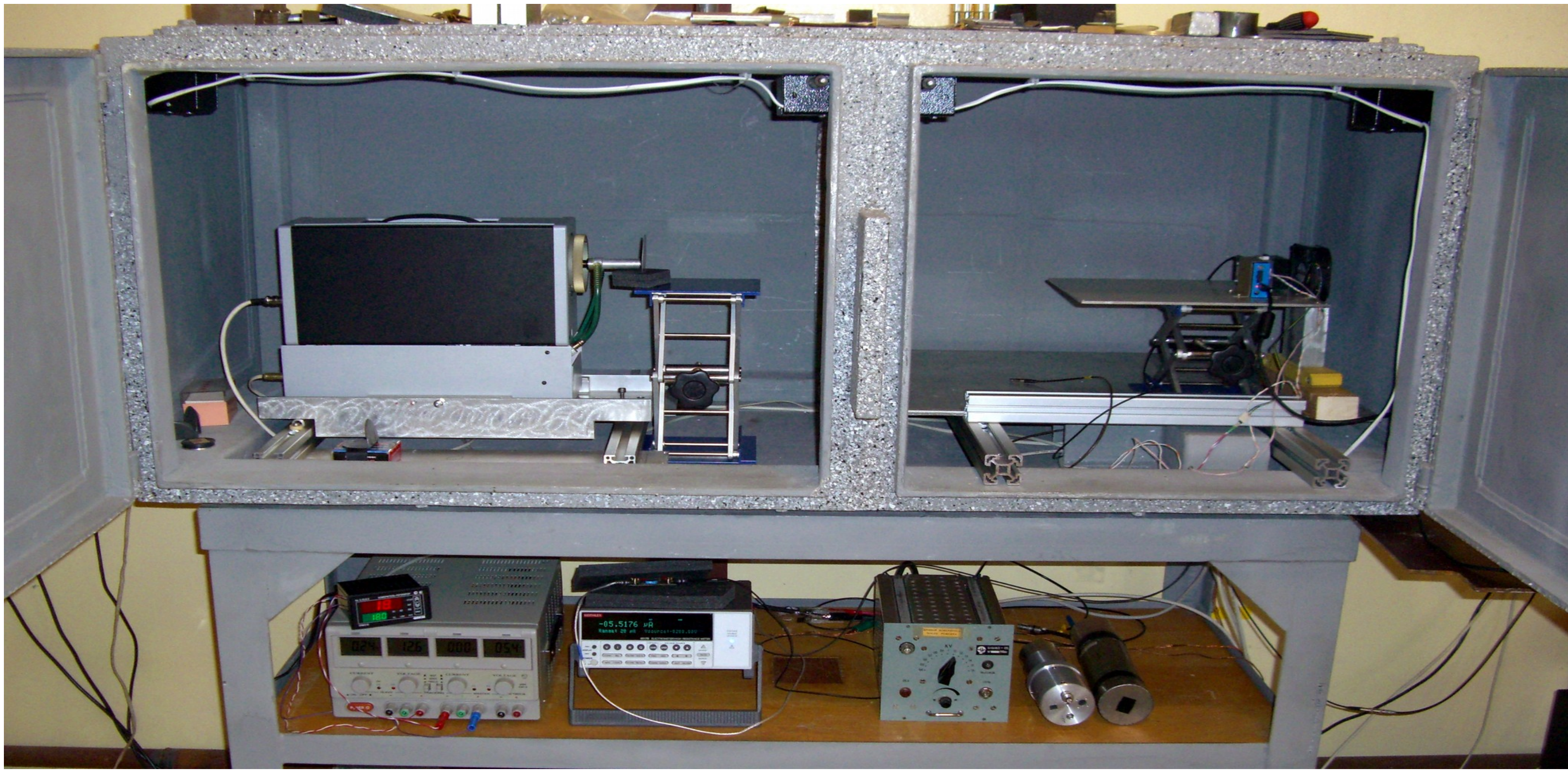






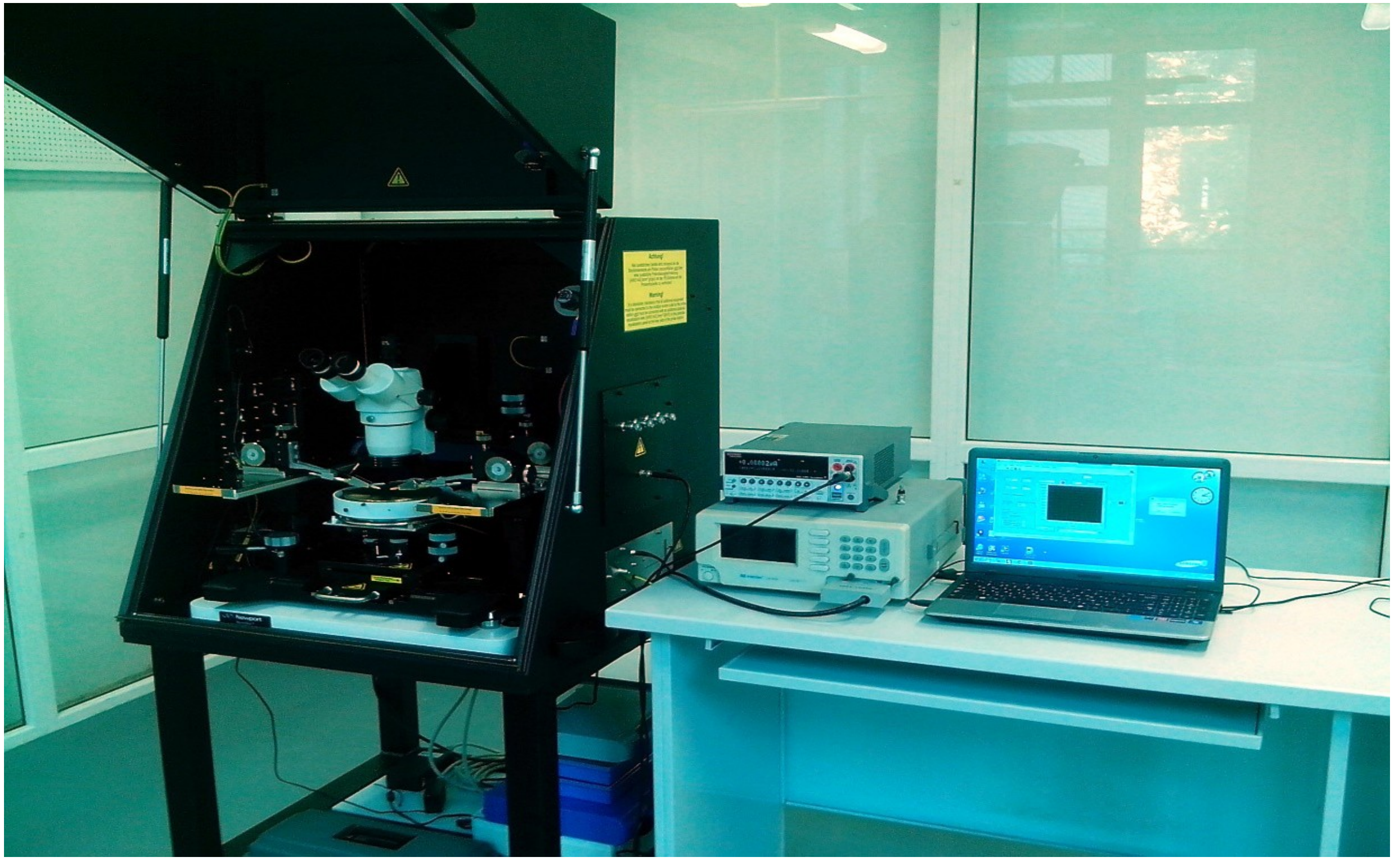
Infrastructure

X-ray facility 'Kalan'



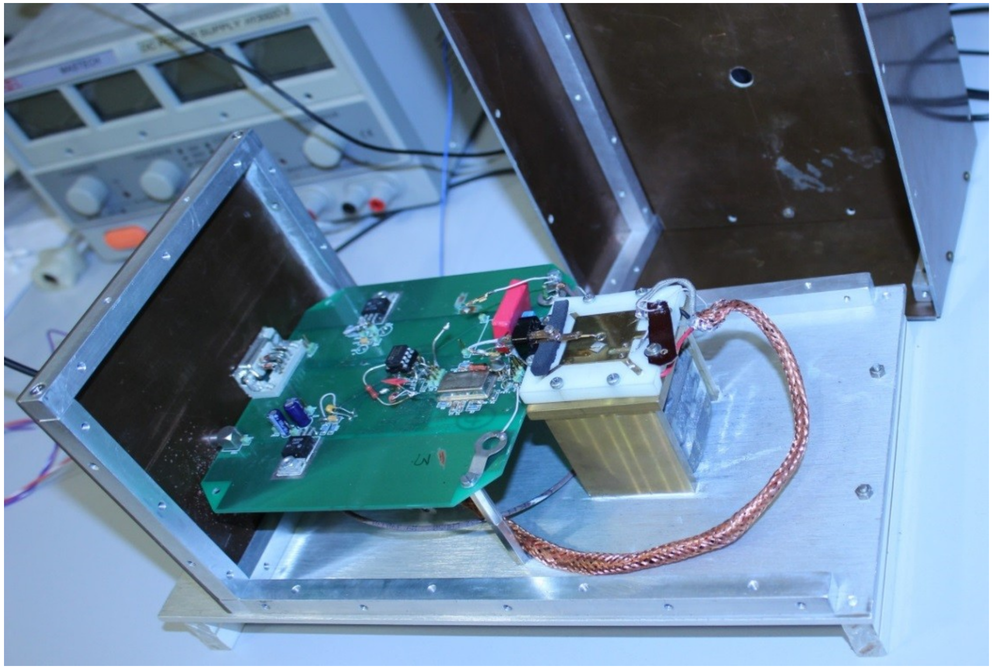
X-ray source SourceRay SB120:
Focal spot ~70 um
X-ray energy up to 120 keV

