New technologies for the vertex detectors at the NICA collider experiments

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Outline

1. Pixel sensors for the Vertex detectors

2. Study of the pixel sensor characteristics at SPbSU

3. Extra lightweight carbon support structures for a new generation of Vertex detectors

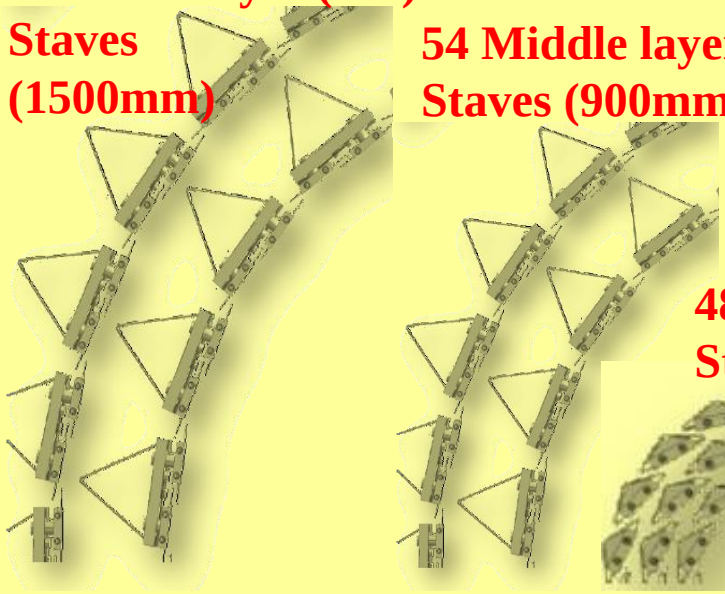
4. Summary

Pixel sensors for the Vertex detectors

90 Outer layer (OL) Staves (1500mm)

54 Middle layer (ML) Staves (900mm)

48 Inner layer (IL) Staves (290mm)

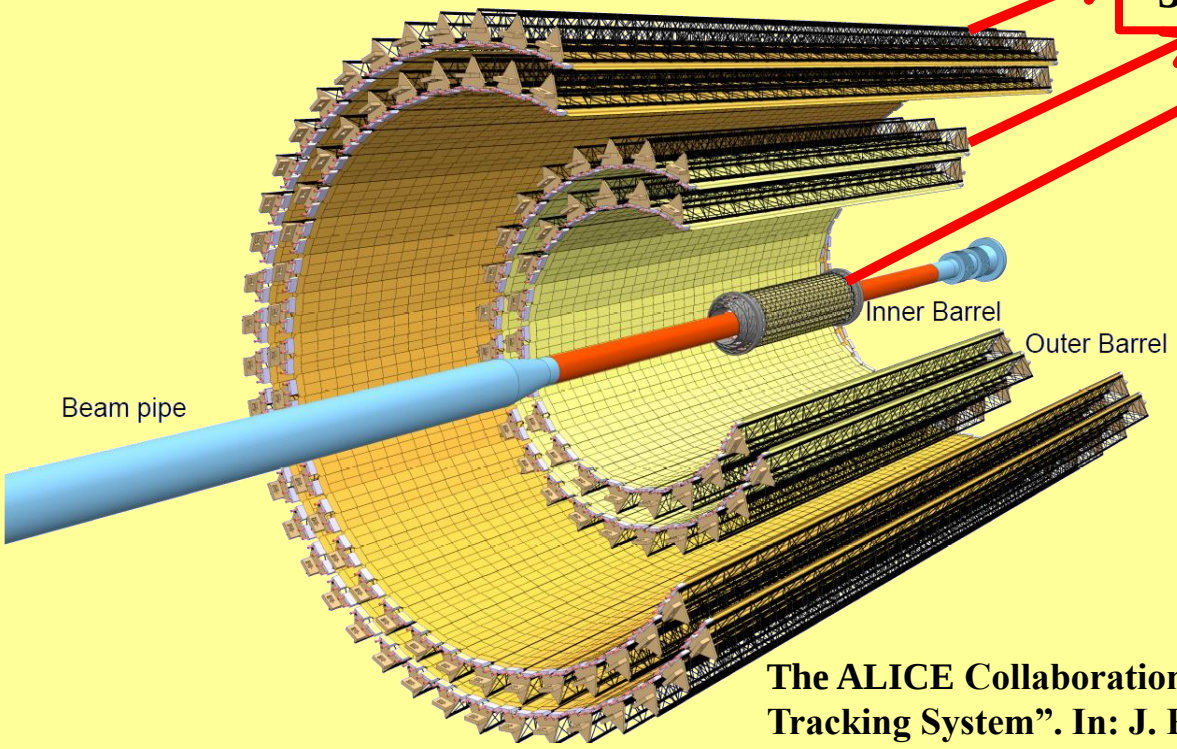


Example: ALICE Inner Tracking System

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:

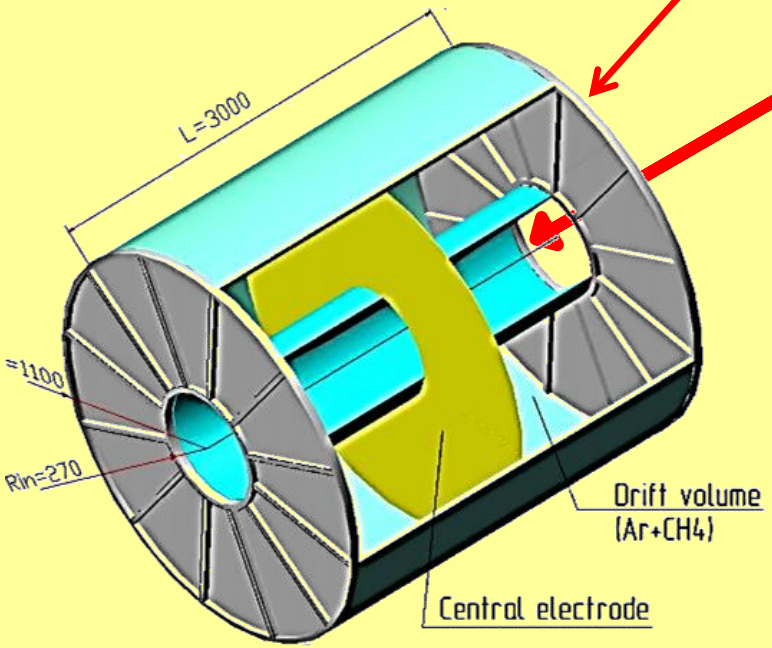
12.5 G pixels

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

Pixel sensors for the Vertex detectors

MPD tracking system: TPC + ITS

I stage of the MPD experiment: TPC only



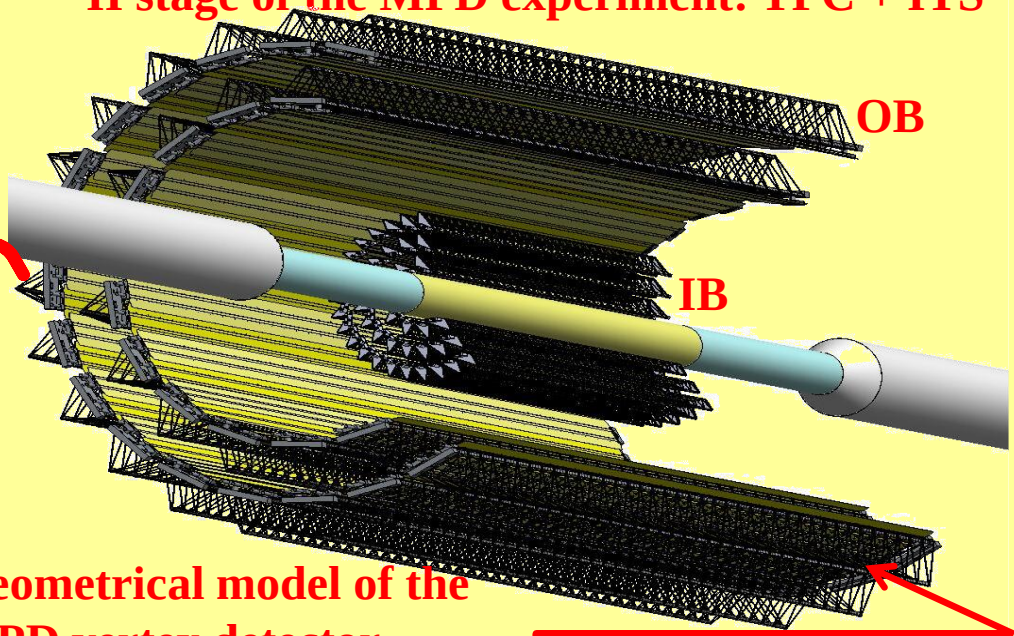
https://nica.jinr.ru/ru/projects/mpd.php

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



Geometrical model of the MPD vertex detector

ALICE technologies: for OB – ALICE Outer layer staves (1526mm)

New technologies for IB – staves 750 mm

STAVES

12, 22, 32	Inner Barrel IB
18, 24	Outer Barrel OB

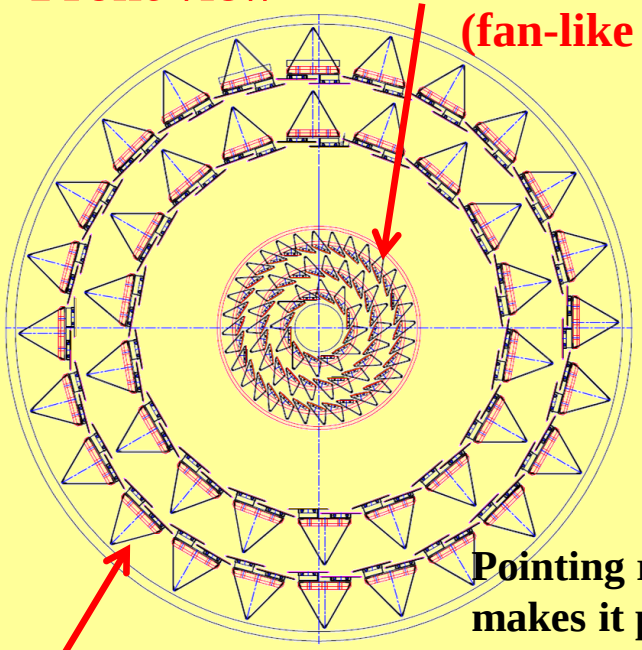
Pixel Detectors Hybrid Integrated Circuit (HIC) + **Cold plate + Space frame**

V.I. Zherebchevsky, V.P. Kondratiev, V.V. Vechernin, S.N. Igolkin, The concept of the MPD vertex detector for the detection of rare events in Au+Au collisions at the NICA collider. Nuclear Inst. and Methods, A 985 (2021), 164668.

