Overview of FCC-hh Tracker Design

Zbyněk Drásal (with M.Mannelli)
CERN

On behalf of the FCC-hh detector working group
Overview

• Introduction
  - Physics motivation & challenges

• Tracker design & expected tracker performance
  - Baseline tracker layout v3.03 ➔ for details of all layouts see: http://fcc-tklayout.web.cern.ch
  - Magnetic field scenarios & tracking resolution
  - Expected tracking performance (see also E. Perez's talk)
  - b,c,τ-tagging ➔ for details see E. Perez's talk

• Implications of high pile-up & high-rate environment
  - Pattern recognition capabilities & granularity in Z ➔ new tilted layout v4.01
  - Vertexing (see also E. Perez's talk) & timing information
  - Data rates & tracker occupancy

• Software toolkits:
  - tkLayout, FCCSW & ACTS ➔ follow FCC SW session: J.Lingemann, J.Hrdinka & V.Volkl's talks

• Summary & Outlook
Physics Motivation & Challenges

- **A few benchmarks to give us an intuitive hints on key tracker parameters:**
  - e.g. Higgs or VBF physics → FCC opens us a new kinematic & dynamical region
    - Need **extended tracking up-to** $|\eta| \sim 4$, efficient VBF jet measurement **up-to** $|\eta| \sim 6$
    - Need **tracker hermeticity** for all tracks coming from the luminous region ($\sigma_z \sim \pm 75$mm)
  - **Direct searches** (higher mass reach), e.g. $Z' \to \mu\mu$ or $Z' \to t\bar{t}$ (high boosted objects)
    - Need for **high** $d\rho_T/p_T$ res. $\sim$10-20% @10TeV/c (cf. LHC: 10%@1TeV)
    - But still keeping **sensitivity for low** $p_T$ tracks
  - **Precise understanding of SM/New physics** → higher mass reach (100TeV)/higher luminosity
    - 30x10$^{34}$ cm$^{-2}$s$^{-1}$ (@25ns) → O(1000) pile-up events per bunch crossing expected
    - **Precision tracking & track association with primary vertex** required
    - **Efficient b, c, τ tagging** despite intense radiation levels at low radii
Baseline Tracker Layout (v3.03)

- **Surface:** ~430m²
- **Channels:**
  - BRL: 489.4M
  - EC: 9964.4M
  - BP: 5460.9M

- **Pixel R**: 0.9 (0.6) m due to occupancy (6T → 4T)
- **4 (seed) BRL layers**

### Material budget
- **BRL**: 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)

### Tracker rad. length map
- **Pixels**
  - 2.5% (1-4th BRL layers, EC R1)
  - 2.0% (100/3x100um² (R2))
  - 1.0% (100/3x400um² (R3,R4))
  - 1.5% (Overall)

FCC Week in Berlin (31st May 2017)
• A snapshot of mag. field scenario a year ago: 6T twin solenoid + balanced conical shape/10Tm dipole in FWD:

→ Solenoid comparable to dipole in tracking res., but solenoid option rotational symmetric!

→ 6T scenario: technology challenging & costly option

→ Focus on 4T scenario & more aggressive detector design:

\[ \frac{\Delta p_T}{p_T} \approx \sigma[m] \frac{p_T[GeV/c]}{0.3B[T] L^2[m^2]} \]

6T → 4T scenario

L: 2.4 → 1.55m
B: 6T → 4T
\[ \sigma_{R-\Phi}: 25um \rightarrow 10(7.5)um \]

res. degrades ~ 2.4x
res. improves ~ 2.5 (3.3)x

Simulated p_T:

• 10 GeV/c → @\eta=5 p~700GeV/c
• 100 GeV/c → @\eta=5 p~7TeV/c
• 1 TeV
• 10 TeV

- solenoid
- dipole

CTRL FWD

δp/T [%] versus η

~15%
Mag. Field & Tracking Performance

- A snapshot of mag. field scenario a year ago: 6T twin solenoid + balanced conical shape/10Tm dipole in FWD:
  - Technology challenging & costly
  - Focus on 4T scenario & more aggressive detector design:

  - Solenoid comparable to dipole in tracking res., but solenoid option rotational symmetric!
  - 6T scenario: technology challenging & costly option
  - Focus on 4T scenario & more aggressive detector design:

\[ \frac{\Delta p}{p} \% \text{ versus } \eta \]

Simulated \( p_T \):
- 10 GeV/c → @\( \eta \approx 5 \) \( p \sim 700 \text{ GeV/c} \)
- 100 GeV/c → @\( \eta \approx 5 \) \( p \sim 7 \text{ TeV/c} \)
- 1 TeV
- 10 TeV
- solenoid
- dipole

\[ @ \eta \approx 3 \rightarrow \text{start losing lever-arm} \]
4T solenoid option → how do the mag. field non-uniformities affect FWD tracking?

