Detector R&D requirements for Muon Colliders > 2045

Specific long-term detector technology R&D requirements of a muon collider operating at 10 TeV and with a luminosity of the order of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

- Status of existing and on-going studies at 1.5 and 3 TeV center-of-mass energy
- Future steps towards 10 TeV and higher center-of-mass energy to exploit physics reach

\[
Hp: \mathcal{L} = 2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \text{ @ 10 TeV}
\]
\[
\int \mathcal{L} dt = (E_{CM}/10\text{TeV})^2 \times 10 \text{ ab}^{-1}
\]

@ 3 TeV \quad \sim \quad 1 \text{ ab}^{-1} \quad 5 \text{ years}

@ 10 \text{ TeV} \quad \sim \quad 10 \text{ ab}^{-1} \quad 5 \text{ years}

@ 14 \text{ TeV} \quad \sim \quad 20 \text{ ab}^{-1} \quad 5 \text{ years}

~ $2 \times 10^{12} \mu\text{/bunch}$

1 bunch/beam colliding each 20-30 $\mu$s

\Rightarrow \text{ max 2 Interaction Points - IP}

ONLY 1 EXPERIMENT CONSIDERED at present
Detector

- Based on CLIC’s detector model + the MDI and vertex detector designed by MAP.

-Muon detectors
- Hadronic calorimeters
- Tracking system
- Shielding nozzles (tungsten cones + BCH₂ cladding) - reduce the BIB rate by a factor ~500
- Electromagnetic calorimeters
- Superconducting solenoid (3.57T)

B = 3.57 T to be studied and tuned

Full simulation available on github

Nozzles limits acceptance to \(\sim \theta = 10^\circ\)
Present Tracker design

Detector Performance Studies at a Muon Collider - ICHEP2020 - July 29, 2020

M. Casarsa

Two examples of MAP's solutions to cope with the BIB:

- **MDI:** two tungsten nozzles with 5-cm polyethylene cladding for neutrons reduce the beam-induced background in the detector by a factor of ~500.

- **VXD geometry:** the vertex detector barrel is designed in such a way not to overlap with the BIB hottest spots around the interaction region.

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**Vertex detector (VXD)**
- **barrel:** 4 cylindrical layers
  - endcaps: 4 + 4 disks
- **double-layer Si sensors:**
  - 25x25 μm² pixels
  - 50 μm thick
  - \( \sigma_T = 30 \) ps

**Inner Tracker (IT)**
- **barrel:** 3 cylindrical layers
  - endcaps: 7 + 7 disks
- **Si sensors:**
  - 50 μm x 1 mm macro-pixels
  - 100 μm thick
  - \( \sigma_T = 60 \) ps

**Outer Tracker (OT)**
- **barrel:** 3 cylindrical layers
  - endcaps: 4 + 4 disks
- **Si sensors:**
  - 50 μm x 10 mm micro-strips
  - 100 μm thick
  - \( \sigma_T = 60 \) ps
# TF3: Solid State Detectors requirements

<table>
<thead>
<tr>
<th>MAPS</th>
<th>Planar/3D/Passive CMOS</th>
<th>LGADS</th>
<th>Muon Collider VD</th>
<th>Muon Collider Tracker</th>
<th>Muon Collider Calorimeter</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>position precision σhit (µm)</td>
<td>5</td>
<td>7</td>
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<td></td>
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<td>≤5 µm</td>
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<td>low X/X0 (%/layer)</td>
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<td>1</td>
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<td>low power (mW/channel)</td>
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<td>&lt; 1 W/cm^2</td>
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<td>timing precision σt (ns)</td>
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<td>large area wafers (&quot;)</td>
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<td>12</td>
<td>8</td>
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<td>&lt;0.5</td>
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<td>radiation tolerance TID (Grad)</td>
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**dose/muon at the tracker inner layer??**
## TF3: Solid State Detectors Technologies