Vertex detectors at the NICA collider experiments

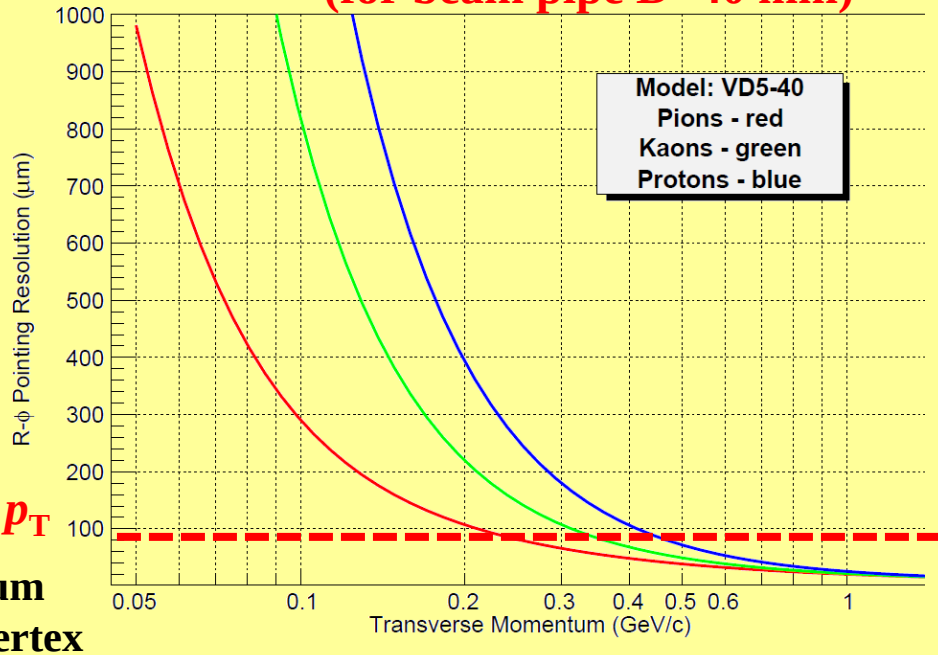
Front view

Inner Barrel
(fan-like arrangement)



Outer Barrel

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

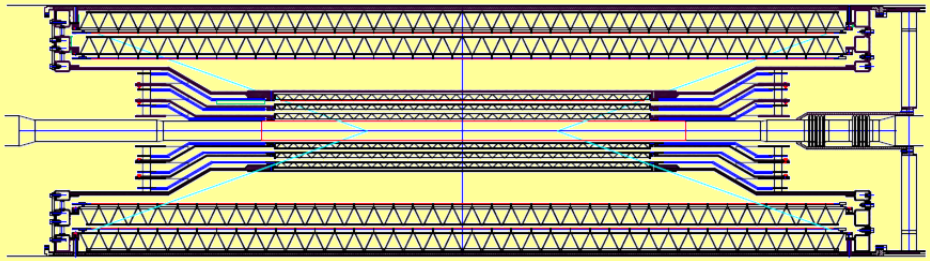


Good pointing resolution at low p_T

Pointing resolution of 120 um makes it possible a decay vertex reconstruction of D^0 (123 um) with p_T down to 500 MeV/c.

For estimations:
5 layers of Pixel Detectors, central collisions, month of collider work, efficiency of D-mesons registration by the MPD tracking system, the multiplicity of D mesons in Au + Au collisions at NICA energies (in the framework of the hadron string dynamic model) = 10^{-2}

longitudinal view



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

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

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

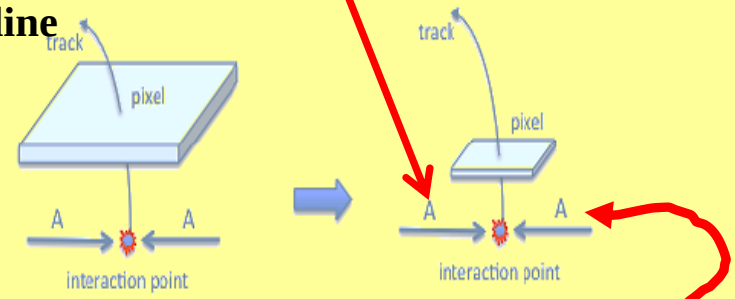
Pixel sensors for the Vertex detectors

Main motivation → **Improve tracking efficiency and p_T resolution at low p_T**

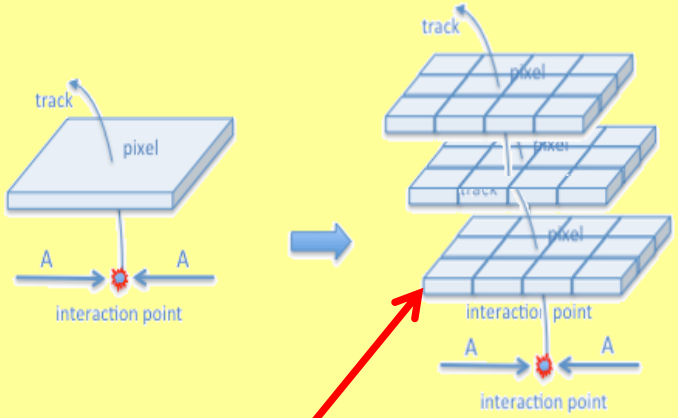
Requirements for the optimal tracking system

1. Good impact parameter resolution

a) First detection layer closer to the beam line



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

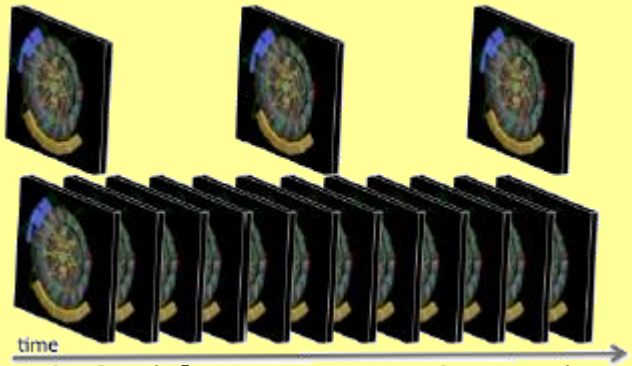


c) Increase in granularity (smaller pixels)

d) more layers

2. Fast readout

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



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

3) Lower power consumption

and optimized scheme for the distribution of Power and signals

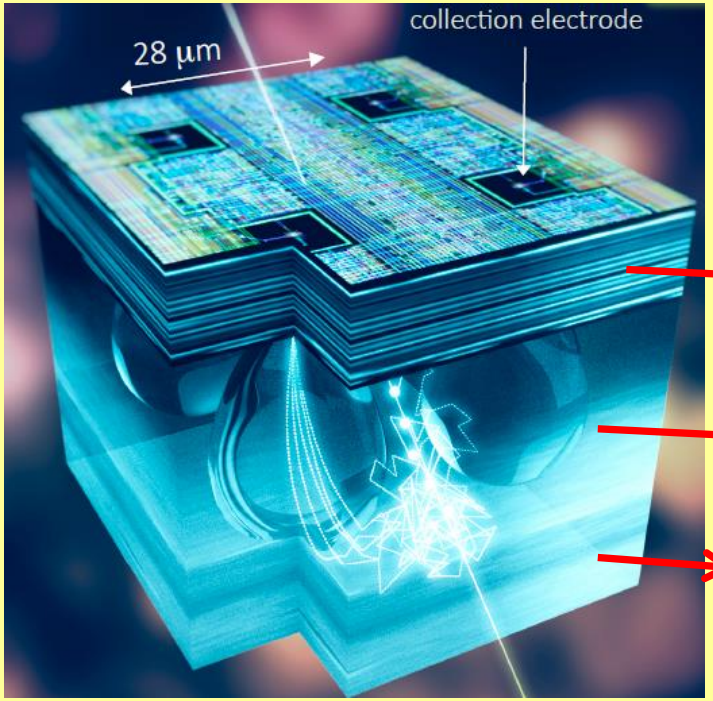
4) Radiation hardness

Pixel sensors for the Vertex detectors

MAPS: TowerJazz 180nm CMOS Imaging Process

512 × 1024 sensitive pixels

How pixel detector works?



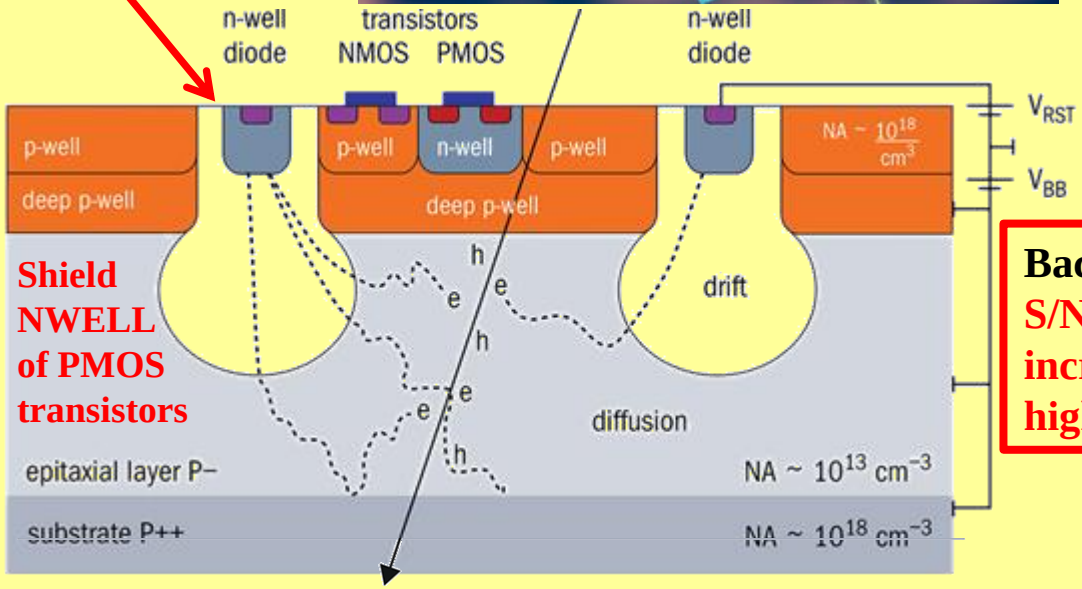
V. Manzari, EICUG2019, Paris

Metal layers (11 µm)

