The very forward hadron calorimeter PSD for the future CBM@FAIR experiment

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Compressed Baryonic Matter (CBM) experiment

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Projectile Spectator Detector (PSD)

**Principle:** detection of forward going projectile nucleons and nuclei fragments (spectators) produced close to the beam rapidity in nucleus-nucleus collisions

**Purpose:** measurement of the reaction centrality and reconstruction of the reaction plane

**Features:**
- compensating calorimeter with lead/scintillator sampling ratio 4:1
  - good energy resolution \(\sim 55%/\sqrt{E}\)
- high transverse granularity by 44 modules
  - transverse homogeneity of energy resolution, reaction plane measurements
- longitudinal segmentation of 10 sections per module
  - longitudinal shower profile measurement, calibration
- light readout from a section through WLS fibers by photodiodes
  - large dynamic range, no nuclear counting effect
- New design with a 20x20 cm\(^2\) beam hole in the center
  - drastic reduction of radiation damage from
- ability to operate at high collision rates up to 1MHz
- total 22 tons of weight on a platform movable in 3 dimensions

Similar calorimeter already operates at NA61@CERN, and another one called Zero Degree Calorimeter (ZDC) is being prepared for BM@N at NICA.

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
CBM PSD module design

Module properties:
• 60 lead+scintillator plates in one module
• 1 section = 6 scintillator plates
• size = 20 x 20 x 120 cm³
• depth ~ 5.6 hadron interaction lengths $\lambda_{int}$

Optimized for beam energy range of 2 – 35 GeV

Light from each consecutive 6 layers is collected together via WLS-fibers and read-out by a single Hamamatsu Multi-Pixel Photon Counter (MPPC)

MPPC S12572-010P properties:
• size: 3x3 mm²
• large dynamical range: 90000 pixels
• photon detection efficiency: ~10%
• high counting rate: ~1 MHz
• requirement: radiation hardness to neutrons
$\sim 2 \times 10^{11}$ $n_{eq}/cm^2$ for CBM

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
CBM PSD readout electronics

Preamplifier
- Attached to photodiode
- Optimized for high capacitance inputs
- Gain ~ 60 V/V
- Good Signal / Noise

PaDiWa-AMPS (GSI)
- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- Time precision: < 50 ps
- Rel. charge resolution: < 0.5 %
- Dynamic range: 250 – 500
- Compact data: max. 50 MB/s

TRBv3 Trigger and Readout Board
- 4 FPGAs, 264 TDC channels
- Single edge & ToT measurement
- Time precision < 20 ps
- 50 MHz hit rate per channel
- Fast data transfer via gigabit Ethernet
- Internal trigger and slow control

2 other readout options are now under test

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
CBM PSD: Alternative readouts

ADC64s/ADC125s electronics (AFI, JINR, Dubna)
- Method: direct waveform digitization
- 64 channels, 12 bit ADCs
- Speed: 62.5/125 MS/s
- Dynamic range: ~150
- Up to 100 kHz real event rate
- Huge amount of data
- DSP is required on top

Time-Over-Threshold (ToT) board
- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- NINO chip based design
- Dynamic range: ~ 250
- Compact data: max. 50 MB/s
- Coupled to TRB3
Centrality measurement in CBM

Particle multiplicities around midrapidity measured by Silicon Tracking System

Energy measured at forward rapidity measured by PSD calorimeter

Two independent ways to measure centrality.
STS generally performs better but can be improved by correlation with PSD by up to 10% for central events

The correlation between the energy deposited in the four central PSD modules ($E_{\text{PSD}}^1$) and the track multiplicity $M_{\text{trk}}$ with cuts

Impact parameter resolution

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Reaction plane reconstruction in CBM

Particle hits around midrapidity measured by Silicon Tracking System

Particle hits at forward rapidity measured by Forward TOF

Energy measured at forward rapidity measured by PSD calorimeter

The best for beam energies > 4 AGeV due to
- sensitivity to neutral particles and fragments
- much stronger flow at forward rapidity

Directed flow $v_1$ for different collision models

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
PSD reaction plane resolution for four heavy-ion collision models

Does not differ much for different models even though they have very different flow

Why?

