Silicon pixel detectors for the Inner Tracking System of MPD experiment at the NICA collider

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RFBR grant № 18-02-40075

Saint-Petersburg State University

LXX International Conference «NUCLEUS – 2020. Nuclear physics and elementary particle physics. Nuclear physics technologies» , Saint-Petersburg, October 2020

Outline

1. Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

2. New pixel sensors for the Inner Tracking System of MPD experiment: ALICE Pixel Detectors (ALPIDE family)

3. Study of the ALPIDE sensor characteristics at SPbSU

4. Extra Lightweight Detector Support Structures for a New Generation of Vertex Detectors

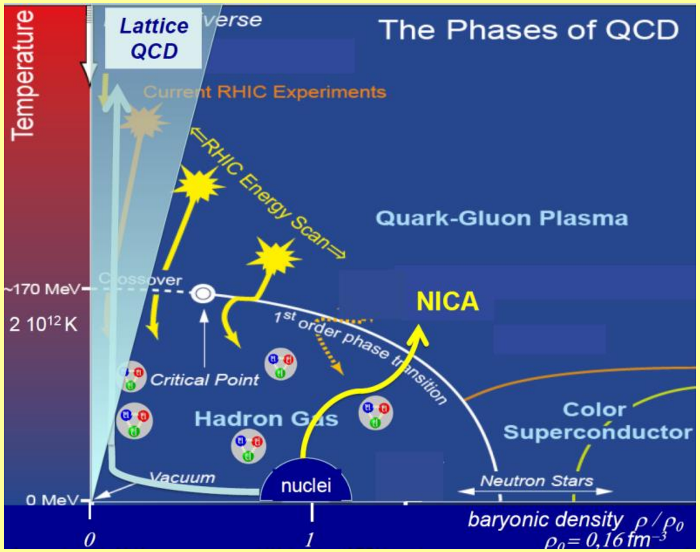
5. Summary

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

Physics motivation

Investigations of the properties of nuclear matter occurred in relativistic heavy-nuclei collisions

Investigations of the processes with heavy flavor hadrons formation



V.Kekelidze, CERN seminar, 14.09.2018

High baryonic density

↓

The studies of the hadron yields containing heavy quarks

↓

An efficient identification of strange and charmed particles in N–N collisions plays a key role in the analysis of possible phase transitions.

↓

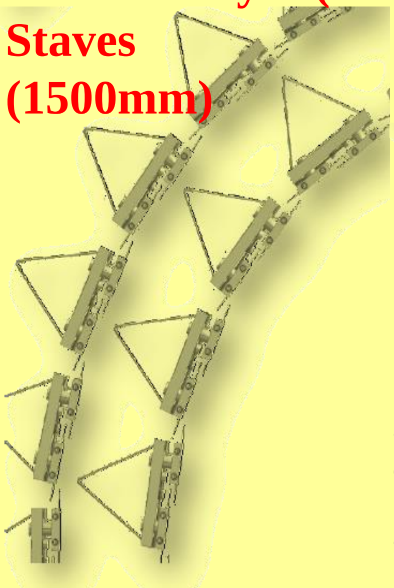
Also at the relatively low NICA energies it is possible to study clusters of dense nuclear matter arisen inside the nuclei

↓

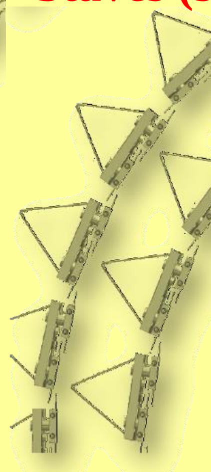
The detector systems are needed to reconstruct the decay vertices of short-lived multi-strange and charmed hadrons, at high pointing resolution

Example: ALICE Inner Tracking System

90 Outer layer (OL) Staves (1500mm)



54 Middle layer (ML) Staves (900mm)

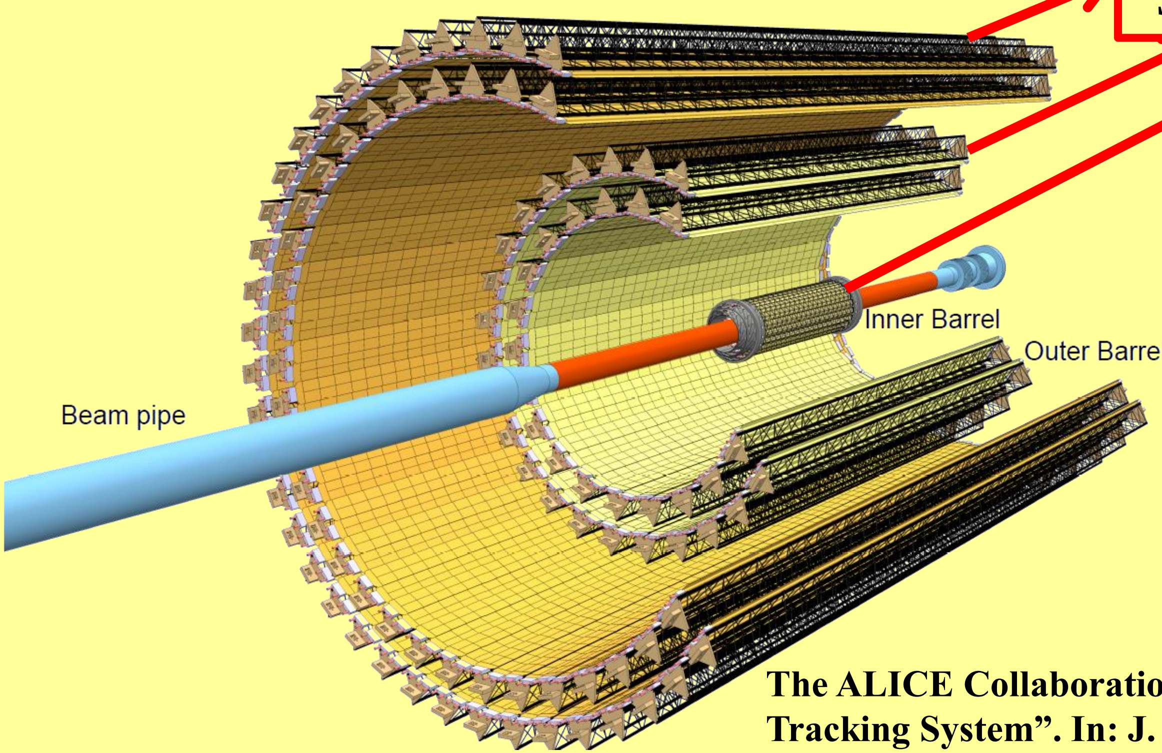


48 Inner layer (IL) Staves (290mm)

STAVES

Total staves:
48 (IL) – Inner Barrel
54(ML) and 90(OL) – Outer Barrel

Stave consists of :
1. **Hybrid Integrated Circuit (HIC)**
2. **Cold plate**
3. **Space frame**



Barrel: 7 layers of Monolithic Active Pixel Sensors (MAPS)

New ITS:

12.5 G pixels

The ALICE Collaboration:"TDR for the Upgrade of the ALICE Inner Tracking System". In: J. Phys. G41 (2014), p. 087002

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

MPD tracking system: TPC + ITS

I stage of the MPD experiment: TPC only

Time projection chamber for multi-purpose detector at NICA, Nucl. Instrum. Methods Phys. Res. A 958 (2020) 162793,

TPC ⟶ accurate reconstruction of particle tracks and their momenta,

+

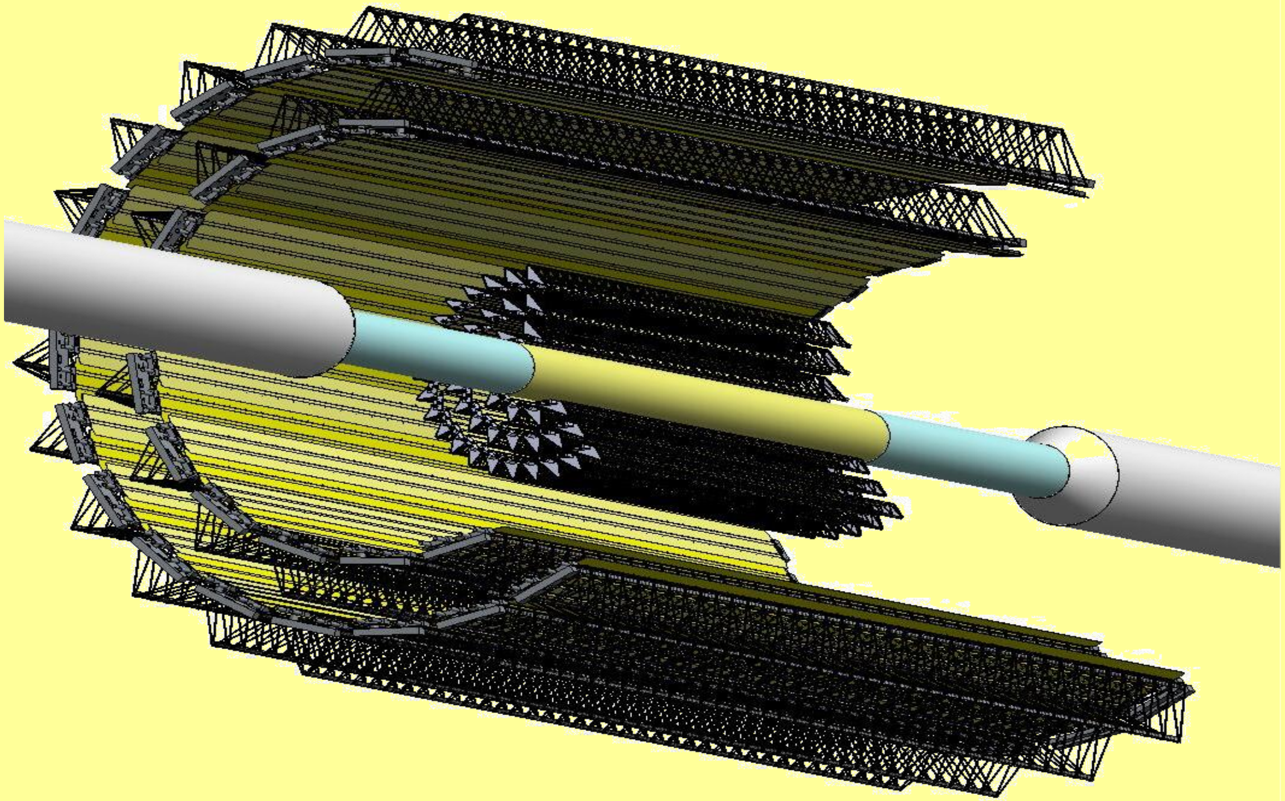
identification of charged particles by measuring their energy losses

II stage of the MPD experiment: TPC + ITS

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

We don't want to reinvent the wheel!

II stage of the MPD experiment



Geometrical model of the MPD vertex detector.

STAVES

12, 22, 32 – Inner Barrel IB

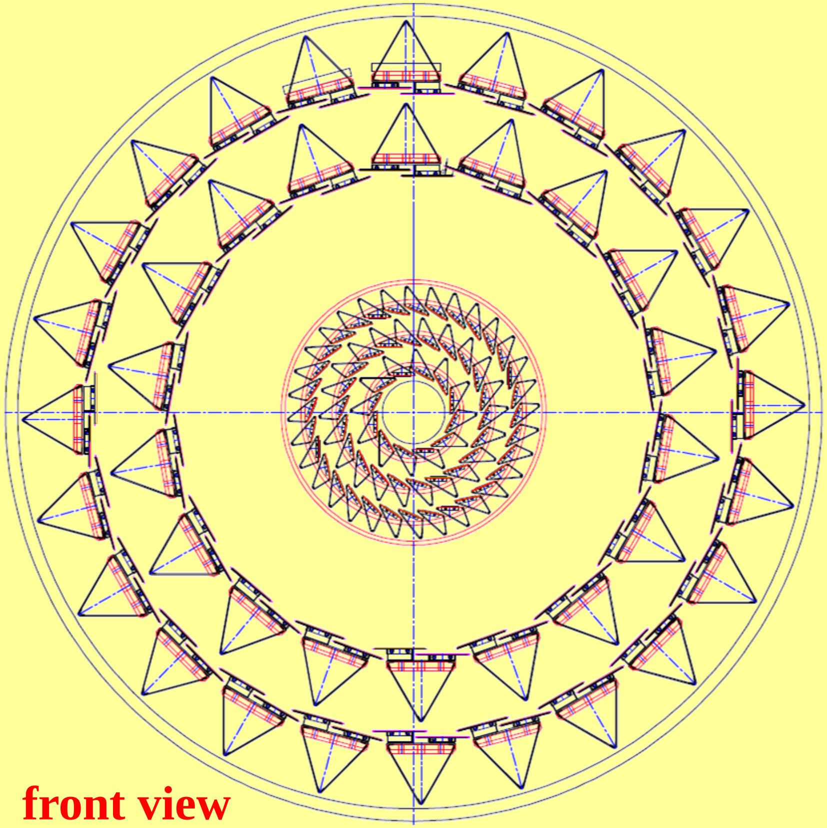
36, 48 – Outer Barrel OB

Stave consists of :
1. Hybrid Integrated Circuit (HIC)
2. Cold plate
3. Space frame

Barrel: 5 layers of Monolithic Active Pixel Sensors (MAPS)

ALICE technologies:
for IB – ALICE Middle layer staves (900 mm modified to 750 mm)
for OB – ALICE Outer layer staves (1500mm)

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider



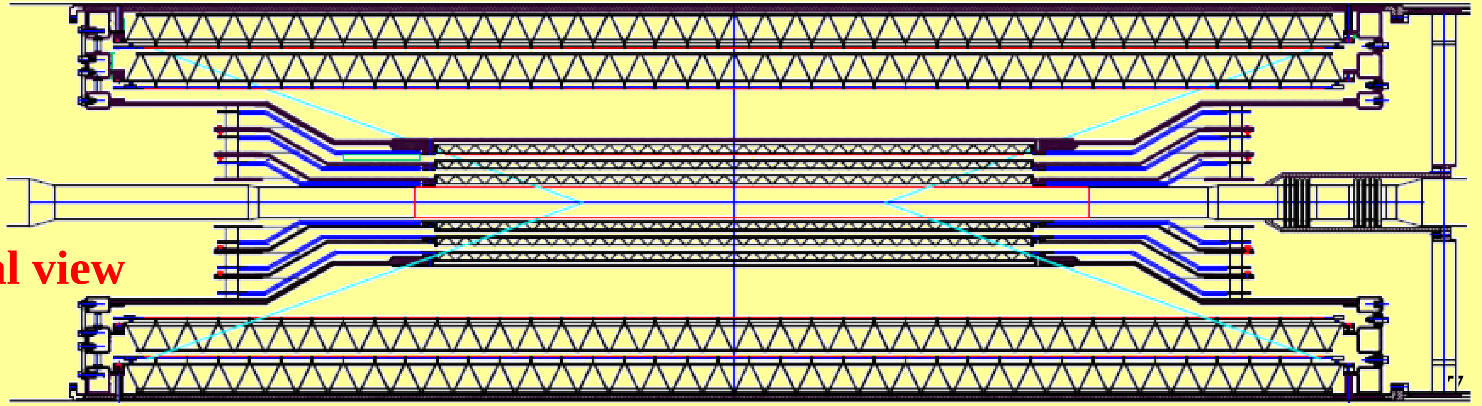
front view

Our proposal:

Five detector layers (for beam pipe D=40 mm)

Inner Barrel (fan-like arrangement): the first three layers (located as close as possible to the beam pipe). These layers are needed to reconstruct the decay vertices of short-lived particles (charmed mesons)

Outer Barrel (staggered arrangement): the two next layers. These layers are needed for the reconstruction of longrange particles (multistrange hyperons) decay vertices



longitudinal view

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

Why such configuration is proposed?