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

low-resistivity p-type substrate (14 µm)

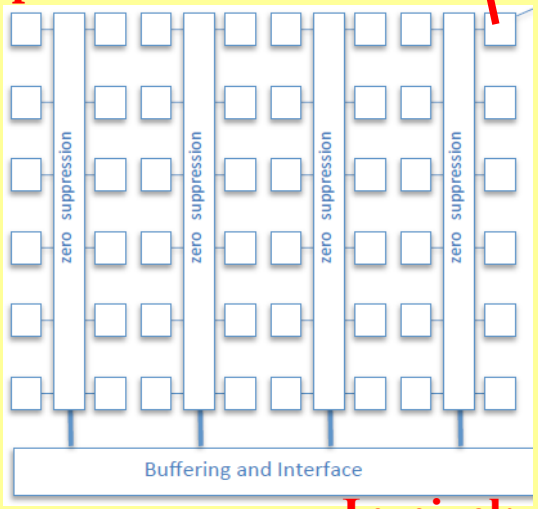
Small n-well diode (2µm diameter), ~ 100 times smaller than pixel → low capacitance



Shield NWELL of PMOS transistors

Back bias S/N ratio increases, higher efficiency

Chip architecture



In-pixel: amplification, discrimination, hit buffer

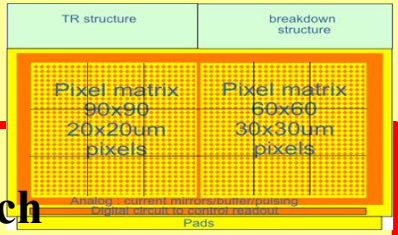
https://cerncourier.com/a/alice-tracks-new-territory/

Pixel detector general requirements and real detector properties (from ALICE ITS-2 TDR)

Parameter	Inner Barrel (IB)	Outer Barrel (OB)	ALPIDE Performance
Silicon thickness	50 μm	100 μm	
Chip dimension	15 mm x 30 mm	15 mm x 30 mm	
Spatial resolution	5 μm	10 μm	5 μm (IB), 5 μm (OB)
Power density	< 300 mW/cm^2	< 100 mW/cm^2	40 mW/cm^2 (IB), 30 mW/cm^2 (OB)
Max. integration time	30 μs	30 μs	10 μs
Detection efficiency	>99%	>99%	>99% **Upper limit!**
Fake-hit rate	<10^{-5}(TDR),<10^{-6}* /event/pixel for IB and OB		<<<10^{-6} /event/pixel
Total Ionizing Dose	270 krad 2.7 Mrad*	10 krad, 100 krad*	Up to 500 krad
Non-Ionizing Energy Loss (1 MeV n_{eq}/cm^2)	1.7 x 10^{12} (TDR), 1.7 x 10^{13}*	1.7 x 10^{11} (TDR), 1.7 x 10^{12}*	Up to 1.7 x 10^{13}

radiation load integrated over the approved program (~ 6 years of operation)
*revised numbers with respect to ALICE TDR (factor 10)

Pixel sensors for the Vertex detectors



2012 — Explorer

Explorer-1,2

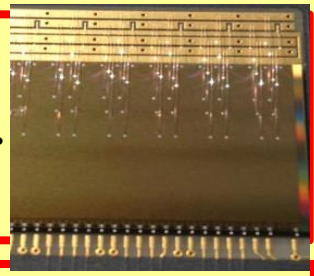
Two submatrices: 90x90 array of 20 x 20µm pixels and 60x60 array of 30x30µm pixels. Each sub-matrix is divided into 9 sectors with one variant of collection electrode(analogue readout). Investigations: pixel geometry, starting material, sensitivity to radiation.

2013 — pALPIDEss

Matrix with 64 columns x 512 rows of 22µm x 22µm pixels. (in-pixel discrimination and buffering). Study priority encoder and the front-end electronics

May-2014 — pALPIDE-1

Full-scale prototype to study system effects: 1024 columns x 512 rows of 28µm x 28µm pixels. 4 sectors with different pixels.



May-2015 — pALPIDE-2

4 sectors with different pixels. Optimization of several circuit blocks. Allows integration into ITS modules

Oct-2015 — **pALPIDE-3**

8 sectors with different pixels. Final interfaces, more features including 1.2 Gbit/s output serial link.

Jul - 2016

ALPIDE – Final Version

Study of the pixel sensor characteristics at SPbSU

Characterization, tests, studies of the non irradiated and 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**

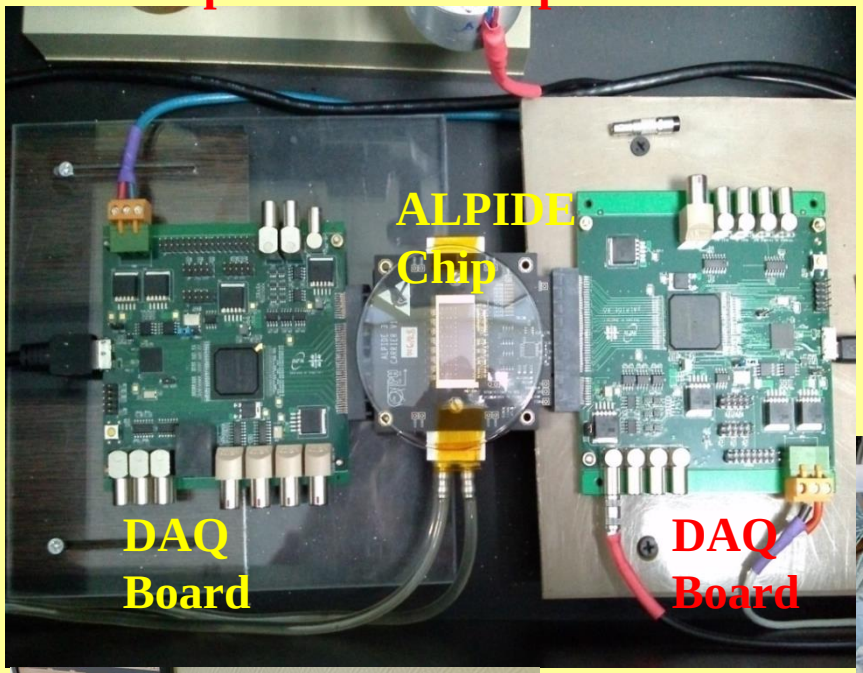
5. **The possibilities for cooling of new generation ultra-thin pixel detectors including nitrogen cooling have been investigated**

   } **Experimental set-up III**
   Experimental set-up IV

For further information see also: V. I. Zherebchevsky, N.A. Maltsev, S.N. Igolkin et.al Silicon Pixel Detectors for the Inner Tracking System of the MPD Experiment at the NICA Collider, Bulletin of the Russian Academy of Sciences: Physics, 2021, Vol. 85, No. 5, pp. 541–547

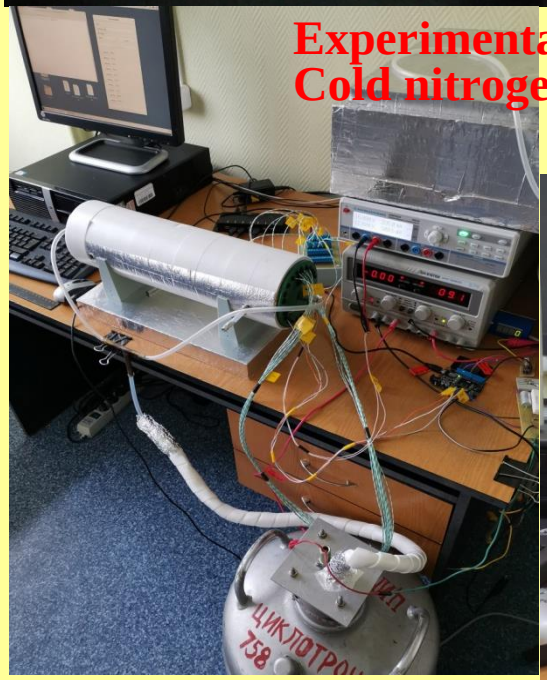
Study of the pixel sensor characteristics

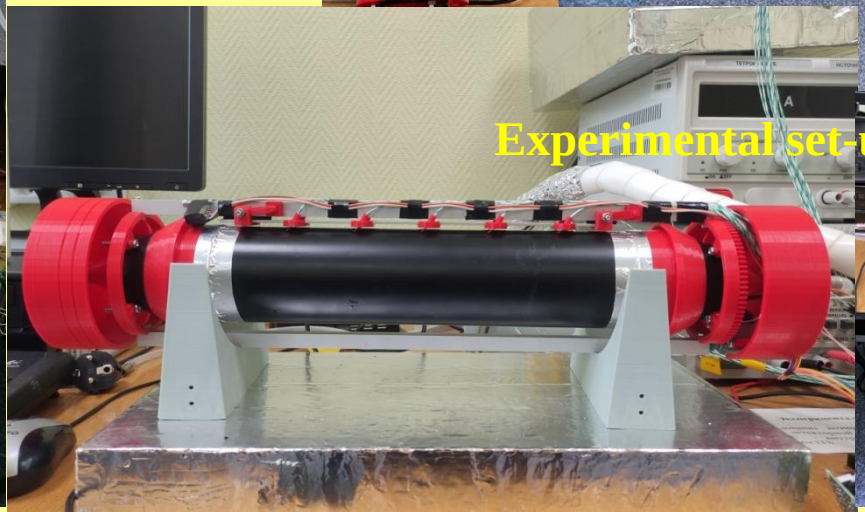
Experimental set-up I



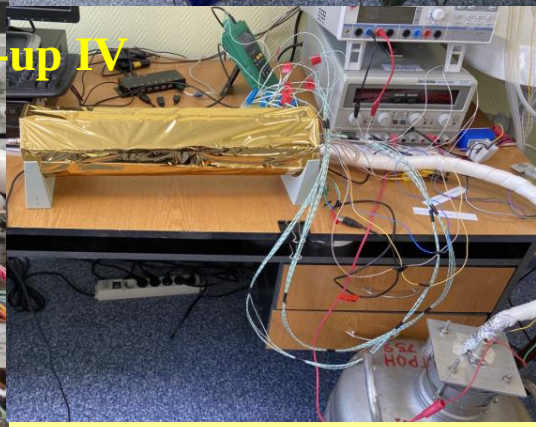
Experimental set-up II with cryogenic module