Reaction plane resolution

Reaction plane resolution correction factor

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
PSD reaction plane resolution for four heavy-ion collision models

**Because**

directed flow is much more different at midrapidity than at forward (projectile) rapidity

In non-central collisions flow of particles is usually described by Fourier decomposition with respect to reaction plane:

\[
\frac{dN}{d\phi} \sim 1 + 2 \sum_n v_n \cos n(\phi - \Psi_{RP}),
\]

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
PSD reaction plane resolution design

Granularity is well chosen and produces almost no bias

Magnetic field produces relatively small bias below 10%

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Array of 3x3 calorimeter modules was assembled for the beam tests at CERN in 2017-2018

All 44+1 modules for PSD are already assembled at INR
Light yield of each of 10 individual sections in module was measured by cosmic muons

Identification of muons: equal energy deposition in first and last halves of module

Measurement with horizontal and inclined tracks
PSD supermodule at CERN

Supermodule performance was successfully tested at CERN T9 and T10 beamlines

\[ \frac{\sigma_{E}}{E} = \left( \frac{0.54}{\sqrt{E}} \right)^2 + 0.046^2 + \left( \frac{0.5}{E} \right)^2 \]

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
CBM PSD radiation conditions

Enlarged beam hole 6x6 cm² -> 20x20 cm² significantly reduces the radiation damage

up to 30 times less ions hitting the calorimeter

up to 2x10¹¹ neutrons_{eq}/cm² for SiPMs located 10 cm close to the beam center
Neutron irradiation of MPPCs at NPI U-120M cyclotron

✓ Hamamatsu S12572-010P MPPCs were irradiated by total fluence in wide range from $6 \times 10^{10}$ up to $9 \times 10^{12}$ n$_{eq}$/cm$^2$

SiPMs placed at Cyclotron beam line

“White” neutron beam by Be(p) thick target

![Image of SiPMs and neutron beam setup]

 Courtesy of M. Majerle and M. Štefánik

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Performance of MPPCs in lab

Signal to noise ratio \[ \frac{\text{Signal}}{\sqrt{\text{Noise}}} \]

SiPM signal response was measured during illumination with 10 ns short pulses from 400 nm LED. Pulse height was chosen such that signal was detectable by all the SiPMs.

\[ 2 \times 10^{11} \text{ neutrons}_{\text{eq}}/\text{cm}^2 : \text{SNR} \sim 50 \]
Performance of MPPCs at CBM supermodule

Energy deposition for 4.2 GeV proton beam in a single module

- Energy resolution dropped only slightly for MPPCs irradiated by \(2 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2\)
- Energy resolution dropped in about 1.5 – 2 for MPPCs irradiated by \(~10^{12} \text{n}_{\text{eq}}/\text{cm}^2\) but SiPMs were proven to operate even after such a high neutron irradiation

Reconstruction was performed with the noise cut, which was applied individually for each section

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Performance of MPPCs at NA61

Energy deposition for 4.2 GeV proton beam in a single module

- Energy resolution dropped up to 2 times for MPPCs irradiated by $\sim 10^{12} \text{n}_{\text{eq}}/\text{cm}^2$ but SiPMs were proven to operate even after such a high neutron irradiation

Reconstruction was performed with the noise cut, which was applied individually for each section

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Performance of MPPCs at CERN

- Calorimeter will operate well under irradiation of $2 \times 10^{11}$ n$_{eq}$/cm$^2$ which corresponds to 1 year of operation at maximum beamrate of 1MHz
- It will operate further, but at some point damaged MPPCs must be replaced, especially at the center of calorimeter
Preparation of mPSD for mini-CBM

mPSD installation and integration in mCBM is planned for 2019

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Summary

- Design and performance study of the Projectile Spectator Detector (PSD) for CBM is presented.
- Physics performance of the PSD design is demonstrated with help of four different collision models and Monte-Carlo GEANT package:
  - up to 10% resolution improvement for collision centrality with PSD correlated to STS
  - reaction plane resolution is well reconstructed with $\sigma < 40\%$
- All the modules are already assembled, QA with cosmic muons completed.
- Energy resolution and linearity were measured with PSD supermodule at CERN and satisfy TDR:
  - stochastic term of energy resolution $\sigma_E \sim 54\%/\sqrt{E}$
- Radiation sustainability is sufficient for 1 year of operation at maximum beamrate of 1MHz and for whole experiment lifetime with exchange of photodiodes.

