Status & Challenges of Tracker Design for FCC-hh

Zbyněk Drásal
CERN

On behalf of the FCC-hh detector working group
Overview

- **Introduction**
  - Future Circular Collider with focus on FCC-hh (pp) option
  - Physics motivation & Reference Detector Layout
- **FCC-hh & Radiation Studies**
- **Tracker design & expected tracker performance**
  - Reference tracker geometry & design driving principles
  - Granularity in R-Φ & tracking resolution
  - Implications of high pile-up & high-rate environment
    - Pattern recognition capabilities & requirements on granularity in Z
    - Primary vertexing in high pile-up & requirements on timing information
    - Expected tracker occupancy & data rates
- **Summary & Challenges**
Road-map & Timescale

- LHC detector R&D started in the 1980's (HL-LHC in the 2000's)
  - **FCC R&D** will build on that for HL-LHC, but with more advanced technologies. That requires long lead times...

```
   Constr.  Physics
   LEP
   Design  Proto  Construction  Physics
   LHC
   Design  Construction  Physics
   HL-LHC
   20 years
   FCC  Design  Proto  Construction  Physics
```
LHC detector R&D started in the 1980's (HL-LHC in the 2000's)
- **FCC R&D** will build on that for HL-LHC, but with more advanced technologies. That requires long lead times...

**1st milestone:** prepare an **FCC Conceptual Design Report** by end of 2018 (for European Strategy Update in 2019/2020)
Future Circular Collider

- **FCC machine:**
  - FCC-hh (pp collider): final goal defining the whole infrastructure
    - $\sim 16T$ magnets $\rightarrow 100\text{TeV}$ pp collider in *97.75km tunnel*
  - FCC-ee: as possible intermediate step
  - FCC-eh: as an option
Future Circular Collider

- **FCC machine:**
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    - $\sim 16T$ magnets $\rightarrow 100\text{TeV}$ pp collider in 97.75km tunnel
  - **FCC-ee:** as possible intermediate step
  - **FCC-eh:** as an option

- **A&G 2 high-luminosity exp.**
- **L&B 2 other exp.**
## Key FCC-hh parameters

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- **Baseline** (phase 1): 10 yrs of operation @ $L_{\text{peak}} = 5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \rightarrow 2.5 \text{ab}^{-1}$ per detector
- **Ultimate** (phase 2): 15 yrs of operation @ $L_{\text{peak}} \leq 30 \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \rightarrow 15 \text{ab}^{-1}$ per detector

→ **Total**: $O(20)\text{ab}^{-1}$ per experiment
### Understanding FCC-hh parameters

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→ the minimum bias events @FCC are quite similar to ones @HL-LHC, but ...

14TeV → 100 TeV
\[ \sigma_{\text{inelastic}} : 80 \text{mb} \rightarrow 108 \text{mb} \]
average \( p_T \): 0.6 → 0.8 GeV/c
multiplicity_{charged/unit \( \eta \)} : 5.4 → 8
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$\sigma_{inelastic}$: 80mb $\rightarrow$ 108mb
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5x increase in pile-up wrt HL-LHC

→ the minimum bias events @FCC are quite similar to ones @HL-LHC, but ...

→ pile-up per bunch crossing $O(1000)$ is a big challenge $\rightarrow$ keeping 5ns (versus 25ns) operation scheme as an option
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- average $p_T: 0.6 \rightarrow 0.8\text{ GeV/c}$
- multiplicity $\frac{\text{charged/unit } \eta}{\text{}}: 5.4 \rightarrow 8$

6x increase in luminosity wrt HL-LHC

- the minimum bias events @FCC are quite similar to ones @HL-LHC, but ...
- pile-up per bunch crossing $O(1000)$ is a big challenge $\rightarrow$ keeping 5ns (versus 25ns) operation scheme as an option
- FCC-hh represents an extremely high luminosity machine $\rightarrow$ expecting huge particle/data rates & significantly higher rad. level in the inner/fwd detector
Physics Requirements on Detector Design