Probe station Cascade Microtech EPS150TESLA



I-V measurements (V up to 1 kV, I range 0.1 nA — 100 mA, precision <=5%)
C-V measurements
Probe size 5 um x 5 um

CCE meter

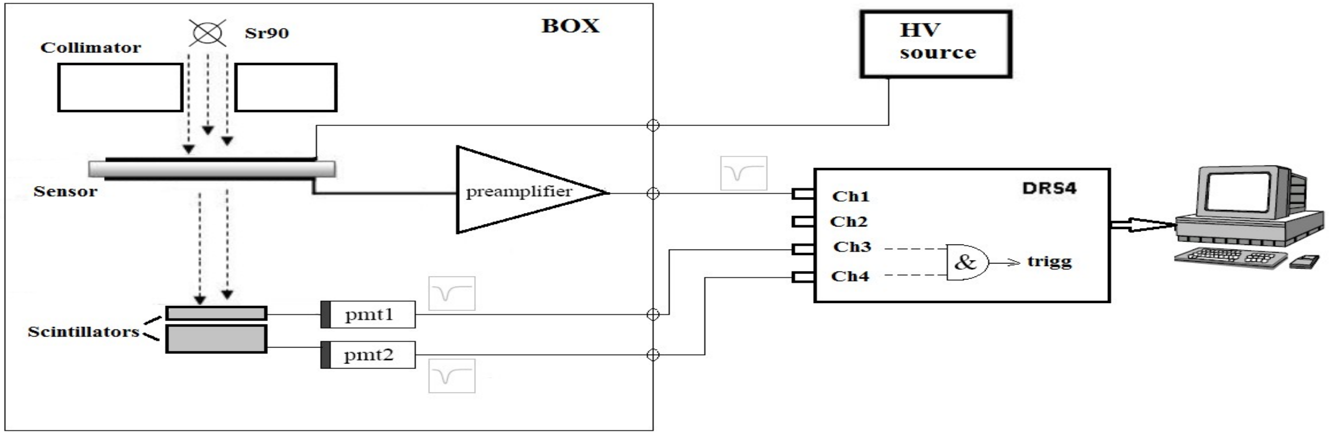


Capable to measure CCE down to 1%

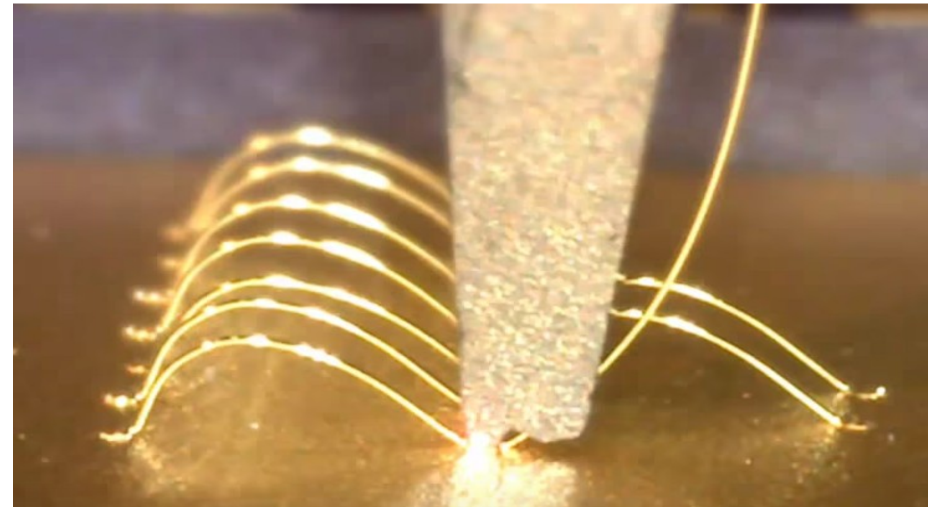
CCE measurement ~ 15 min

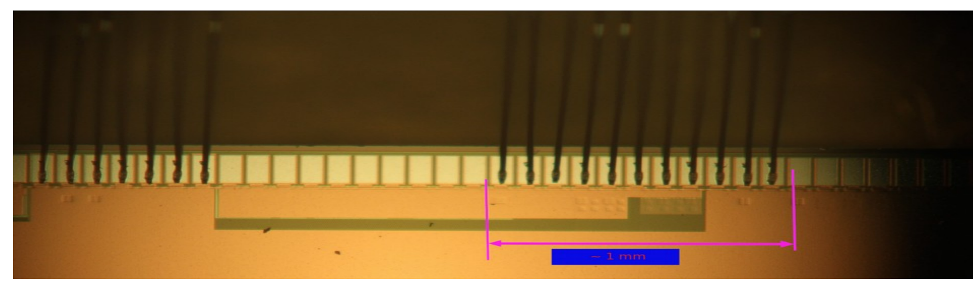
I-V measurement ~ 10 min

Mounting the sample to a PCB is not necessary



Ultrasound wire bonder





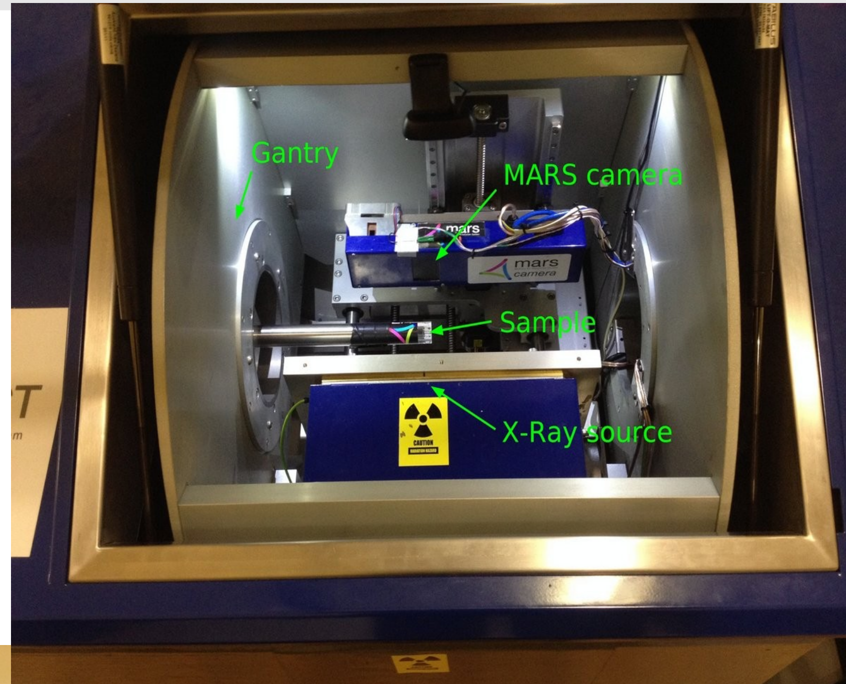
TPT HB16
Programmable
Gold, aluminium, silver & copper wire
Wire sizes from 17μm to 75μm
Wedge, ball & ribbon bonding