- 2 techniques used to estimate the effects:
  - N-parabola approx. (tkLayout) & numerical solution by W. Riegler (Mathematica SW)

\[ \frac{\Delta p}{p} \text{ due to non-uniformity of } B \text{ field (Bz & Br)} \approx 35-45\% \text{ @ } \eta = 2.5 \text{ or higher} \]
Granularity in Z strongly affects **pattern recognition capabilities**, so how to study PR analytically? Strategy: study “**weak**” spots in layout!

→ Assume **perfect seeding** (triplet) → propagate $\sigma_{r\phi}$, $\sigma_z$ to $i^{th}$ layer

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

\[
p = 1 - \prod_{i=4}^{N} (1 - p_{bkg95\%})
\]
Pattern recognition (PR) Capabilities

- Granularity in $Z$ strongly affects pattern recognition capabilities, so how to study PR analytically? Strategy: study “weak” spots in layout!

  $\rightarrow$ Assume perfect seeding (triplet) $\rightarrow$ propagate $\sigma_{\phi}$, $\sigma_{z}$ to $i^{th}$ layer

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

$$p = 1 - \prod_{i=4}^{N} (1 - p^{i}_{bkg95\%})$$

- How to “qualitatively” interpret $p$? c.f. CMS Ph2 layout @PU~140...

CMS trk layout: 3.6.5

(1-$p$) $\sim$ 80%

$\rightarrow$ To keep similar PR for FCChh @PU~1000, set bkg. prob. contamination $p$ @20%

FCC Week in Berlin (31st May 2017)
Understanding Pattern Recognition Results

- 4 key parameters affecting propagation of error ellipse:
  - Multiple scattering & mat. effect @ \( \Theta \) (may be compensated by tilt angle \( \alpha \))
  - Propagation distance
  - Projection factor on det. plane
  - Detector resolution

\[
\sigma^2_{MS} \approx \langle \varphi^2_{PT} \rangle \frac{d/X_0}{\sin(\vartheta + \alpha)} \Delta r^2 f_{proj}
\]

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

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

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

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

\[
A = \Delta r/2R
\]
Understanding Pattern Recognition Results

- 4 key parameters affecting propagation of error ellipse:
  - Multiple scattering & **mat. effect @ $\vartheta$** (may be compensated by tilt angle $\alpha$)
  - Propagation distance
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\[
\sigma_{MS}^2 \approx \langle \dot{\vartheta}_{PT}^2 \rangle \frac{d/X_0}{\sin(\vartheta + \alpha)} \Delta r^2 f_{proj}
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f_{proj} = \left( \frac{1}{\sin(\vartheta + \alpha)} \right)^2 \text{ proj. in } Z
\]

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

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

\[
A = \frac{\Delta r}{2R}
\]

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

**Propagated $\sigma_{R-\phi}$ on 4th BRL layer**

**Propagated $\sigma_z$ on 4th BRL layer**
Tilted Geometry: Design Proposal v4.01

- Tilted layout of **outer tracker** driven by requirement to achieve ~0.2 bkg. contam. level (BCL) in PR:
  - uppermost layer designed non-tilted to keep the highest possible lever-arm
  - modules positioned to hermetically cover full luminous region ±75mm
  - ECs strips res. in Z needed to be set to ~500um (~1mm OK)

- Tilted layout of **inner tracker** driven by ~0.2 BCL in PR & **highest achievable z0 res.** (to deal with primary vertexing @PU~1000):
  - tilt angle of 1st layer: $\theta_{\text{tilt}} \approx 10^\circ$ optimized to achieve a compromise between low MB & higher radial position
With tilted layout the bkg. contam. level @~20% achievable in PU~1000 for $p_T=1\text{GeV/c}$ (limit value driven by HL-LHC scenario with PU~140 & CMS Phase 2 upgrade tracker layout)

Limits: Mat. budget assumed per module → NOT fully realistic tilted design → need to consider services & support structure (engineering input necessary)!
Tracking Performance: tilted versus non-tilted

$\delta z_0 \, [\text{um}] \, \text{versus} \, \eta$

Non-tilted layout

Tilted layout

$1^{\text{st}} \, \text{layer \, tilt \, at} \, \eta \approx 2.2$

$\delta d_0 \, [\text{um}] \, \text{versus} \, \eta$

Non-tilted layout

Tilted layout

$p_T = 1 \, \text{GeV/c}$
$p_T = 5 \, \text{GeV/c}$
$p_T = 10 \, \text{GeV/c}$
$p_T = 100 \, \text{GeV/c}$
$p_T = 1 \, \text{TeV/c}$
$p_T = 10 \, \text{TeV/c}$

$\rightarrow$ For tilted layout, the shape of 1GeV/c curve dominated by beam-pipe material!