- Design strongly depends on outcome of future LHC discoveries:
  - In case of new discoveries ➔ precise understanding of new physics will motivate the design
  - In case no new physics is discovered ➔ mass scale of new physics may be beyond LHC reach or final states are too elusive ➔ higher mass reach, high luminosity machine & precise det. are the key!
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- **FCC opens us a new kinematic & dynamical regime, so requirements on tracker:**
  - Extended tracking up-to $|\eta|\sim 4$ (c.f. $|\eta|\sim 2.5$ for LHC exp.) + efficient VBF jet meas. up-to $|\eta|\sim 6$
  - High $p_T$ res. $\sim 10-20\%$ @ 10TeV (cf. LHC: 10% @1TeV) & still keep sensitivity to low $p_T$ tracks + provide efficient $b,c,\tau$-tagging despite huge PU
  - High Tracker granularity essential to resolve jet-substructure (E/HCAL), reject bkg,...
Reference Detector Layout

Muon system

(i)Fwd + Central Tracker

Be beam-pipe @R=20+0.8mm

Hadr. Cal. Fwd (Pb/LAr), BRL(Fe/Sci)

Electromag. Calorimeter (Pb/LAr)

η = 2.0
η = 2.5
η = 3.0
η = 4.0
Central region inspired by ATLAS/CMS
Reference Detector Layout

Central region inspired by ATLAS/CMS

Forward region inspired by LHCb

\[ \eta = 2.0 \]
\[ \eta = 2.5 \]
\[ \eta = 3.0 \]
\[ \eta = 4.0 \]
Reference Detector Layout & Magnet

4T solenoid (10m free bore) + 2x 4T Fwd solenoids (no shielding)
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Courtesy M. Mentink
- Neutron fluence rates @L=30x10^{34} \text{ cm}^{-2}\text{s}^{-1}

→ 2 main hot spots: FWD calorimeter & TAS
• Neutron fluence rates @L=30\times10^{34} \text{ cm}^{-2}\text{s}^{-1}

→ 2 main hot spots: **FWD calorimeter** & **TAS**

→ **Shielding scheme effective**, but several leakage channels appear due to service channels etc.

![Diagram showing neutron fluence rates and shielding](image)

**Shielding FwdCAL:** 5cm Li polyethylene between 2mm Al

**Cast iron shielding**

**Shields:**
- 1m steel
- 5cm Li polyethylene
- 1cm lead

*Courtesy of M.I. Besana*
Tracker & Long-term Damage after $30 ab^{-1}$

- 1 MeV neq fluence after $30 ab^{-1}$

Long-term damage for Tracker after $30 ab^{-1}$

<table>
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<tr>
<th>R [mm]</th>
<th>z[m]</th>
<th>Dose [MGy]</th>
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Radiation @ FCC:

- @R=25mm: $\sim 6 \times 10^{17}$ neq cm$^{-2}$, TID $\sim 0.4$GGy
- LHC $= 1$
- HL-LHC $\rightarrow 20 \times$ LHC
- FCC $\rightarrow 600 \times$ LHC

Courtesy of M.I. Besana
Tracker & Long-term Damage after 30ab\(^{-1}\)

- 1 MeV neq fluence after 30ab\(^{-1}\)

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Radiation @ FCC:

- \(R=25\) mm: \(\sim 6 \times 10^{17}\) neq cm\(^{-2}\), TID\(\sim 0.4\) GGy
- LHC = 1
- HL-LHC → 20x LHC
- FCC → 600x LHC
- HL-LHC rad. tolerance limit @R\(\sim 270\)mm for z=0m
  (z-pos. dependent)

Courtesy of M.I. Besana
Tracker Layout & Design Driving Principles

- **Key tracker parameters:**
  
  - **Granularity in R-Φ** → driven by requirement on $\Delta p_T / p_T$, efficient tagging of displ. vertices (d0) & occupancy limit (~1%)

  $\frac{\Delta p_T}{p_T} = \frac{\sigma[m] p_T [GeV/c]}{0.3 B[T] L^2 [m^2]} f(N)

  \[\begin{align*}
  L & : 1.55m \\
  B & : 4T \\
  \sigma_{R-\Phi} & : 10(7.5)\mu m \\
  N_{\text{layers}} & : 12
  \end{align*}\]

  \[\sim 20\% @ 10\text{TeV/c}\]
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\(~20\% @ 10\text{TeV/c}\)