1) The diameter of the innermost detector layer is limited by the size of the beam pipe. The diameter of the beam pipe can vary from 40 to 60 mm;

2) The diameter of the outermost detector layer is limited by the dimensions of the TPC, the inner radius of which is 270 mm (A.V. Averyanov, et al., Time-projection chamber development for the multi-purpose detector in the NICA project, Phys. Part. Nuclei 49, 2018)

3) The ladders of the pixel detectors forming cylindrical layer should be partially overlapping to avoid insensitive areas;

4) The number of cylindrical layers is determined by the minimum distance between them, which is limited by the dimensions of the ultra-lightweight carbon support structures and cannot be less than 50 mm;

5) The number of ladders in each layer is determined by the transverse dimension of the MAPS of 15 × 30 mm^2

Therefore two possible configurations of the vertex detector with 5 and 6 layers were considered

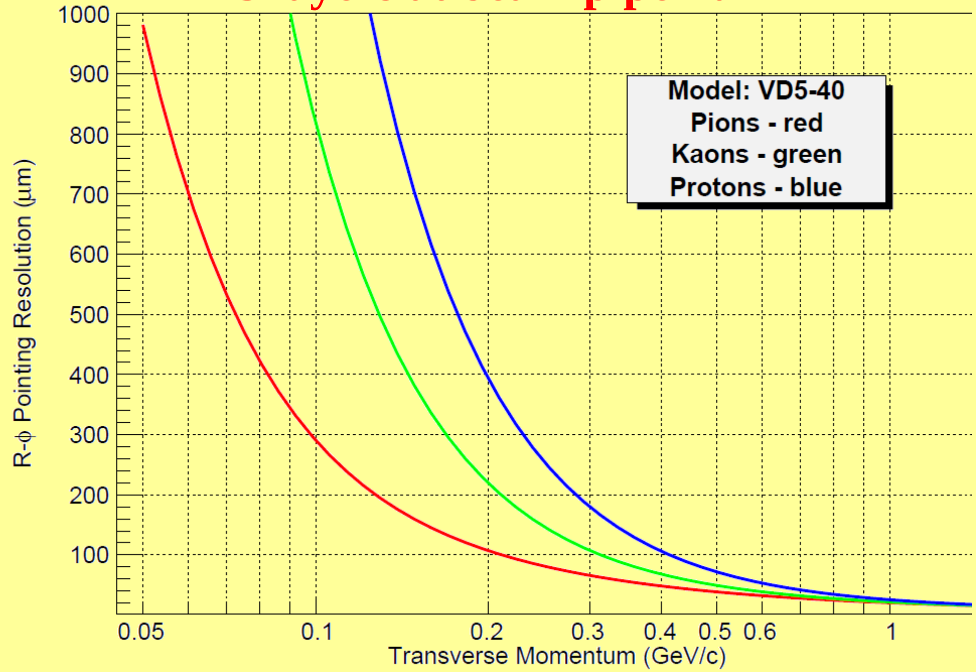
Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

Why this five layers ??

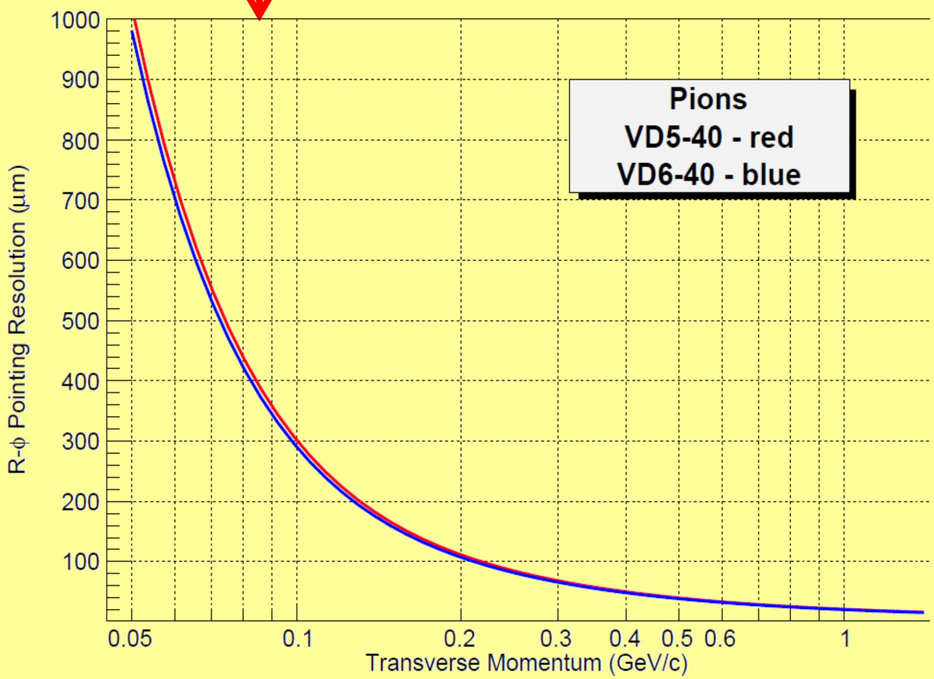
Our estimations of Pointing resolution for the different models of the vertex detector

In the framework of the semi-analytical model developed by ALICE collaboration
(A. Mastroserio, et al., Simulation Tools for the ALICE ITS Upgrade, ALICE Internal Note QCD-09-010, 2012)

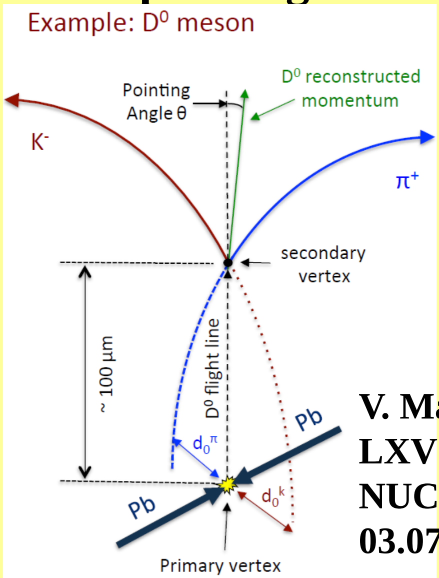
5 layers at beam pipe 40 mm



There is no big difference between 5 and 6 layers



Good pointing resolution at low p_T



for 300 MeV/c:
pions – 60 um
kaons – 100 um
protons – 160 um

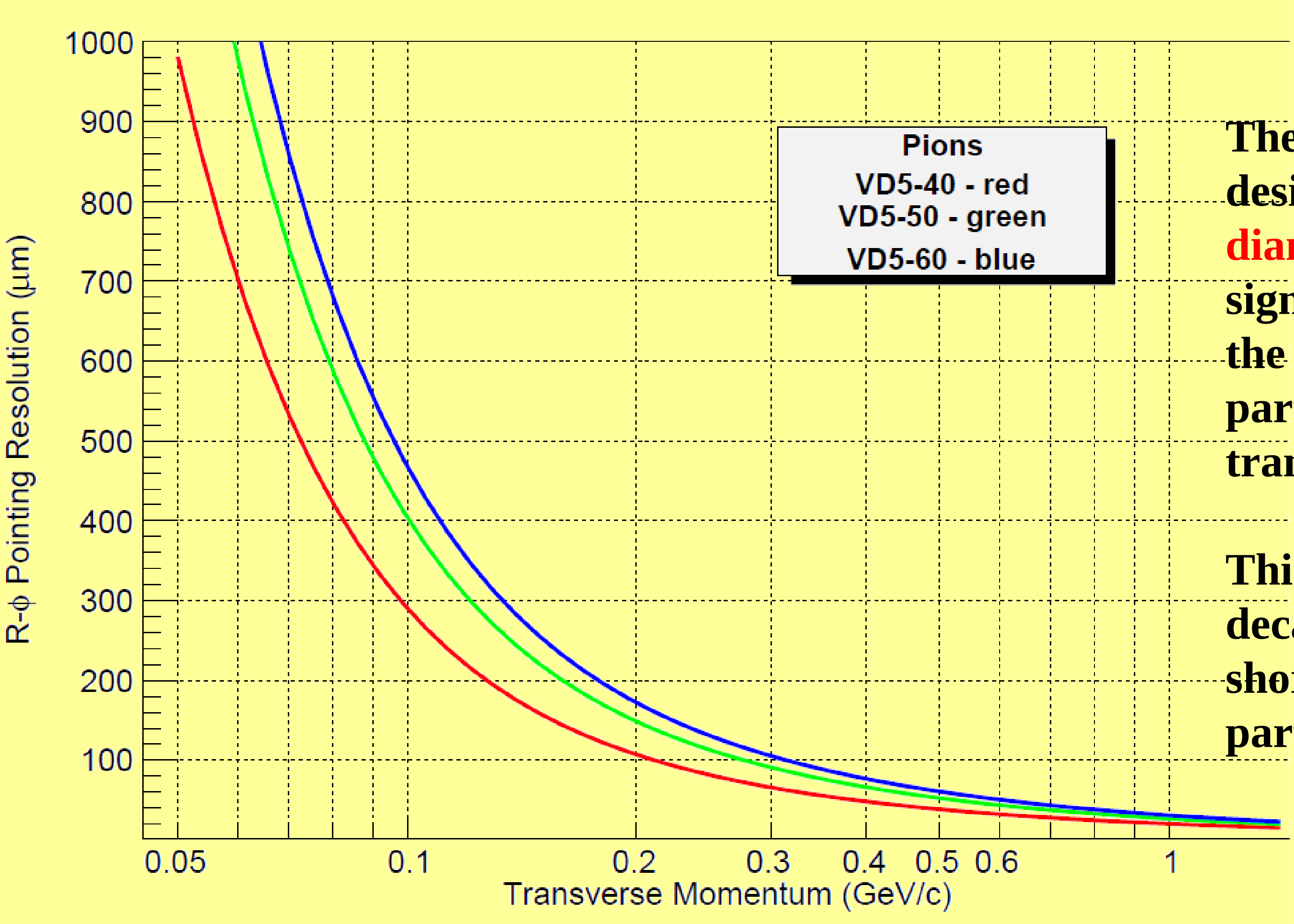
V. Manzari, LXV International Conference NUCLEUS-2015, 29.06-03.07.2015, St.-Petersburg

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

5 layers beam pipe 40 mm

We need beam pipe diameter 40 mm

Example for pion track pointing resolution



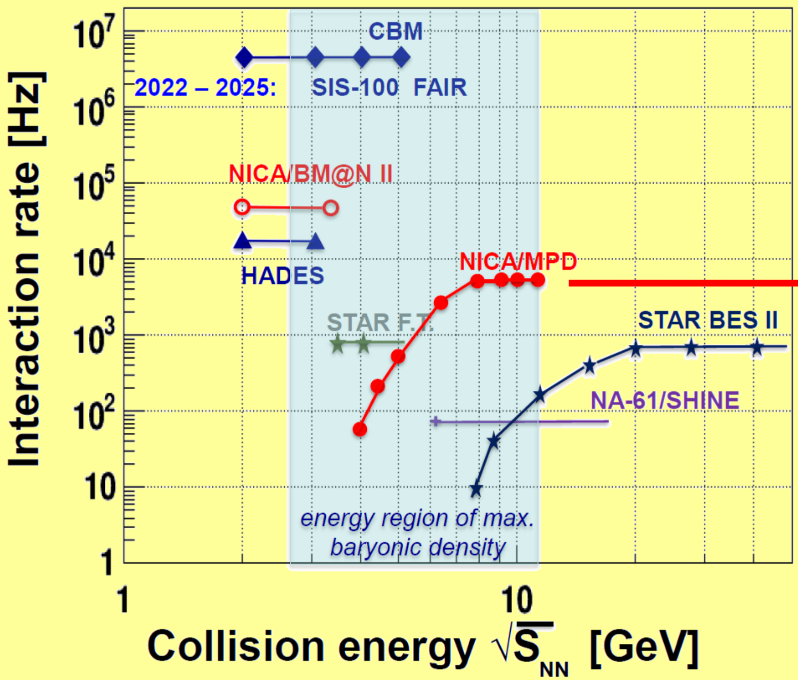
The 5-layer vertex detector, designed for a beam pipe diameter of 40 mm, can significantly improve the pointing resolution for particles with a small transverse momentum.

This is important for the decays reconstruction of short-lived charmed particles.

(For further information see also report of V.Kondaratiev and N.Maltsev, SPbSU)

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

Yield of strange and charmed particles (at threshold particle energy) in nucleus-nucleus collisions at energies of the NICA collider Sqrt(S_{NN}) = 4-11 GeV (Au^{79+})



V.Kekelidze, CERN seminar, 14.09.2018

Estimation of the expected yield of D mesons in the MPD experiment.

(estimations by V.Kondaratiev, SPbSU)

Interaction rate 8 kHz for Au-Au

concept of 5 layer MAPS
central collisions
one month of collider work
efficiency of D-mesons registration by the MPD tracking system – 2%

The multiplicity of D mesons (M) in Au + Au collisions at NICA energies was estimated in the framework of the hadron string dynamic model (HSD) M = 10^{-2} meson/event [W. Cassing, E. Bratkovskaya, et al, Open charm production in relativistic nucleus–nucleus collisions, Nuclear Phys. A 691, 2001]

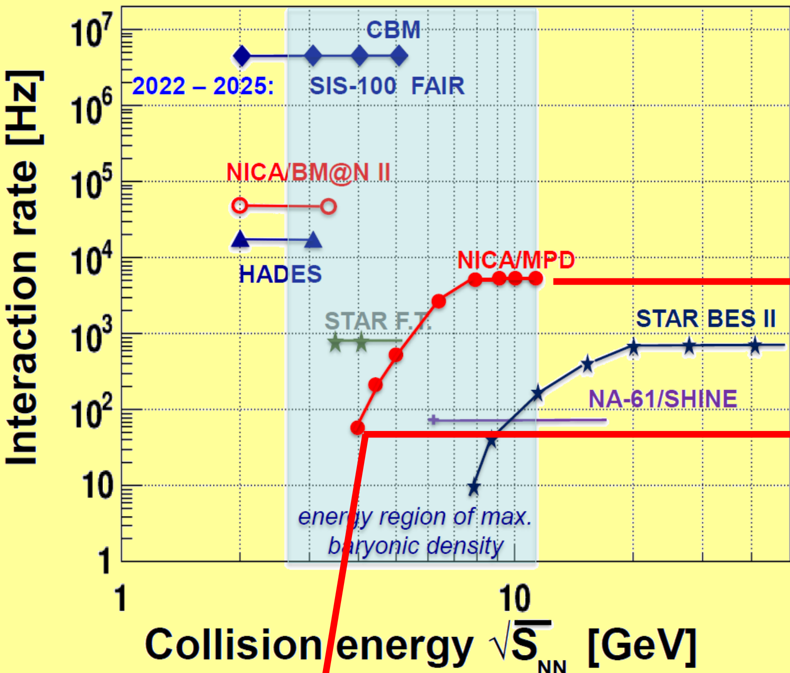
for $D^+ \rightarrow 2\pi^+K^-$ (9.2%): ≈ 38 000 mesons

for $D^0 \rightarrow \pi$+K- (3.9%): ≈ 16 000 mesons

For more read see: V.I. Zherebchevsky, V.P. Kondratiev, V.V. Vechernin, S.N. Igolkin, Nuclear Inst. and Methods, A 985 (2021), 164668.

Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider

With NICA collider parameters it becomes possible to study clusters of cold and dense quark–gluon matter inside the nuclei.



Estimations of the yields of cumulative, pions and protons with large transverse momenta outside the p + p kinematics at central rapidities in Au + Au collisions at NICA collider were done
(estimations by V.Vechernin, SPbSU)

Cumulative particles yields during one hour of the collider operation

Particle	Yeld at Sqrt(S_{NN})= 4 GeV	Yeld at Sqrt(S_{NN})= 8 GeV
π	50	$2\cdot10^{-3}$
^{1}p	70	$9\cdot10^{-7}$

The observation of cumulative particle production with is more favorable at the lowest possible energies of the NICA collider – Sqrt(S_{NN})= 4 GeV.

The calculations predict new effect in this cumulative region: the yields of the π will dominate over yields of the ^{1}p.
The MPD setup with vertex detector should allow us to verify the theoretical ideas about the mechanisms of cumulative particle formation.