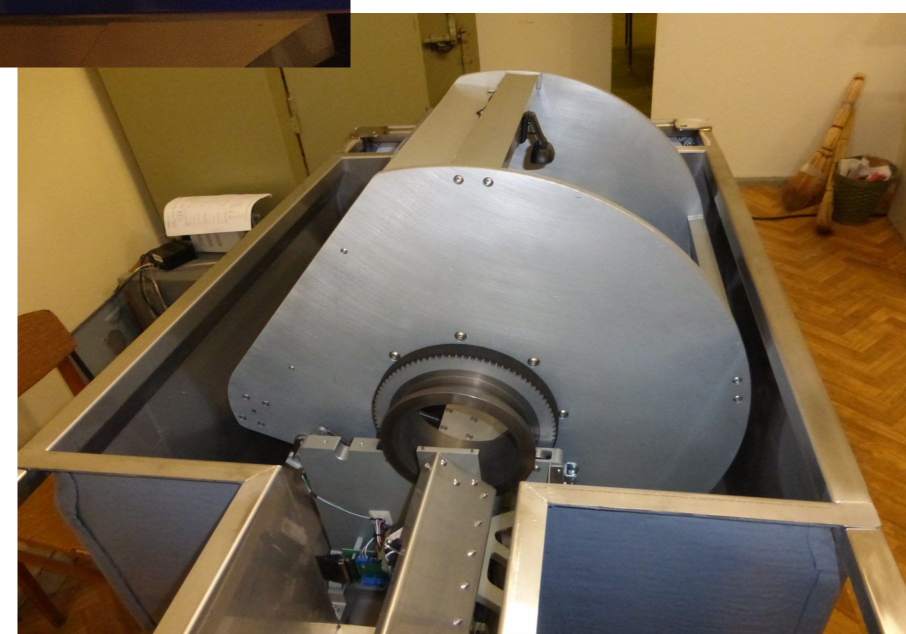
microCT

MARS-CT

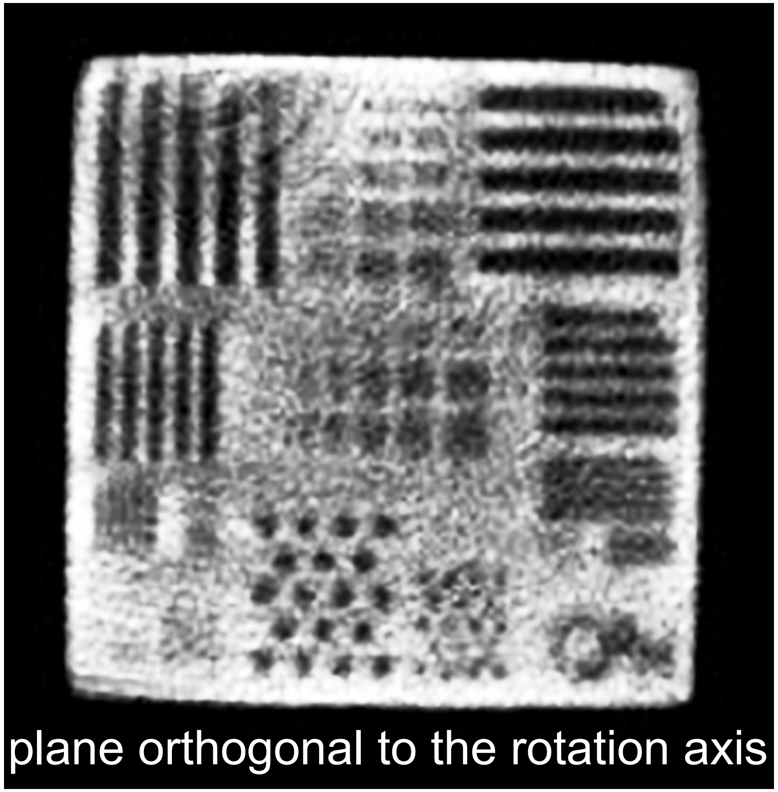
- Fully-functional microCT scanner equipped with GaAs:Cr Medipix detectors
- X-ray energy up to 120 keV
- Current up to 350 uA
- Sample size up to Ø 10 cm X 30 cm
- The sample is immovable
- Geometrical magnification up to 1.8 times (big samples) or up to 4 times (small samples)

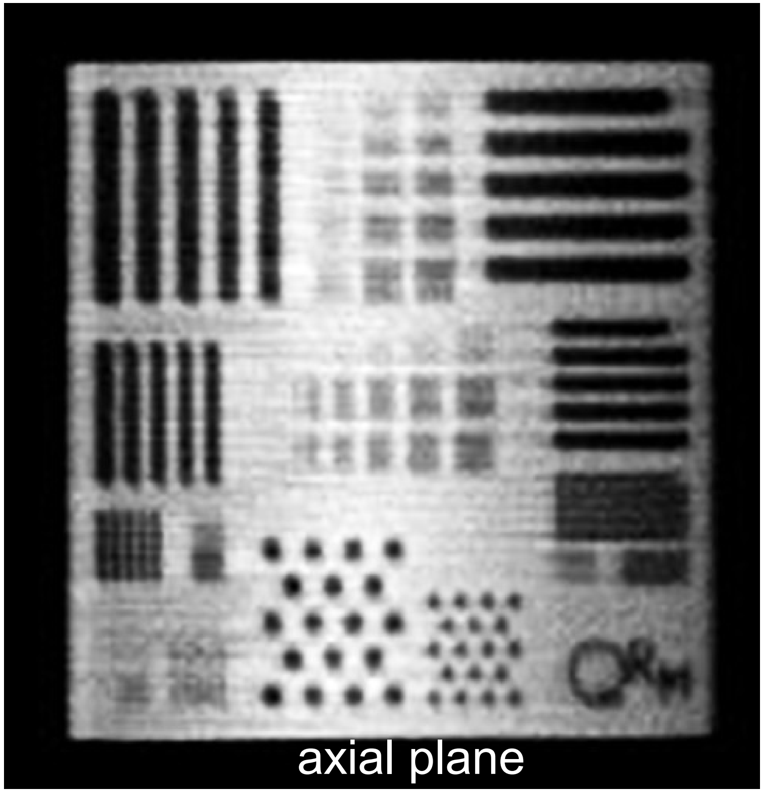
Manufactured by MARS Bioimaging Ltd., New Zealand