Experimental set-up III
Cold nitrogen flow

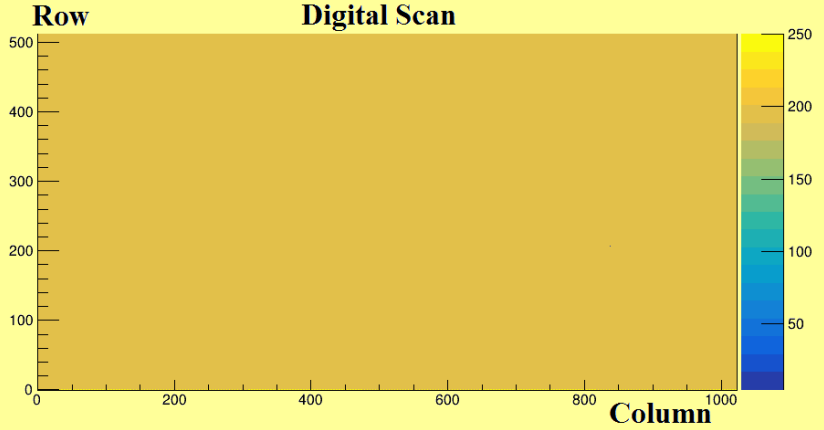




Experimental set-up IV



Study of the pixel sensor characteristics

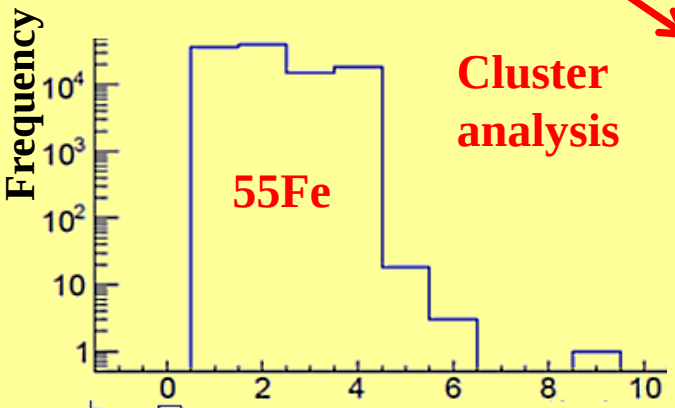


Not working pixels searching

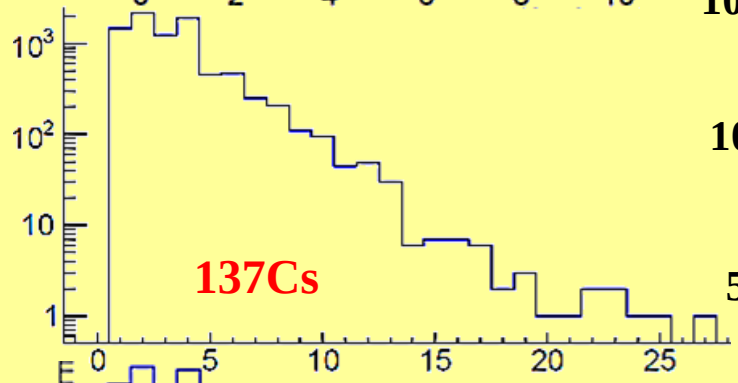
Characterization and tests

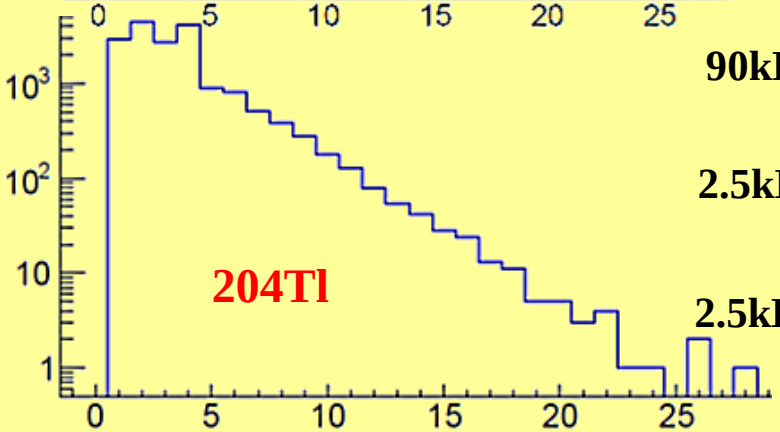
Investigations of pixel matrix

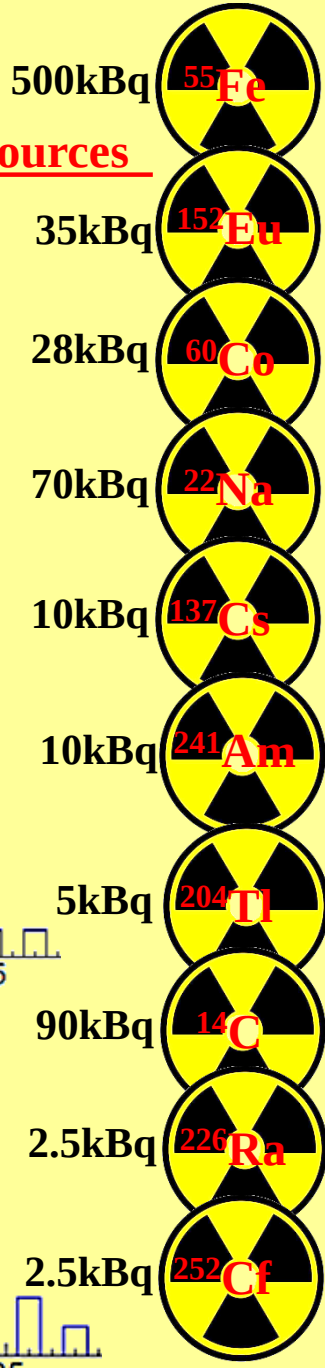
Properties with different radioactive sources