New pixel sensors for the Inner Tracking System of MPD experiment: ALICE Pixel Detectors (ALPIDE family)

Main motivation

Improve tracking efficiency and p_T resolution at low p_T

Requirements for the optimal tracking system

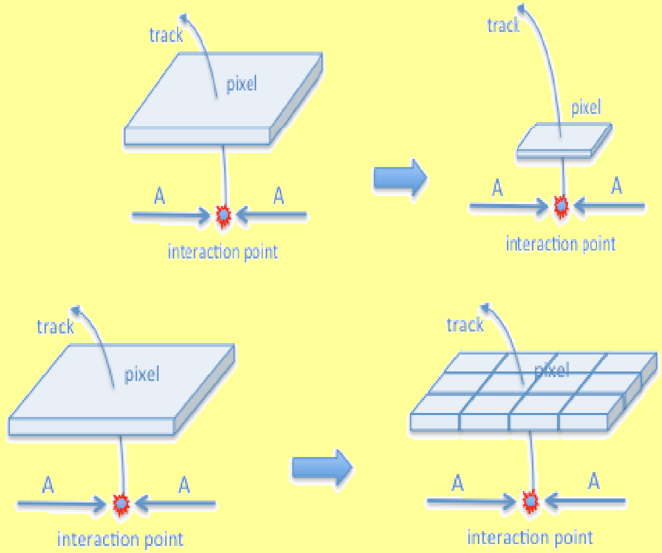
1. Good impact parameter resolution

a) First detection layer closer to the beam line

b) Reduction of material budget: min. radiation length per layer

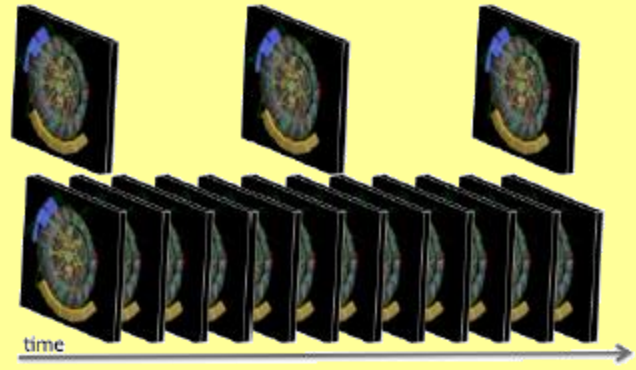
c) Increase in granularity (smaller pixels)

d) more layers



2. Fast readout

readout Au-Au interactions at 8 kHz (for the NICA design luminosity of 10^{27} cm^{-2} c^{-1} in the most central Au + Au collisions at $\sqrt{s_{NN}}$ = 11GeV) →



Also:

lower power consumption and optimized scheme for the distribution of power and signals;

L.Musa, ECFA High Luminosity LHC Experiments Workshop, 3-6.10. 2016 and F. Reidt, PIXEL2016 , 5-9.09.2016

Development of the Inner Tracking System (IT) concept for the Multi-Purpose Detector (MPD) at the NICA collider

For the Inner Tracking System (IT) concept we should take into account:

1. First detection layer closer to the beam line

2. Reduction of material budget

3. Geometry and segmentation

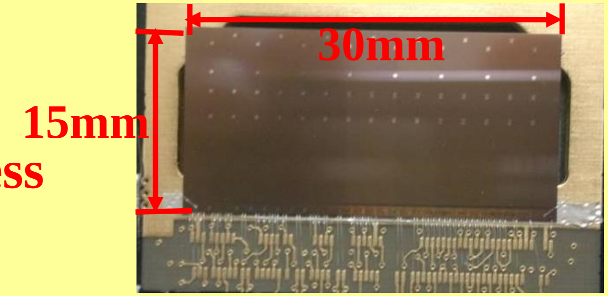
4. Read-out time

Detector should read the data related to the event rate of minimum bias interactions of about 8 kHz for Au-Au collisions

5. Radiation hardness

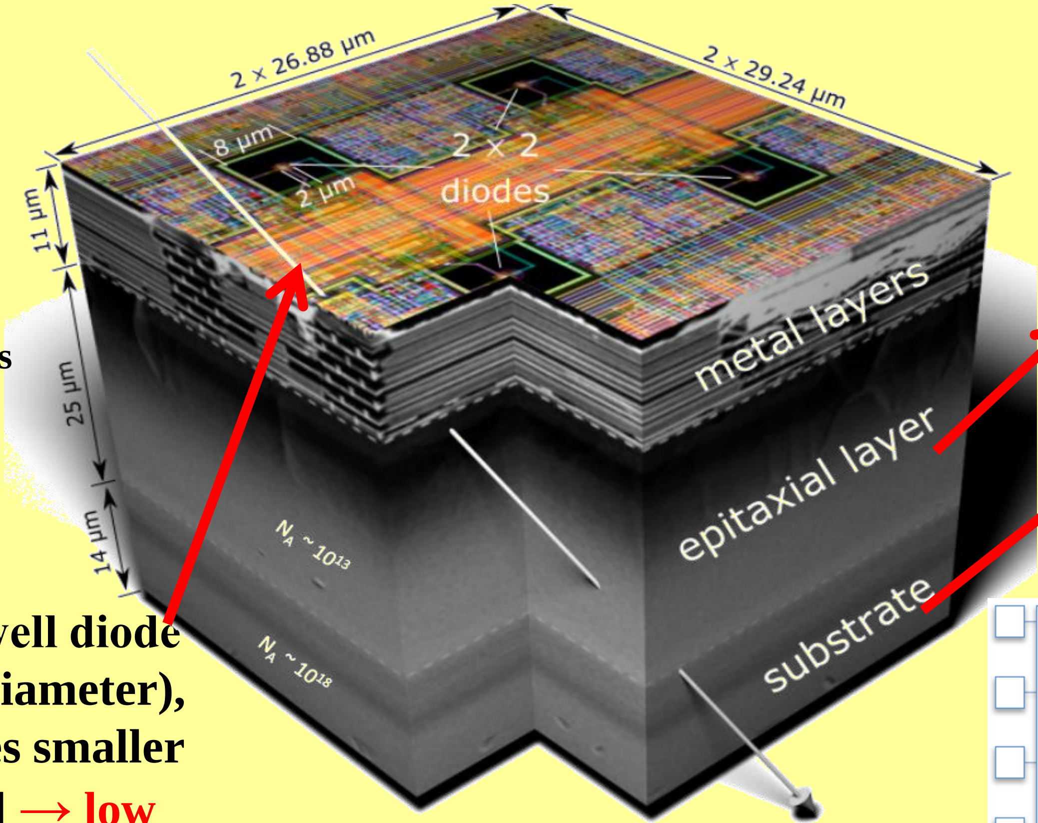
New pixel sensors for IT-MPD: ALICE Pixel detectors (ALPIDE family)

MAPS using TowerJazz 180nm CMOS Imaging Process



512 × 1024 sensitive pixels

L.Musa, ECFA High Luminosity LHC Experiments Workshop, 3-6.10. 2016

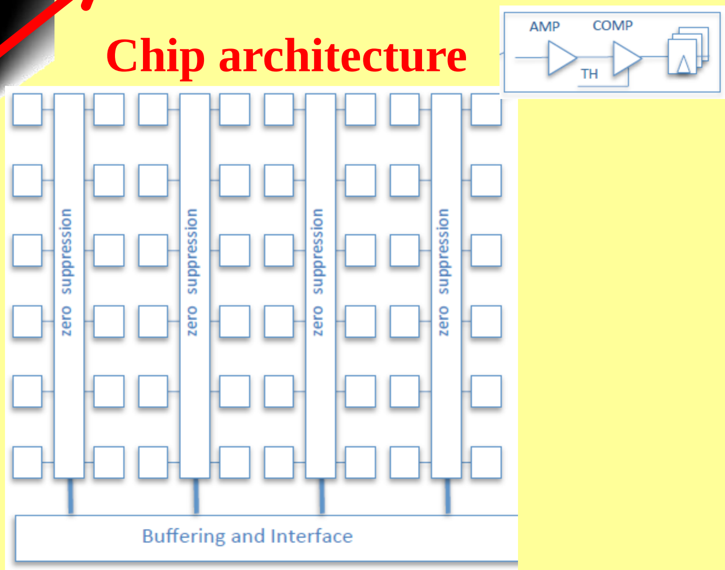


High resistivity(> 1kΩ ·cm) p-type epitaxial layer (25μm)

low-resistivity p-type substrate

Small n-well diode (2-3 μm diameter), ~100 times smaller than pixel → low capacitance

Chip architecture



The gate oxide thickness of 3 nm →robustness to Total Ionizing Dose

In-pixel: amplification, discrimination, hit buffer

Appling the back bias to the substrate one can increase depletion zone around NWELL collection diode: S/N ratio increases, higher efficiency

Study of the ALPIDE sensor characteristics at SPbSU

Characterization, tests, studies of the irradiated sensors

1. **Electrical tests:**

   a) On-chip Digital-Analogue Converter Test.
   b) Digital Scan.
   c) Analogue Scan.
   d) Threshold Scan.

   } **Experimental set-up I**

2. The noise characteristics of the sensors (also at different temperatures) were studied } **Experimental set-up I**, **Experimental set-up II**

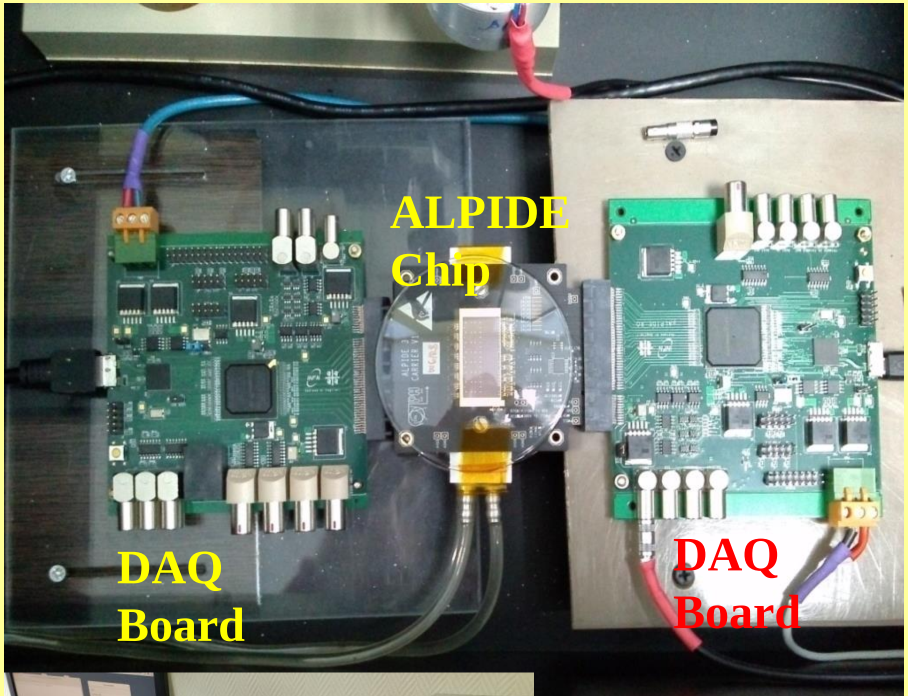
4. The characteristics of irradiated sensors at different temperatures, including cryogenic temperatures were studied } **Experimental set-up II**

5. The possibilities for cooling of new generation ultra-thin pixel detectors at different temperatures (including nitrogen cooling) have been investigated } **Experimental set-up III**

(For further information see also report of D.Nesterov, SPbSU)

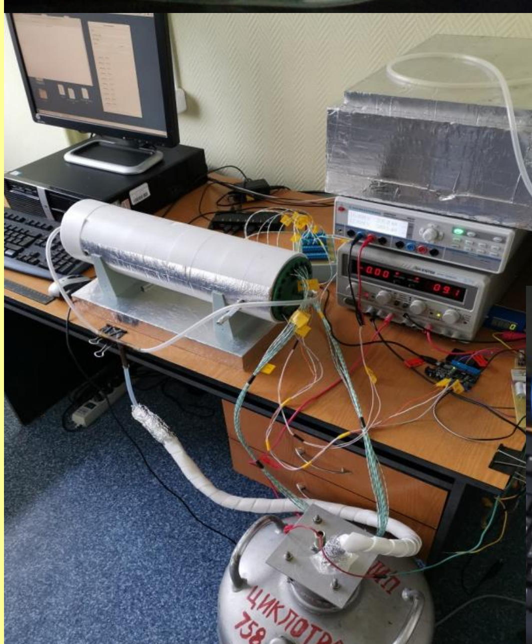
Study of the ALPIDE sensor characteristics at SPbSU

Experimental set-up I



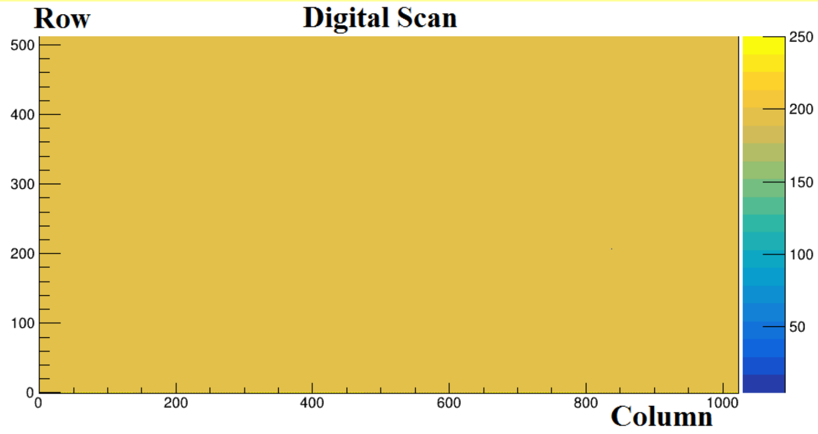
Experimental set-up II with cryogenic module

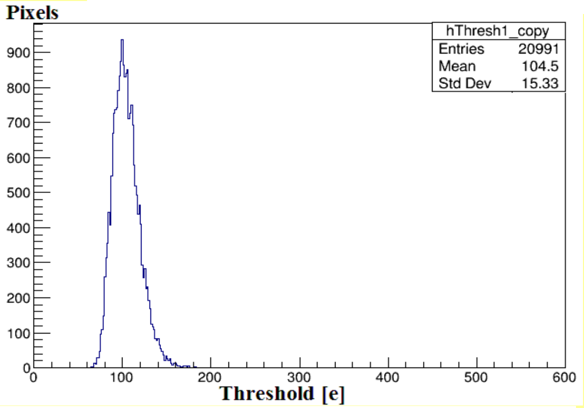
Experimental set-up III
Cold nitrogen flow

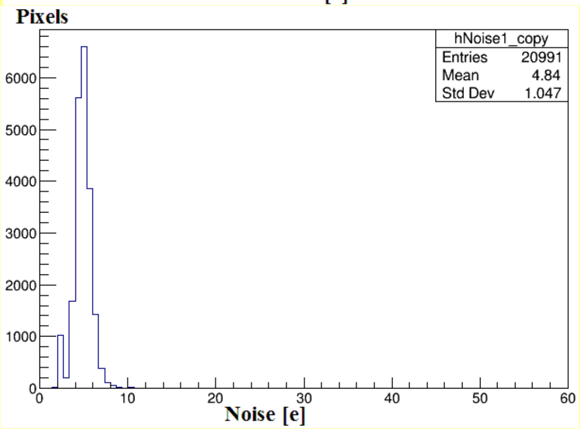


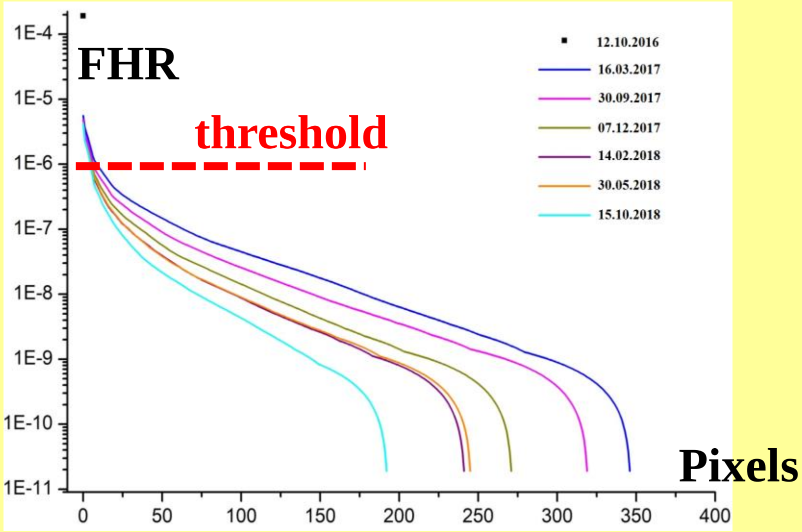
Study of the ALPIDE sensor characteristics at SPbSU

