Muon Phase 2 Upgrade

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Phase-2 L1 Muon Trigger Algorithms and Muon Upgrade Workshop
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Current Muon System

- DT (drift tubes): trigger, precision, low rate
- CSC (cathode strip chambers): trigger, precision, high rate
- RPC (resistive plate chambers): trigger, fast

Redundancy (4 stations with 2 detector technologies on the path of a muon in ≈any direction) ensure:
- robust trigger
- efficient reconstruction

Acceptance: $|\eta| < 2.4$

L1 Trigger: $p_T > 25$ GeV ($\mu$); $p_T > 4$ GeV ($\mu^+\mu^-$, $\Delta R < 1.2$)

Reconstruction: $p > 3$ GeV (yes, $p$), $\delta p_T/p_T \approx 1-2\%$ (with the Tracker)
Three technologies

DTs

- Sensitive layers area: 18,500 m²
- Number of channels: 172K

CSCs

- Sensitive layers area: 6,300 m²
- Number of channels: 477K

RPCs

- Sensitive layers area: 4,000 m²
- Number of channels: 137K
All LHC experiments were designed for the LHC specs

New specs require detector upgrades
Muon System Upgrade

Present DT, CSC, RPC detectors will stay
- extensive longevity studies

Electronics of the legacy detectors
- replace what will fail the HL-LHC L1/DAQ specs
  - DT: replace on-detector/BE electronics
  - CSC: selective on-detector board replacements and all BE
  - RPC: replace off-chamber readout/control system
- enhance capabilities of what is being replaced
  - DT Trigger: improved timing, more flexibility
  - RPC Trigger: improved timing

Enhance the challenging forward system
- GE1/1: 2 extra points
- ME0: 6 layers, \( \eta \) coverage is extended from 2.4 to 2.8
- GE2/1: 2 extra points
- iRPC: 1 extra point per station
Detector longevity
**Detector longevity**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Maximum Expected Q* at L=3000 fb⁻¹</th>
<th>Accumulated Q (test detectors at GIF++ &amp; B904)</th>
<th>Results obtained with test detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT</td>
<td>20 mC/cm</td>
<td>25 mC/cm</td>
<td>Gas gain drop is observed (next slide)</td>
</tr>
<tr>
<td>CSC</td>
<td>110 mC/cm</td>
<td>340 mC/cm</td>
<td>No deterioration in performance</td>
</tr>
</tbody>
</table>
| RPC      | 280 mC/cm²  
500 mC/cm² | 425 mC/cm²  
90 mC/cm²  | No deterioration in performance             |
| iRPC     | 280 mC/cm²  
250 mC/cm²  | No deterioration in performance             |
| GE1/1    | 6 mC/cm²   
3 mC/cm²   | 1400 mC/cm²                                  | No deterioration in performance     |
| GE2/1    | 280 mC/cm²  |                                             |                                     |
| ME0      | 280 mC/cm²  |                                             |                                     |

* The maximum expected accumulated charge per wire length or surface area is for the hottest spots in the system.
DT longevity

- **Hottest spots:**
  - $\text{MB} \pm 2/1$: $Q \sim 20 \text{ mC/cm}$ at nominal HV
  - other DTs will accumulate substantially smaller charge (see backup)

- **Wire aging:**
  - expect gas gain drop by a factor of 3 at $20 \text{ mC/cm}$
  - cause: DT material outgassing

- **Mitigation measures**
  - selectively reduce HV (half the gas gain) to slow down aging and reduce signal discriminator thresholds to keep efficiency intact (implemented)
  - precaution: change from close-loop to open-loop gas flow (implemented)
  - add MB4 shielding (to be implemented in LS2)
  - considering $\text{O}_2$ and $\text{H}_2\text{O}$ additives having aging-preventive properties
  - high redundancy in the original DT system design plus new scheme to trigger/reco efficiency higher than 90%

- **Need a good model of the net effect for Phase-2 simulation**
  This is a bit more involved than just assumptions on the number of dead channels (often in groups corresponding to one FE board)
Replacement of electronics of the legacy detectors
DT electronics upgrade

MAIN PROBLEM:
• Readout cannot cope with the new L1/DAQ specs
• Minicrate electronics (FE Trigger/DAQ) are aging

SOLUTION:
• Replace readout system (keep FE analog electronics)

PROTOTYPING STATUS:
• One sector will operate with prototypes of new electronics during LS2 and, partially, into Run 3 (all in parallel with the legacy readout)

