RPCs for the SND Muon System of the SHiP experiment

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• The SHiP experiment;
• The SHiP Scattering and Neutrino Detector (SND);
• RPCs for the SND Muon System;
• Prototypes of the SHiP RPCs;
• Test results of RPC prototypes;
• R&D for SHiP RPCs.
Hints of New Physics: dark matter, neutrino oscillations, matter/antimatter asymmetry

Several theories suggest the existence of “hidden” neutral feebly interacting particles with low masses (around the GeV scale)

need to probe the intensity frontier [e.g. Search for Hidden Particles (SHiP) experiment]
The SHiP experiment

Proposed beam dump experiment at CERN SPS
$2 \cdot 10^{20}$ expected p.o.t @400 GeV in 5 years

Magnetised muon shield:
- $\sim 10^{11} \mu$ in 1 spill reduced to $< 10^5$
- muon spectrum validated in a dedicated experiment

High density target
optimised for heavy meson production
+ hadron absorber

Hidden Sector detector:
Hidden Sector (HS) decay volume +
HS particle ID system


Scattering and Neutrino detector
designed in order to study the large neutrino flux produced at the beam dump

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Neutrino physics goals @SND:

- cross section measurements of all $\nu$ flavours;
- $\nu$-induced charm production studies;
- $\nu_\tau$ and $\bar{\nu}_\tau$ physics with high statistics;
- evaluation of F4 and F5 not accessible with $\nu_e,\nu_\mu$.

Expected neutrino flux @ beam dump

<table>
<thead>
<tr>
<th>$\langle E \rangle$ [GeV]</th>
<th>Beam dump</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\nu_e}$</td>
<td>4.1</td>
</tr>
<tr>
<td>$N_{\nu_\mu}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$N_{\nu_\tau}$</td>
<td>7.4</td>
</tr>
<tr>
<td>$N_{\bar{\nu}_e}$</td>
<td>4.7</td>
</tr>
<tr>
<td>$N_{\bar{\nu}_\mu}$</td>
<td>1.6</td>
</tr>
<tr>
<td>$N_{\bar{\nu}_\tau}$</td>
<td>8.1</td>
</tr>
</tbody>
</table>

So far:

- 9 $\nu_\tau$ events by DONUT + 10 $\nu_\mu$-$\nu_\tau$ oscillations by OPERA
- $\bar{\nu}_\tau$ never been observed

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$\nu_\tau$</th>
<th>$\bar{\nu}_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>1200</td>
<td>1000</td>
</tr>
<tr>
<td>$\tau \rightarrow h$</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>1000</td>
<td>700</td>
</tr>
<tr>
<td>total</td>
<td>6200</td>
<td>4700</td>
</tr>
</tbody>
</table>

Total number of expected $\nu_\tau$ and $\bar{\nu}_\tau$ events to be observed @SND
• τ decay vertex reconstructed thanks to the sub-micrometric resolution of the emulsion target;
• target magnetisation allows to distinguish between $\nu_\tau$ and $\overline{\nu}_\tau$. 

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SND precision spectrometer

- Magnetised volume of ~10 m³;
- B~1.2 T, spatial field omogenity ~1%;
- maximum external stray field ~10 mT;
- opening / closing mechanism to allow for emulsion film replacement during run.
SND Muon Identification system

Detector planes are hanging from the top of a support structure and extracted through upper trails.

Maximum expected charged particle rate $\sim 400 \text{ Hz/cm}^2$: RPCs operated in avalanche mode.

8 tracking planes based on RPCs identifying muons with high efficiency interleaved with iron walls, acting as hadron filters.

RPC tracking planes

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RPCs for SND muon system

RPC tracking plane (~2 x 4 m²):
• 3 gaps (~1.9 x 1.2 m² each), operated in avalanche mode;
• readout by 2 panels of perpendicular strips (pitch ~1cm, length ~2m);
• mechanical structure including all services (HV, gas distribution, front-end boards).

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In 2018 the SHiP Collaboration installed a small-scale replica of the experiment target in the H4 beam line in order to measure the muon flux generated by the SHiP target. 3 \times 10^{11} \text{ protons at 400 GeV}

5 single gap RPCs, prototypes of SHiP muon planes, interleaved with iron slabs
Prototypes for SHiP RPCs

A pilot production of five RPCs, prototypes of the SHiP tracking planes, was made for the muon-flux measurement by the Bari, Napoli and KODEL SHiP groups.

- Dimension: \(\sim (1.9 \times 1.2) \text{ m}^2\);
- Gap width: 2 mm;
- Readout by 2 panels of perpendicular strips with pitch of \(\sim 1\) cm;
- Bakelite electrodes thickness: 2 mm;
- Operated in avalanche mode.