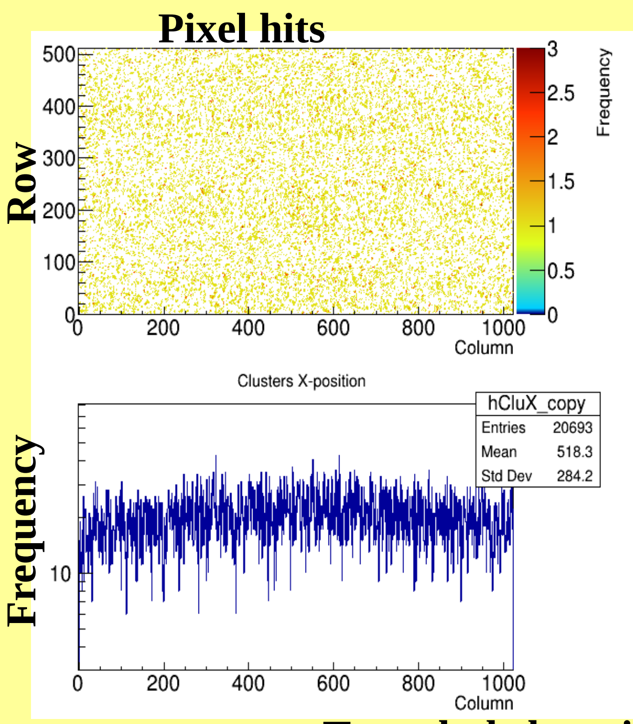
Characterization and tests

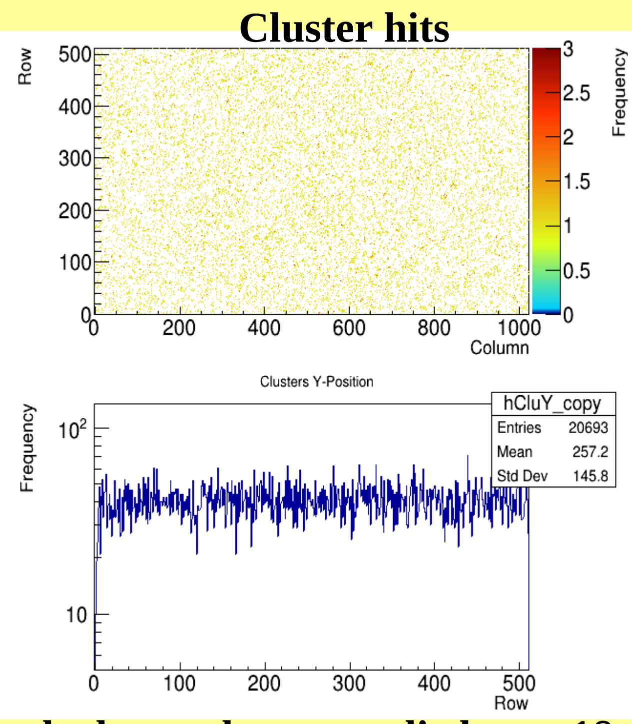






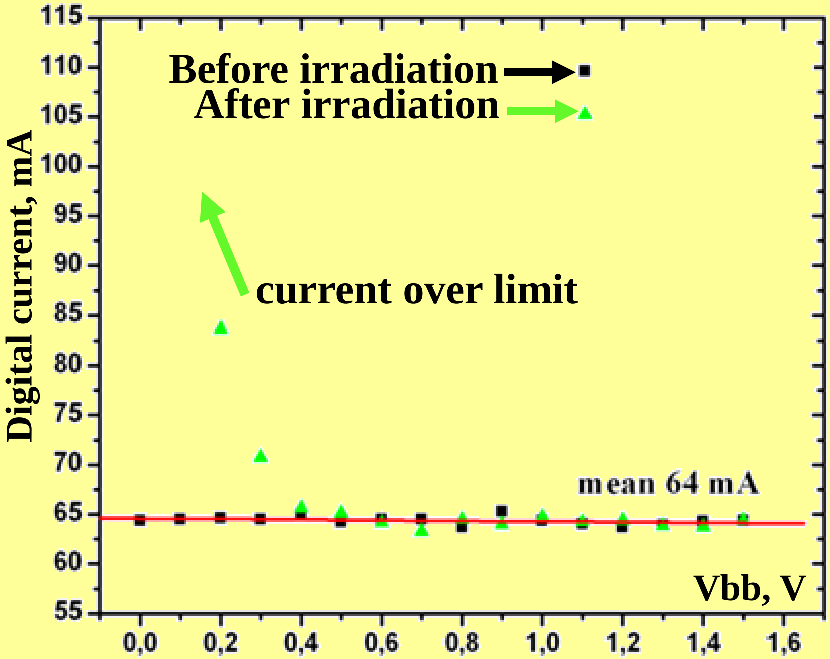


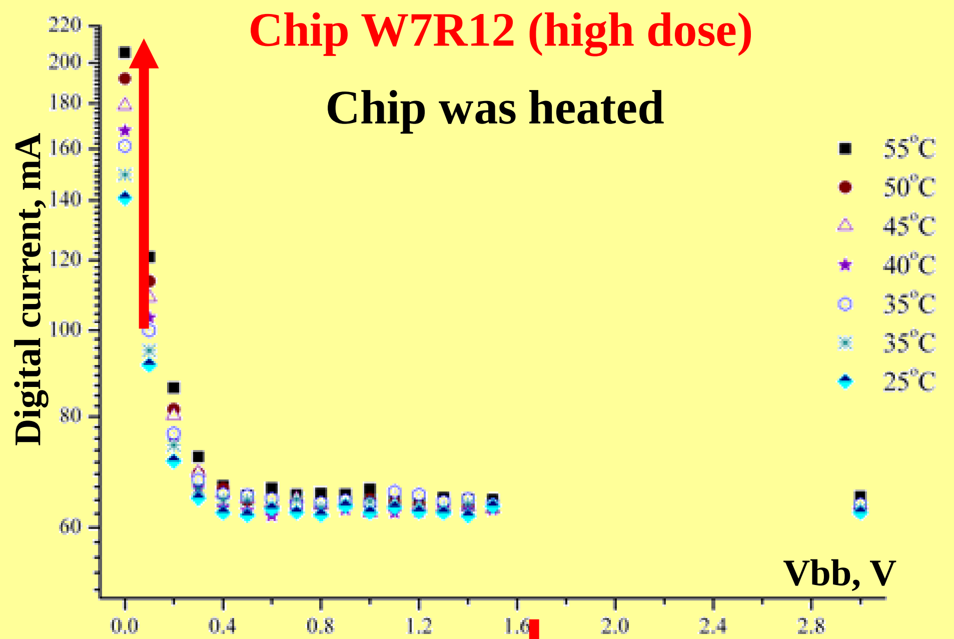




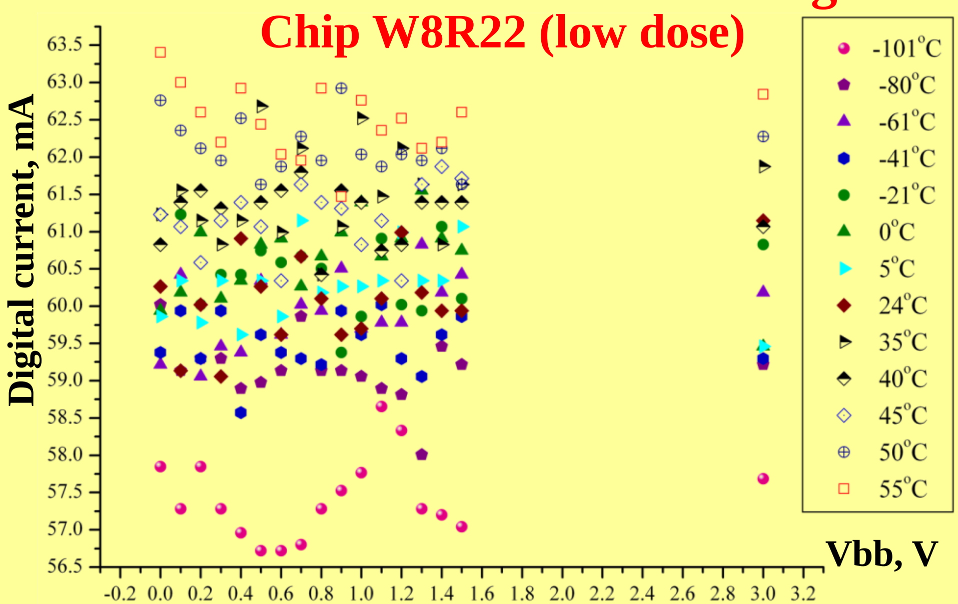
To exclude hot pixels the mask was applied

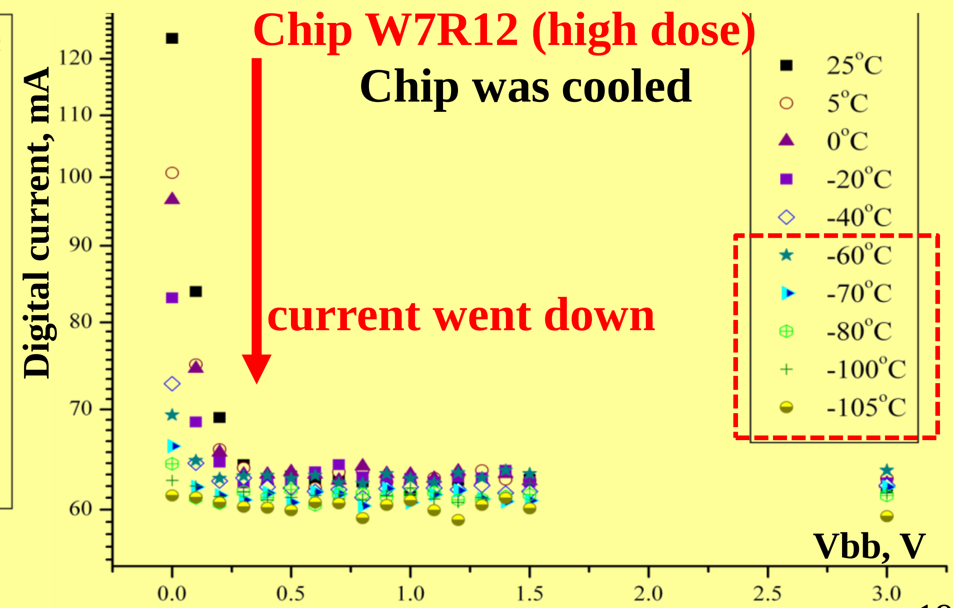
Study of the ALPIDE sensor characteristics at SPbSU





Digital Currents



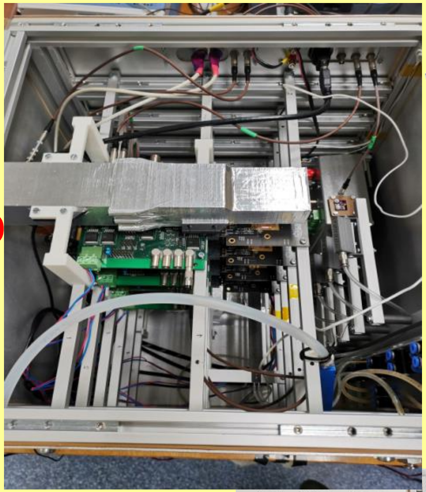


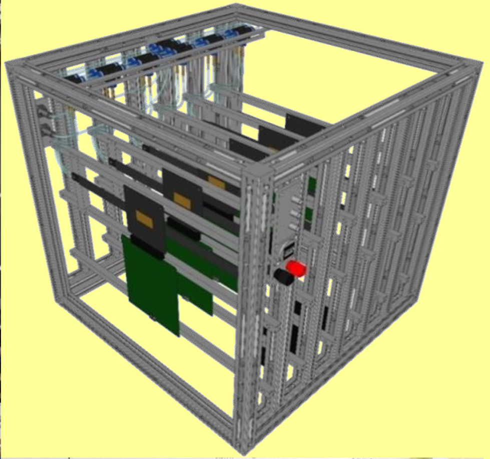
Study of the ALPIDE sensor characteristics at SPbSU

Beam tests in JINR

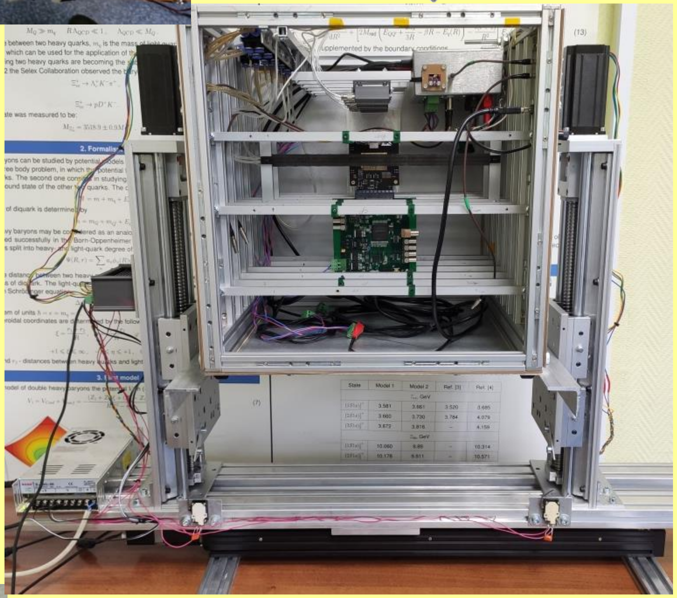
November 2018 (run 1)
April 2019 (run 2)

Experimental set-up IV for the NICA MPD Inner Tracker

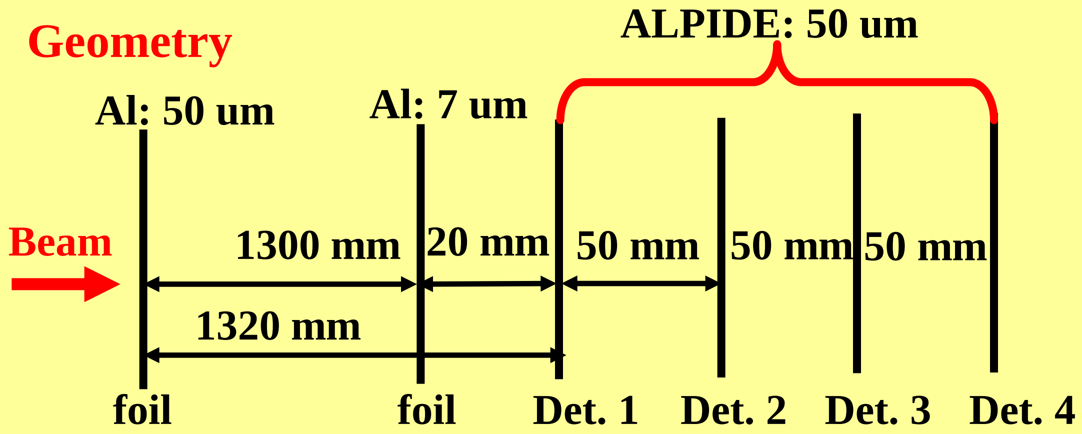




Accelerator: LINAC-200
Beam: electrons ~ 50-60 MeV
electrons ~ 150 MeV



Geometry



GEANT 4 calculation of the doses on the detectors

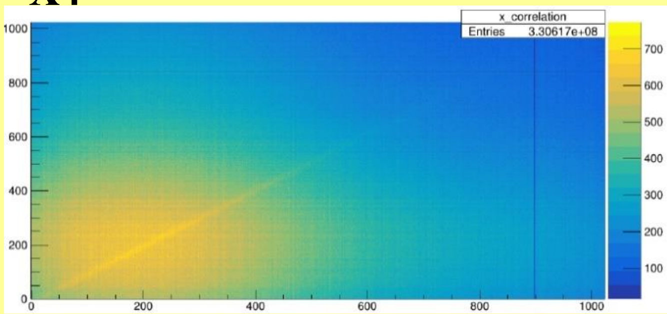
Cooling (water, air),
Two scintillators for the trigger,
Precise X-Y movement
(3 synchronized moving stage)