Cluster analysis

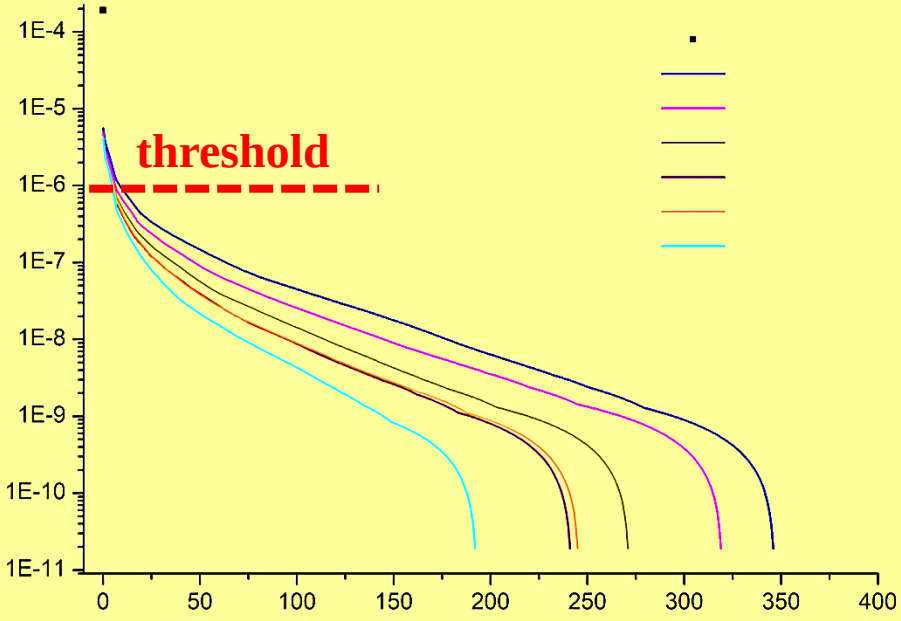






Fake Hit Rate

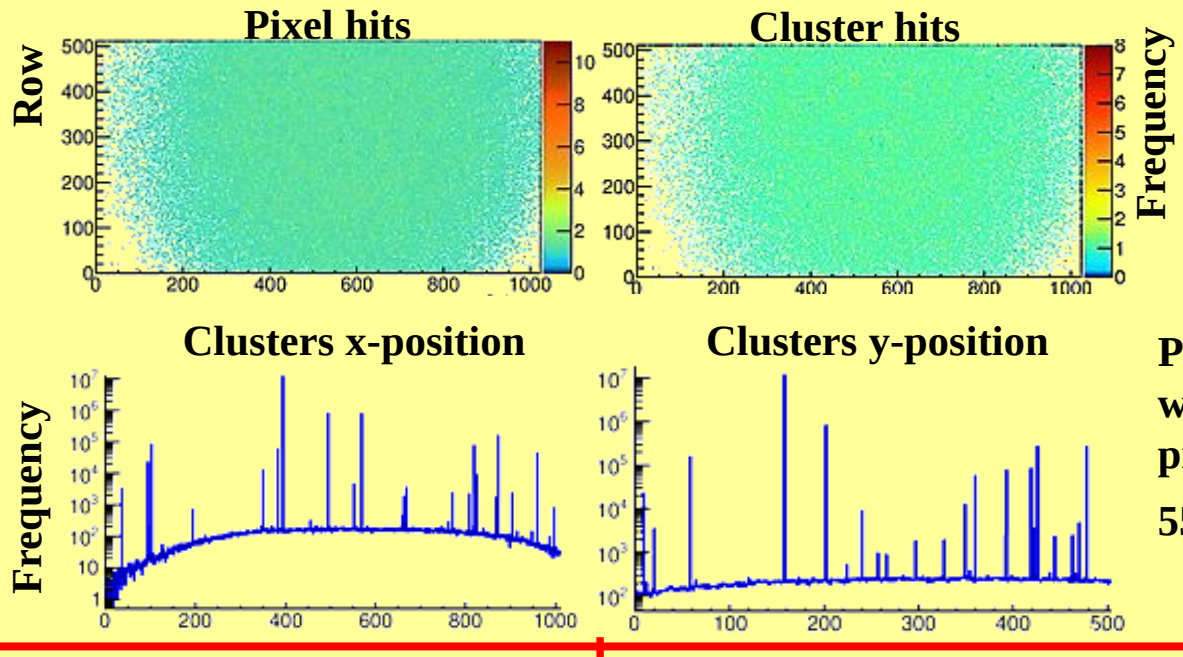
Noise characteristics of the sensors



Study of the pixel sensor characteristics

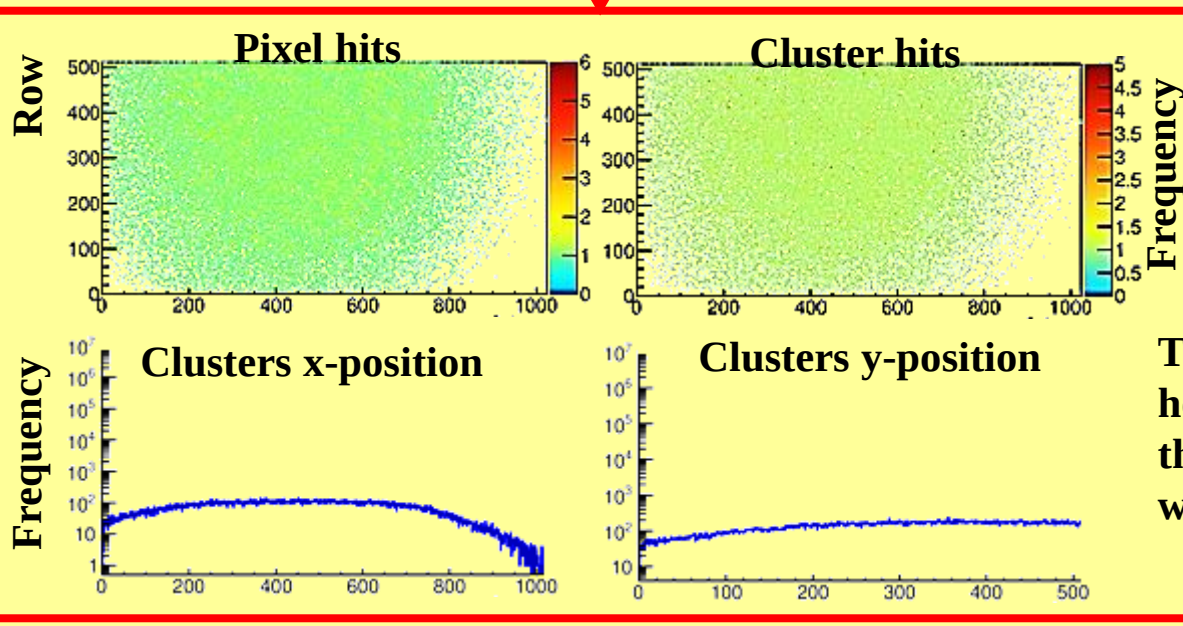
Investigations of noise performances

Characterization and tests



Pixel matrix with hot pixels

55Fe



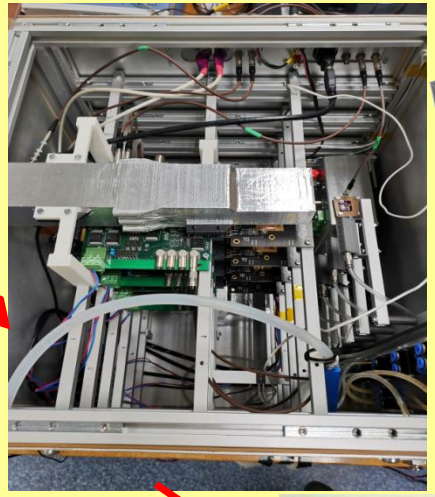
To exclude hot pixels the mask was applied

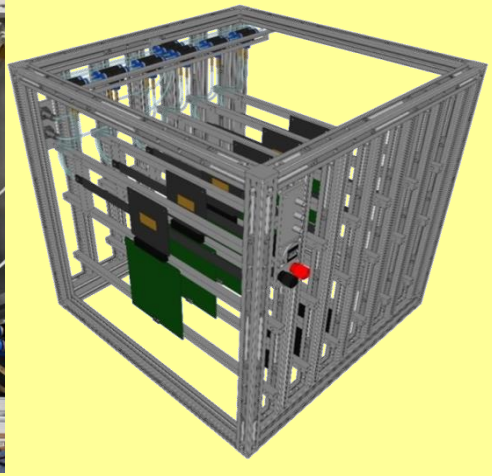
Development of an especial mask to exclude the noises pixels

Study of the pixel sensor characteristics

Beam tests in JINR

The TERMINATOR - Experimental set-up for the NICA MPD Inner Tracker





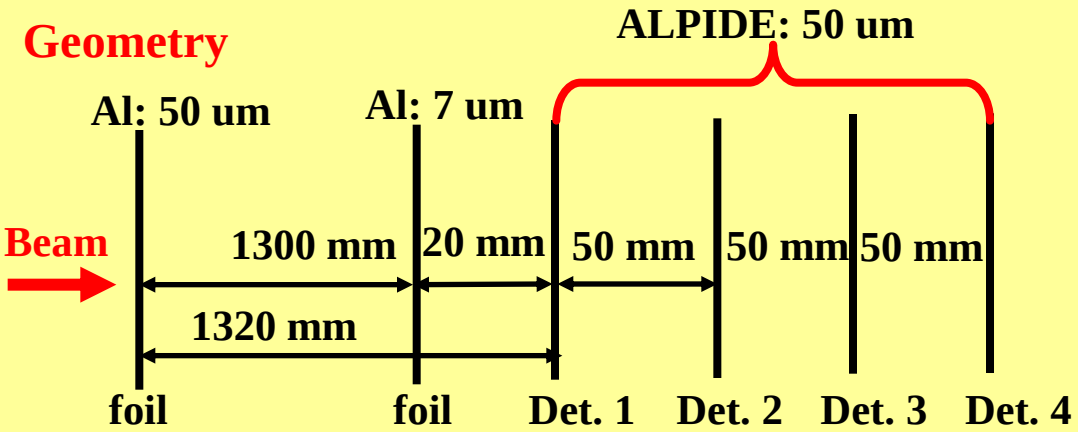
Run 1, Run 2

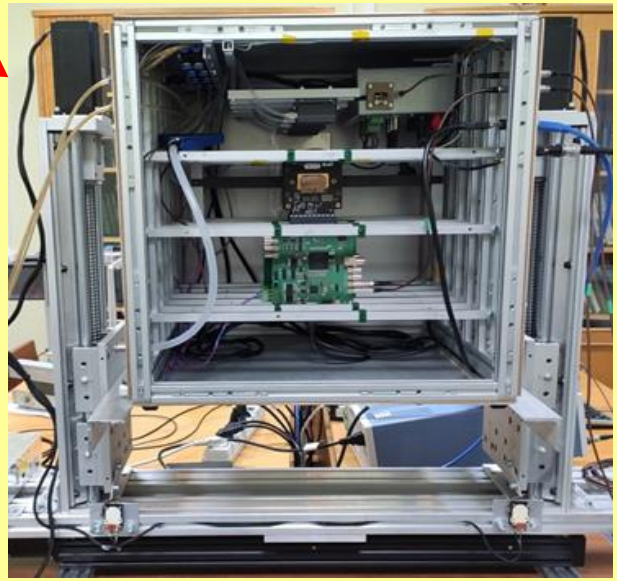
Accelerator: LINAC-200

Beam: electrons ~ 50-60 MeV

electrons ~ 150 MeV

Geometry





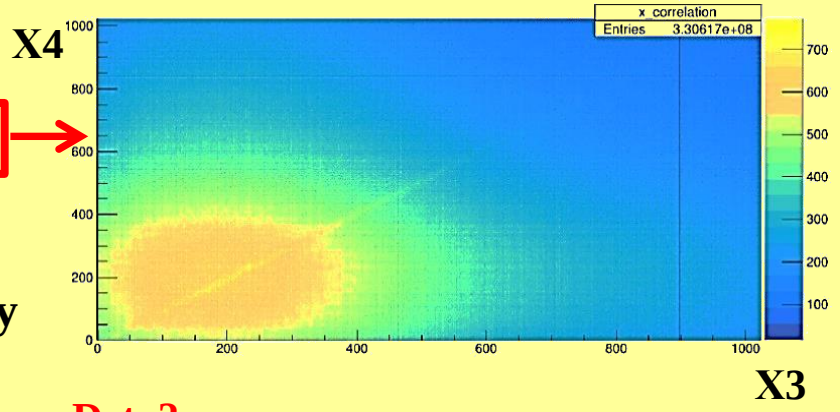
GEANT 4 calculation of the doses on the detectors