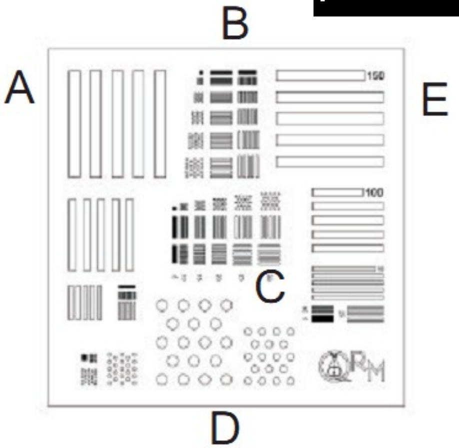

Gantry
MARS camera
Sample
X-Ray source



Spatial resolution



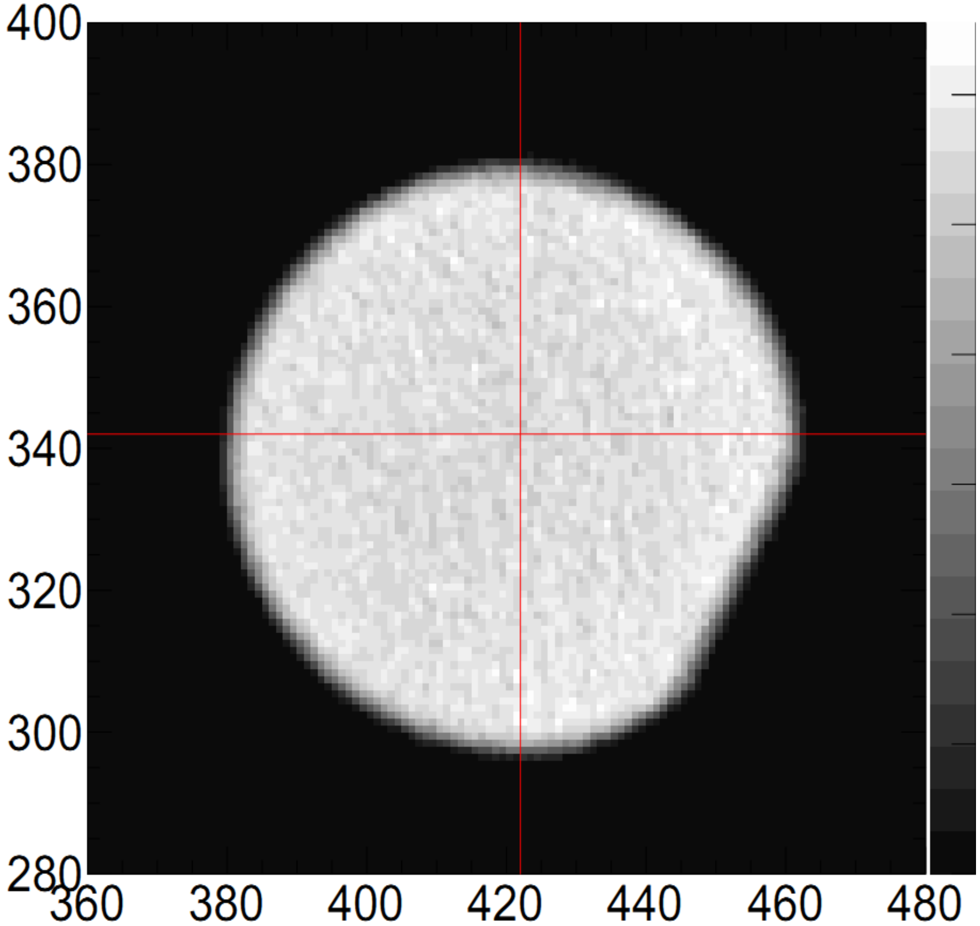


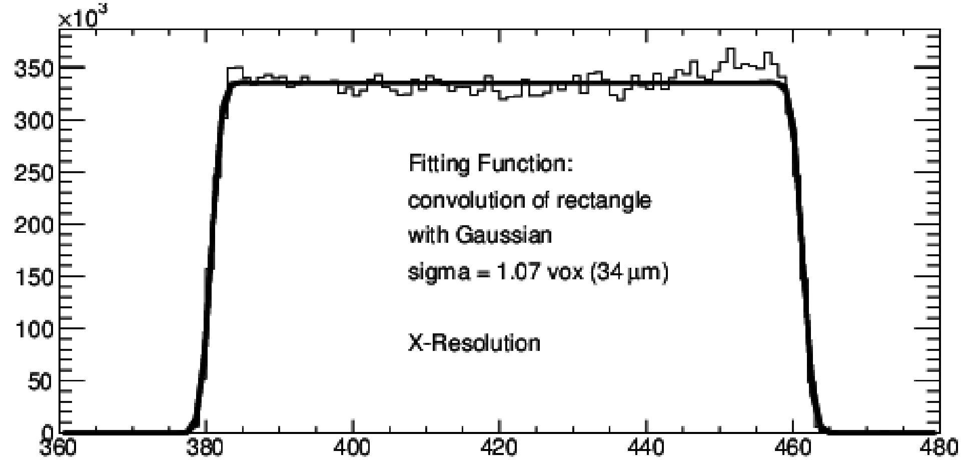


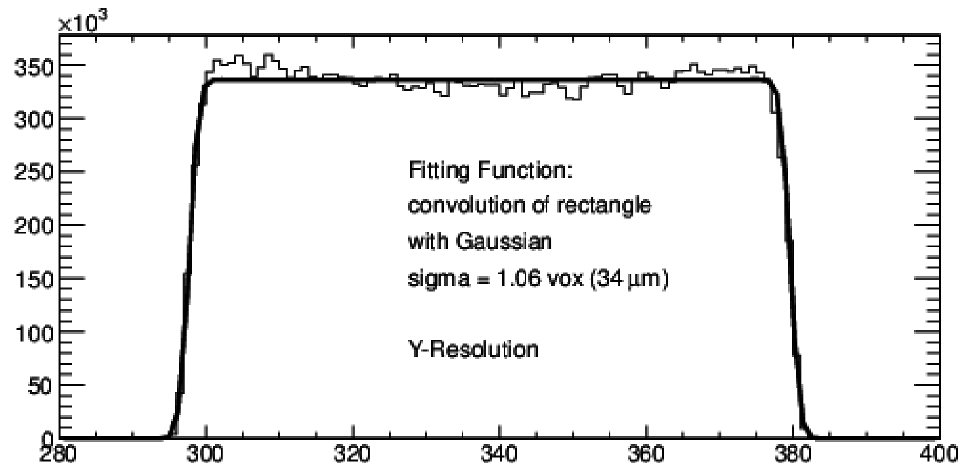
Block	linewidth (µm)	linepairs per pattern	points (µm)	points per pattern
A	5, 10, 25, 50, 100, 150	5		
B	5, 10, 15, 20, 25, 30	5	5, 10, 15, 20, 25, 30	18
C	5, 10, 15, 20, 25, 30	5	5, 10, 15, 20, 25, 30	18
D			5, 10, 25, 50, 100, 150	18
E	5, 10, 25, 50, 100, 150	5		