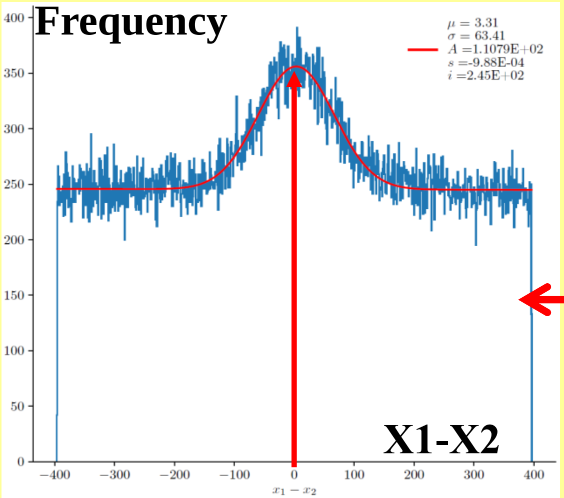
Study of the ALPIDE sensor characteristics at SPbSU

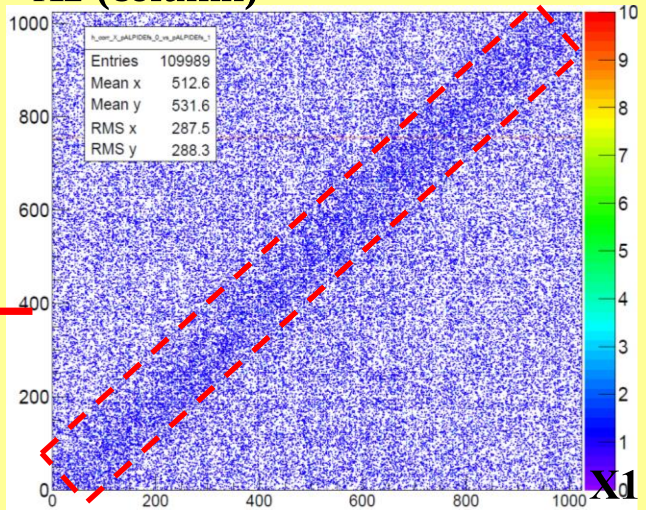
Beam tests in JINR

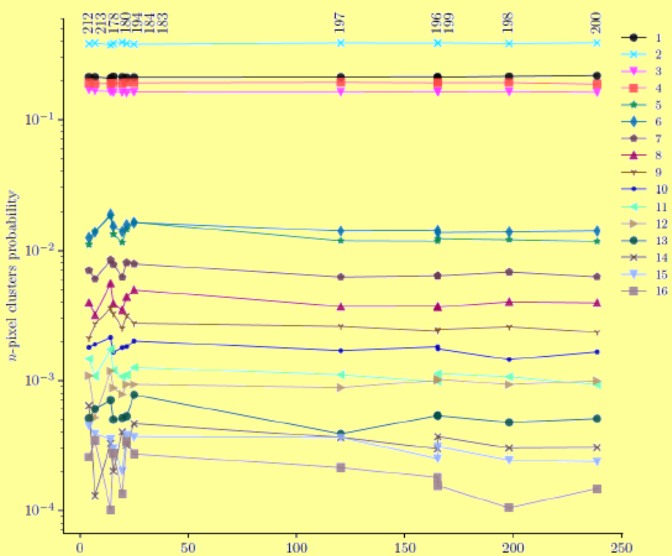
Correlations of pixel clusters between the detector planes:

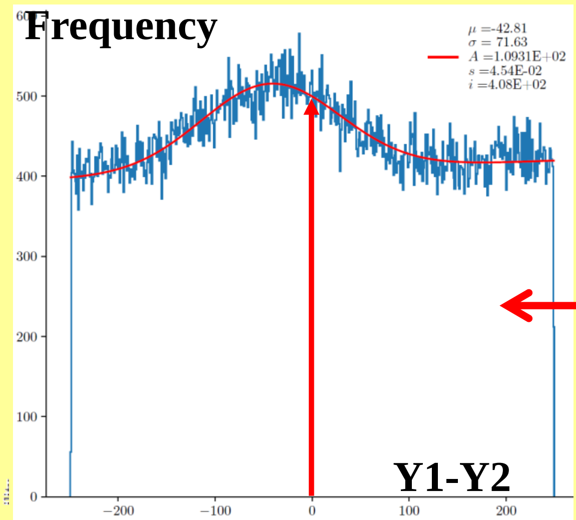
First results

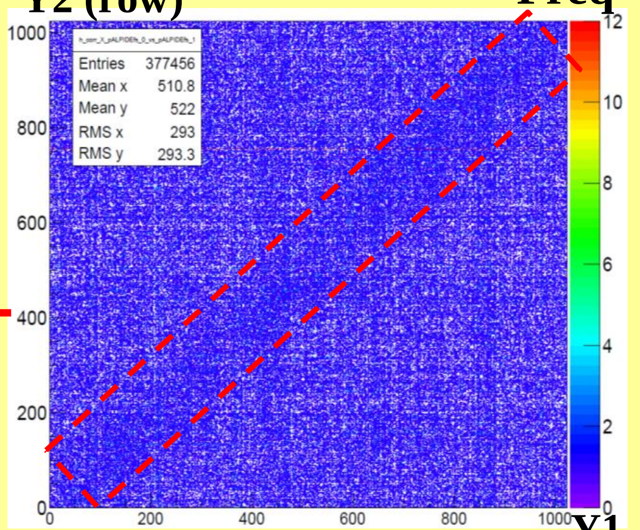










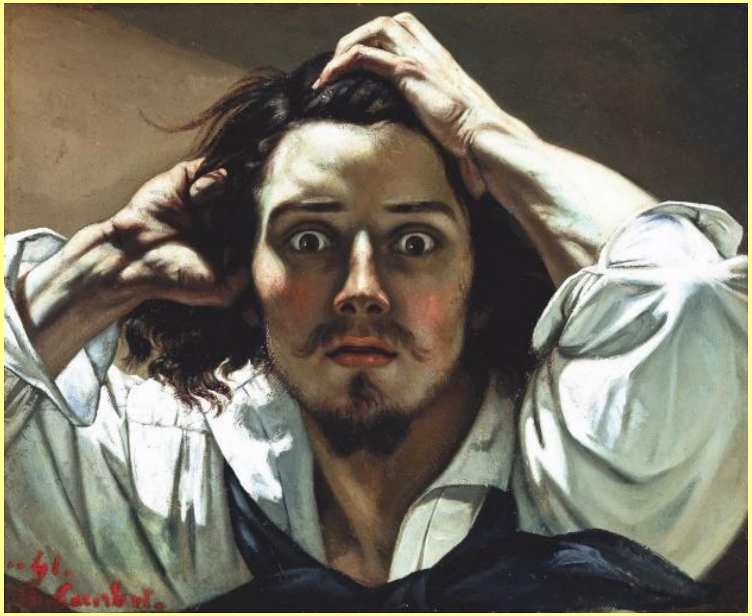


Gate on correlation

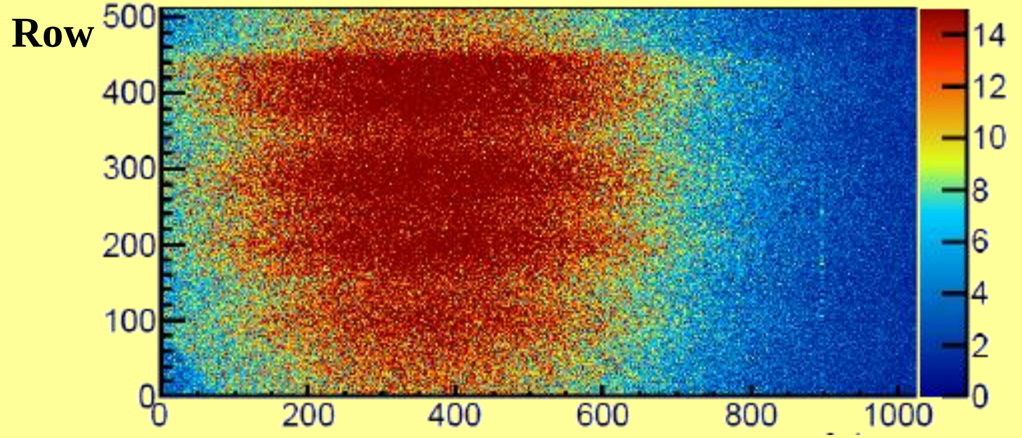
Study of the ALPIDE sensor characteristics at SPbSU

Beam tests in JINR

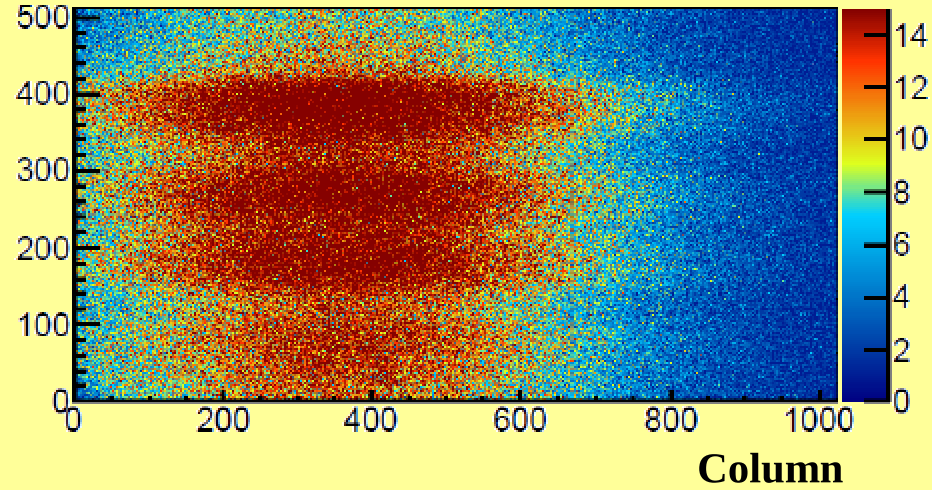
High beam intensity!
And low energies



Cluster hits (Det. 3)



Cluster hits (Det. 4)



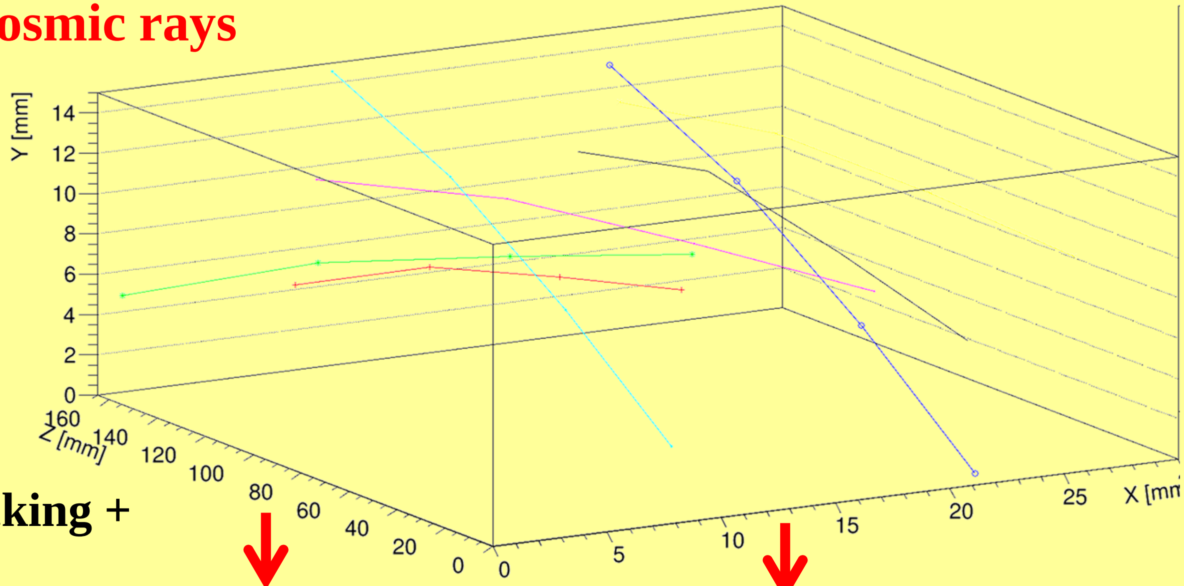
Water cooling was replaced by air cooling

For the next track finding we will adopt the Cellular Automaton method

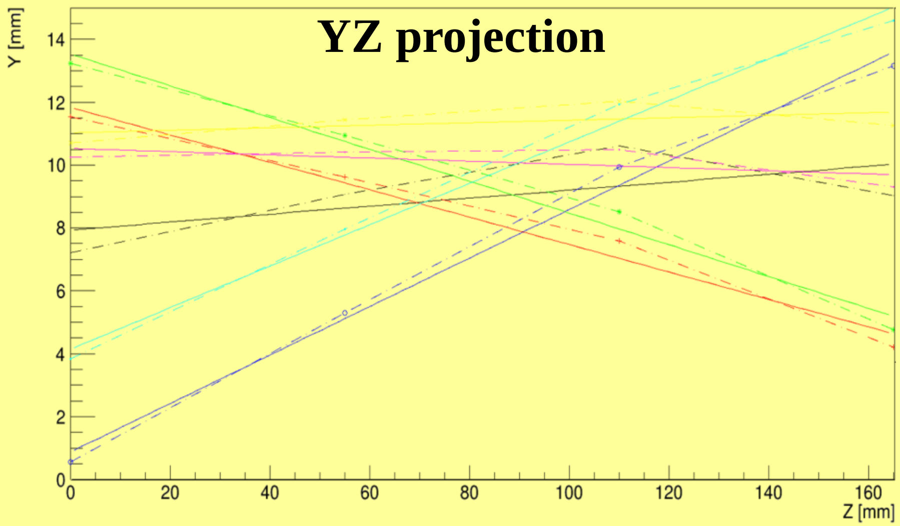
Next plans for the beam tests:
tracking, calorimetry (lead absorber), GEANT simulations

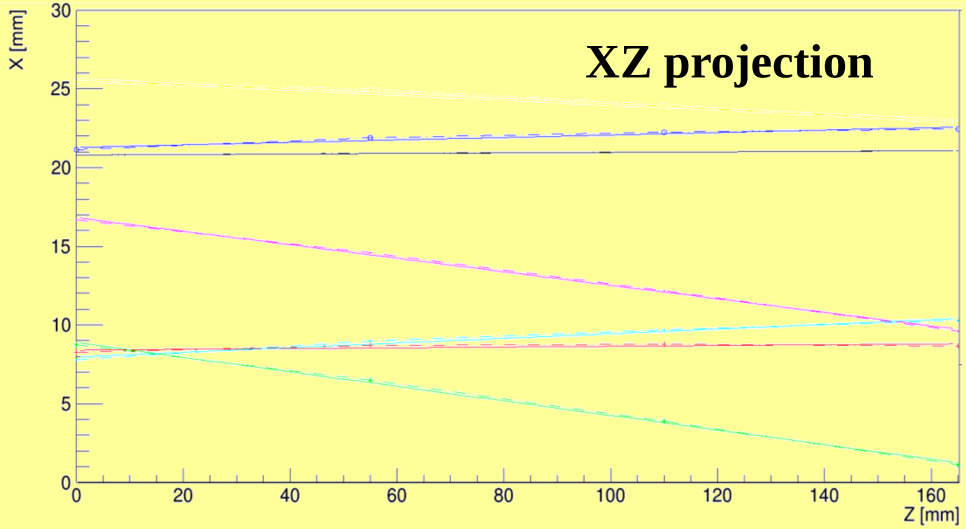
Study of the ALPIDE sensor characteristics at SPbSU