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

Study of the pixel sensor characteristics

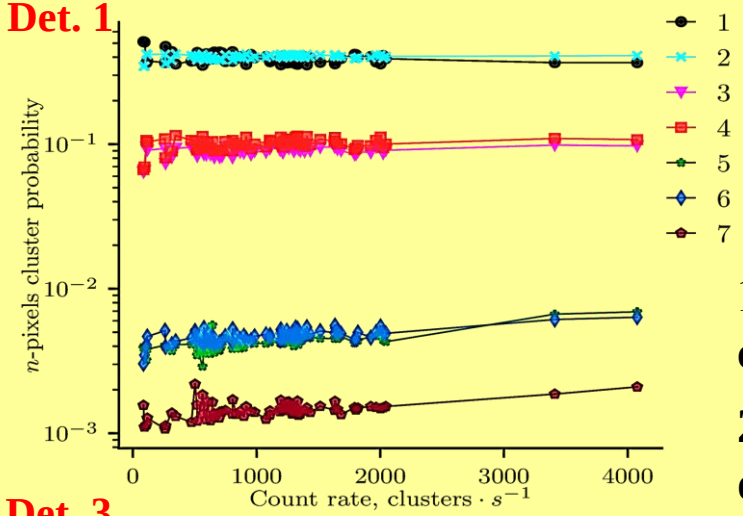
Beam tests in JINR

Correlations of pixel clusters between the detector planes

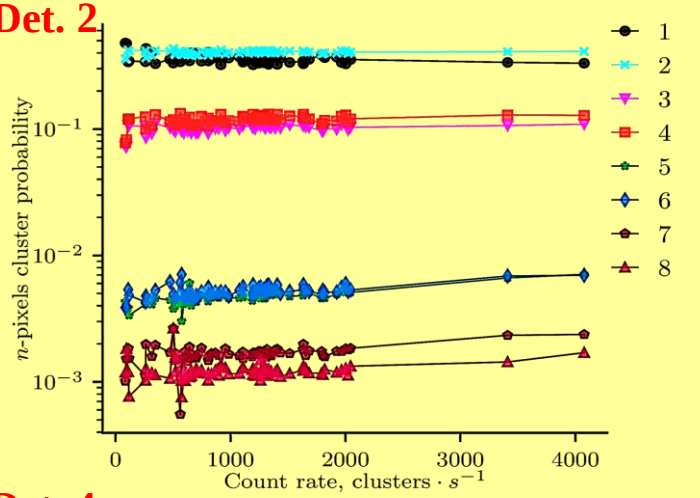


The probability of occurring the clusters with multiplicity n vs. electron beam (150 MeV) intensity

Det. 1



Det. 2

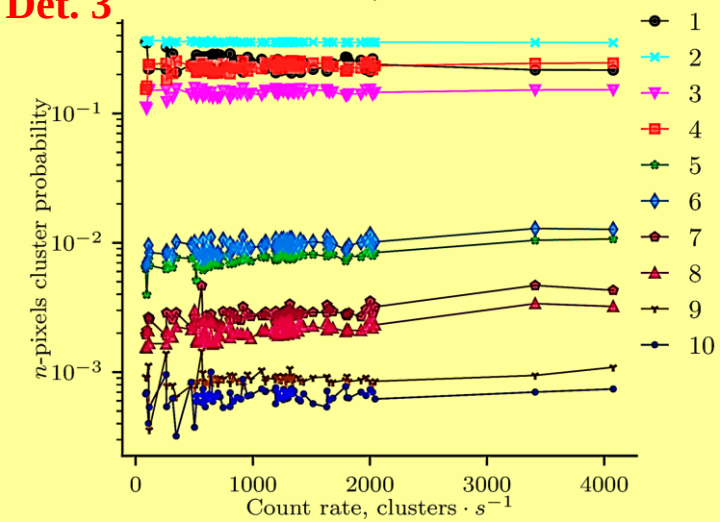


1) n ≤ 4 -95% clusters

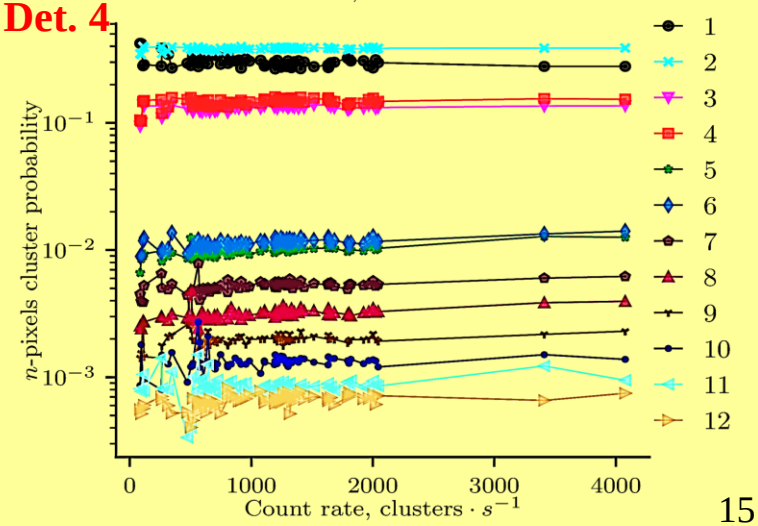
2) n ≤ 4 – there is no dependency on the beam intensity

3) There is no big clusters (n only up to 12)

Det. 3



Det. 4



Study of the pixel sensor characteristics

Beam tests in PNPI

Run 1

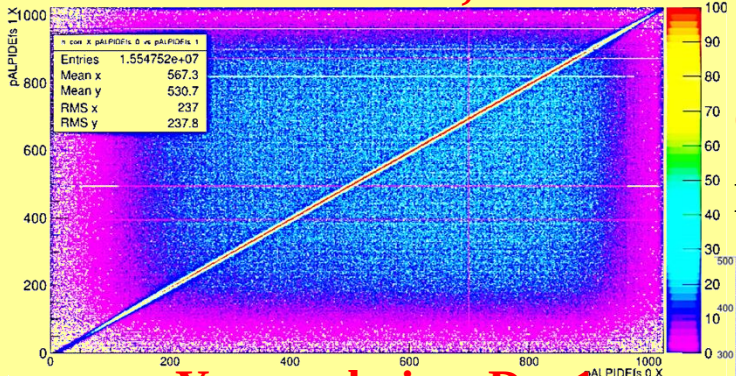
Synchrocyclotron- 1000

Beam: protons - 1 GeV

http://www.pnpi.nrcki.ru/

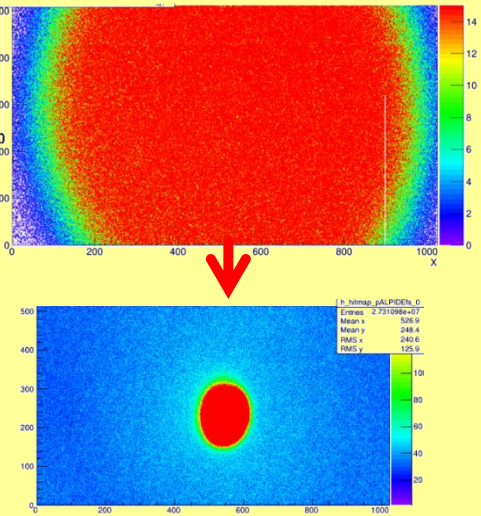
Excellent correlations of pixel clusters between all detector planes (X and Y)

X- correlation, Det.1

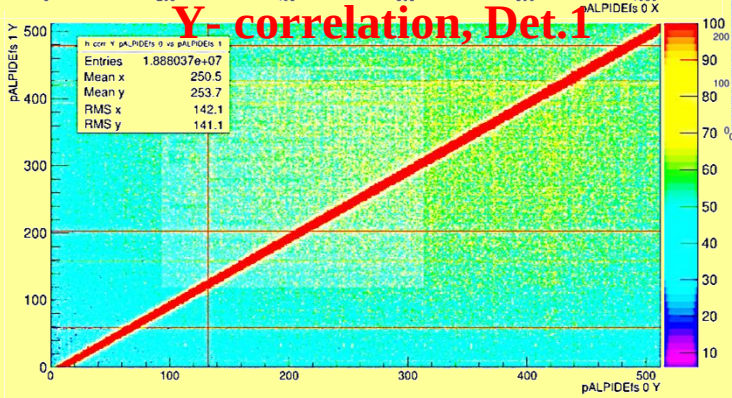


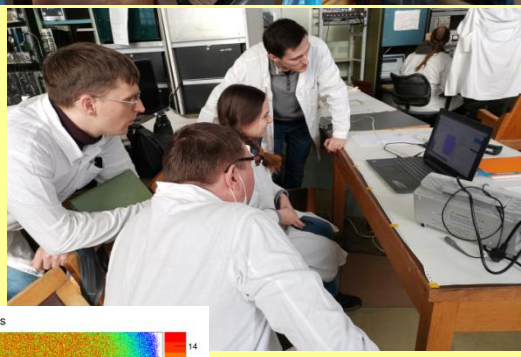
Good beam collimation

Det.1 Row HitMap

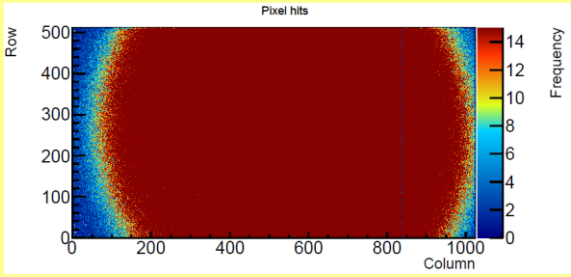


Y- correlation, Det.1

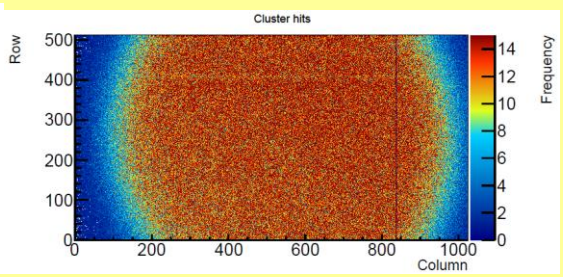




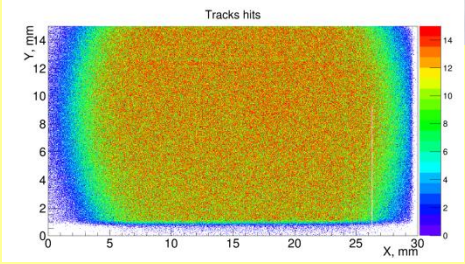
Pixel hits



Cluster hits



Tracks hits



Study of the pixel sensor characteristics

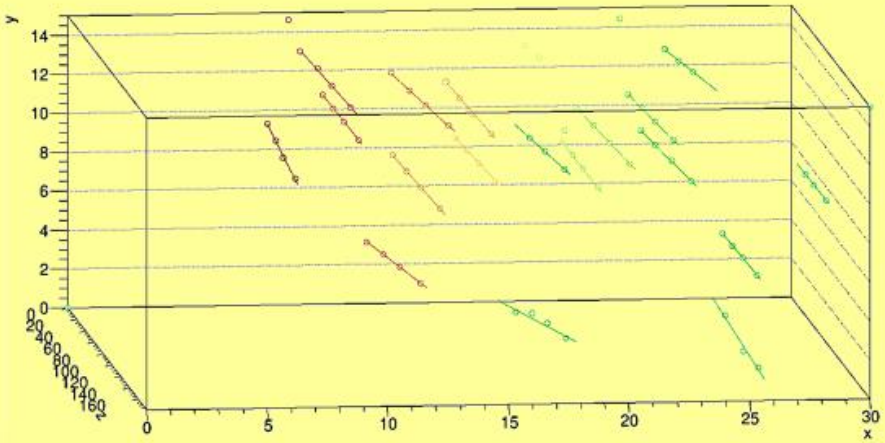
One can define the beam emittance by using tracking analysis