ENHANCEMENTS FOR L1 TRIGGER
• better timing (12.5 ns digitization $\rightarrow$ 1 ns)
  • better suppression out-of-time background
  • better momentum measurement
  • trigger on HSCP (Heavy Slow Charged Particles)
• move trigger primitive logic to back-end electronics:
  • more versatile trigger logic (e.g., TPs can be made from more than 4 layers, easy to mix in RPC hits, more FPGA power in general)
  • more robust w.r.t. potential DT efficiency deterioration
  • easier to maintain/upgrade
CSC electronics upgrade

MAIN PROBLEM:
• Part of readout cannot cope with the new L1/DAQ specs
• Rad-hard issues for ME1/1 electronics

SOLUTION:
• Replace electronic boards selectively, as needed

STATUS
• All on-detector work is to be done during LS2

ENHANCEMENTS FOR L1 TRIGGER
• more FPGA resources for forming trigger primitives
  • ALCT boards (anode 1D TP): all CSCs
  • TMB boards (cathode 1D TP, (anode)x(cathode) 2D TP): ME*/1 CSCs
  • can form joint ME2/1-GE2/1 trigger primitives

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Phase-2 L1 Muon Trigger Algorithms and Muon Upgrade Workshop
(28-30 Nov 2018)
**RPC electronics upgrade**

**MAIN PROBLEM**
- Readout system will have non-sustainable rate of losing configuration communications at HL-LHC
- Readout system is aging; we will run out of spares

**SOLUTION**
- Replace trigger/readout system (so-called Link System)

**PROTOTYPING STATUS**
- First prototype design is due in June 2019

**ENHANCEMENTS FOR L1 TRIGGER**
- better timing (25 ns digitization → 1.6 ns)
  - better suppression out-of-time background
  - trigger on HSCP
- better integration of RPC hits into RPC+DT TPs
New detectors
New detectors in the forward direction

 VERY CHALLENGING FORWARD REGION
• high rates due to n/γ-induced background, punchthrough, and muons
• small bending of muons by magnetic field
• small number of hits per muon in the forward direction (present system); smaller than in the barrel!

Enhance the forward system by adding:
• GE1/1: 2 extra points
• ME0: 6 layers (and, opportunistically, η coverage is extended from 2.4 to 2.8)
• GE2/1: 2 extra points
• iRPC: 1 extra point per station
iRPC (improved RPC) detectors

**STATUS**
- Next iRPC prototype with FEBv3 is due in March 2019

**improved RPC**

Conventional double-layer RPC units (1 hit) with critical improvements:
- lower resistivity, smaller gas gain, more sensitive FE: higher rate capability
- two-end strip readout with O(0.1) ns time resolution: true 2D hits with 1 cm localization

**RE3/1 and RE4/1 stations:**
Overall area: 90 m²
Number of channels: 14K
**iRPC (improved RPC) detectors**

**ENHANCEMENTS FOR L1 TRIGGER**

- 2 more muon measurements in the forward direction
- iRPC hits excellent timing of $O(1)$ ns should help suppress out-of-time background
- iRPC hits will help disentangle combinatorial ambiguities in CSCs with multiple muons

**Conventional double-layer RPC units (1 hit) with critical improvements:**
- lower resistivity, smaller gas gain, more sensitive FE: higher rate capability
- two-end strip readout with $O(0.1)$ ns time resolution: true 2D hits with 1 cm localization

**RE3/1 and RE4/1 stations:**

- Overall area: 90 m$^2$
- Number of channels: 14K

In ME3/1 and ME4/1 chambers, probability per chamber to have a spurious segment will be about 10% at HL-LHC (from Run 2 data extrapolation)
Rate of trigger primitives (LCT) in forward CSCs

Probability per chamber: $p = \frac{n}{N} \times 3$

- $n$ - average number of chambers with LCTs per BX
- $N$ – number of chambers of that type
- 3 – accounts for 3 BXs, the time window for LCTs to be possibly associated with the same muon in EMTF

ME1/1: $\sim 70\%$
ME2/1: $\sim 30\%$
ME3/1 and ME4/1: $\sim 15\%$
GEM detectors

GEM – gas electron multiplier

Avalanches in strong electric field concentrated in pin holes
Triplet GEM: gas gain $10^4$
Operate well in high rate
Tests show excellent longevity

**GE1/1, GE2/1 stations**: 2 layers of triplet-GEM units
**ME0**: 6 layers of triplet-GEM units
Overall area (triplet-GEM): **220 m$^2$**
Number of channels: **1.5M**

**STATUS**
- GE1/1 will be installed in LS2
- Final GE2/1 prototype (detector+electronics) – Dec 2018
- Final ME0 prototype comes in 2021
GEM detectors

