Novel Technologies for the MPD-ITS

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Yangtze
The outline:

- The physics case – creation of deconfined matter in the lab and role of the rare probes (heavy hyperons and charmed mesons) in search of hints of critical point
- A story of silicon detectors in High Energy physics (after Luciano Musa, CERN, Bormio School, 2018)
- Transition from strips to pixels and MAPS “invasion”
- The new ALICE ITS experience
- Plans for its implementation for the NICA MPD ITS
Look for a needle in a “hay” of tracks for rare events

The Inner Tracking System or Vertex tracker is a multilayer telescope which measures the position of particle hits positions to restore the track trajectory. It’s special task to be located as close as possible to the interaction point and to be as precise as possible to identify specific decays of particles carrying strangeness, charm or beauty i.e. S, C, or B - quarks.
The basic task for the Inner Tracking System

Identification of particles through inspection of Inverse Mass distributions

\[ M^2 = \text{sum}(E_i)^2 - \text{sum}(P_i)^2 \quad (c=1) \]

Yu.Murin. Lecture to WUT students
Current and future experiments on CBM

Interaction rate [Hz]

Collision energy $\sqrt{S_{NN}}$ [GeV]

2022 – 2025: SIS-100 FAIR

NICA/BM@N II

HADES

STAR F.T.

CBM

NICA/MPD

STAR BES II

NA-61/SHINE

energy region of max. baryonic density

August 23, 2019

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The rise of silicon detectors in HEP

Towards end of 1970’s: intensive R&D on devices which could measure short-lived particles (10^{-12} - 10^{-13} s)

R&D at CERN^{(A)} and Pisa^{(B)} demonstrated that strip detectors (100-200μm pitch):
- high detection efficiency (>99%), good spatial resolution (~20μm) and good stability
- precise vertex reconstruction

However: fabrication of these devices was very tricky, thus limiting their availability

1980 – fabrication of silicon detectors using standard IC planar process (PIN diode \(\rightarrow\) μstrip detector)


First use of silicon strips detectors by NA11(CERN SPS) and E706 (FNAL)

(A) NA11 (1981): 6 planes (24 x 36mm²): resistivity 2-3 kΩcm, thickness 280μm, pitch 20μm
(B) E706 (1982): 4 planes (3x3 cm²) + 2 planes (5x5cm²)

Erik Heine, Joseph Kemmer and Gherard Lutz: 2017 EPS prize for “Outstanding Contributions to HEP” (pioneering the development of silicon μstrip)
The rise of silicon detectors in HEP

The next step forward came with the advent of the VLSI technology that allowed coupling ASIC amplifier chips directly to the detectors

1990s - LEP, first silicon vertex detectors were installed in DELPHI and ALEPH experiments, then OPAL and L3

1989 - first DELPHI vertex detector, consisting of two layers of single-sided strip detectors

Projective geometry \(\Rightarrow\) ambiguity at high multiplicities (high occupancy)

This started to become apparent already at DELPHI:

- High number of ambiguities \(\Rightarrow\) reconstruction efficiency suffered a lot, especially in the forward direction

Not usable close to IP in hadron colliders (LHC) or HI experiments at SPS

Another problem at (very) high particle load \(\Rightarrow\) degradation of the sensor by the high radiation dose

This implies starting with a very large signal-to-noise ratio, which can only be obtained with detector with small capacitance
The Inception of Silicon Pixel Detectors

“The silicon micropattern detector: a dream?”

“Development of silicon micropattern detectors”

1995 – First Hybrid Pixel detector installed in WA97 (CERN, Omega facility)

1996/97 – First Collider Hybrid Pixel Detector installed in DELPHI (CERN, LEP)

CERN – WA97 Experiment (1995)

- 5 x 5 cm² area
- 7 detector planes
- ~0.5 M pixels
- Pixel size 75 x 500 μm²
- 1 kHz trigger rate
- Omega2 chip

Work carried out by RD19 for WA97 and NA57/CERN
Pixel Detectors at the LHC

10 years after the first use in WA97... hybrid pixel detectors at the heart of the LHC experiments

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ALICE</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nr. layers</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Radial coverage [mm]</td>
<td>39 - 76</td>
<td>50 - 120</td>
<td>44 - 102</td>
</tr>
<tr>
<td>Nr of pixels</td>
<td>9.8 M</td>
<td>80 M</td>
<td>66 M</td>
</tr>
<tr>
<td>Surface [m²]</td>
<td>0.21</td>
<td>1.7</td>
<td>1</td>
</tr>
<tr>
<td>Cell size (rφ x z) [μm²]</td>
<td>50 x 425</td>
<td>50 x 400</td>
<td>100 x 150</td>
</tr>
<tr>
<td>Silicon thickness (sens. + ASIC) - x/X₀ [%]</td>
<td>0.21 + 0.16</td>
<td>0.27 + 0.19</td>
<td>0.30 + 0.19</td>
</tr>
</tbody>
</table>
Beyond Hybrid Pixel Detectors ...