Tracking with the cosmic rays



First attempt to the tracking + track corrections

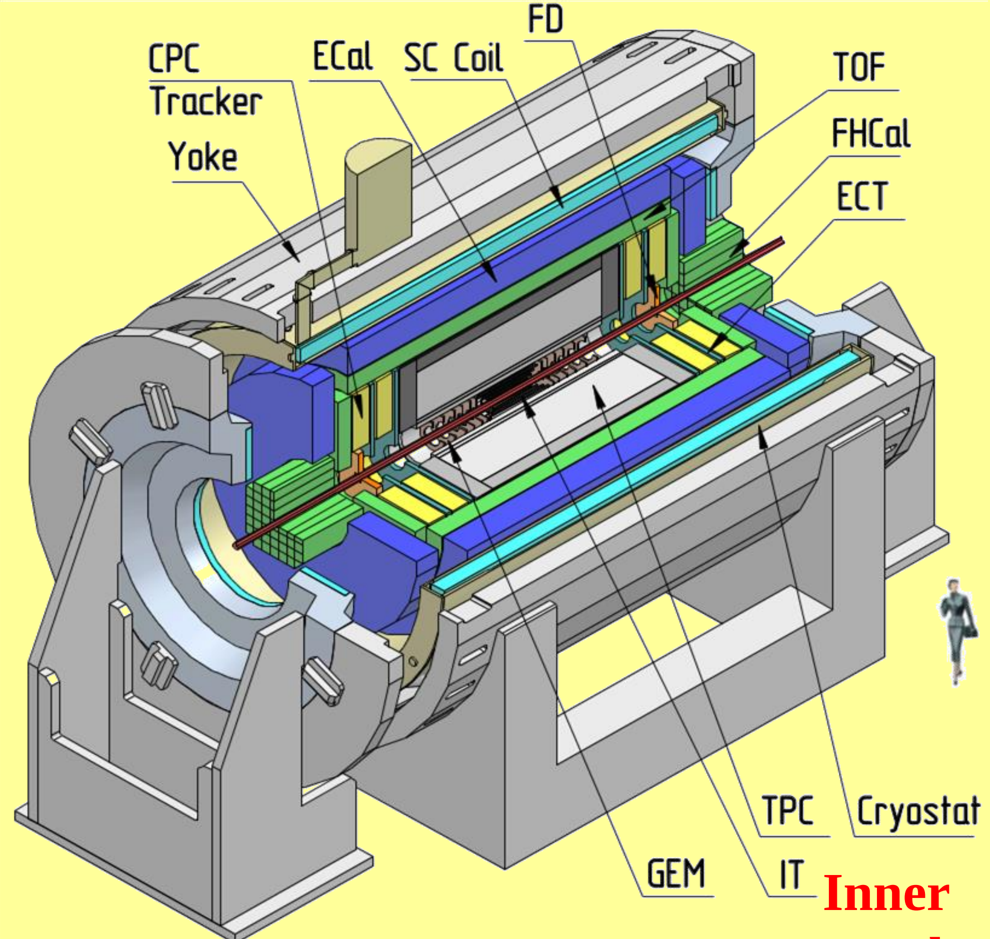




For the next track finding we will adopt the Cellular Automaton method

Study of the ALPIDE sensor characteristics at SPbSU

NICA MPD



Inner Tracker

V. Golovatyuk1, V. Kekelidze et.al. Eur. Phys. J. A (2016) 52

High vertex resolution
Fast readout (for Au-Au collisions the luminosity will be 10^{27} cm^{-2}s^{-1})
Low material budget

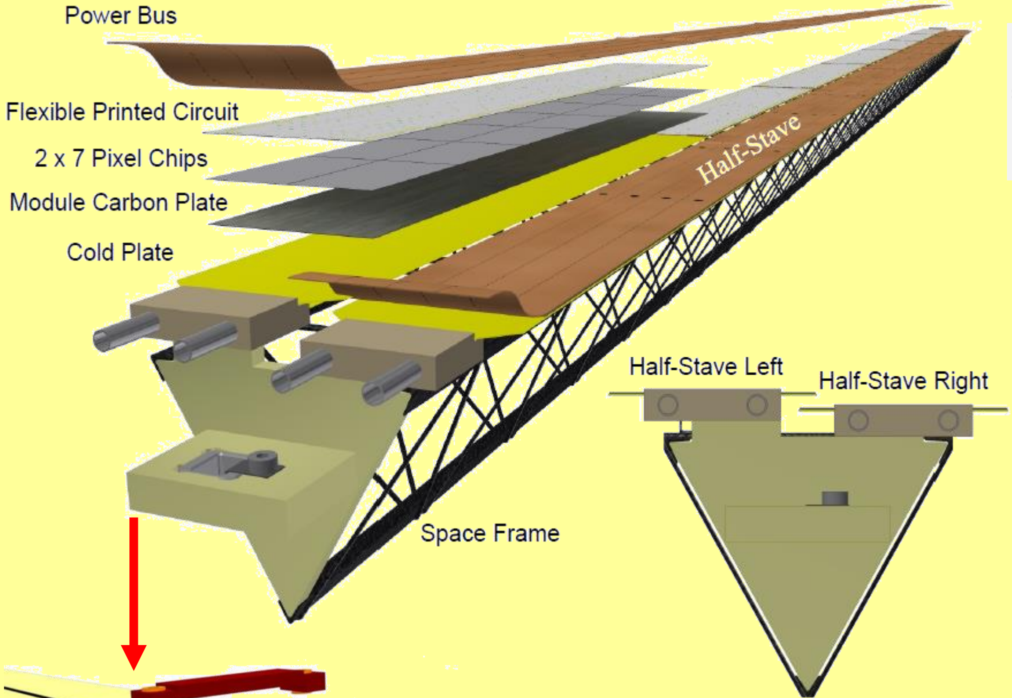
Parameter	**ALPIDE Performance**
Silicon thickness	50 µm
Chip dimension	15 mm x 30 mm
Spatial resolution	5 µm
Power density	40 mW/cm^2
Max. integration time	10 µs
Detection efficiency	>99%
Fake-hit rate	<<<10^{-6} /event/pixel
Total Ionizing Dose	Up to 500 krad

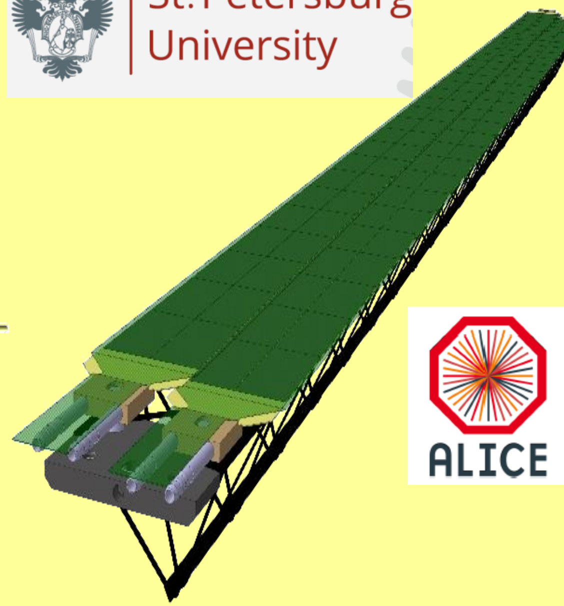
One of the possible solutions:

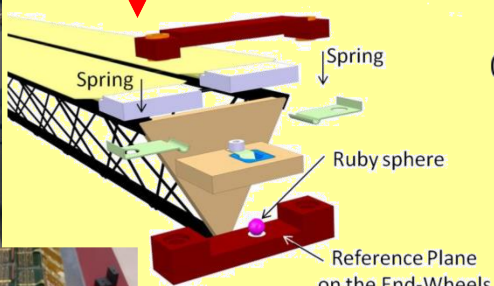
1. **Use ALICE MAPS – ALPIDE**
2. **Use carbon ultra-lightweight support and cooling structures developed for the upgrade of ALICE at the LHC**

Extra Lightweight Detector Support Structures for a New Generation of Vertex Detectors

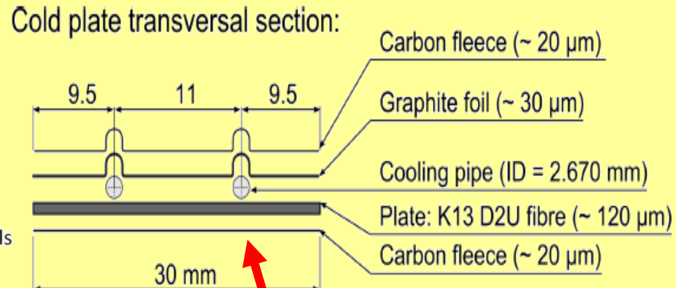
ALICE Outer Barrel Stave





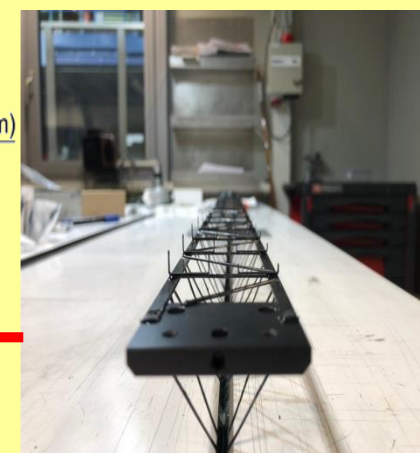


The ALICE Collaboration: "TDR", J. Phys. G41 (2014)



Cold plate

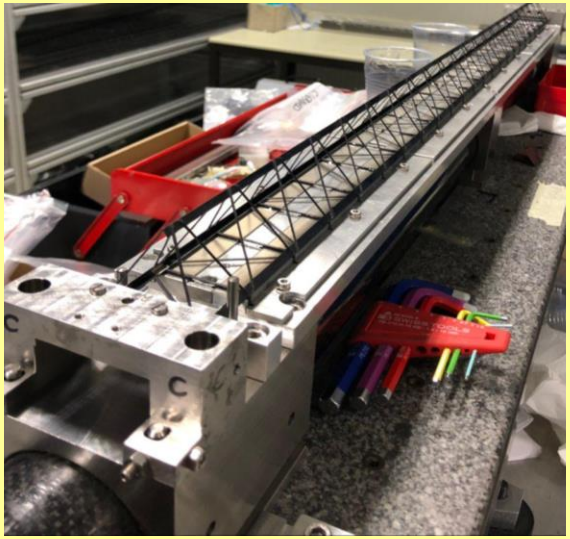
+

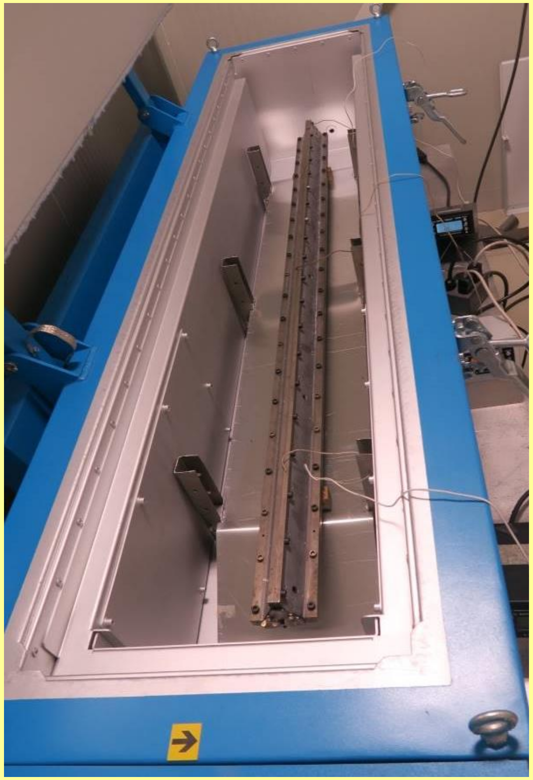


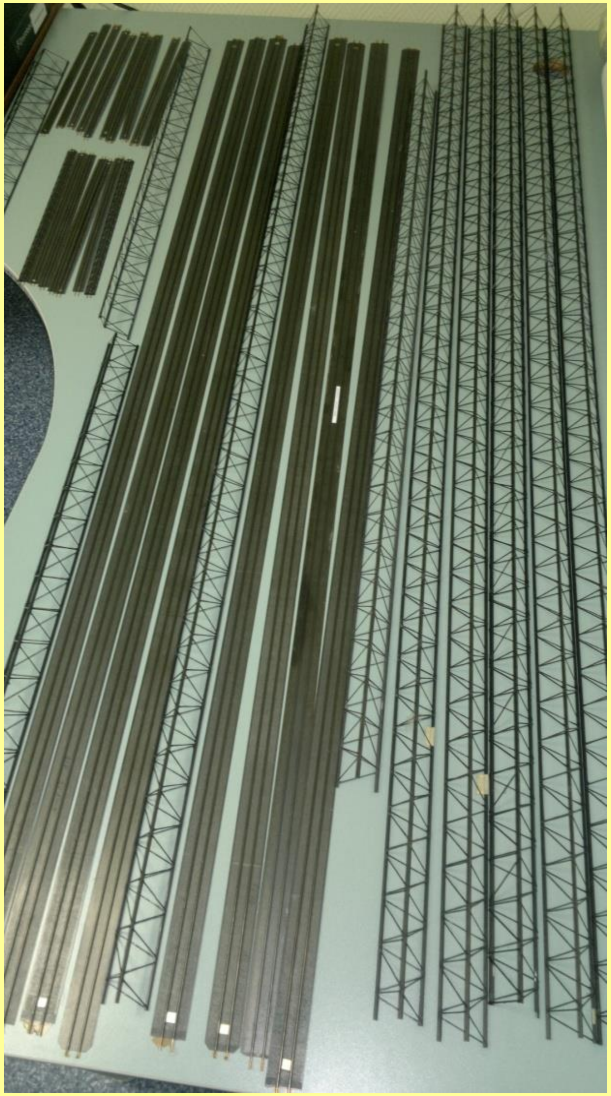
Space Frame

Extra Lightweight Detector Support Structures for a New Generation of Vertex Detectors

ALICE
Outer Barrel Stave







S.N. Igolkin, G.A. Feofilov,
V.M. Dobulevich, O.I. Stolyarov:

<u>RF Patent no. 2396168 </u> and

<u>RF Patent no. 79268 U1 РФ.</u>
<u>МПК B29C 53/56, 2008</u>

Summary

1. The concept of the Vertex detector of the Multi-Purpose Detector (MPD) setup for the registering of rare events in Au+Au collisions at the NICA collider has been proposed.

2. The characteristics and properties of new pixel sensors: ALICE Pixel Detectors (ALPIDE family) were investigated in context of the MPD NICA tasks.

3. The Extra Lightweight Detector Support Structures were proposed for Inner Tracker of MPD NICA

4. Experimental set-up for the future characterization of ALPIDE MAPS for the NICA MPD Inner Tracker has been developed, constructed and tested.

For more read see: V.I. Zherebchevsky, V.P. Kondratiev, V.V. Vechernin, S.N. Igolkin, Nuclear Inst. and Methods, A 985 (2021), 164668.

Next plans

1. Modernization of Experimental set-up for new beam measurements at JINR.

2. Studies of the ALPIDE characteristics using electron beams (LINAC-200) and NUCLOTRON beams in JINR

3. Studies of the ALPIDE characteristics at Petersburg Nuclear Physics Institute (Gatchina) 1 GeV protons primary beam. Secondary pions 750 MeV/c

4. Studies of the ALPIDE characteristics at the Ioffe Physical-Technical Institute of the Russian Academy of Sciences Cyclotron: heavy Ions up to 6 MeV/u, from ^{1}p up to Ar.