$\rightarrow$ Similar $d\rho_T/p_T \, \text{res.}$ for both tilted & non-tilted layout
Vertexing @ PU=1000 & Timing Information

- How the pile-up (PU)~1000 degrades primary vertexing? Does 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:
  
  \[
  \frac{\sqrt{1+\phi^2}}{\sqrt{\pi}\sigma_z} e^{-\left( 1+\phi^2 \right) \left( \frac{z}{\sigma_z} \right)^2}
  \]

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

- **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)

- $\delta z_0$ & $\delta t_0$ play the crucial role!

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

\[\text{Line PU distr.: gaussian versus rectangular shaped bunches!}
\]

\[\text{Piwinsky angle } \Phi \sim 0.67
\]

\[\text{Time Piw. angle } \Psi \sim 0.40
\]
→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

**HL-LHC scenario @ PU=140**
CMS Ph2 Upgr. tracker

Fraction of tracks being unambiguously assigned to PV @95% CL: $\mu_{\eta}$=140

**FCC-hh scenario @ PU=1000**
Tilted layout

Fraction of tracks being unambiguously assigned to PV @95% CL: $\mu_{\eta}$=1000

→ With current FCC-hh scheme the primary vertexing @ PU~1000 seems very difficult for $\eta$>4.0, even with timing res. ~5ps (several time measurements being assumed per track)
• Have a look at the tracker granularity in a view of hit occupancy (~ <1%), what data rates may we expect at PU~1000?

→ Use Fluka simulated charged particles fluence per pp collision [cm\(^{-2}\)] scaled by 1000 PUs

→ Calculate occupancy & hit rates for 2 scenarios:
  • Non-triggered data @ f = 40MHz
  • Triggered data @ f ~ 1MHz (given ~ by hardware limits, e.g. FPGA)
### Inner: Occupancy & Expected Data Rates

#### Layer data rate (40MHz)

<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>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>
</tr>
<tr>
<td>Module max occupancy (max[sen1,sen2])[%]</td>
<td>0.45</td>
<td>0.11</td>
<td>0.05</td>
<td>0.02</td>
<td>0.08</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Hit-channels per module per BX</td>
<td>2694</td>
<td>741</td>
<td>333</td>
<td>166</td>
<td>314</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Module avg occupancy (max[sen1,sen2])[%]</td>
<td>0.38</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>0.08</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Module bandwidth/(addr+clsWidth=2b)[b]</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>21</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Mod. bandwidth(#chnls*(addr+clsWidth))[kb]</td>
<td>57.88</td>
<td>15.93</td>
<td>7.16</td>
<td>3.57</td>
<td>6.44</td>
<td>3.08</td>
<td></td>
</tr>
<tr>
<td>Mod. bandwidth (matrix*1b/channel)[kb]</td>
<td>685.00</td>
<td>820.00</td>
<td>820.00</td>
<td>820.00</td>
<td>384.00</td>
<td>384.00</td>
<td></td>
</tr>
<tr>
<td>Data rate per layer - 40MHz, spars [Tb/s]</td>
<td>603.7</td>
<td>379.9</td>
<td>277.3</td>
<td>202.2</td>
<td>138.7</td>
<td>97.5</td>
<td>212.4</td>
</tr>
<tr>
<td>Data rate per layer - 1MHz, spars [Tb/s]</td>
<td>15.1</td>
<td>9.5</td>
<td>6.9</td>
<td>5.1</td>
<td>3.5</td>
<td>2.4</td>
<td>5.3</td>
</tr>
<tr>
<td>Data rate per ladder - 40MHz, spars [Gb/s]</td>
<td>44159.7</td>
<td>24313.2</td>
<td>10920.7</td>
<td>5449.3</td>
<td>4177.1</td>
<td>1996.5</td>
<td></td>
</tr>
<tr>
<td>Data rate per ladder - 1MHz, spars [Gb/s]</td>
<td>1104.0</td>
<td>607.8</td>
<td>273.0</td>
<td>136.2</td>
<td>104.4</td>
<td>49.9</td>
<td></td>
</tr>
<tr>
<td>Data rate per module - 40MHz, spars [Gb/s]</td>
<td>2207.99</td>
<td>607.83</td>
<td>273.02</td>
<td>136.23</td>
<td>245.71</td>
<td>117.44</td>
<td></td>
</tr>
<tr>
<td>Data rate per module - 1MHz, spars [Gb/s]</td>
<td>55.20</td>
<td>15.20</td>
<td>6.83</td>
<td>3.41</td>
<td>6.14</td>
<td>2.94</td>
<td></td>
</tr>
<tr>
<td>Data rate per cm^2 - 40MHz, spars [Gb/s/cm^2]</td>
<td>251.82</td>
<td>57.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data rate per cm^2 - 1MHz, spars [Gb/s/cm^2]</td>
<td>6.30</td>
<td>1.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Challenge: 6.3 Gb/s/cm^2