Since the very beginning of pixel development (CERN RD 19):

dream to integrate sensor and readout electronics in one chip

Motivation to reduce: cost, power, material budget, assembly and integration complexity

Several major obstacles to overcome:

- CMOS generally not available on high resistivity silicon (needed as bulk material for the sensor)
- Full CMOS circuitry not possible within the pixel area (only one type of transistor → slow readout)

MAPS exist in many different flavors: CMOS, HV CMOS, DEPFET, SOI

The following will cover only CMOS Active Pixel Sensors (CMOS MAPS) = CMOS Active Pixel Sensors (CMOS APS)
Owing to the industrial development of CMOS imaging sensors and the intensive R&D by HEP community.

... several HI experiments have selected CMOS pixel sensors for their inner trackers and intensive R&D for ATLAS.
### Open charm

<table>
<thead>
<tr>
<th>Particle</th>
<th>Decay Channel</th>
<th>$c\tau$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$K^- \pi^+$ (3.8%)</td>
<td>123</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$K^- \pi^+ \pi^+$ (9.5%)</td>
<td>312</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$K^+ K^- \pi^+$ (5.2%)</td>
<td>150</td>
</tr>
<tr>
<td>$\Lambda_c^+$</td>
<td>$p K^- \pi^+$ (5.0%)</td>
<td>60</td>
</tr>
</tbody>
</table>

### Example: $D^0$ meson

Analysis based on invariant mass, PID and decay topology.
Secondary Vertex Determination

Example: $D^0$ meson

Analysis based on invariant mass, PID and decay topology

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Home task: to prove that spacious resolution of the strip or pixel sensor depends on size of the strip/pixel pitch $D$ as $\Sigma^2 = D^2/12$
STAR Pixel Detector – First application of CMOS APS to HEP

Mechanical support with kinematic mounts (insertion side)

- 2 layers
- 10 sectors total (in 2 halves)
- 4 ladders/sector

Ladder with 10 MAPS sensors (~ 2x2 cm² each)

Power ~ 160mW/cm²

Rolling Shutter ~180μs integr. time

2-layer kapton flex cable with AI traces

Key dates
- 3-sector prototype May 2013
- Full detector Jan 2014

Physics Runs in 2015-2016
A new ITS: closer to IP, thinner, higher position resolution

Closer to IP: 39mm → 22mm
Thinner: ~1.14% → ~ 0.3% (for inner layers)
Smaller pixels: 50μm x 425μm → 27μm x 29μm
Increase granularity: 20 chan/cm³ → 2k pixel/cm³
Faster readout: x 10² Pb-Pb, x 10³ pp
10 m² active silicon area: 12.5 G-pixels, σ ≈ 5μm

ALPIDE (ALICE Pixel Detector) - Developed for the ALICE upgrade (ITS and MFT) will be used (or it is proposed) for several other HEP detectors and non HEP applications.

NICA MPD (@JINR) sPHENIX (BNL) proton CT (tracking) CSES – HEPD2 ...
ALICE CMOS Pixel Sensor

CMOS Pixel Sensor using 0.18μm CMOS Imaging Process

- pixel capacitance ≈ 5 fF (@ V_{bb} = -3 V)
- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < V_{BB} < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors

Artistic view of a SEM picture of ALPIDE cross section

2 x 2 pixel volume

C_{in} ≈ 5 fF

Q_{in} (MIP) ≈ 1300 e → V ≈ 40mV
Low capacitance $\rightarrow$ large S/N at low power

NWELL DIODE output signal = $Q/C$
- Minimize spread of charge over many pixels
- Minimize capacitance:
  - small diode surface
  - large depletion volume

- Silicon strip capacitance: $> 10$ pF (\(\sim 1.5\) pF / cm)
- Hybrid pixel capacitance: $\sim 300$ fF
- MAPS “small electrode” pixel capacitance: $< 5$ fF

$C_d = 1$fF: $1300$ e$^-$ $\rightarrow$ 200mV (almost a digital signal)
ALICE Pixel DEtector (ALPIDE)