Extra Lightweight Detector Support Structures at SPbSU


Thank you

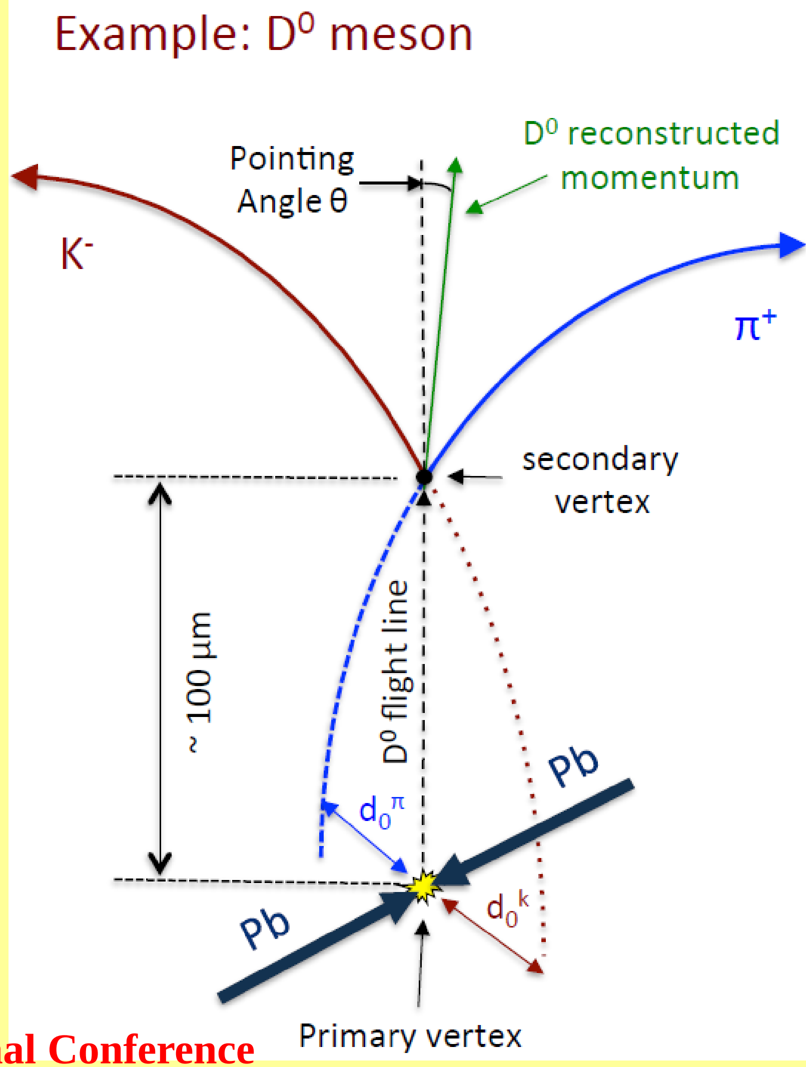
BACK-UP SLIDES

Physics

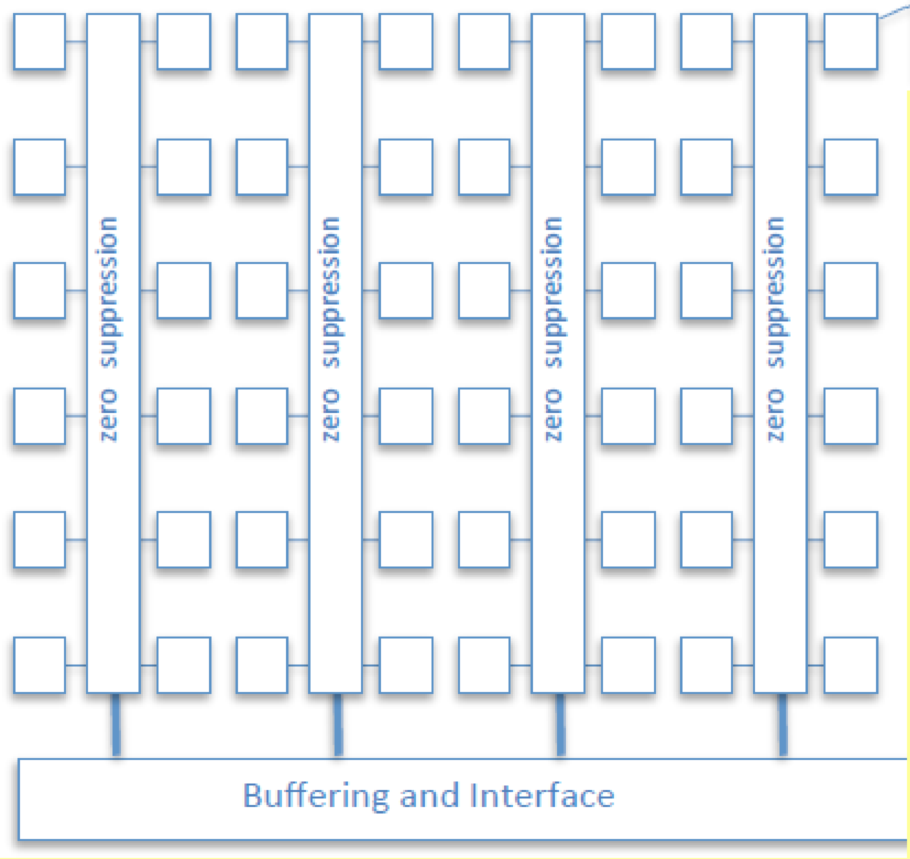
Improve primary vertex reconstruction, momentum and impact parameter Resolution

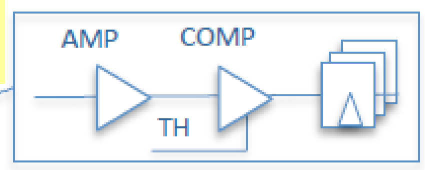
Reconstruction of secondary vertices from c decays with high resolution

Secondary vertex determination

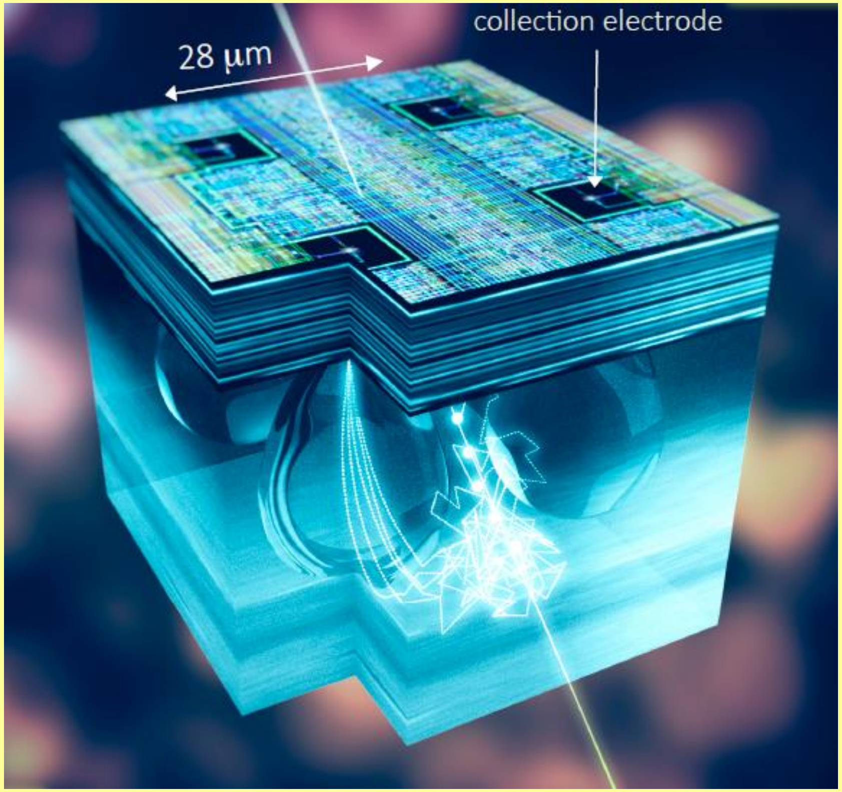


ALPIDE chip architecture





In-pixel amplification
In-pixel discrimination
In-pixel (multi-) hit buffer



The zero suppression is performed within the matrix. Address-Encoder Reset-Decoder circuit is employed. It can either be controlled by an external trigger signal or operated in continuous acquisition mode.

Power consumption 40 mW/cm^2

Contains a matrix of 512 × 1024 sensitive pixels

Study of the ALPIDE sensor characteristics at SPbSU

Characterization, tests, studies of the irradiated sensors

1. **Electrical tests:**

   a) **On-chip Digital-Analogue Converter Test.** **The output of the on-chip DACs is connected to monitoring pins of the detector and measured by ADCs on the DAQ board.**

   b) **Digital Scan.** **Scan generates a digital pulse in a number of pixels and reads the hits out. The number of injections per pixel and the group of pixels can be set.**

   c) **Analogue Scan.** **A programmable charge is injected into the preamplifier. The values of the injected charge, as well as the number of injections per pixel and the groups of pixels can be set.**

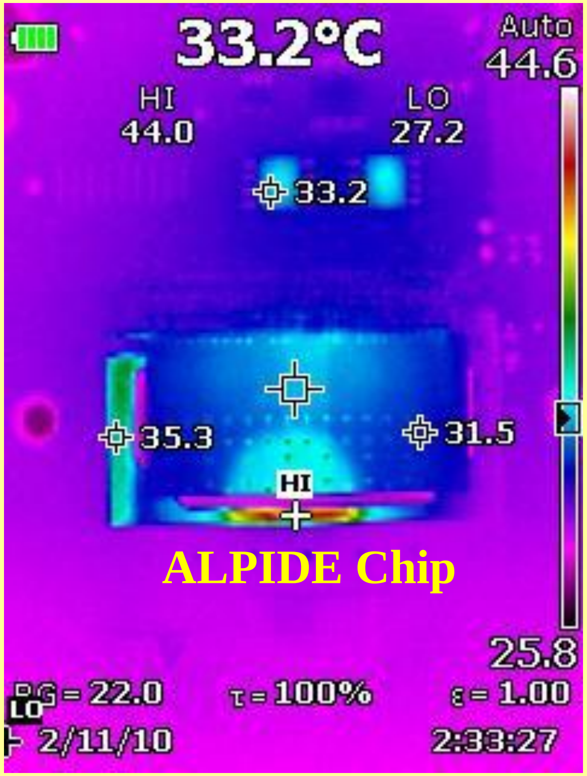
   d) **Threshold Scan.** **Scan performs analogue injections, looping over the charge ranging from 7 to 350 electrons. The values of the threshold can be set.**

2. **Noise characteristics of the sensor and its temperature dependence were studied**
   The scan gives a selectable number of random triggers and returns the number of hits. The values of threshold current (ITHR) and threshold voltage (VCASN) and also chip temperature can be set.

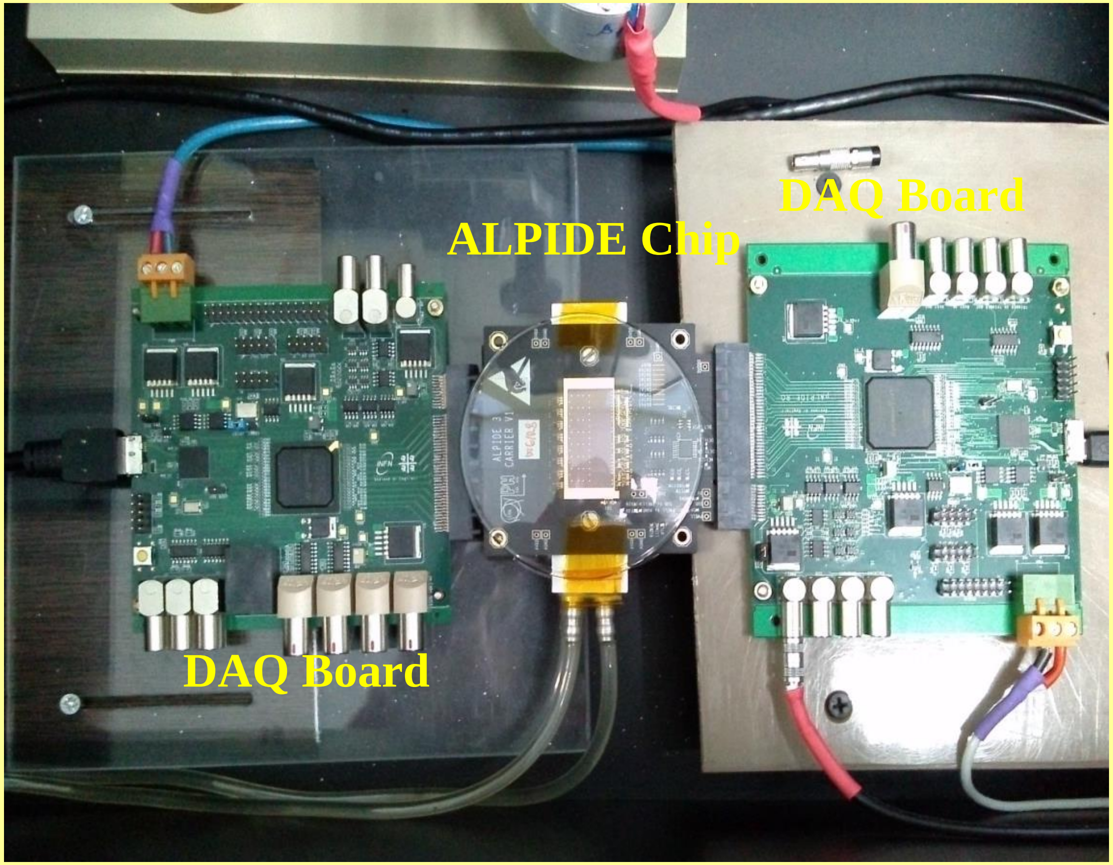
3. **Studies with a variety of gamma and beta sources were carried out**
   The scan gives the number of hits using the selectable number of random triggers. Radioactive source measurements are needed to study the uniformity of hit-maps and to evaluate cluster shape and size. The noise mask is prepared before the scan and can then be used in measurements.

New pixel sensors for the Inner Tracking System of MPD experiment: ALICE Pixel Detectors (ALPIDE family)

1. Two different chip types (telescope geometry) with own DAQ boards were installed.
2. Detector Power supply(current control).
3. Dark box with electrical earthing inside. Temperature control inside the box.
4. Radioactive source ($\gamma\beta$) positioning system.
5. The water cooling(heating) system was implemented.
6. Thermo-camera for detector heating investigations.



Experimental set-up I



All generations of ALPIDE chip: pALPIDE-1,2,3 and final version were studied

Study of the ALPIDE sensor characteristics at SPbSU

1. Cryo-box.
2. Irradiated ALPIDE chip + DAQ board.
3. Chip was mounted on cooled platform.
4. Three thermocouples (1 copper-constantan, 2 chromel-alumel) mounted on cooled platform. Each thermocouple has own controller and DAQ

Experimental set-up II + cryogenic module

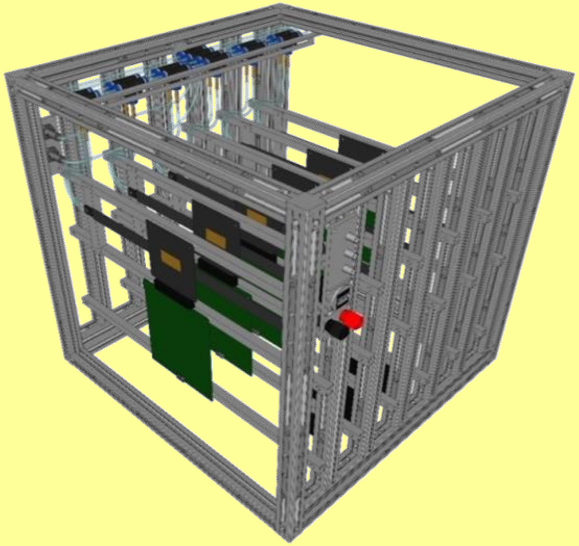
5. Dewar vessel with heater system.
6. Source holder.
7. Analytical balance

With using liquid Nitrogen the chip can be cooled till -110 ^{o}C

With using "heater" the chip can be heated till +60 ^{o}C

Study of the ALPIDE sensor characteristics at SPbSU

Experimental set-up for in-beam ALPIDE characterization



I Four ALPIDE chip now + 2 additional places

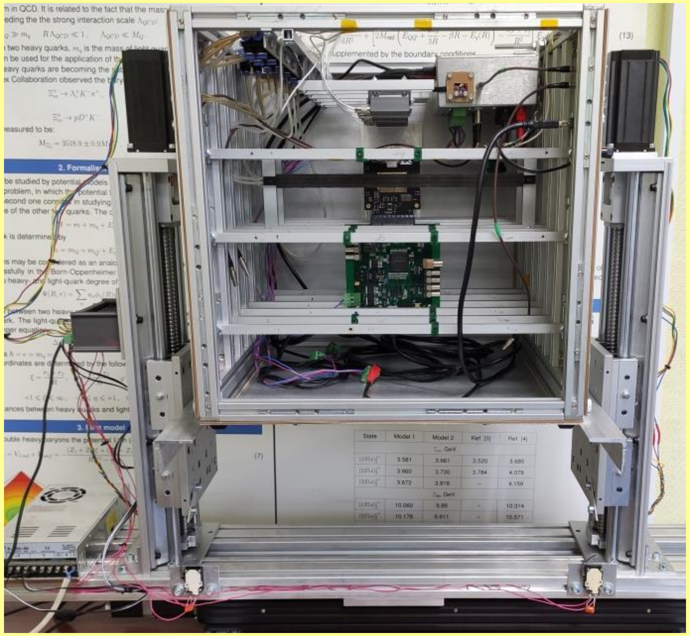
II Cooling

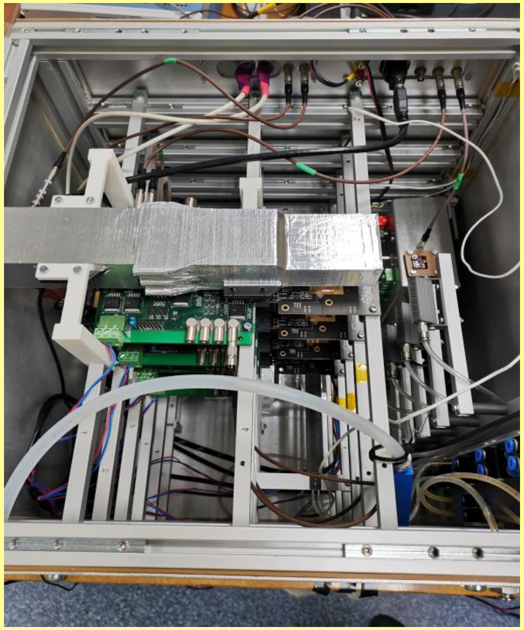
1) Cooling system with water (ITS-2 staves 30 mm)

2) Air cooling system:
dray air and the radiator with Thermoelectric Cooler (TEC) has been used for air cooling

III Two scintillators for the trigger

IV Precise X-Y movement (3 synchronized moving stage)





First beam tests were done at JINR in spring 2019 (150 MeV e^-).