Эксперименты в PNPI

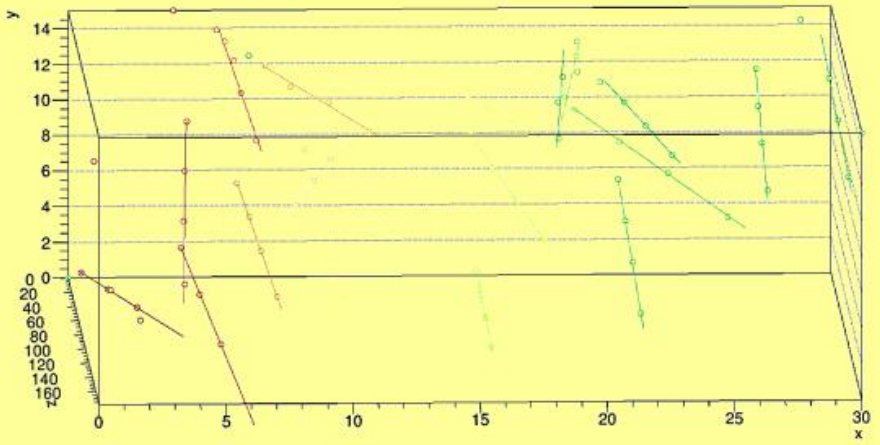
Synchrocyclotron- 1000

Протоны: 1 ГэВ, 200 МэВ

Идентификация и реконструкция треков

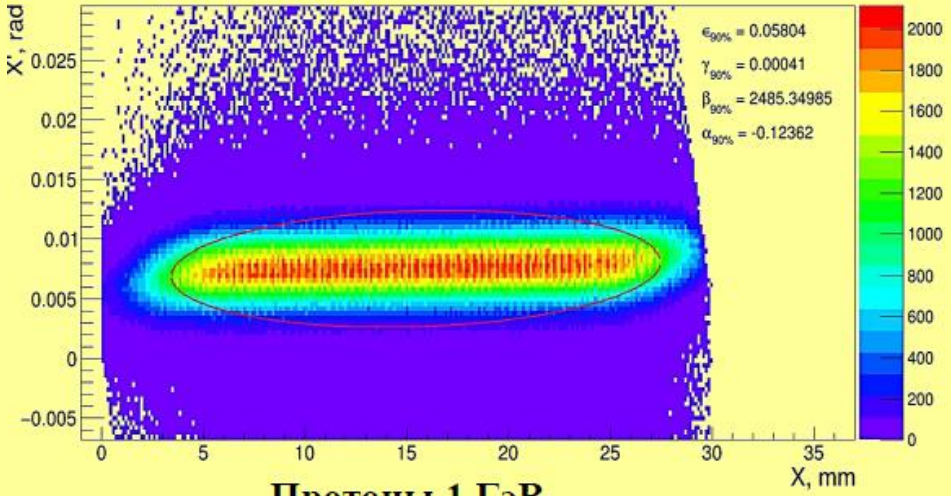


Протоны 1 ГэВ

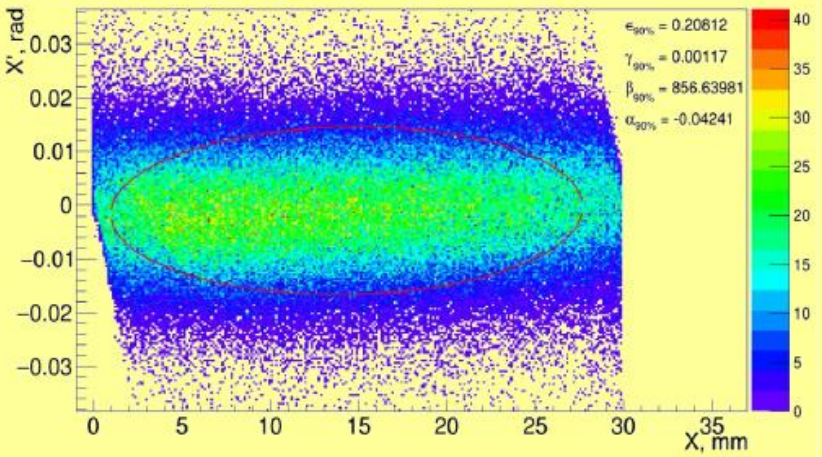


Протоны 200 МэВ

Определение эмиттанса



Протоны 1 ГэВ



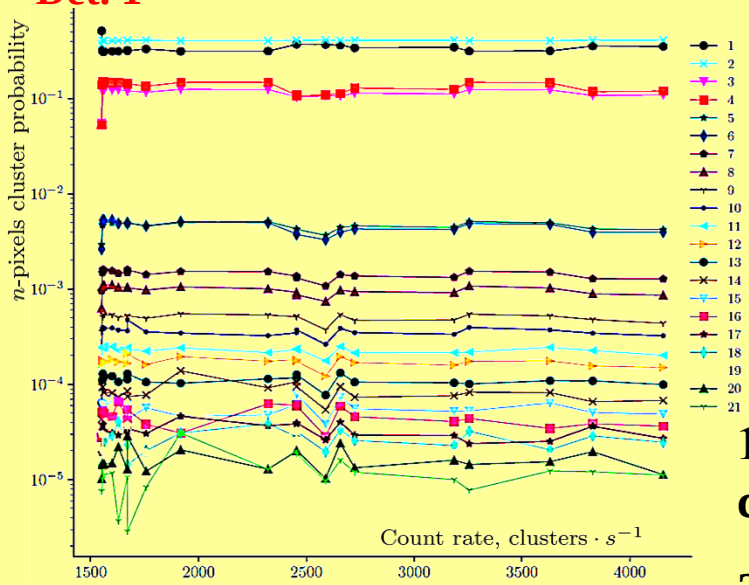
Протоны 200 МэВ

Study of the pixel sensor characteristics

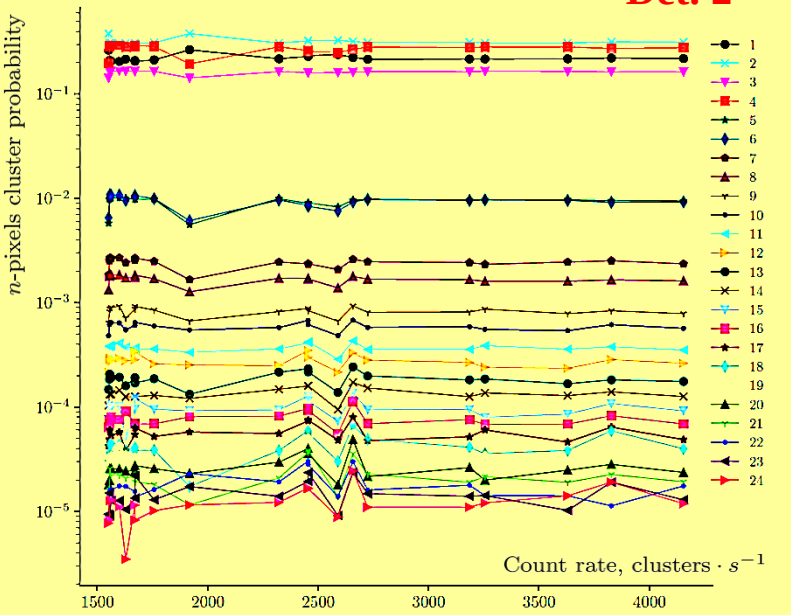
Beam tests in PNPI

The probability of occurring the clusters with multiplicity n vs. proton beam (1 GeV) intensity

Det. 1



Det. 2

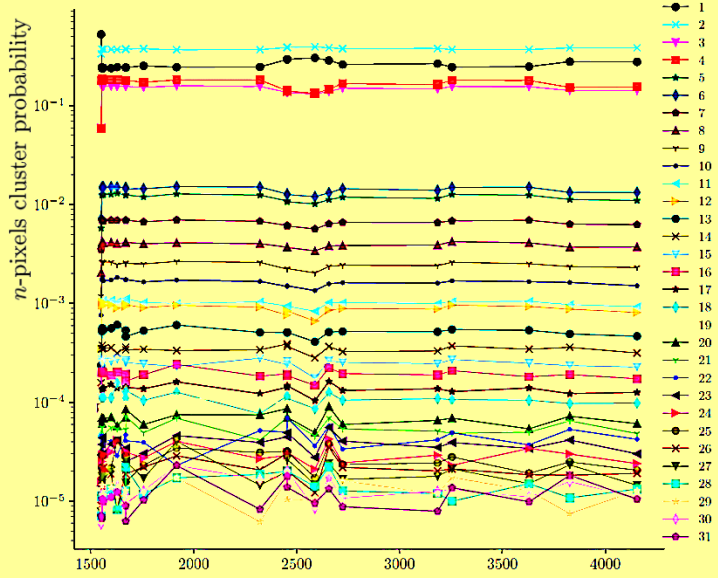


1) n ≤ 4 -95% clusters

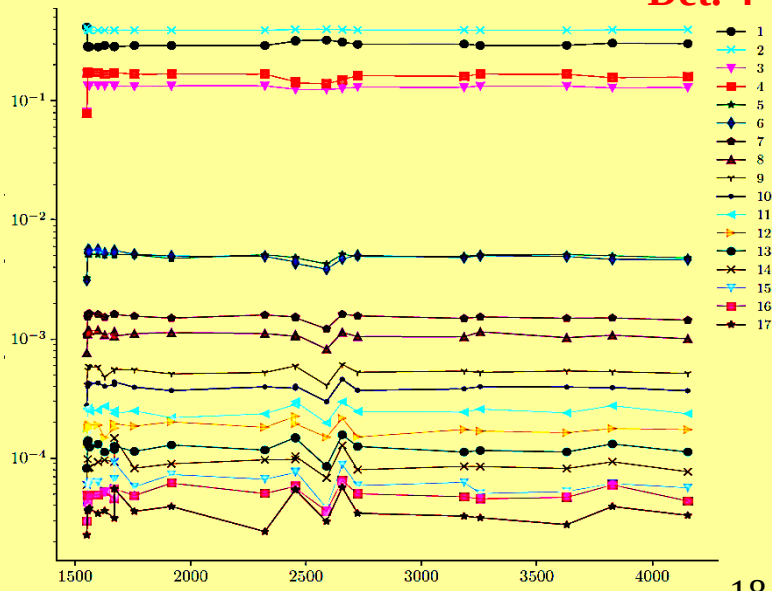
2) There is no dependency on the beam intensity for all clusters