Spatial resolution

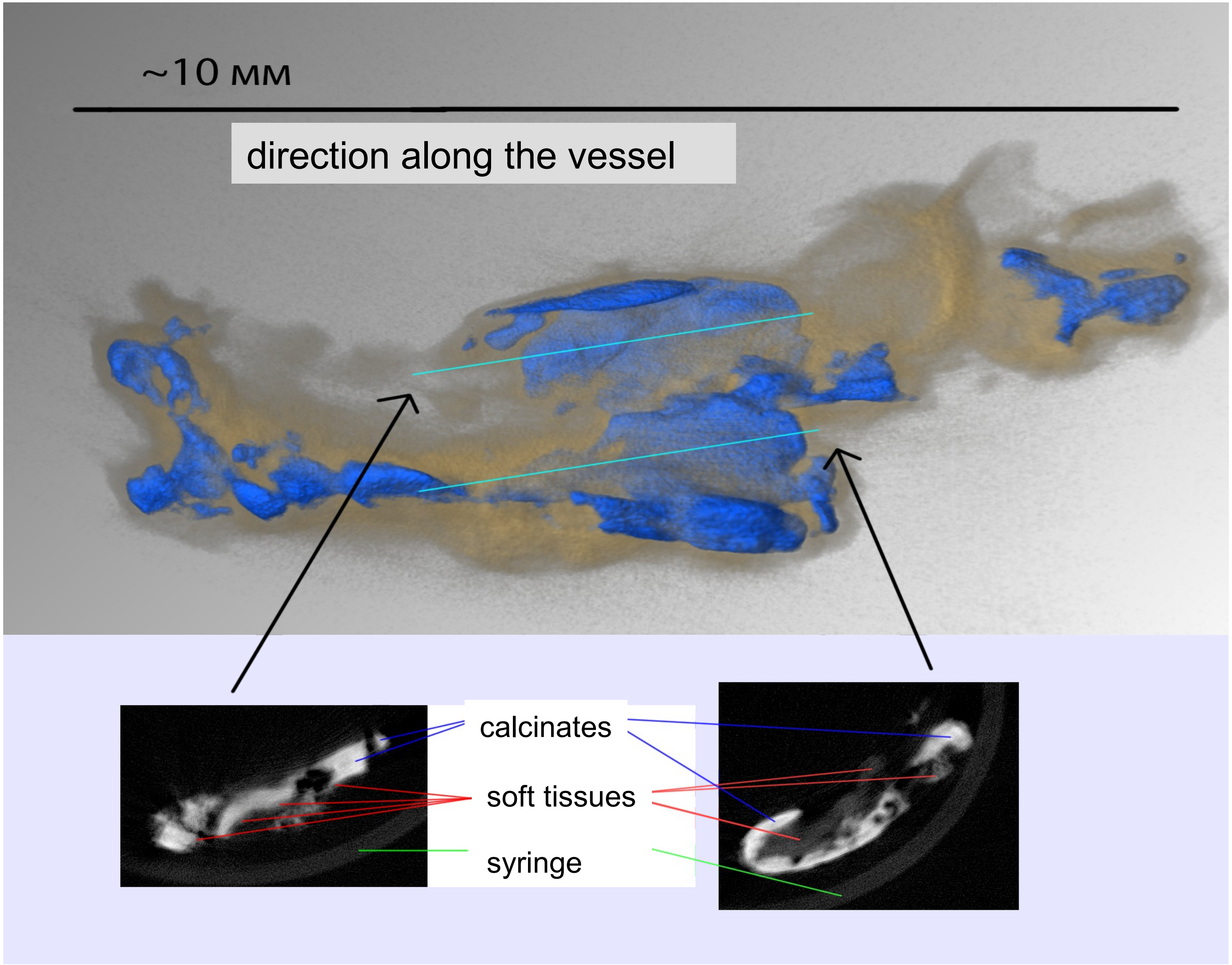
2.7 mm Al wire



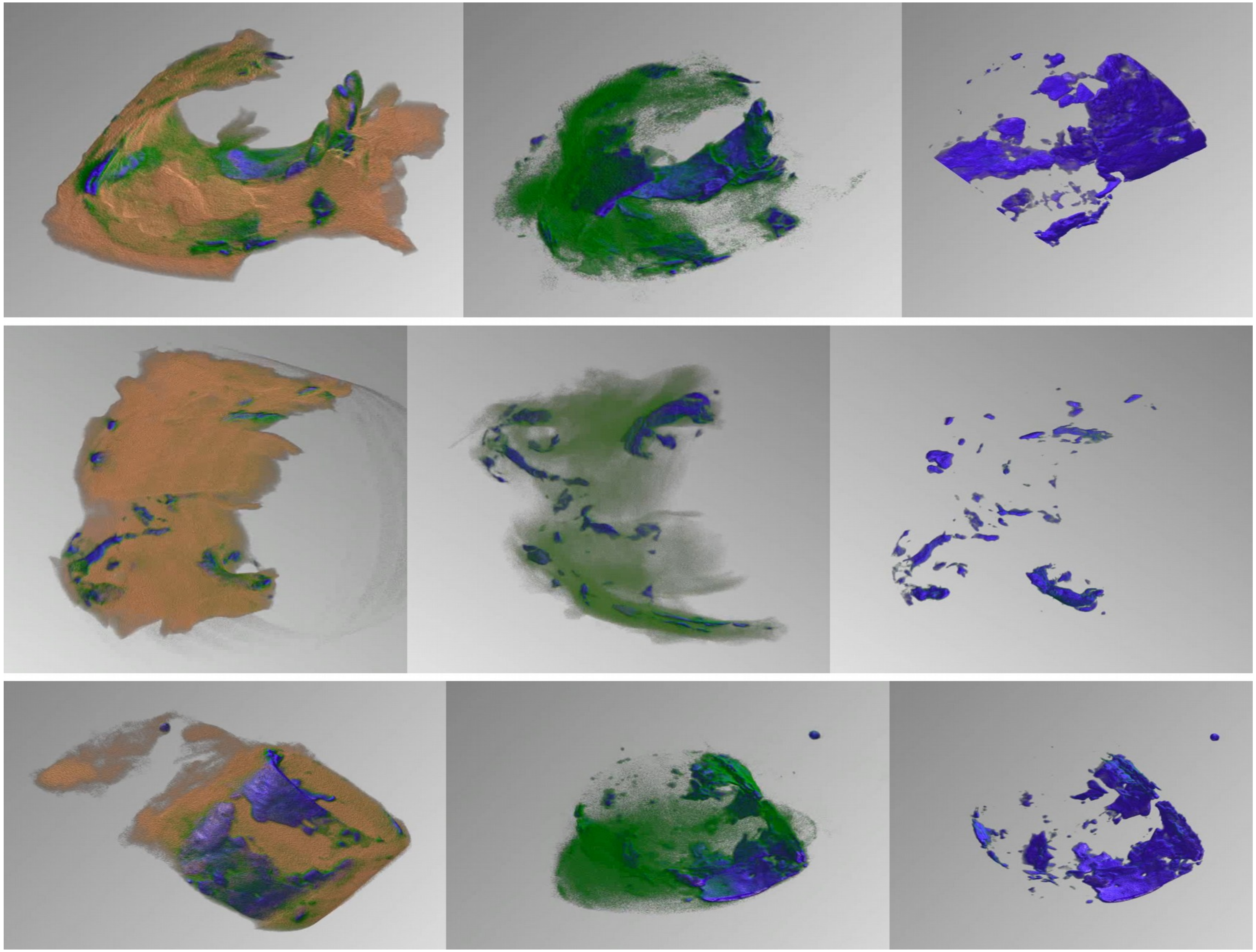




Atherosclerotic plaque

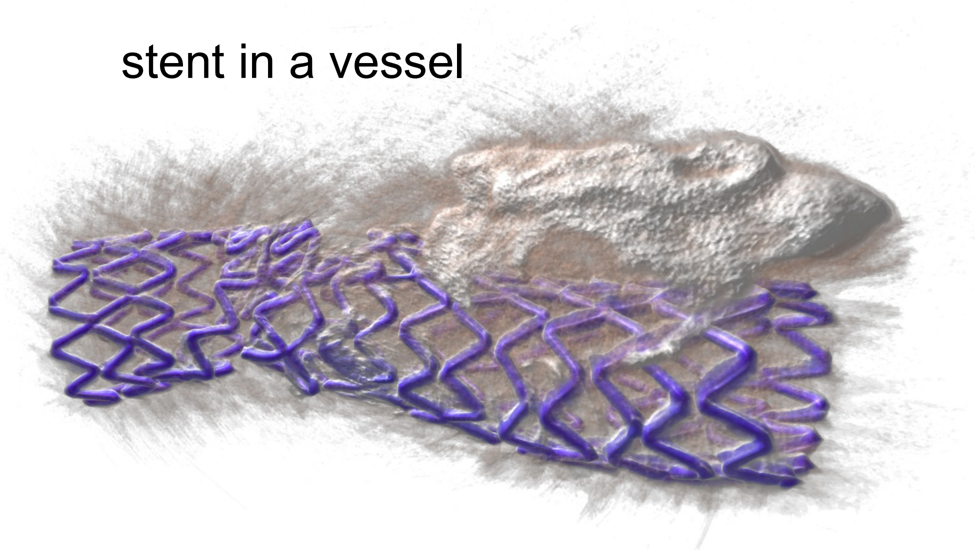


Sample of an abdominal aorta

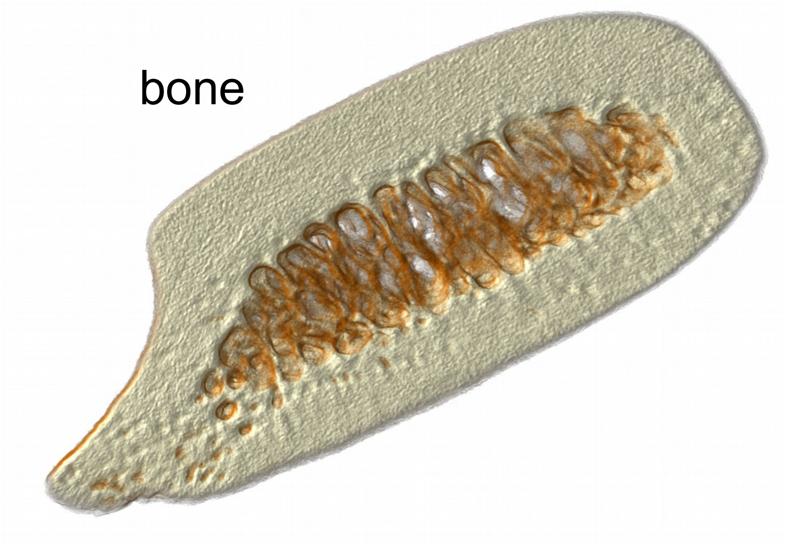


More samples

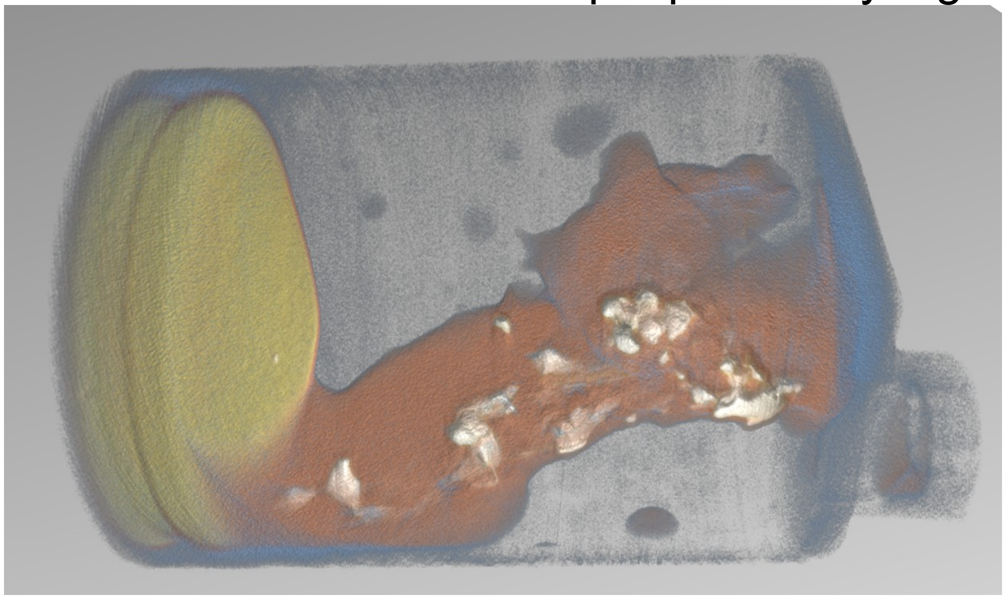
stent in a vessel



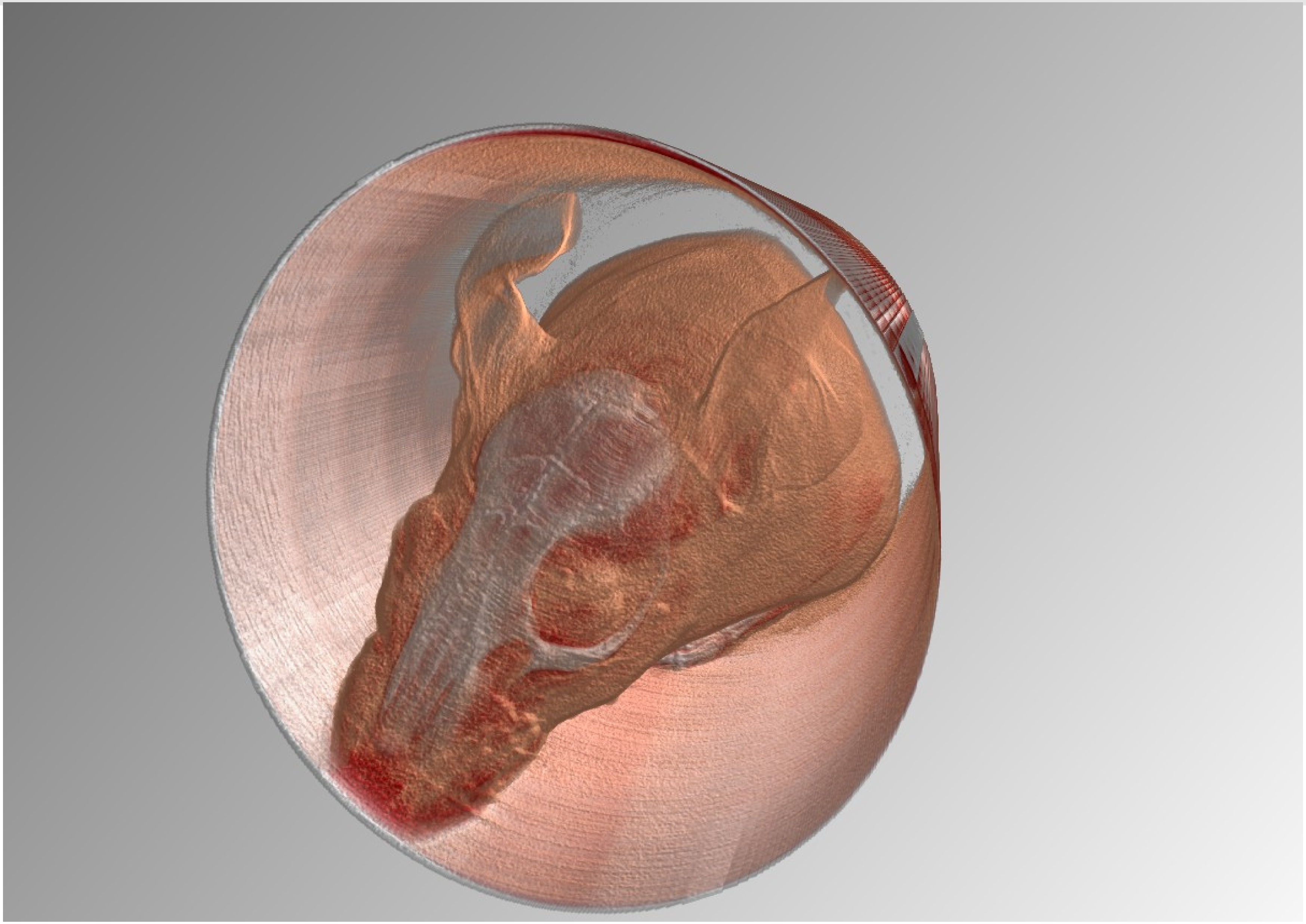
bone



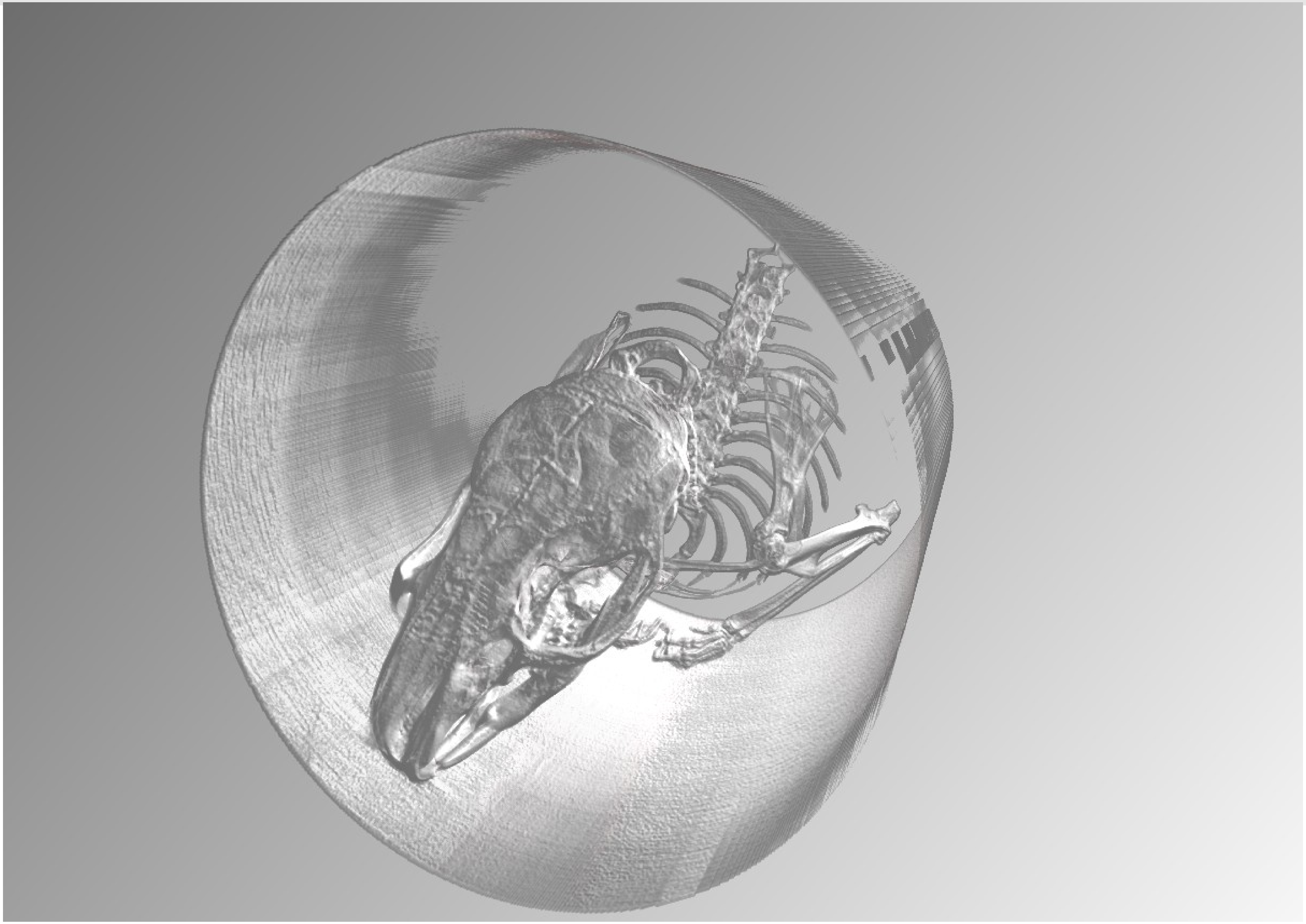