GEM – gas electron multiplier

Avalanches in strong electric field concentrated in pin holes

Triplet GEM: gas gain $10^4$

Operate well in high rate

Tests show excellent longevity

GE1/1, GE2/1 stations: 2 layers of triplet-GEM units

ME0: 6 layers of triplet-GEM units

Overall area (triplet-GEM): $220 \text{ m}^2$

Number of channels: $1.5M$

ENHANCEMENTS FOR L1 TRIGGER

• more muon measurements in the forward direction

• GEM hits help disentangle combinatorial ambiguities in CSCs with multiple muons

• GEM-CSC tandems in the 1<sup>st</sup> and 2<sup>nd</sup> muon stations allow for muon track “bending angle” measurements:
  • sharpen muon trigger efficiency turn-on
  • reduce trigger rate

• ME0 extends eta from 2.4 to 2.8, which enhances sensitivities for searches for and measurements of processes with muons in the forward region (getting these muon at trigger level is a challenge!)
Muon $p_T$ with CSC+GEM tandems

CONCEPT (axial view)

- $\eta = 2.4$
- $\eta = 2.8$

CMS Phase II Simulation

CMS Phase Simulation $\sqrt{s}=14$ TeV, $<\text{PU}> = 200$

Data taken with CSC+GE11+GE21+ME0

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DT, CSC, RPC electronics will be upgraded to cope with HL-LHC L1/DAQ requirements. New electronics will have considerably enhanced L1 trigger capabilities.

New GEM and iRPC detectors will make triggering in the challenging forward region far more robust.
Backup
Highlighted are the people coordinating simulation, emulation, reconstruction.
Table 3.1: Estimated integrated charge in mC/cm up to the end of HL-LHC operations (3000 fb$^{-1}$) based on measured currents as a function of instantaneous luminosity corrected for the effect of the MB4 top shielding and of operating at 3550 V. No safety factor was included. The quoted uncertainty includes instantaneous luminosity measurement (5%) and stability among fills (3%).

<table>
<thead>
<tr>
<th></th>
<th>Wheel-2</th>
<th>Wheel-1</th>
<th>Wheel 0</th>
<th>Wheel +1</th>
<th>Wheel+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB4 S4</td>
<td>3.6 ± 0.3</td>
<td>3.7 ± 0.3</td>
<td>3.1 ± 0.2</td>
<td>3.4 ± 0.2</td>
<td>4.3 ± 0.4</td>
</tr>
<tr>
<td>MB4 S3-S5</td>
<td>3.4 ± 0.4</td>
<td>2.1 ± 0.2</td>
<td>2.7 ± 0.2</td>
<td>3.0 ± 0.2</td>
<td>3.5 ± 0.3</td>
</tr>
<tr>
<td>MB4 S1-S7</td>
<td>7.0 ± 0.4</td>
<td>5.0 ± 0.3</td>
<td>3.8 ± 0.2</td>
<td>4.6 ± 0.3</td>
<td>6.0 ± 0.2</td>
</tr>
<tr>
<td>MB4 S12-S8</td>
<td>4.8 ± 0.3</td>
<td>3.0 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.6 ± 0.2</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>MB1</td>
<td>9.9 ± 0.6</td>
<td>4.4 ± 0.3</td>
<td>1.6 ± 0.2</td>
<td>4.2 ± 0.3</td>
<td>10.0 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>17.0 ± 0.7 (3600 V)</td>
<td>1.6 ± 0.2</td>
<td>4.2 ± 0.3</td>
<td>16.0 ± 1 (3600 V)</td>
<td></td>
</tr>
<tr>
<td>MB2</td>
<td>2.1 ± 0.2</td>
<td>0.90 ± 0.05</td>
<td>0.50 ± 0.03</td>
<td>0.80 ± 0.05</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>MB3</td>
<td></td>
<td></td>
<td></td>
<td>0.4 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>
CSCs at P5

CSC efficiency, space and time resolution are stable since early running

Gas gains are now equalized:
• no chambers run at too high gas gain and, thus, run unnecessarily fast their longevity resource
• no chambers run at too low gas gains, which gives room to reduce gas gain

Current instabilities:
• Observed in Run 2 an increase in occurrences of current spikes and some Malter currents (self-sustained discharges ignited at high hit rates).
• The fraction of “flaky” HV channels seems to have stabilized over the last year at O(5%) of about 12,000 HV channels. Channels with Malter are a small fraction (1-6%) of unstable channels.
• A full characterization of the Malter effect, the use of regeneration techniques, the study of the plasma chemistry and the spectroscopy of the affected materials are actively pursued at CERN GIF++, PNPI, Dubna, Sarov, and Belgrade.
RPCs at P5

Stable performance:
efficiency, cluster size

Observe an increase of dark currents in the most exposed RPC stations, partially recovered during breaks (TS & YETS)

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