1024 pixel columns
512 rows

130,000 pixels / cm²  27x29x25 µm³
charge collection time  <30ns (Vbb = -3V)
Max particle rate: 100 MHz/cm²
fake-hit rate:  < 1 Hz/ cm²
power :  ≈300 nW /pixel (<40mW/cm²)

signal processing circuitry integrated in pixel matrix

Matrix Layout

Pixel Layout

L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019

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ALICE Pixel DEtector (ALPIDE)

Large operational margin with only 10 masked pixels (0.002%), fake-hit rate < 2 x 10^{-11} pixel/event

Non irradiated and TID/NIEL chips similar performance

5 µm resolution @ 200 e^- threshold
Chip-to-chip negligible fluctuations

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ALICE Pixel DEtector (ALPIDE)

Sensor test and HIC assembly using ALICIA machine

Inner Barrel is built at CERN

ALICIA - High-precision automated machine

Sensors

150 μm
100 μm

pixel matrix
pixel matrix

E. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019
ALICE Pixel DEtector (ALPIDE)

Inner Barrel Production completed and all layers assembled

L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019
ALICE Pixel DEtector (ALPIDE)

102 Million pixel, average noise uniform ~ 5e
Ultra-thin curved silicon chips

Can we exploit flexible nature of thin silicon?

SiliconGenesis: 20 micron thick wafer

Chipworks: 30µm-thick RF-SOI CMOS

Ultra-thin chip (<50 µm): flexible with good stability

<table>
<thead>
<tr>
<th>Die type</th>
<th>Front/back side</th>
<th>Ground/polished/plasma</th>
<th>Bumps</th>
<th>Die thickness (µm)</th>
<th>CDS (MPa)</th>
<th>Weibull modulus</th>
<th>MDS (MPa)</th>
<th>$r_{min}$ (mm)</th>
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<tr>
<td>Blank</td>
<td>Front</td>
<td>Ground</td>
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<td>494</td>
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<td>Polished</td>
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<td>25–35</td>
<td>1044</td>
<td>4.17</td>
<td>334</td>
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<td>Polished</td>
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<td>2.98</td>
<td>107</td>
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<td>Plasma</td>
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<td>2340</td>
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<td>18–22</td>
<td>1207</td>
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<td>833</td>
<td>2.05</td>
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<tr>
<td>IZM28</td>
<td>Back</td>
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<td>18–22</td>
<td>2139</td>
<td>3.74</td>
<td>362</td>
<td>4.72</td>
</tr>
</tbody>
</table>

**Vertex Detector (innermost 3 layers)**

Truly cylindrical vertex detector

- **Beampipe**
  - IR: 16 mm
  - $\Delta R$: 0.5 mm

- **Pipe**
  - $r \approx 16\text{ mm}$, $\Delta R = 0.5\text{ mm}$

- **L0**
  - $r \approx 18\text{ mm}$

- **L1**
  - $r \approx 24\text{ mm}$

- **L2**
  - $r \approx 30\text{ mm}$

0.05% $x/X_0$ per layer

Layers supported by high-thermal conductive carbon foam

- **Open cell carbon foam**

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L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019

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August 23, 2019

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**Stage I:**
TPC, TOF, ECAL, ZDC, FFD + ITS(OB) 

**Stage II:**
ITS(IB) + EndCap (CPC, Straw, TOF, ECAL)

Transfer of High Tech Instrumentation
Know-How from CERN to NICA-MPD

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**Stage I: overall commissioning starts in 2022 (t.b.c.)**
CERN will procure, test and deliver to NICA

- 19'000 ALPIDE Monolithic Active Pixel Sensors for the MPD ITS
- 4'500 SAMPA electronic circuits for the TPC readout
- 5'000 FEAST DC/DC converters for the ECAL MPD
- Jigs and fixtures for module and supermodule assembly for the MPD ITS
- Training of personal for assembly and QA certification modules and supermodules of the MPD ITS
- Provision of complete technical and commercial information on parts of the new ALICE Inner Tracking System, including drawings, internal technical reports, quotes, etc.
MPD ITS based on the ALPIDE MAPS CERN technology

Beam pipe $\varnothing = 38$ mm

<table>
<thead>
<tr>
<th>Layer</th>
<th>Number of staves</th>
<th>Number of ALPIDEs per a stave</th>
<th>$R_{\text{min}}$, mm</th>
<th>$R_{\text{max}}$, mm</th>
<th>Ladder active length, mm</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>12</td>
<td>22.4</td>
<td>26.7</td>
<td>360</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>23</td>
<td>40.7</td>
<td>45.9</td>
<td>608</td>
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<td>3</td>
<td>32</td>
<td>37</td>
<td>59.8</td>
<td>65.1</td>
<td>708</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>196</td>
<td>144.5</td>
<td>147.9</td>
<td>1190</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>196</td>
<td>194.4</td>
<td>197.6</td>
<td>1468</td>
</tr>
</tbody>
</table>
ITS pointing resolution within STAR-ALICE toy model