Now we are using this set-up for the cosmic rays detection. Tracking.

Study of the ALPIDE sensor characteristics at SPbSU

The performance of irradiated sensors at different temperatures, including cryogenic temperatures

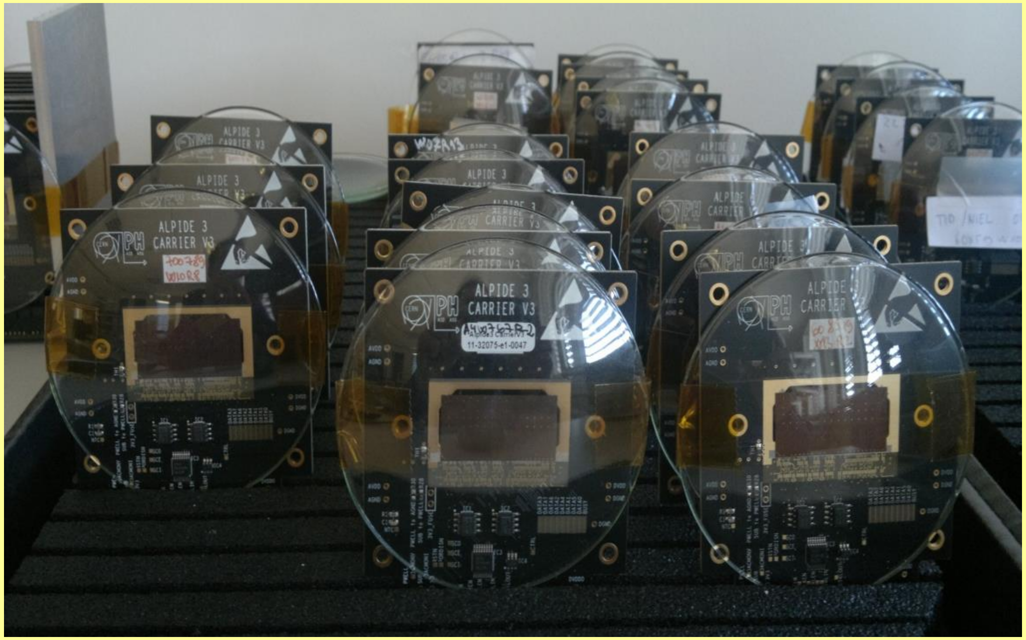
Detectors ALPIDE (final version)

Detectors were irradiated by:

X-rays (from X-ray machine)

Chip W8R22 – 60 krad (low dose)

Chip W7R12 – 300 krad (high dose)



Before irradiation Chip W7R12 was measured at lab.

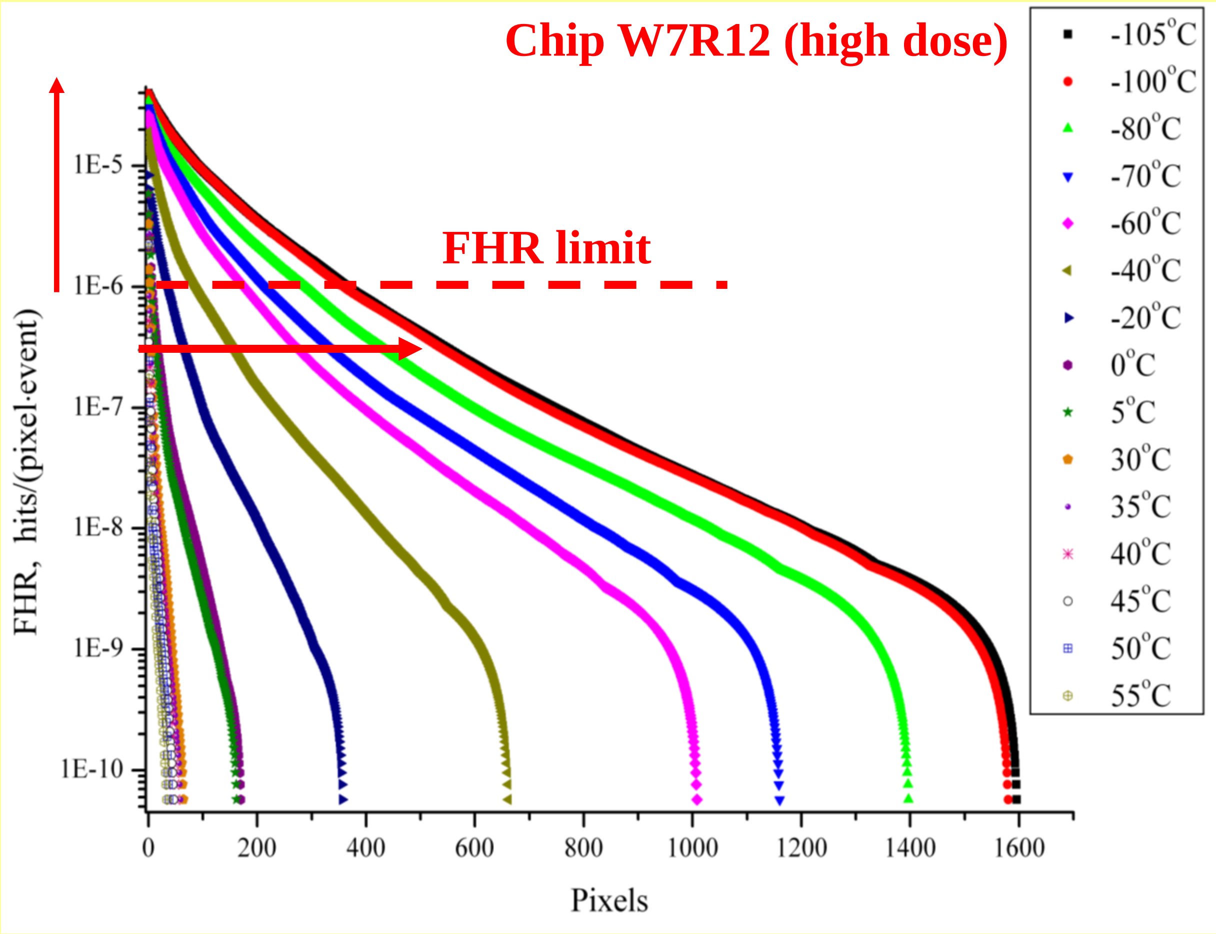
All measurements were done at back bias voltage Vbb = -3V

Development of the Inner Tracking System (ITS) concept for the Multi-Purpose Detector (MPD) at the NICA collider

Geometry of a 5-layer vertex tracker design

Layer number	Number of the staves	R_{min}, mm	R_{max}, mm	Staves length, mm
1	12	22.4	26.7	750
2	22	40.7	45.9	750
3	32	59.8	65.1	900
4	36	144.5	147.9	1500
5	48	194.4	197.6	1500

Results for high dose irradiated chip **Noise Occupancy Scan**



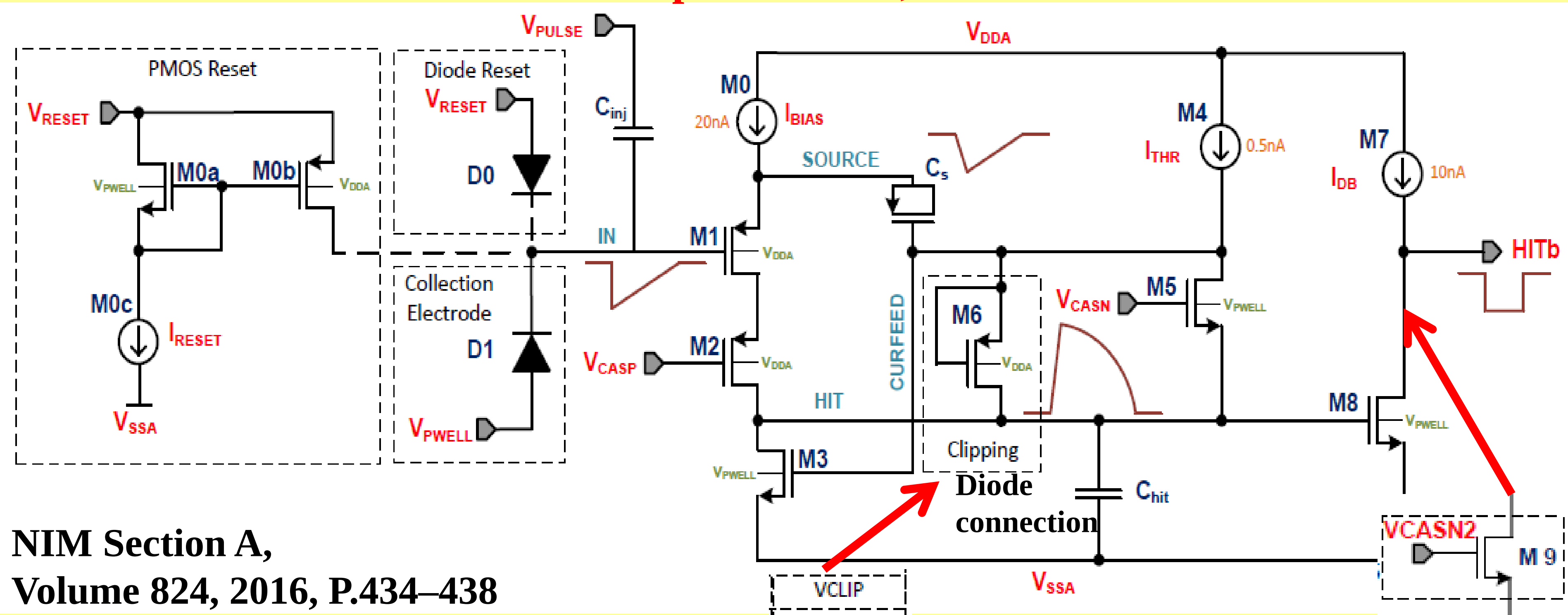
1. The number of pixels to be masked to achieve certain **fake-hit rate increases** with the lowering of temperature.

2. FHR also increases with temperature decreasing

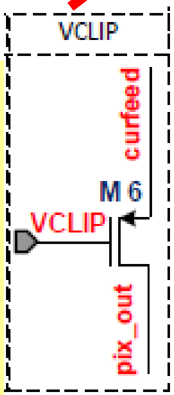
3. For low dose irradiated chip and non irradiated chip fake-hit rate **DID NOT change** over the full temperature range: **from -115 to +30 °C**

A comprehensive scheme for the pixel front-end circuit
Including all possible variations

For pALPIDE-1,2



NIM Section A,
Volume 824, 2016, P.434–438



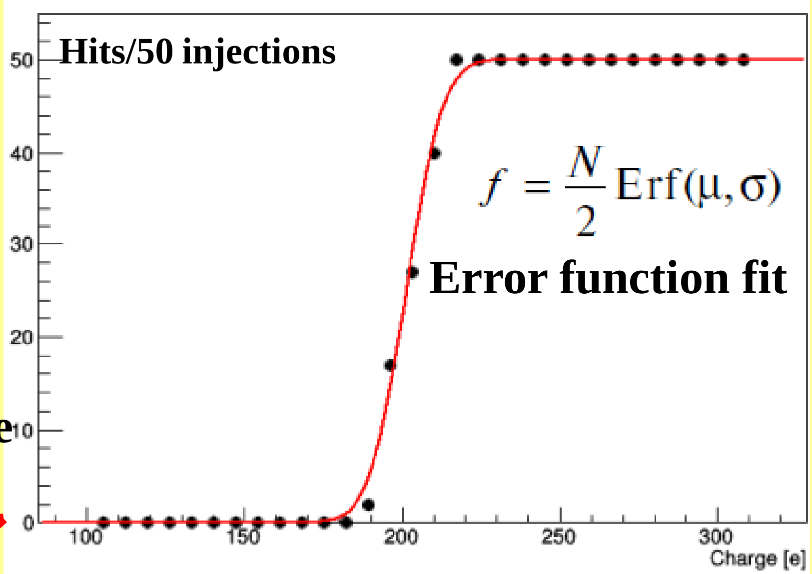
For pALPIDE-3
for sectors: 3,4,5,7
add VCLIP

For pALPIDE-3
for sectors: 0,3,4,5,7
add VCASN-2 (M9)

Study of the characteristics of ALICE ITS pixel detectors

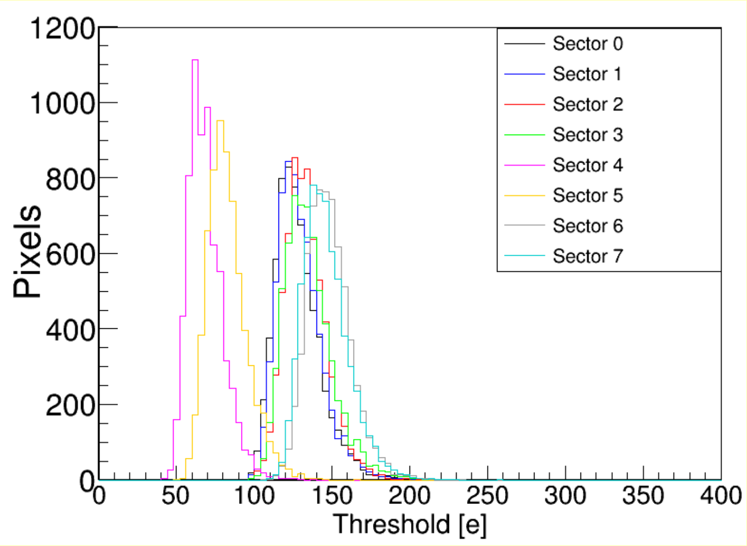
Threshold Scan

The operational thresholds for a certain set of detector's pixels depending on the charge delivered to the chosen pixels was determined

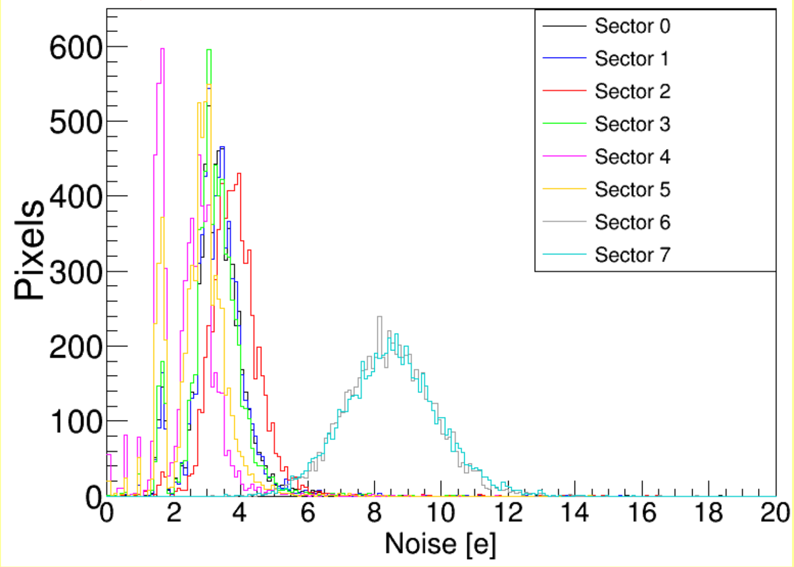


In order to extract threshold a number of charge injections with different amplitude are performed (50 points with 50 injections per point). A probability distribution of fired pixels measuring a pixel response (S-curve) has been obtained.

N - number of injections, μ - threshold value
σ- temporal noise value (threshold dispersion)



Pixel threshold distribution for 8 sectors



Temporal noise values for the pixels for 8 sectors