- **Important!**

\[\text{Low MB}\]

Note: res. improves as \( 1/\sqrt{N_{\text{layers}}} \), but material budget (MB) increases as \( N_{\text{layers}} \)
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    \]
  - Number of layers $N$ → driven by $\Delta p_T/p_T$ res. & pattern recognition capabilities
    Note: res. improves as $1/\sqrt{N_{\text{layers}}}$, but material budget (MB) increases as $N_{\text{layers}}$
    \(\text{Low MB Important!}\)
  - Granularity in Z → driven by pattern recognition capabilities, occupancy limit (~1%) & primary vertexing in given pile-up \(O(1000)\)

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Z. Drásal, Vertex 2017 Asturias Spain (10-15th September 2017)
Reference Tracker Layout (v3.03)

Surface: ~430m²
#Channels: 489.4M, 9964.4M, 5460.9M

Pixel R ≥ 0.9 m due to occupancy

4 (seed) BRL layers

Pixels: 25x50um² (1-4th BRL layers, EC R1),
100/3x100um² (R2),
100/3x400um² (R3,R4)

Macro-pixels: 100/3x400um²

Strips: 100/3umx50mm (BRL),
100/3umx10mm (EC)

→ Assumed binary R/O → res. ~ pitch/√12
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Huge increase in #pixel channels wrt LHC exp. due to:
• requirements on tracking up to η=6
• resilience to high rad. levels generated by FCC-hh

For details see http://fcc-tklayout.web.cern.ch
Material Budget & Tracking Resolution

- A simplified model for MB assumed:
  - $x/x_0 \sim 1\text{-}2.5\%$ per layer (services accumul. effect)
    - (20\% Si, 42\% C, 2\% Cu, 6\% Al, 30\% Plastic)

  $\rightarrow$ technology input needed for more real. estimate
Material Budget & Tracking Resolution

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  → **technology input needed** for more real. estimate

- Tracking resolution (tkLayout SW):
  - \( p_T \) resolution versus $\eta$ - const $p_T$ across $\eta$

  \[ \sim 20\% @10\text{TeV/c} \]
Flavour tagging represents another important aspect of vertex detector & tracker design:

- Tagging of very high-energy jets ($p_T > 1\,\text{TeV}/c$) is extremely challenging, not only because of very collimated particles, but also due to extremely long-lived hadrons (displaced vertices):
  - E.g. $5\,\text{TeV}$ central $b$-jets $\rightarrow$ B-hadrons decay outside the vertex detector in $\sim 50\%$ cases

**Example of B-tagging efficiency versus MB & granularity**

- $p_T(q)=500\,\text{GeV}$
- Central dijets
- No pile-up
- $2.0\%$
- $\sim 0.1\%$

- VTX det. pitch $20\times20\,\mu\text{m}^2$
  - Worse than default geometry
  - Better than default geometry
- Tracker: half MB/default

Courtesy of E. Perez Codina
Pattern Recognition (PR) Capabilities

- **Tracker granularity in Z** is strongly affected by requirement on **PR capabilities**! How to study such effects analytically? Use **track propagator** & analyze **layout “weak” spots**:
  - Assume **perfect seeding** → propagate analytically $\sigma_{r\Phi}$, $\sigma_z$ to $i^{th}$ layer in → out
  - Calculate probability $p$ to mis-match a **real hit anywhere on the track** with a **bkg hit @95% CL in PU=1000**

\[
p = 1 - \prod_{i=4}^{N} (1 - p^i_{bkg95\%})
\]

@ 95% conf. level $n \approx 2.45$
Pattern Recognition (PR) Capabilities

- **Tracker granularity in Z** is strongly affected by requirement on PR capabilities! How to study such effects analytically? Use **track propagator** & analyze layout “weak” spots:

  ➔ Assume **perfect seeding** ➔ propagate analytically $\sigma_{r\phi}$, $\sigma_z$ to $i^{th}$ layer in ➔ out

  ➔ Calculate probability $p$ to mis-match a real hit anywhere on the track with a bkg hit @95% CL in PU=1000

\[
p = 1 - \prod_{i=4}^{N} (1 - p_{\text{bkg95\%}})
\]

➔ How to interpret & set a limit value on $p$?