<table>
<thead>
<tr>
<th>MAPS</th>
<th>Muon Collider</th>
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<tbody>
<tr>
<td>technology node</td>
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</tr>
<tr>
<td>wafer size (stitching)</td>
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<tr>
<td>RO rate</td>
<td>&lt;100 kHz</td>
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<tr>
<td>RO integration time</td>
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<tr>
<td>ultrafast timing</td>
<td></td>
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<tr>
<td>new process/material</td>
<td></td>
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<tr>
<td>new design</td>
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<table>
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<table>
<thead>
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<th>LGADS</th>
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<td>technology node</td>
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<td>wafer size</td>
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<tr>
<td>integration time</td>
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<td>ultrafast timing</td>
<td>20-30 ps</td>
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<table>
<thead>
<tr>
<th>backend processing</th>
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<tbody>
<tr>
<td>Thickness</td>
<td></td>
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<tr>
<td>3D integration - Heterogenous process/nodes</td>
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</table>

Technology << 28nm
TF4: PID and photon detector

- SiPM technology flagged essential for the muon collider, in regard to timing and rad hardness (possibly) in relation to calorimetry (anything else?). Do you consider any other photon detector technology as important (eg MCP-PMTs or similar ?), or even useful. How about scintillating fibres?

- Secondly PID. So far we have not listed PID as being considered for the muon collider, which is clearly an oversight on our part. Would you consider PID as “essential”, “important” or “unimportant”? What technologies are being considered for PID – TOF maybe ? dE/dx ? Transition radiation? Or maybe compact RICH detectors? Or maybe PID detectors are not even being considered?
**TF7: Electronics – on-detector processing**

- buffering of this much data at the front end for readout
- inclusion of precision timing information substantially increases raw data volume
  - 30Tb per crossing is a lot to store
- comment: a couple of orders of magnitude over the state of the art in terms of Mb/cm² – so a serious R&D topic

Current conservative estimate of the data rates from the detector is ~50 Tbps (the old tracker only number was 30). This is per second, not per crossing. The number can be reduced substantially by optimizing the timing cuts, the pT module filtering, etc...

Furthermore, this number is input to the HLT, not suggesting to send all this data to storage,. As far as the amount data to storage I assumed same bandwidth as in CMS for Phase-2, which is ~70 GB/s, and this would correspond to 1.5 kHz of events. If we manage to reduce the event size or the technology allows to store more data, we may be able to get the number to ~3-5kHz. But based on my estimates of Higgs and EWK event rates, 1.5k Hz should be enough.

- A streaming system with software based trigger allows a lot of flexibility. One can certainly consider a “classic” approach with data sitting in the detector FE awaiting an L1 decision. However, the classic approach has its own set of issues that I’d be happy to discuss. My estimates demonstrate that from the bandwidth perspective we are not far from a “streaming” system using technology of the HL-LHC. With proper R&D we should get there in 20+ years.
extras
ECFA Detector R&D Roadmap

Organization for Consultation of Relevant Communities

RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement

Publication

Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn

Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, ...

Consultation with the particle physics community & other disciplines with technology overlap

https://indico.cern.ch/e/ECFADetectorRDRoadmap
### Considered future facilities

**Broad Topic Areas**

**Organization for Consultation of Relevant Communities**

- Focus on the technical aspects of detector R&D requirements given the EPPSU deliberation document listed “High-priority future initiatives” and “Other essential scientific activities for particle physics” as input and organise material by Task Force.
- Task Forces start from the future science programmes to identify main detector technology challenges to be met (both mandatory and highly desirable to optimise physics returns) to estimate the period over which the required detector R&D programmes may be expected to extend.
- Within each Task Force create a time-ordered technology requirements driven R&D roadmap in terms of capabilities not currently achievable.