**Ongoing:**
- PSD platform design and construction
- Readout electronics options evaluation
- Preparation for mini-CBM

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
backup
Motivation for collective flow and PSD performance simulations

- The collective flow reflecting the azimuthal anisotropy of the collision is used to study the equation of state of baryonic matter.
- Heavy-ion collision generator consistent with the existing experimental flow data has to be determined for PSD simulations.
- PSD performance for the reaction plane reconstruction has to be simulated. Magnitude of directed flow \( v_1 \) affects the reaction plane resolution.
- Effects of the detector granularity and bias due to magnetic field shall be studied during the PSD performance simulation.

In non-central collisions flow of particles is usually described by Fourier decomposition with respect to reaction plane:

\[
\frac{dN}{d\varphi} \sim 1 + 2\sum_n v_n \cos n(\varphi - \Psi_{RP}),
\]

Directed flow

\( v_1 = \langle \cos(\varphi - \Psi_{RP}) \rangle \)

Elliptic flow

\( v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle \)

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018

Modified illustration from C. Cain for STAR
**Ratios of $v_1$**

- **Slope of $v_1(y_{\text{norm}})$ at midrapidity**
  \(-0.5 \leq y_{\text{norm}} \leq 0.5\)

- **$v_1$ at projectile rapidity**
  \((y_{\text{norm}} = 1)\)

- **Ratio of $v_1$ slopes at midrapidity**

- **Ratio of $v_1$ at projectile rapidity**

**Answer:**

$v_1$ differs a lot at midrapidity, but PSD measures at forward rapidity, where $v_1$ differs much less!
Centrality measurement in CBM

Particle multiplicities around midrapidity measured by Silicon Tracking System

Energy measured at forward rapidity measured by PSD calorimeter

Two independent ways to measure centrality.
STS generally performs better but can be improved by correlation with PSD by up to 10% for central events

Average impact parameter versus centrality

Impact parameter resolution
Motivation for radiation hardness investigation of Silicon Photomultipliers (SiPM)

- High intensity beams at FAIR SIS100/300 up to $10^6/10^7$ interactions/s will lead to the high radiation emission to the detectors.
- PSD calorimeter works as a spallation target with moderator for neutron production.
- Passive parts of PSD including the scintillators are not very sensitive to the neutrons, but the active readout parts including the SiPMs are.

$$n_{eq} / \text{cm}^2 \text{/ 2 months}$$

up to $5 \times 10^{11}$ neutrons$_{eq}$/cm$^2$ for SiPMs located at 10 cm close to the beam hole
Choice of the SiPM

SiPMs with 3x3 mm² area sensitive to 400 – 550 nm light were chosen for the test

<table>
<thead>
<tr>
<th></th>
<th>Zecotek MAPD-3A</th>
<th>Zecotek MAPD-3N</th>
<th>Hamamatsu S12572-010P</th>
<th>Sensl uF-C30020</th>
<th>Sensl uF-B30020</th>
<th>Ketek PM-3350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating voltage (V)</td>
<td>~ 65</td>
<td>~ 90</td>
<td>~ 70</td>
<td>~ 25</td>
<td>~ 25</td>
<td>~ 25</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>135000</td>
<td>135000</td>
<td>90000</td>
<td>11000</td>
<td>11000</td>
<td>3600</td>
</tr>
<tr>
<td>Effective pixel size (µm)</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>29</td>
<td>29</td>
<td>50</td>
</tr>
<tr>
<td>Gain</td>
<td>~ 6x10⁴</td>
<td>~ 1x10⁵</td>
<td>~ 1x10⁵</td>
<td>~ 1x10⁶</td>
<td>~ 1x10⁶</td>
<td>~ 6x10⁶</td>
</tr>
<tr>
<td>PDE (%)</td>
<td>~ 20</td>
<td>~ 30</td>
<td>~ 10</td>
<td>~ 25</td>
<td>~ 25</td>
<td>~ 40</td>
</tr>
<tr>
<td>Pixel recovery time (ns)</td>
<td>~ 2x10³</td>
<td>~ 10⁴</td>
<td>~ 10</td>
<td>~ 100</td>
<td>~ 100</td>
<td>~ 200</td>
</tr>
</tbody>
</table>

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
Experiments at NA61 PSD in CERN

SiPMs soldered to PSD readout boards

PSD readout board assembled

NA61 PSD

Readout board mounted to PSD

V. Mikhaylov, PSD calorimeter for CBM@FAIR, XXIV Baldin Conference, Dubna, September 2018
## Difference between conducted tests