- CMS trk layout: 3.6.5
  
  @ PU=140
  
  (1-$p$) $\sim$ 80%

  ➔ Try to achieve $p$ $\sim$20% for FCC-hh

   ![Diagram](image)
Understanding Track Propagator in PR

- 4 key parameters affecting propagation of error ellipse:
  - Multiple scattering & **material effect @ $\vartheta$** (tilt angle $\alpha$)
  - **Propagation distance**
  - **Projection factor** on det. plane
  - **Detector resolution**

\[
\sigma_{MS}^2 \approx \langle \hat{\vartheta}_{PT}^2 \rangle \frac{d/X_0}{\sin(\vartheta + \alpha)} \Delta r^2 f_{proj} \\
\langle \hat{\vartheta}_{PT}^2 \rangle = \left( \frac{13.6 \text{ MeV}}{\beta p_{TC}} \right)^2 \left( 1 + 0.038 \ln \frac{d/X_0}{\sin(\vartheta + \alpha)} \right)^2 \\
f_{proj} = \left( \frac{1}{\sin(\vartheta + \alpha)} \right)^2 \text{ proj. in } Z \\
f_{proj} = 1 \quad \text{proj. in } R-\Phi \\
\sigma_{R\Phi} = \sqrt{\sigma_{R\Phi_{loc}}^2 + \left( A/\sqrt{1 - A^2 \sin(\alpha)} \right)^2 \sigma_{Z_{loc}}^2} \\
A = \frac{\Delta r}{2R}
\]
Understanding Track Propagator in PR

- 4 key parameters affecting propagation of error ellipse:
  - Multiple scattering & material effect @ $\vartheta$ (tilt angle $\alpha$)
  - Propagation distance
  - Projection factor on det. plane
  - Detector resolution

\[
\sigma_{\text{MS}}^2 \approx \langle \hat{\vartheta}_{pT}^2 \rangle \frac{d/X_0}{\sin(\vartheta + \alpha)} \Delta r^2 f_{\text{proj}}
\]

\[
\langle \hat{\vartheta}_{pT}^2 \rangle = \left( \frac{13.6 \text{ MeV}}{\beta p_T c} \right)^2 \left( 1 + 0.038 \ln \frac{d/X_0}{\sin(\vartheta + \alpha)} \right)^2
\]

\[
f_{\text{proj}} = \left( \frac{1}{\sin(\vartheta + \alpha)} \right)^2 \text{proj. in } Z
\]

\[
f_{\text{proj}} = 1 \quad \text{proj. in } R-\Phi
\]

\[
\sigma_{R\Phi} = \sqrt{\sigma_{R\Phi,\text{loc}}^2 + (A/\sqrt{1 - A^2 \sin(\alpha)})^2 \sigma_{Z,\text{loc}}^2}
\]

\[
A = \Delta r/2 R
\]
Understanding Track Propagator in PR

- 4 key parameters affecting propagation of error ellipse:
  - Multiple scattering & material effect @ θ (tilt angle α)
  - Propagation distance
  - Projection factor on det. plane
  - Detector resolution

  \[ \sigma_{MS}^2 \approx \langle \dot{\theta}_{PT}^2 \rangle \frac{d/X_0}{\sin(\dot{\theta} + \alpha)} \Delta r \iff f_{proj} \]

  \[ \langle \dot{\theta}_{PT}^2 \rangle = \left( \frac{13.6 \text{ MeV}}{\beta p_T c} \right)^2 \left( 1 + 0.038 \ln \frac{d/X_0}{\sin(\dot{\theta} + \alpha)} \right)^2 \]

  \[ f_{proj} = \left( \frac{1}{\sin(\dot{\theta} + \alpha)} \right)^2 \text{ proj. in } Z \]

  \[ f_{proj} = 1 \text{ proj. in } R-\Phi \]

  \[ \sigma_{R\Phi} = \sqrt{\sigma_{R\Phi_{loc}}^2 + (A/\sqrt{1 - A^2 \sin(\alpha)})^2 \sigma_{Z_{loc}}^2} \]

  \[ A = \Delta r/2R \]

- To min. mat. effects, tracker in tilted layout advantageous!