### Grouped targeted facilities/areas emerging from the EPPSU

1. Detector requirements for full exploitation of the HL-LHC (R&D still needed for LS3 upgrades and for experiment upgrades beyond then) including studies of flavour physics and quark-gluon plasma (where the latter topic also interfaces with nuclear physics).
2. R&D for long baseline neutrino physics detectors (including aspects targeting astro-particle physics measurements) and supporting experiments such as those at the CERN Neutrino Platform.
3. Technology developments needed for detectors at $e^+e^-$ EW-Higgs-Top factories in all possible accelerator manifestations including instantaneous luminosities at 91.2GeV of up to $5 \times 10^{36} \text{cm}^{-2}\text{s}^{-1}$.
4. The long-term R&D programme for detectors at a future 100 TeV hadron collider with integrated luminosities targeted up to $30 \text{ab}^{-1}$ and 1000 pile-up for 25ns BCO.
5. **Specific long-term detector technology R&D requirements of a muon collider operating at 10 TeV and with a luminosity of the order of $10^{35} \text{cm}^{-2}\text{s}^{-1}$**.
Detector R&D Roadmap timeline

Organisation
- May 2020: EPPSU mandate to ECFA to develop a roadmap for detector R&D efforts in Europe
- Sep 2020: Structure in place with Detector R&D Roadmap Panel
- Dec 2020: Task Forces active

Website: https://indico.cern.ch/e/ECFADetectorRD_Roadmap

Expert & Community Consultation
- Feb 2021: Collection of requirements of future facilities & projects
- Feb/March 2021: Questionnaires of Task Forces to national contacts
- Task Forces liaise with experts in
  - ECFA countries
  - adjacent disciplines
  - industry

March-May 2021 Open Symposia

Process and Timeline

Drafting Roadmap & Feedback
- May 2021: Task Forces collate input from symposia
- 25-28 May 2021: Drafting sessions
  - opening session with all experts involved
  - plenary & parallel sessions with Task Force members
  - final session of Roadmap Panel
- July 2021: Near final draft shared with RECFA*
- 30 July 2021: Presentation at Joint ECFA-EPS session
- Until Sep 2021: Collect final community feedback*
- Oct 2021: Detector R&D Roadmap Document submission to RECFA and afterwards to PECFA and Council

*community feedback via RECFA delegates and National Contacts
Muon and neutron fluences @ 1.5 TeV

Muon flux map in IR.
Muons – with energy of tens and hundreds GeV – illuminate the whole detector. They are produced as Bethe-Heitler pairs by energetic photons in EMS originated by decay electrons in lattice components.

Neutron fluence map inside the detector.
Maximum neutron fluence and absorbed dose in the innermost layer of the Si tracker for a one-year operation are at a 10% level of that in the LHC detectors at the nominal luminosity. High fluences of photons and electrons in the tracker and calorimeter exceed those at LHC, and need more work to suppress them.

Expected fluence < HL-LHC HL-LHC < Expected dose < FCC-hh
Still expecting radiation hardness
To play a significant role, but unlikely to be a major problem
Leaves more flexibility in adapting detector design to such requirements
Fluences and dose requests to be able to compare mainly tracker constraints

JINST 13 (2018), P09004
JINST 15 (2020) 05, P05001

muon beams
@ 0.75 TeV with \(2 \times 10^{12}\) muons/bunch ➔
4\( \times 10^5 \) muon decays/m single bx

The simulation of MDI and BIB was done with MARS15 by the MAP collaboration and later a FLUKA tool was developed to reproduce results @ 1.5 TeV center of mass with MAP lattice with optimised IR.
Data refer to this energy.