**ALICE**

- **New ITS**
- **Old ITS**

**MPD**

- $\varnothing = 40$ mm
- $\varnothing = 50$ mm
- $\varnothing = 60$ mm

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Selection criteria

D⁰ selection parameters:
• distances of closest approach to the collision vertex \( DCA_{\pi,K} \),
• two-track separation \( DCA_D \),
• decay path \( \lambda_D \),
• pointing angle \( \theta_D \).

Selection criteria:
\[ DCA_\pi > C_1 \&\& DCA_K > C_2 \&\& DCA_D < C_3 \&\& \lambda_D > C_4 \&\& \theta_D < C_5 \]

The parameters of the corresponding selections are optimized by maximizing the signal significance:

\[ Sg(a) = \int_{0}^{a} \frac{S}{\sqrt{S+B}} da \]

where \( S \) and \( B \) are the estimated numbers of the signal and background events.
**D⁰ reconstruction – cut selection**

- **D⁰ pointing angle significance**
  - **Signal**
  - **Background**
  - **Significance**

- **D⁰ distPiK significance**
  - **Signal**
  - **Background**
  - **Significance**

- **D⁰ path significance**
  - **Signal**
  - **Background**
  - **Significance**

\[ dcaK > 0.01 \text{ cm} \& \]
\[ dcaPi > 0.01 \text{ cm} \& \]
\[ distPiK < 0.02 \text{ cm} \& \]
\[ path(D⁰) > 0.025 \text{ cm} \& \]
\[ angle(D⁰) < 0.2 \text{ rad} \]
D⁰ reconstruction – invariant mass spectrum for ITS#1

ITS – option#1:

\[ t_1 = t_2 = t_3 = 50 \mu \text{m} \]

\[ t_4 = t_5 = 700 \mu \text{m} \]

\[ D^0 \rightarrow K^- + \pi^+ \]
**D⁰ reconstruction – invariant mass spectrum for ITS #1**

\[ D^{0} \rightarrow K^{-} + \pi^{+} \]

**Counts**

- \( t_1 = t_2 = t_3 = 50 \mu \)
- \( t_4 = t_5 = 700 \mu \)

- \( S/\sqrt{B+S} = 9.8 \)
- \( S/B = 0.21 \)
- \( S = 552 \)
- \( \text{Eff} = 1.4\% \)

- \( M(D^{0}) = 1.863 \pm 0.002 \text{ GeV} \)
- \( \sigma(D^{0}) = 0.020 \pm 0.001 \text{ GeV} \)
D⁰ reconstruction – TMVA selection

IT – option #1:
\[ t_1 = t_2 = t_3 = 50 \mu \text{IB ITS3} \]
\[ t_4 = t_5 = 700 \mu \text{OB ITS2} \]

IT – option #2:
\[ t_1 = t_2 = t_3 = 200 \mu \text{IB ITS2} \]
\[ t_4 = t_5 = 700 \mu \text{OB ITS2} \]

DCA(π, K, D⁰), path(D⁰), angle(D⁰) cuts

BDTD cut
**D⁰ reconstruction – invariant mass spectrum**

**ITS – option #1:**
- \( t₁ = t₂ = t₃ = 50 \mu \) (IB ITS3)
- \( t₄ = t₅ = 700 \mu \) (OB ITS2)

**ITS – option #2:**
- \( t₁ = t₂ = t₃ = 200 \mu \) (IB ITS2)
- \( t₄ = t₅ = 700 \mu \) (OB ITS2)

---

**Preliminary results of TMVA-BDTD simulations of 10M 9 GeV central Au-Au central collisions (V. Kondratiev)**
D$^+$ reconstruction – TMVA selection

ITS – option#1:
\[ t_1 = t_2 = t_3 = 50\mu \text{ (IB ITS3)} \]
\[ t_4 = t_5 = 700\mu \text{ (OB ITS2)} \]

IT – option#2:
\[ t_1 = t_2 = t_3 = 200\mu \text{ (IB ITS2)} \]
\[ t_4 = t_5 = 700\mu \text{ (OB ITS2)} \]