Propagated σ_{R-Φ} on 4^{th} BRL layer

Propagated σ_{Z} on 4^{th} BRL layer
Tilted Geometry: Design Proposal v4.01

- Layout of **outer tracker** driven by requirement on $p \sim 0.2$:
  - uppermost layer designed non-tilted to keep the highest possible lever-arm
  - modules positioned as to hermetically cover full luminous region

- Layout of **inner tracker** driven by $p \sim 0.2$ & requirement on best $z_0$ res.:
  (to deal with primary vertexing @PU~1000):
  - tilt angle of 1st layer: $\theta_{\text{tilt}} \approx 10^\circ$ set as a compromise between low MB & high radius
Tilted Layout: Improvement in Performance

In-Out: Bkg contam. prob. accumulated across N layers @95% CL

Non-tilted layout:

\[
(1-p) \sim 10\%
\]

Tilted layout v4.01:

\[
(1-p) \sim 80\%
\]

→ Approach constraint: Mat. budget assumed per module → need to add realistic engineering: services etc.
Tilted Layout: Improvement in Performance

In-Out: Bkg contam. prob. accumulated across N layers @95% CL

Non-tilted layout:

\[ (1-p) \approx 10\% \]

Tilted layout v4.01:

\[ (1-p) \approx 80\% \]

Approach constraint: Mat. budget assumed per module → need to add realistic engineering: services etc.

\[ \delta z_0 \text{ [um]} \]

1st layer tilt @|\eta| \approx 2.2

\[ \delta z_0 \text{ [um]} \]

\[ p_T = 1 \text{ GeV/c} \]

\[ p_T = 5 \text{ GeV/c} \]

\[ p_T = 10 \text{ GeV/c} \]

\[ p_T = 100 \text{ GeV/c} \]

\[ p_T = 1 \text{ TeV/c} \]

\[ p_T = 10 \text{ TeV/c} \]
Tilted Layout: Improvement in Performance

In-Out: Bkg contam. prob. accumulated accross N layers @95% CL

Non-tilted layout:

(1-p) ~ 10%

Tilted layout v4.01:

(1-p) ~ 80%

Approach constraint: Mat. budget assumed per module → need to add realistic engineering: services etc.

δz₀ [um]

MS by beam-pipe

Z. Drásal, Vertex 2017 Asturias Spain (10-15th September 2017)

Tilted layout:
The dominant effect for “low” p_T tracks is beam-pipe mat.!
How the pile-up (PU)~1000 degrades primary vertexing? Would the timing info help?

→ Dependent on scenario for luminous region (Gauss, “rectangular”,...) → simulate 1000 PU vertices according to Gaussian (HL-LHC) Line & Time PU densities (c.f.: PhysRevSTAB.17.111001)

• **Gauss. bunch:** 
  \[ \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2} \]

• **Line PU:** 
  \[ e^{-\frac{(1+\phi^2)\left(\frac{\sigma_z}{\sigma}\right)^2}{\sqrt{\pi\sigma_z}}} \]

• **Time PU:** 
  \[ e^{-\frac{(1+\psi^2)\left(\frac{\sigma_z}{\sigma}\right)^2}{\sqrt{\pi\sigma_z}}} \]

Piwinsky angle \( \Phi \sim 0.67 \)

Time Piw. angle \( \Psi \sim 0.40 \)
Vertexing @ PU=1000 & Timing Information

- How the pile-up (PU)~1000 degrades primary vertexing? Would the timing info help?
  - Dependent on scenario for luminous region (Gauss, “rectangular”,...): simulate **1000 PU** vertices according to Gaussian (HL-LHC) Line & Time PU densities (c.f.: PhysRevSTAB.17.111001)

  - **Gauss. bunch:**
    \[
    \frac{1}{\sqrt{2\pi\sigma_z}} e^{-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2}
    \]

  - **Line PU:**
    \[
    \sqrt{1+\phi^2} \frac{e^{-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2}}{\sqrt{\pi\sigma_z}}
    \]

  - **Time PU:**
    \[
    \sqrt{1+\psi^2} \frac{e^{-\frac{1}{2}\left(\frac{ct}{\sigma_z}\right)^2}}{\sqrt{\pi\sigma_z}}
    \]