<table>
<thead>
<tr>
<th></th>
<th>Summer 2016 and 2017</th>
<th>September 2017</th>
<th>November 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamline</td>
<td>NA61</td>
<td>T10</td>
<td>T9</td>
</tr>
<tr>
<td>Proton selection</td>
<td>Not available</td>
<td>by TOF scintillators</td>
<td>By Cherenkov detector</td>
</tr>
<tr>
<td>Proton selection approx. mom. range</td>
<td>Not available</td>
<td>2 – 6 GeV/c</td>
<td>3.5 – 10 GeV/c</td>
</tr>
<tr>
<td>SiPMs utilized</td>
<td>Irradiated by 4E10, 4E11, 1E12 and 3E12 n/cm²</td>
<td>Irradiated by 1E12 and 3E12 n/cm²</td>
<td></td>
</tr>
<tr>
<td>SiPMs calibration of overvoltages</td>
<td>Calibrated by LED relative to the muon calibration of non-irradiated SiPMs</td>
<td>Previous calibration from NA61 was utilized</td>
<td>Relative to the breakdown voltage measured in lab (seems to be more accurate)</td>
</tr>
<tr>
<td>Temperature stabilization</td>
<td>All SiPMs kept at 20 °C</td>
<td>Not available</td>
<td></td>
</tr>
<tr>
<td>Temperature in the test hall</td>
<td>Not available</td>
<td>~ 26 °C</td>
<td>~ 18 °C</td>
</tr>
</tbody>
</table>

V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018
How the signals from 6 GeV/c protons look like

- Very high noise is clearly visible.

V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018
Energy scan

Non-irradiated

Irradiated 1E12 n/cm²

V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018
Noise reduction by the amplitude cut

- The amplitude cut = 15 mV per section was chosen to have the minimal efficiency drop along with the good noise suppression.
- The energy resolution improved by 30 – 50 %.

*First 5 sections of NA61 PSD module were equipped with Hamamatsu SiPMs*

V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018
Next steps

- We preliminarily estimated the 1MeV neutron fluence equivalent hardness factor to be: $k \approx 1.5$.

Then $1 \times 10^{12}$ and $3 \times 10^{12}$ n/cm$^2$ translate into $1.5 \times 10^{12}$ and $4.5 \times 10^{12}$ n$_{eq}$/cm$^2$.

To be continued
Neutron shielding simulation

- We reduced the neutron flux by 50-70% adding borated polyethylene between the PSD module lead/scintillator blocks and SiPMs.
- Low energetic neutrons are shielded the best, so we reduce the neutrons captured in SiPM by silicon and dopants, especially $^{10}\text{B}$ dopant having huge n cross-section.

V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018

8 cm boron (3%) polyethylene
In newly assembled module

Direction of neutrons hitting PSD module
Lightguides to SiPMs placement space

Courtesy of O. Svoboda
Hamamatsu SiPM performance in lab: Noise

- Dark current increases linearly with neutron fluence and can reach mA range.
- Noise increases in 10 – 20 times after irradiation.
Hamamatsu SiPM performance in lab: Signal response to LED

- Signal drops to 50% of its original value at neutron fluence around $1 \times 10^{12}$ n/cm$^2$.
- Signal to noise ratio drops to 10 at neutron fluence around $1 \times 10^{12}$ n/cm$^2$. 

V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018
**NA61: Energy resolution for 80 GeV/c protons**

*First 5 sections of NA61 PSD module equipped with Hamamatsu SiPMs*

- Very high noise was cut out, significantly improving the energy resolution.

*V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018*
NA61: Energy resolution for 20 – 80 GeV/c protons

July 2016 & June 2017

- Energy resolution dropped in 1.5 – 2.5 times after irradiation.
- SiPMs were proven to operate even after such a high neutron irradiation.

* First 5 sections of NA61 PSD module were equipped with Hamamatsu SiPMs
Test of Hamamatsu SiPMs response at NA61 PSD: Waveforms

Non-irradiated
ADC,Ev1,Mod36,Sect6

RMS ~ 50 ADC

Irradiated 3e11 n/cm2
ADC,Ev4,Mod36,Sect6

RMS ~ 500 ADC

Irradiated 3e12 n/cm2
ADC,Ev4,Mod36,Sect8

RMS ~ 1500 ADC

With the noise increased at 10-30 times SiPM cannot detect MIPs (~10-15 photons)!