#### Data rate per cm^2 (40MHz)

#### Extreme data flows >>10Gb/s/module (even triggered at 1MHz)

#### Layer data rate (1MHz, trigger)

<table>
<thead>
<tr>
<th>Ring no</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Total [TB/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radius [mm]</td>
<td>64.8</td>
<td>153.0</td>
<td>251.1</td>
<td>353.3</td>
<td></td>
</tr>
<tr>
<td>Module max occupancy (max[sen1,sen2])[%]</td>
<td>0.46</td>
<td>0.13</td>
<td>0.18</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Data rate per ringLayer - 40MHz, spars [Tb/s]</td>
<td>194.2</td>
<td>148.2</td>
<td>105.1</td>
<td>74.3</td>
<td>65.2</td>
</tr>
<tr>
<td>Data rate per ringLayer - 1MHz, spars [Tb/s]</td>
<td>4.9</td>
<td>3.7</td>
<td>2.6</td>
<td>1.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Data rate per cm^2 - 40MHz, spars [Gb/s/cm^2]</td>
<td>64.44</td>
<td>15.67</td>
<td>6.62</td>
<td>3.42</td>
<td></td>
</tr>
<tr>
<td>Data rate per cm^2 - 1MHz, spars [Gb/s/cm^2]</td>
<td>1.61</td>
<td>0.39</td>
<td>0.17</td>
<td>0.09</td>
<td></td>
</tr>
</tbody>
</table>

#### Challenge: 1.6 Gb/s/cm^2
### Outer & Fwd: Occupancy & Data Rates

> **Expected huge tracker data rates:** 766 TB/s (untriggered), 19 TB/s (triggered @ 1MHz)

#### Outer:

<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>530.0</td>
<td>742.4</td>
<td>937.2</td>
<td>1132.0</td>
<td>1326.7</td>
<td>1539.5</td>
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<tr>
<td>Module max occupancy (max[sen1, sen2]) [%]</td>
<td>0.02</td>
<td>0.01</td>
<td>0.75</td>
<td>0.43</td>
<td>0.27</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Data rate per layer - 40MHz, spars [Tb/s]</td>
<td>226.0</td>
<td>134.5</td>
<td>63.6</td>
<td>43.9</td>
<td>31.7</td>
<td>28.1</td>
<td><strong>66.0</strong></td>
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<tr>
<td>Data rate per layer - 1MHz, spars [Tb/s]</td>
<td>5.6</td>
<td>3.4</td>
<td>1.6</td>
<td>1.1</td>
<td>0.8</td>
<td>0.7</td>
<td><strong>1.6</strong></td>
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<tr>
<td>Data rate per cm² - 40MHz, spars [Gb/cm²*2]</td>
<td>1.38</td>
<td>0.61</td>
<td>0.23</td>
<td>0.13</td>
<td>0.08</td>
<td>0.06</td>
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<tr>
<td>Data rate per cm² - 1MHz, spars [Gb/cm²*2]</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
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#### iFWD:

<table>
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<tr>
<th>Ring no</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<th>6</th>
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<th>11</th>
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<th>14</th>
<th>15</th>
<th>16</th>
<th>Total [TB/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radius [mm]</td>
<td>64.6</td>
<td>151.5</td>
<td>251.0</td>
<td>352.0</td>
<td>451.6</td>
<td>553.6</td>
<td>651.1</td>
<td>753.6</td>
<td>850.8</td>
<td>953.5</td>
<td>1049.7</td>
<td>1152.6</td>
<td>1247.6</td>
<td>1350.8</td>
<td>1444.7</td>
<td><strong>1522.8</strong></td>
<td></td>
</tr>
<tr>
<td>Module max occupancy (max[sen1, sen2]) [%]</td>
<td>0.58</td>
<td>0.15</td>
<td>0.21</td>
<td>0.10</td>
<td>0.06</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.23</td>
<td>0.20</td>
<td>0.13</td>
<td>0.12</td>
<td>0.08</td>
<td>0.08</td>
<td><strong>0.05</strong></td>
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<tr>
<td>Data rate per ringLayer - 40MHz, spars [Tb/s]</td>
<td>263.8</td>
<td>213.3</td>
<td>153.4</td>
<td>109.8</td>
<td>93.2</td>
<td>63.1</td>
<td>63.8</td>
<td>49.9</td>
<td>42.5</td>
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<td>13.8</td>
<td>11.4</td>
<td>4.6</td>
<td><strong>146.0</strong></td>
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<tr>
<td>Data rate per ringLayer - 1MHz, spars [Tb/s]</td>
<td>6.6</td>
<td>5.3</td>
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<td>2.7</td>
<td>2.3</td>
<td>1.6</td>
<td>1.2</td>
<td>1.1</td>
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<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Data rate per cm² - 40MHz, spars [Gb/cm²*2]</td>
<td>71.30</td>
<td>18.72</td>
<td>7.98</td>
<td>4.18</td>
<td>2.65</td>
<td>1.54</td>
<td>1.18</td>
<td>0.78</td>
<td>0.62</td>
<td>0.36</td>
<td>0.26</td>
<td>0.21</td>
<td>0.15</td>
<td>0.13</td>
<td>0.10</td>
<td>0.08</td>
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<tr>
<td>Data rate per cm² - 1MHz, spars [Gb/cm²*2]</td>
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<td>0.47</td>
<td>0.20</td>
<td>0.10</td>
<td>0.07</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
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#### FWD:

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<th>Ring no</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>Total [TB/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radius [mm]</td>
<td>72.8</td>
<td>167.5</td>
<td>266.5</td>
<td>366.3</td>
<td>464.9</td>
<td>564.8</td>
<td>664.6</td>
<td>766.8</td>
<td>866.7</td>
<td>969.0</td>
<td>1068.4</td>
<td>1170.9</td>
<td>1269.8</td>
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<tr>
<td>Module max occupancy (max[sen1, sen2]) [%]</td>
<td>0.99</td>
<td>0.13</td>
<td>0.20</td>
<td>0.11</td>
<td>0.07</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.48</td>
<td>0.24</td>
<td>0.12</td>
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<tr>
<td>Data rate per ringLayer - 40MHz, spars [Tb/s]</td>
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<td>114.5</td>
<td>81.6</td>
<td>64.9</td>
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<td>Data rate per cm² - 40MHz, spars [Gb/cm²*2]</td>
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<tr>
<td>Data rate per cm² - 1MHz, spars [Gb/cm²*2]</td>
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</table>

### FCC Week in Berlin (31st May 2017)
Summary & Conclusions

- The key tracker parameters have been studied & optimized:
  - **Current layout:** ~430m$^2$ (391m$^2$ in tilted layout) of Si with #channels: 5461M (pixels), 9964M (macro-pixels), 489M (strips)
  - The granularity in R-Φ driven mostly by $d\eta/p_T$ @ $p_T=10\text{TeV/c}$ → achieved ~20% res. (From $\eta$~3 $d\eta/p_T$ starts degrading due to natural loss of lever-arm)
  - Non-uniformities of solenoid mag. field lead to degradation of $d\eta/p_T$ res. by in max. 45% at $\eta$>2.5 compared to ideal 4T scenario, dipole in FWD region still remains an option (c.f. PV @PU=1000)
  - The granularity in Z driven by vertexing & pattern recognition capabilities @ PU=1000:
    - Tracker in tilted layout very advantageous (even for vertex detector) to achieve similar pattern recognition performance as with PU~140 & HL-LHC conditions
    - Primary vertexing & correct PV assignment @ PU=1000 seems feasible up-to $\eta$~4, but only with extra timing information (2D vertex fitting) → current view on PV from $\eta$~4 to 6 seems very difficult (even using the timing information)
  - Expected data rates (766 TB/s untriggered, 19 TB/s triggered @1MHz) implicate need for new read-out technologies (follow J.Brooke's talk on trigger design)
  - Expected 1MeV neq fluence ~$5\times10^{17}\text{cm}^{-2}$ @ $R=25\text{mm}$ (see M.I.Besana's talk) represents a true challenge for the tracker technologies and dedicated R&D