- Study **what fraction of tracks may be unambiguously assigned to the primary vertex @ 95% CL?** Use 2D info (PV assumed to be “precisely” found from e.g. high p\(_T\) tracks)

  - Beam spot
    - 1-st layer
    - 2-nd layer

  - \(\delta z_0 \& \delta t_0\) interplay crucial!

\[\frac{\partial \mu}{\partial z} \text{ distr.}\]

- \(\sigma_z = 75\text{mm}\)
- \(\sigma_z = 100\text{mm}\)

- Piwinsky angle \(\Phi \sim 0.67\)
- Time Piw. angle \(\Psi \sim 0.40\)
Compare FCC-hh to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

Why such shape? Follow z0 res. curve...

Decrease in δz0 needs to be “compensated” by extra timing info (in FWD)
Effective Pile-up Rate & Timing Information

→ Compare FCC-hh to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

Why such shape? Follow z0 res. curve...

Decrease in δz0 needs to be “compensated” by extra timing info (in FWD)

FCC-hh: 2D vertexing (time & z) essential, but may not be sufficient to mitigate the PU effect, namely for η>4.0
Occupancy & Expected Data Rates @ PU=1000

- Tracker granularity in a view of hit occupancy (~ <1%) & data rates @ PU~1000?
  - use Fluka sim. charged particles fluence & calculate hit occupancy (binary R/O):

- E.g. inner tracker:

<table>
<thead>
<tr>
<th>Layer no</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Total [TB/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius [mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td>60.0</td>
<td>100.0</td>
<td>150.0</td>
<td>270.0</td>
<td>400.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Module max occupancy (max[sen1,sen2])[%] | 0.45 | 0.11 | 0.05 | 0.02 | 0.08 | 0.04 |
- Data rate per layer - 40MHz, spars [Tb/s] | 603.7 | 379.9 | 277.3 | 202.2 | 138.7 | 97.5 | 212.4 |
- Data rate per layer - 1MHz, spars [Tb/s] | 15.1 | 9.5 | 6.9 | 5.1 | 3.5 | 2.4 | 5.3 |

| Data rate per cm^2 - 40MHz, spars [Gb/s/cm^2] | 251.82 | 57.91 |
| Data rate per cm^2 - 1MHz, spars [Gb/s/cm^2] | 6.30 | 1.45 |

- Expected huge tracker data rates: 766 TB/s (untrig. @40MHz), 19 TB/s (trig. @1MHz)
- Expected extreme data flows>>10Gb/s/module (from innermost layers/discs, even when being triggered @1MHz)

Challenge: 6.3 Gb/s/cm^2
Summary & Challenges

• The key tracker parameters have been studied & optimized:
  → Layout: ~430m² (391m² in tilted layout) of Si, with: 5461M (pixels), 9964M (macropixels), 489M (strips)
  → The granularity in R-Φ driven mostly by \( \frac{d\mathbf{p}_T}{\mathbf{p}_T} \) @\( \mathbf{p}_T = 10 \text{TeV/c} \) → achieved \( \frac{d\mathbf{p}_T}{\mathbf{p}_T} \approx 20\% \)
  → The granularity in Z driven by prim. vertexing & pattern recognition capabilities @PU=1000:
    • Due to minimized mat. budget the tracker (even vertex detector) in tilted layout very advantageous to achieve similar pattern recognition performance as with PU~140 & HL-LHC conditions
      → realistic engineering (technology input) with services, cooling & support structure important!
    • Primary vertexing & correct PV assignment @PU=1000 seems feasible up-to \( \eta \approx 4 \), but only with precise timing information \( \sigma_t \approx 5\text{ps} \) (2D vertexing, several timing layers assumed) → the limiting factor for high \( \eta \) coverage is beam-pipe material
  → Expected data rates (766 TB/s untriggered, 19 TB/s triggered @1MHz) implicate need for new read-out technologies (high speed, low power optical links) & dedicated trigger design!
  → 1MeV neq fluence \( \sim 6 \times 10^{17} \text{cm}^{-2} \) & TID \( \sim 0.4 \text{GGy} \) @ \( R=25\text{mm} \) represent new challenges for the tracker (vertex detector) technologies
  → Dedicated R&D is needed to meet the challenging requirements!