carotid plaque in a syringe



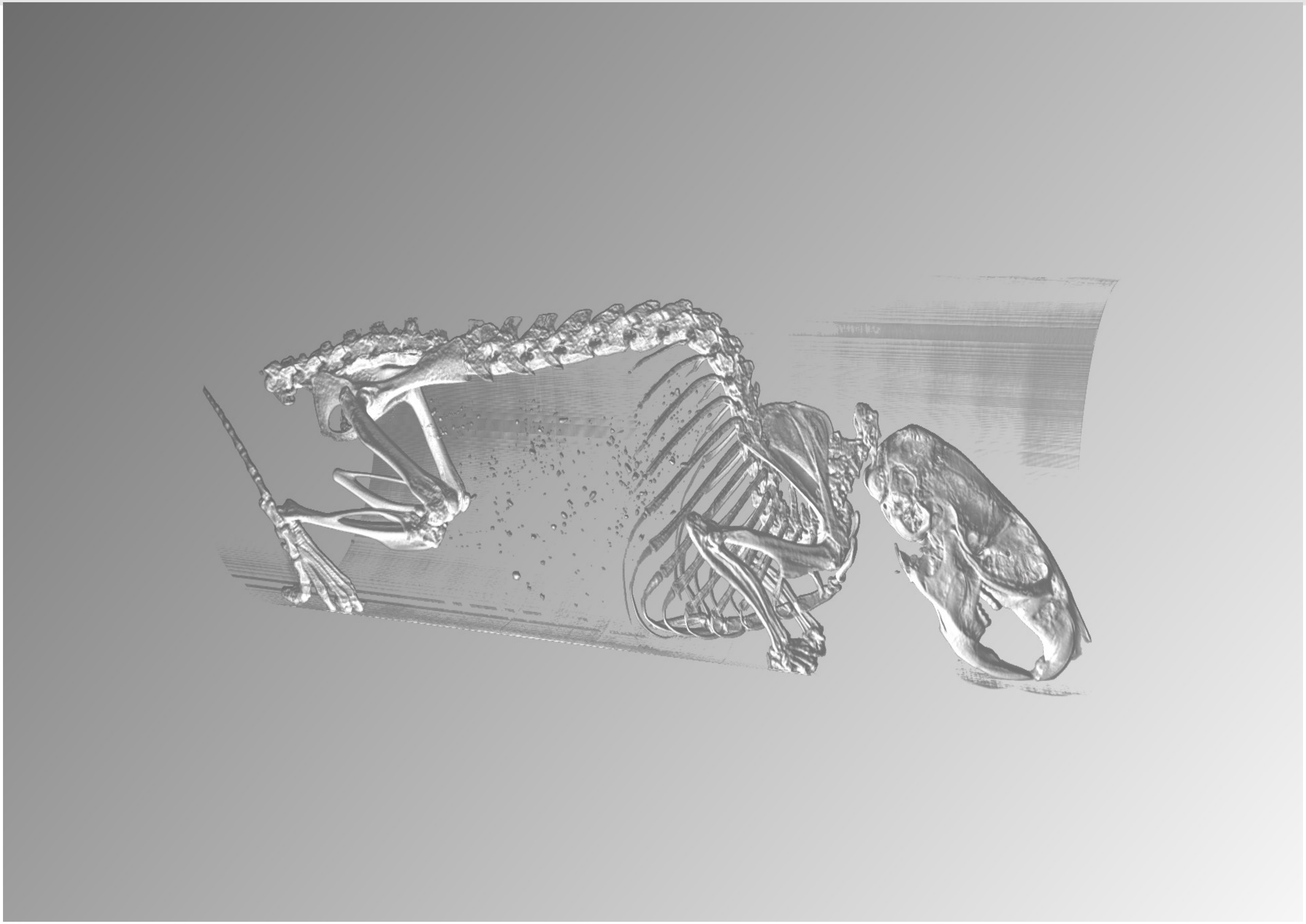
Mouse



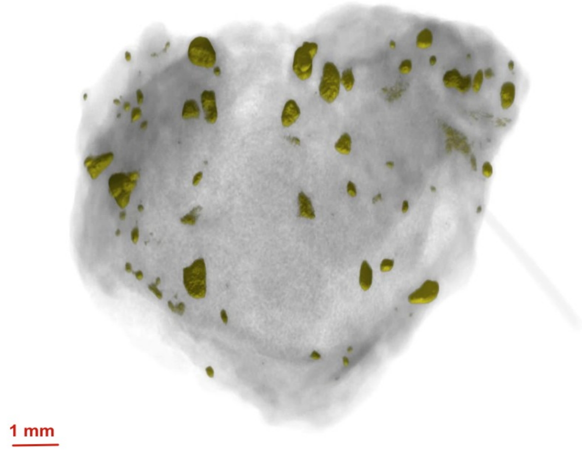
Mouse

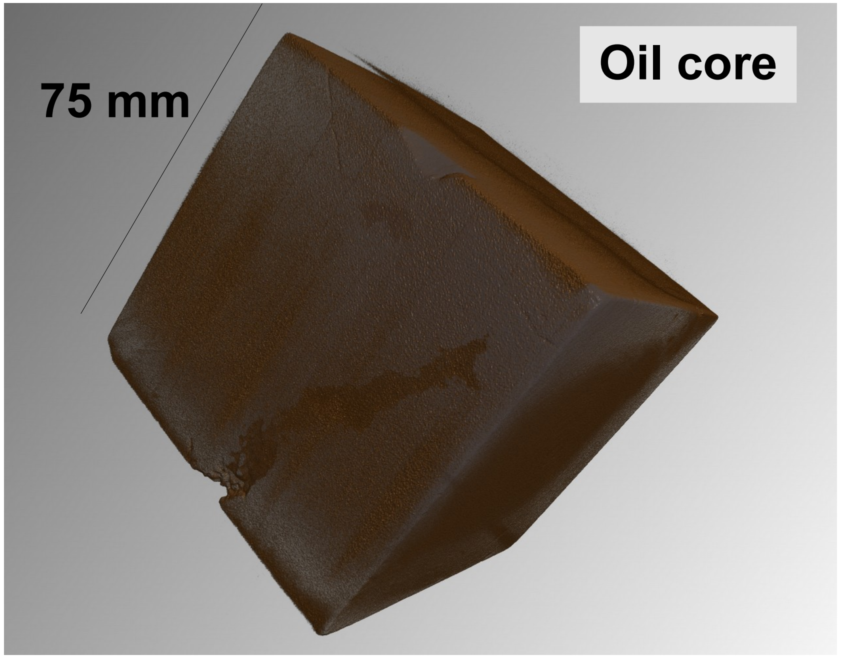


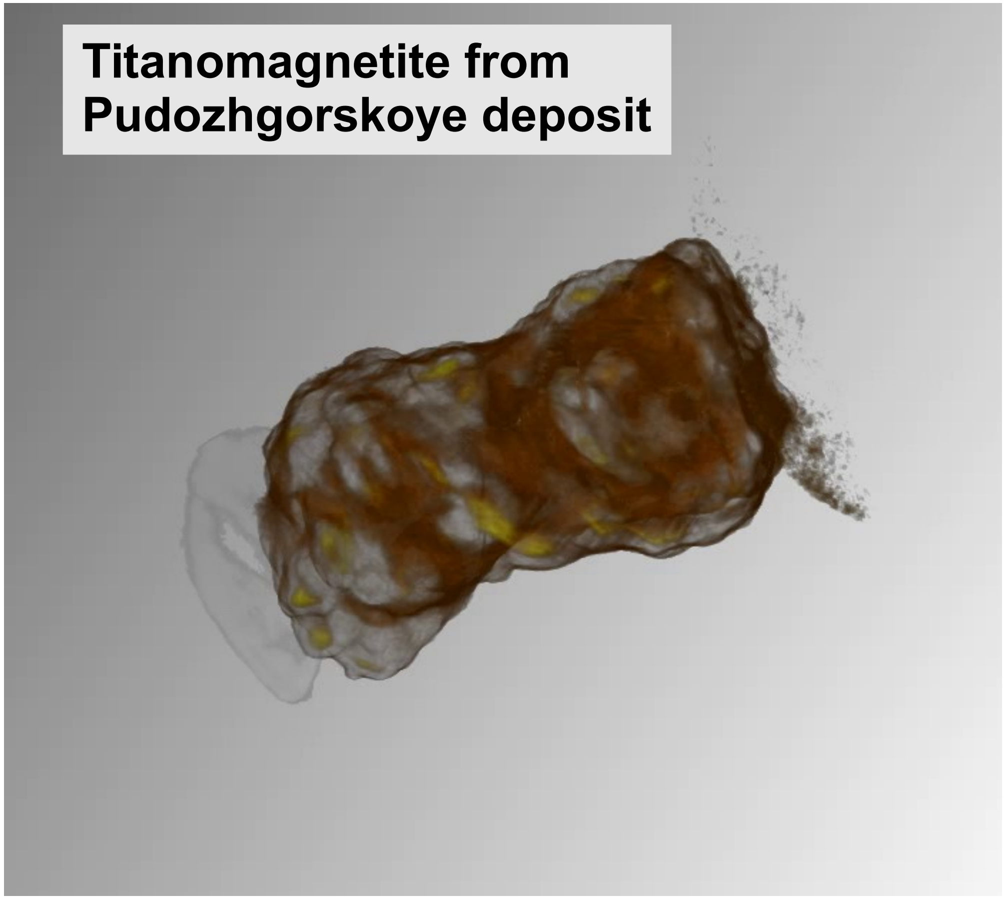
Mouse



Chromites in manganese ore

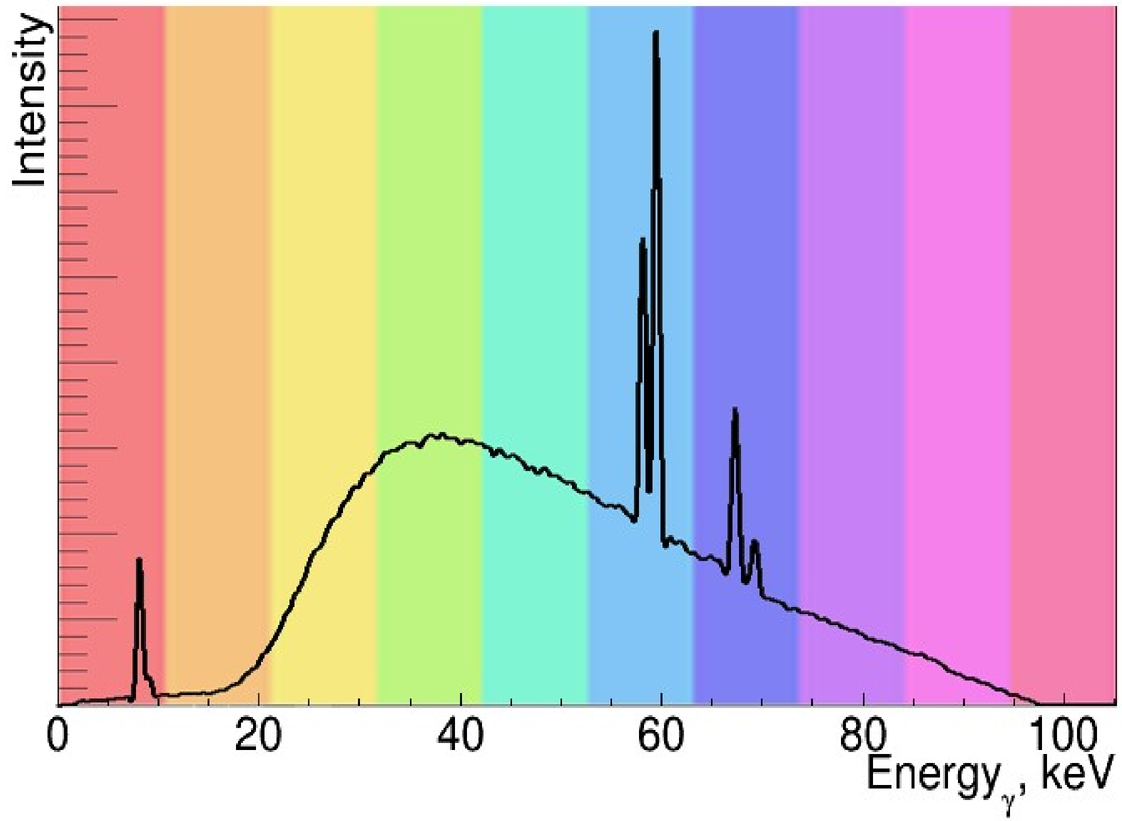


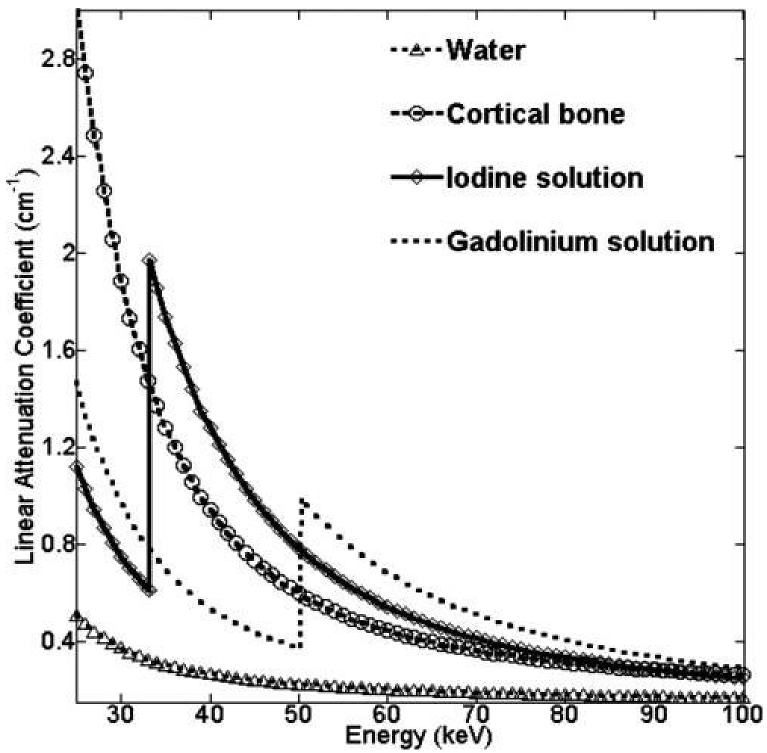




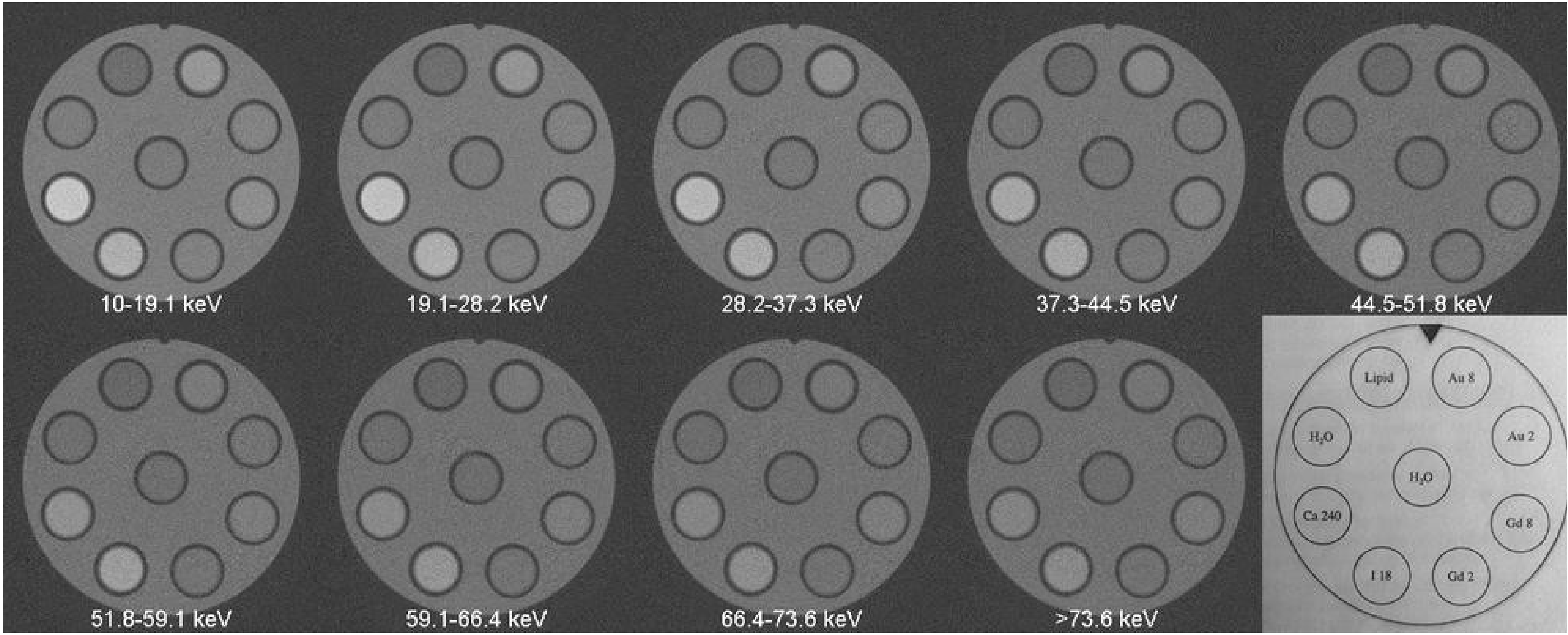
Spectral CT

The idea