3) The big clusters (n up to 31) can occure

Det. 3



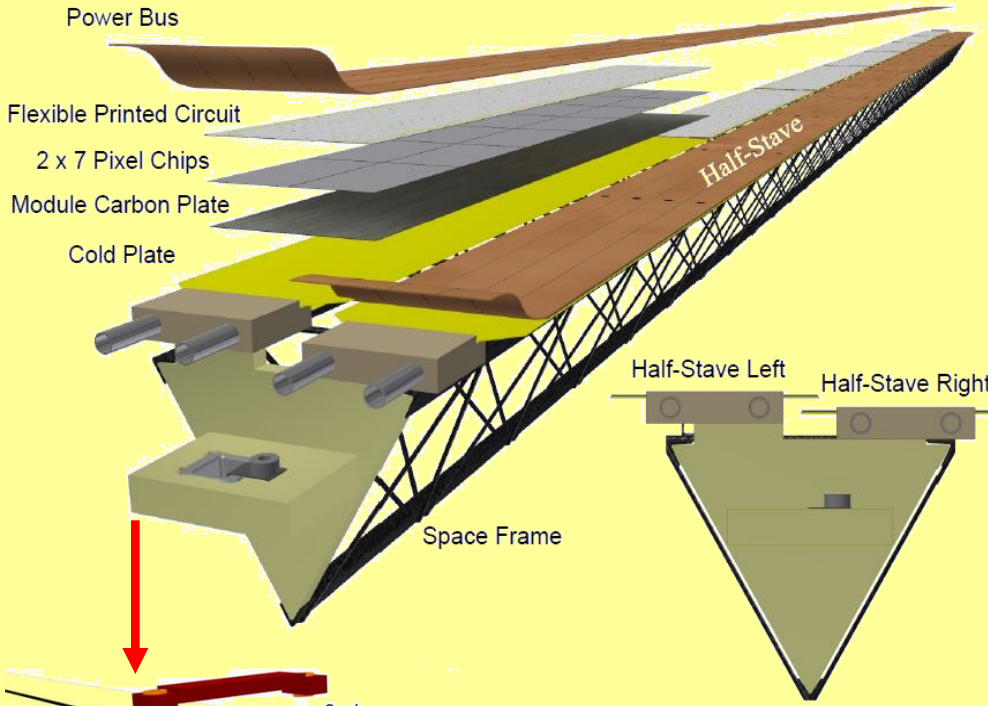
Det. 4

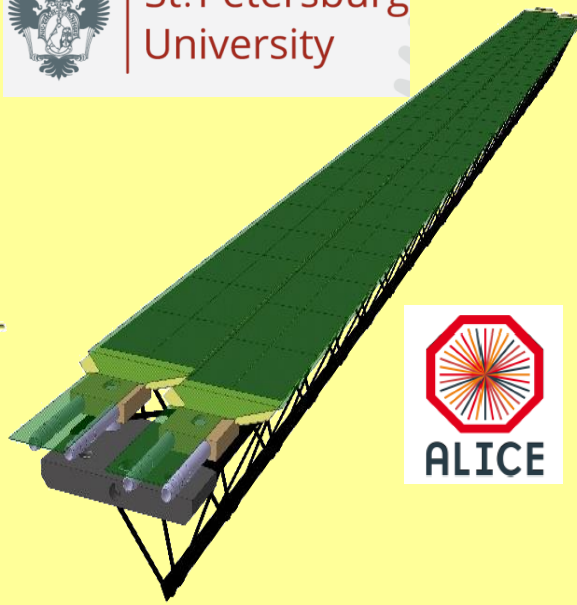


Extra lightweight carbon support structures for a new generation of Vertex detectors

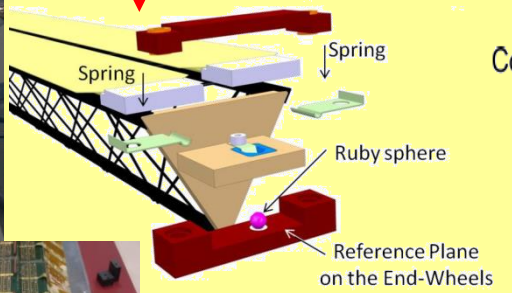
ALICE Outer Barrel Stave

St. Petersburg University

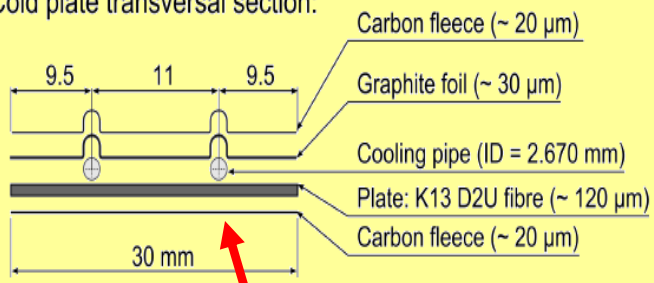


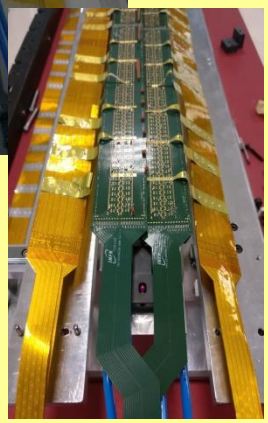


ALICE



Cold plate transversal section:





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

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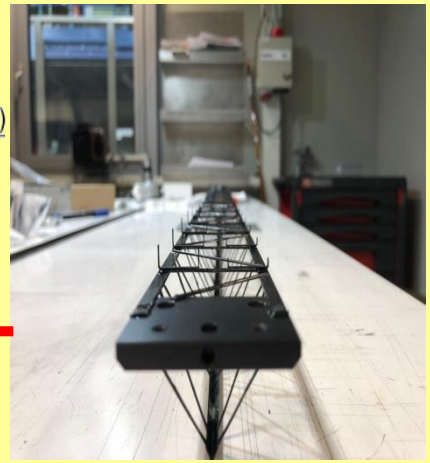


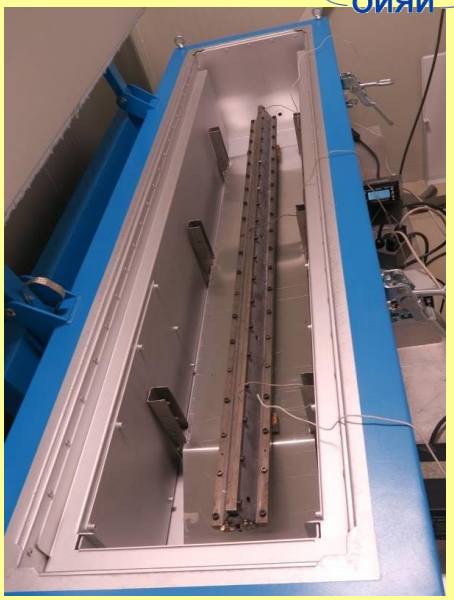
Cold plate **Space Frame**

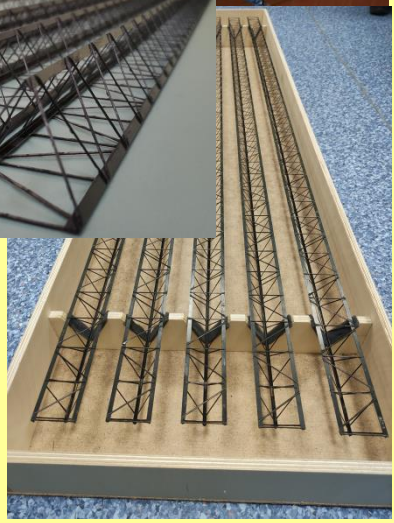
Extra Lightweight Detector Support Structures for the Inner tracking System of the MPD experiment

MPD Outer Barrel Stave

1) The technology of production of Extra Lightweight Detector Support Structures was modified for Russian prepreg «НИИКАМ-PC/M55» (Research Institute of Space and Aviation Materials)

2) The studies of mechanical, space, deformation characteristics produced structures were done





S.N. Igolkin, G.A. Feofilov, RF Patent no. 2396168 and RF Patent no. 79268 U1 РФ.МПК B29C 53/56, 2008

30 Wound-truss structures were produced at SPbSU and shipped to JINR

For the MPD ITS Extra Lightweight Detector Support Structures the new technology for cold plate, wound-truss structures have been developed at SPbSU

Wound-truss structures - SPbSU

Cold plate - JINR

Final production SPbSU + JINR

V. I. Zherebchevsky, S. N. Igolkin, G.A. Feofilov et al. New Technologies for the Vertex Detectors in the NICA Collider Experiments, Bull. of the Russian Academy of Sciences: Physics, 2022, Vol. 86, No. 8, pp. 948–955

Summary

1) The technologies for the vertex detectors at the NICA collider experiments together with new ultra-light radiation-transparent carbon fiber support structures as basic elements for these detectors and CMOS monolithic active pixel sensors are discussed

2) Experimental set-ups for the characterization of pixel sensors have been developed, constructed and tested.

3) The characteristics and properties of new pixel sensors were investigated in context of the NICA collider experiments tasks.

4) The Extra Lightweight Detector Support Structures were produced for the Inner Tracker of MPD NICA

For more read see: V.I. Zherebchevsky, V.P. Kondratiev, V.V. Vechernin, S.N. Igolkin, Nuclear Inst. and Methods, A 985 (2021), 164668.
V. I. Zherebchevsky, S. N. Igolkin, G.A. Feofilov et al., Bull. of the Russian Academy of Sciences: Physics, 2022, Vol. 86, No. 8, pp. 948–955

Next plans

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

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

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

4. Studies of the pixel sensors 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