V. Mikhaylov, Irradiated SiPMs at PSD supermodule at CERN, CBM Collaboration Meeting 19.03.2018
Dark currents of SiPMs irradiated by $\sim 4 \times 10^{11}$ n/cm$^2$ reach 50 µA at overvoltage = 2V

Dark currents of SiPMs irradiated by $\sim 1 \times 10^{12}$ n/cm$^2$ reach 200 µA at overvoltage = 2V

Dark currents of SiPMs irradiated by $\sim 1 \times 10^{13}$ n/cm$^2$ reach 1 mA at overvoltage = 2V

We need external power supply (5 channels) for the next tests in CERN!
SiPM details

Dynamic range of different SiPMs

\[ N_{\text{fired}} = N_{\text{pixels}}(1 - \exp\left(-N_{\text{photons}} \times PDE / N_{\text{pixels}}\right)) \]

- Zecotek
- Hamamatsu

Normalized response vs proton beam rate

Study by NA61 PSD team

V. Mikhaylov, Tests of PSD module response with irradiated SiPMs at CERN beams in 2017
Details on neutron irradiation experiments

Proton energy = 35 MeV

Intensity for fluence = 1E12 n/cm²

Intensity for fluence = 3E12 n/cm²

16 cm from target
$T_{irr} = 8 \text{ min}$

16 cm from target
$T_{irr} = 24 \text{ min}$

SiPMs prepared for irradiation

SiPMs located at the holder

SiPMs located at cyclotron

V. Mikhaylov, Tests of PSD module response with irradiated SiPMs at CERN beams in 2017
SiPM breakdown voltage after irradiation

Variation of $V_{\text{breakdown}}$ measured for few SiPMs is less than 0.5V.

*SiPMs irradiated by “white” neutron spectrum*

<table>
<thead>
<tr>
<th>SiPM type -&gt;</th>
<th>Zecotek MAPD-3A</th>
<th>Hamamatsu S12572-010P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample N</td>
<td>$V_{\text{breakdown}}$ V ± 0.2V</td>
<td>$V_{\text{breakdown}}$ V ± 0.2V</td>
</tr>
<tr>
<td>20</td>
<td>64.4</td>
<td>66.7</td>
</tr>
<tr>
<td>21</td>
<td>64.8-65.2</td>
<td>67.6-67.1</td>
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<tr>
<td>22</td>
<td>65</td>
<td>67</td>
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<td>23</td>
<td>64.9</td>
<td>67.1</td>
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<tr>
<td>24</td>
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<td>67.4</td>
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<td>25</td>
<td>64.7</td>
<td>66.7</td>
</tr>
<tr>
<td>26</td>
<td>64.7</td>
<td>66.7</td>
</tr>
<tr>
<td>27</td>
<td>64.4</td>
<td>66.1</td>
</tr>
<tr>
<td>28</td>
<td>64.4</td>
<td>66</td>
</tr>
<tr>
<td>29</td>
<td>64.2-64.3</td>
<td>65.9</td>
</tr>
</tbody>
</table>

$V_{\text{break}} = 65 \pm 0.2$ V

$\Delta V_{\text{break}} (6.4e11 \text{ n/cm}^2) \sim 0.4$ V

V. Mikhaylov, Tests of PSD module response with irradiated SiPMs at CERN beams in 2017
Displacement damage in Silicon for neutrons, protons, pions and electrons

A. Vasilescu & G. Lindstroem

V. Mikhaylov, Tests of PSD module response with irradiated SiPMs at CERN beams in 2017
Projectile Spectator Detector (PSD)

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  *good energy resolution* \(\sim 55\%/\sqrt{E}\)

- high transverse granularity by 44 modules
  
  *transverse homogeneity of energy resolution, reaction plane measurements*

- module of 5.6 hadron interaction lengths and transverse size of 20x20x120 cm\(^3\)
  
  *optimized for beam energy range from 2 up to 35 GeV*

- longitudinal segmentation: 10 sections/module, 1 section = 6 scintillator plates
  
  *longitudinal shower profile measurement, calibration*

- light readout from a section through WLS fibers by 3x3 mm\(^2\) Hamamatsu MPPC
  
  *large dynamic range, no nuclear counting effect*

- ability to operate at high collision rate up to 1MHz

- total 22 tons of weight on a platform movable in 3 dimensions

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