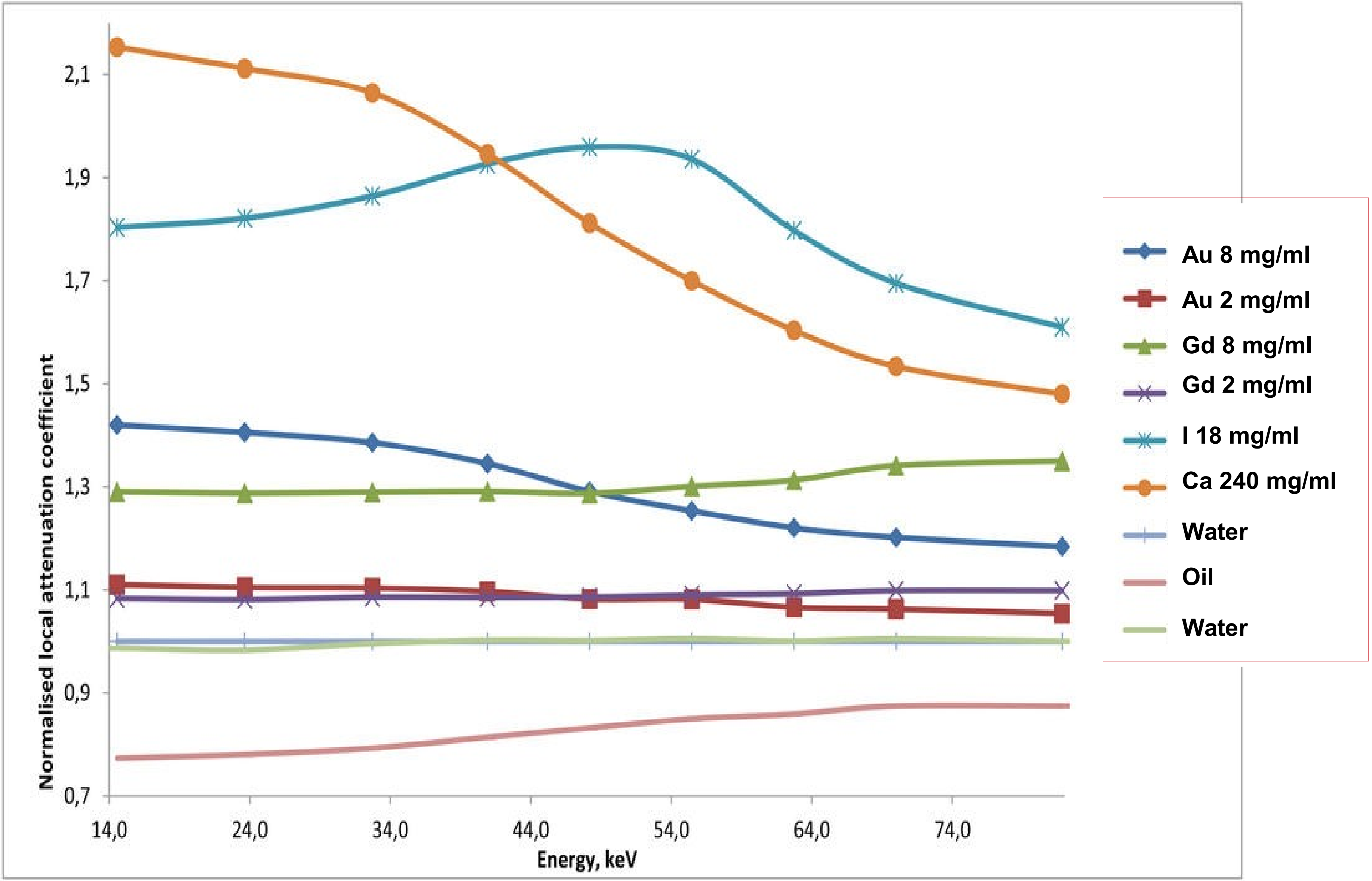

Intensity
0
20
40
60
80
100
Energy$_\gamma$, keV


Water
Cortical bone
Iodine solution
Gadolinium solution
Linear Attenuation Coefficient (cm^{-1})
2.8
2.4
2
1.6
1.2
0.8
0.4
30
40
50
60
70
80
90
100
Energy (keV)

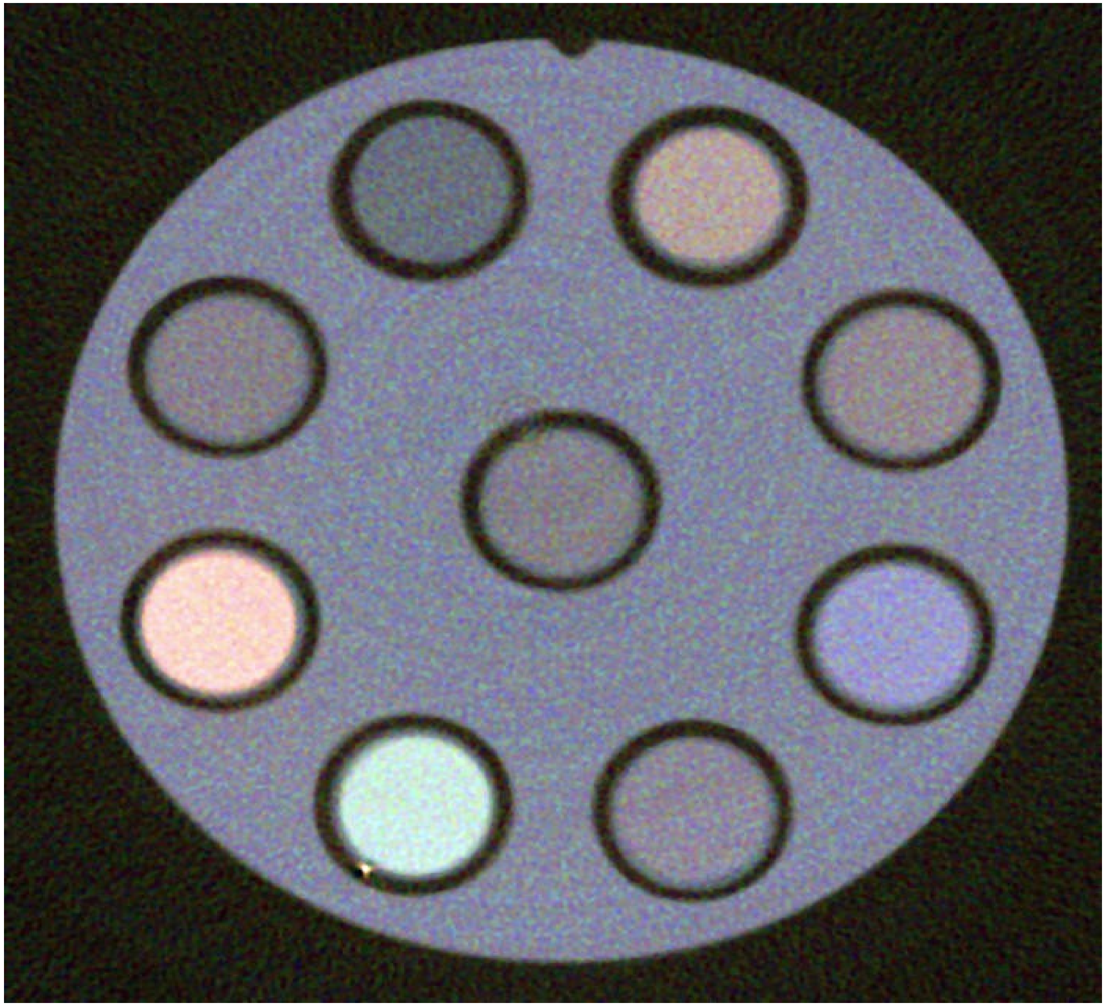
Tests with a standard phantom



Attenuation vs. X-ray Energy (measured)



Colour X-ray CT



Plans for 2018-2020

- Systematic study of response of GaAs:Cr based Medipix detectors to
  - heavy ions
  - neutrons
- Particle identification
- Model of radiation damage in GaAs:Cr → way to increase the radiation hardness?
- Spectral CT and further applications of GaAs:Cr based microCT in medicine and other fields
- Development of the relevant research infrastructure at LNP
- Preparation to develop our own Medipix4-based detectors