Parallel signal transmission

Data processed and transmitted via Ethernet to the DAQ by custom readout boards [INFN-Bari]

FE board with 2 FEERIC ASICs by ALICE [JINST 9 (2014) C09013]
Performance of SHiP RPCs with standard gas mixture

Standard gas mixture:
95.2% R134a - 4.5% iC$_4$H$_{10}$ - 0.3% SF$_6$

- Efficiency reached by all chambers: $\sim$98%;
- Spatial resolution: about 3 mm;
- Uniform spatial response provided.
R&D activities: eco-friendly gas mixtures

- Fluorinated greenhouse gases (GHGs) with high **Global Warming Potential (GWP)** have been recently limited in EU [EU regulation 517/2014].

quantifies the contribution of a gas to the greenhouse effect, normalized to the effect of CO\(_2\)

- CERN is committed to reducing its direct greenhouse gas emissions [CERN Env. Report].

Alternative eco-friendly gas mixtures for RPCs under study. Requirements:
- low toxicity;
- not flammable;
- detector performance comparable with standard gas mixture.

- R134a is being replaced in industrial applications with HydroFluoro-Olefins (HFOs). Initial strategy:

R134a: standard gas mixture main component, GWP=1430

R134a, GWP=1430

HFO-1234ze, GWP=6

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R&D activities: eco-friendly gas mixtures

- Standard gas mixture: GWP≈1470
  - 94.5% R134a-0% HFO-5% iC$_4$H$_{10}$-0.5% SF$_6$
- 84.5% R134a-10% HFO-5% iC$_4$H$_{10}$-0.5% SF$_6$ [GWP≈1330]
- 25% HFO-69.5% CO$_2$-5% iC$_4$H$_{10}$-0.5% SF$_6$ [GWP≈120]
- 35% HFO-60% CO$_2$-4.5% iC$_4$H$_{10}$-0.5% SF$_6$ [GWP≈120]

The direct replacement of R134a with HFO moves the plateau to values > 13 kV.

CO$_2$ addition: eff. plateau decreased to values < 12 kV.

- Eff@HV$_{ref}$+200V:
  - ~96%
  - ~94.5%
  - ~95%

Ref points@92%

Efficiency vs. HV$_{eff}$
R&D activities: eco-friendly gas mixtures

Probability of observing events with cluster size > 4

- Std: 94.5% R134a-5% iC₄H₁₀-0.5% SF₆
- 25% HFO-69.5% CO₂-5% iC₄H₁₀-0.5% SF₆
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Performance of HFO/CO₂ based mixtures wrt standard case

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<tr>
<th>mix</th>
<th>GWP</th>
<th>HVref+200V</th>
<th>eff</th>
<th>Av. cluster size</th>
<th>P(Cs&gt;4)</th>
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<tbody>
<tr>
<td>~1470</td>
<td>~9800 V</td>
<td>~96%</td>
<td>~2.3</td>
<td>~2%</td>
<td></td>
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- The probability of observing large cluster size events increases with the CO₂ amount;
- For the eco-gas mixture with 60% CO₂ @HV_{ref}+200V:
  - P(Cs>4) is ~1.7 higher than standard case;
  - the efficiency is ~1% less wrt std case.
R&D activities: eco-friendly gas mixtures

New gaps with reduced thickness are under study:

- Decreased average charge delivered;
- Improvement of RPC performance with eco-gas;
- Higher rate capability;
- Improved detector longevity.

Probability of observing events with cluster size > 4

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1.6 mm thick gap produced in KODEL
**R&D activities: readout system for SHiP RPC**

- The current readout system for RPCs is based on parallel signal transmission.
- A new front-end board hosting an FPGA for the **high-speed serial transmission of data** is designed.
- Data transmitted serially by FE boards are concentrated and transmitted via optical link to the DAQ.

**New front-end board**

- **FEERIC ASIC**
- **FPGA**
- **Services**

**Concentration boards**

- **304 FE boards**

**Tracking Plane 1**

- **Tracking Plane 8**

**Optical link** (10Gb Ethernet)

- **trigger, pulse**

**Auxiliary board**

- used for test functionalities

**Global FC**

**Front End Host computer**

**Optical switch**

**Data, SC**

**16 FEERIC ASIC Services**

**16 IN**

**16 TX**

**16 RX**
The SHiP SND Muon System

• The SHiP experiment could study neutrino physics with unprecedented statistics. A dedicated Scattering and Neutrino Detector (SND) is thus being designed.
• The SND is equipped with a Muon Identification System based on RPC technology.

Prototypes of SHiP RPCs

• Five 2 mm-gap prototypes of SHiP RPCs have been produced, tested with cosmic rays and exposed at H4 beam line with standard gas mixture.
• RPCs showed uniform spatial response, efficiency of ~98% and resolution of ~3 mm.

R&D for SHiP RPCs

• Eco-friendly gas mixtures based on HFO and CO₂ for SHiP RPCs are currently under study.
• In order to improve RPC performance with eco-gas, gaps with reduced thickness are being tested.
• The readout system for SHiP RPCs including a new FE board for the high-speed serial transmission of data from detector planes to the DAQ is being designed.
Thank you!