Now studies are on-going at the 3 TeV and soon planning to extrapolate to 10 TeV.
Tracker simulation

entirely silicon-based detector:

- **Vertex detector**: 4 barrels + 4 endcaps / side
- **Inner Tracker**: 3 barrels + 7 endcaps / side
- **Outer Tracker**: 3 barrels + 4 endcaps / side

Simulation including estimate of support structures and services
### Tracker with timing considerations

<table>
<thead>
<tr>
<th></th>
<th>cell size</th>
<th>sensor thickness</th>
<th>time resolution</th>
<th>spatial resolution</th>
<th>number of cells</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VXD</strong></td>
<td>25 μm × 25 μm pixels</td>
<td>50 μm</td>
<td>30 ps</td>
<td>5 μm × 5 μm</td>
<td>729M</td>
</tr>
<tr>
<td></td>
<td>25 μm × 25 μm pixels</td>
<td>50 μm</td>
<td>30 ps</td>
<td>5 μm × 5 μm</td>
<td>462M</td>
</tr>
<tr>
<td><strong>IT</strong></td>
<td>50 μm × 1 mm macropixels</td>
<td>100 μm</td>
<td>60 ps</td>
<td>7 μm × 90 μm</td>
<td>164M</td>
</tr>
<tr>
<td></td>
<td>50 μm × 1 mm macropixels</td>
<td>100 μm</td>
<td>60 ps</td>
<td>7 μm × 90 μm</td>
<td>127M</td>
</tr>
<tr>
<td><strong>OT</strong></td>
<td>50 μm × 10 mm microstrips</td>
<td>100 μm</td>
<td>60 ps</td>
<td>7 μm × 90 μm</td>
<td>117M</td>
</tr>
<tr>
<td></td>
<td>50 μm × 10 mm microstrips</td>
<td>100 μm</td>
<td>60 ps</td>
<td>7 μm × 90 μm</td>
<td>56M</td>
</tr>
</tbody>
</table>

Parametric digitization, realistic digitization developed for the critical innermost layers
Timing window to reduce hits from out-of-time BIB
Granularity optimized to ensure <= 1% occupancy in each layer

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**Vertex layer 1/2:** $\sigma_1 = 30$ ps, Rest of Vertex: $\sigma_1 = 60$ ps
**Inner:** $\sigma_1 = 60$ ps, **Outer:** $\sigma_1 = 100$ ps

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Background hits overlay in [-360, 480] ps range

- VXD disks
- IT disks
- OT disks

### Background hits overlay in [-360, 480] ps range

- $\hat{S} = 1.5$ TeV
- $\sigma_{VXD}^{\text{VXD}} = 30$ ps
- $\sigma_{IT,OT}^{\text{IT,OT}} = 60$ ps
- Preliminary
- No time window
- Time window $[-3\sigma_1, +5\sigma_1]$
**Detector simulation**

BIB introduces $\sim 10^8$ particles in a single event → a tremendous computation load

- hits at $t > 10$ns are outside realistic readout time windows
  - accounting for TOF: particles with $t > 25$ns at MDI ignored
- low-energy neutrons reach the calorimeter too late
  - neutrons with $E_{\text{kin}} < 150$ MeV can be safely excluded

DL: double layer

**Calorimeter hits**

$E_{\text{kin}}(n) \geq 150$ MeV
Tracking performances

- Can successfully reconstruct muons with high purity of measurements associated to the track
- Further algorithm and geometry tuning needed to ensure high efficiency at all $\theta$ and smooth detector resolution
Calorimeters

About 6 TeV (2.5 TeV) of energy deposited in ECAL (HCAL) by BIB

Lorenzo Sestini et al.

- **BIB is diffused in the calorimeters**: at the ECAL barrel surface the flux is 300 particles/cm², most of them are photons with \( <E> = 1.7 \text{ MeV} \).

- BIB occupancy is lower in HCAL with respect to ECAL. **Timing and longitudinal measurements play a key role in the BIB suppression**

Energy deposition in calorimeters per bunch crossing

**Muon Collider \( \sqrt{s} = 1.5 \text{ TeV} \)**

- ECAL/HCAL Longitudinal occupancy

- Longitudinal coordinate of ECAL Barrel hit (weighted for energy) [mm]

- Hit time in ECAL Barrel - \( t_0 \) [ns]

- Acquisition time of \([-0.25, +0.25]\)