DCA(\pi, K, D^+), path(D^+), angle(D^+) cuts

BDTD cut

TMVA response for classifier: BDTD

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D\(^+\) reconstruction – invariant mass spectrum

ITS – option#1:
\(t_1=t_2=t_3=50\mu\) (IB ITS3)
\(t_4=t_5=700\mu\) (OB ITS2)

ITS – option#2:
\(t_1=t_2=t_3=200\mu\) (IB ITS2)
\(t_4=t_5=700\mu\) (OB ITS2)

\[M(\pi\pi K): \text{signal+background}(10M)\]

**Preliminary results of TMVA-BDTD simulations of 10M 9 GeV central Au-Au central collisions (V. Kondratiev)**
### D-meson parameters in 100M central Au+Au collisions at $\sqrt{s_{NN}} = 9$ GeV

<table>
<thead>
<tr>
<th>Particle</th>
<th>$D^0$</th>
<th>$D^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay channel</td>
<td>$D^0 \rightarrow K^- + \pi^+$</td>
<td>$D^+ \rightarrow K^- + \pi^+ + \pi^+$</td>
</tr>
<tr>
<td>Multiplicity (HSD)</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>BR, %</td>
<td>3.9</td>
<td>9.1</td>
</tr>
<tr>
<td>IT option</td>
<td>#1</td>
<td>#2</td>
</tr>
<tr>
<td>S/B(2σ)</td>
<td>0.43</td>
<td>0.10</td>
</tr>
<tr>
<td>Significance</td>
<td>15.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>1.9</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Current limitations of experimental data on D meson

Identificaion achieved

Thermal generator: D meson’s $p_t$ - spectrum

Abdel Nasser TAWFIK† and Ehab ABBAS
Thermal Description of Particle Production in Au-Au Collisions at STAR Energies

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MC and reconstructed $p_t$-spectra of $D^0$-mesons and their decay products

D$^0$ mesons

Pions

Kaons
MC and reconstructed $p_t$-spectra of $D^+$-mesons and they decay products

D$^+$ mesons

Pions

Kaons
ITS realization in two Steps (OB first) due to BP sequence

Stage I: Installation of OB (2022-23)

Stage II: OB+IB (2022+25) ?

~ 9 500 ALPIDE MAPS in 5 cylinders of 2 barrels

4,9 \times 10^9 pixels, active area 3,9 m^2.

Stage I: 64 mm in diameter

Stage II: 38 mm in diameter
Task 1. Mechanics for integration with the TPC - JINR
Task 2. FC trusses (60), cooling plates (120)
JINR & SPbSU

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Task 3: Assembly of HICs and OB Staves (60 pcs incl.)

JINR & CCNU

Truss length is 1540 mm. Modules (HICs) are located on two cooling plates.

OB stave carriers 196 sensors.

The MPD ITS need is 42 OB staves.
Task 4. **R@D for the IB as part ALICE ITS3 upgrade plan (under supervision of CERN)**

**Vertex Detector (innermost 3 layers)**

- Truly cylindrical vertex detector
- Beampipe IR 16 mm, ΔR 0.5 mm
- Pipe: r ≈ 16 mm, ΔR = 0.5 mm
- L0: r ≈ 18 mm, L1: r ≈ 24 mm, L2: r ≈ 30 mm

**Layers supported by high-thermal conductive carbon foam**

- Open cell carbon foam

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August 23, 2019

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Conclusions and summary
major milestones of the MPD ITS project (tentatively!)

- **2018** – paper work and infrastructure
- **2018–2019** – simulations and start of delivery of parts from CERN
- **2019** – organization of the Russian-Chinese Consortium
- **2019** – Writing TDR (Draft)
- **2019-2020** – Production of first HICs at VBLHEP and CCNU
- **2020–2021** – Mechanics including parts for integration
- **2020–2021** – updating the readout chain (with China and ?)
- **2020–2023** – R@D effort on IB together with ALICE
- **2021–2023** – Production HICs, assembly of OB staves (with China)
- **2023 (?)** – ITS-OB assembly, bench testing, commissioning
- **2025 (?)** – ITS-OB+IB commissioning (Stage II)
The MPD-ITS project is both scientific- and time-wise well justified

The project has a solid reason to be accomplished in two stages

The MPD-ITS(OB) (stage 1) one is now recognized and approved for financing at JINR

The MPD-ITS(IB) (stage 2) contains R&D proposed to be performed under the supervision of ALICE Collaboration (ITS-3)

The project effort due to its technical complexity cannot be undertaken by JINR alone and calls for organization of a Consortium of Institutes from Russia and China (and elsewhere!) functioning at least till 2025