Detector concepts, relation of LHC detector R&D to e+e- detectors

11th FCC-ee workshop, Jan. 9th 2019
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ALICE TC, convenor of FCC-hh detectors and experiments

... mainly basic questions and comments from someone who has worked on hadron detector for the past 25 years ...
An FCC-ee detector has to be ready in 2038 at the earliest i.e. in 20 years from now.

It does not make sense to go into detailed engineering designs of FCC-ee detectors at this moment. This should be done in 2025 at the earliest.

The current detector concepts for ILC/CLIC/CEPC are fairly traditional and the costs of the different subsystems sometimes does not seem to be well balanced.

We should use the next 5 years to think about general detector concepts and principles.

In addition there will (hopefully) be significant advances in technology within the upgrades of the LHC detectors and other experiments.

E.g. detectors and sensors developed for Heavy Ion Physics are very well suited for application to e+e- colliders. The requirement of excellent momentum resolution and secondary vertex resolution for very low pt together with moderate radiation levels for HI physics match well the requirements for e+e- detectors.
Example: ALICE Upgrade

Some details about the present upgrade. More details about the silicon detectors and future ideas by Luciano in the next talk.
ALICE in Run 1 and Run 2

ALICE detector
- Central Barrel: $-0.9 < \eta < 0.9$
- Muon spectrometer: $-4.0 < \eta < -2.5$
- Forward detectors: trigger, centrality

Operation in Run 1 and Run 2
- Tracking and PID in large kinematic range
- High resolution vertex reconstruction

Run 1 (2009 – 2013)
- Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV
- p-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
- pp @ $s = 0.9, 2.76, 7, 8$ TeV

Run 2 (2015 – 2018)
- Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
- Xe-Xe @ $\sqrt{s_{NN}} = 5.44$ TeV
- p-Pb @ $\sqrt{s_{NN}} = 5.02, 8.16$ TeV
- pp @ $s = 5, 13$ TeV
Heavy-Ion Collisions at LHC

**ALICE strategy for Run 3 + Run 4:**
- 50 kHz Pb-Pb interaction rate (now <10 kHz)
- Experiment upgrades (LS2)
- Collect $L_{\text{Pb-Pb}} > 13 \text{ nb}^{-1}$

**ALICE physics goals**
- Heavy-flavour mesons and baryons ([down to very low $p_T$]) $\rightarrow$ mechanism of quark-medium interaction
- Charmonium states $\rightarrow$ dissociation/regeneration as tool to study de-confinement and medium temperature
- Di-leptons from QGP radiation and low-mass vector mesons $\rightarrow$ $\chi$ symmetry restoration, initial temperature and EOS
- High-precision measurement of light and hyper-nuclei $\rightarrow$ production mechanism and degree of collectivity
- Need MB readout at highest possible rate $\rightarrow$ no dedicated trigger possible

W. Riegler - ALICE upgrade: ITS & TPC
**New ITS**

**ALPIDE (ALICE Pixel Detector)**
- Developed for the ALICE upgrade (ITS and MFT)
- 130,000 pixels/cm²
- Max. particle rate: ~100 MHz/cm²
- Spatial resolution: ~5 μm
- Thickness: 50 μm for the inner layers
- Fake-hit rate: < 10⁻⁹ per pixel per event

**10 m² active silicon area, 12.5×10⁹ pixels**
- Closer to IP: 39 mm → 22 mm
- Thinner (X₀ for innermost layers): ~1.14 % → ~0.30 %
- Smaller pixels: 50 × 425 μm² → 27 × 29 μm²
- Granularity: 20 ch/cm³ → 2000 pixels/cm³
- Readout rate: 1 kHz → 100 kHz
ALICE TPC

- Diameter: 5 m, length: 5 m
- Gas: Ne-CO$_2$-N$_2$, Ar-CO$_2$
- Max. drift time: ~100 μs
- 18 sectors on each side
- Inner and outer read out chambers: IROC, OROC

- Current detector (Run 1, Run 2):
  - 72 MWPCs
  - ~550 000 readout pads
  - Wire gating grid (GG) to minimize Ion Back-Flow (IBF)
  - Rate limitation: few kHz

Operate TPC at 50 kHz → no gating grid
Continuous Readout with GEMs

TPC Upgrade requirements:

• Nominal gain = 2000 in Ne-CO₂-N₂ (90-10-5)
• IBF < 1% (ε = 20)
• Energy resolution: $\sigma_E/E < 12\%$ for $^{55}$Fe
• Stable operation under LHC Run 3 conditions
• Unprecedented challenges in terms of loads and performance

Baseline solution: 4-GEM stack

• Combination of standard (S) and large pitch (LP) GEM foils
• Highly optimized HV configuration
• Result of intensive R&D
Read-Out Chambers (ROCs)

- Production of 40 IROCs and 40 OROCs until September 2018
  
  **ROC assembly**: Yale (IROC), GSI (OROC), HPD Bucharest (OROC); **ROC bodies**: Heidelberg, Frankfurt, UT Knoxville

- Production of 640 GEM foils + spares finishes within the next weeks
  
  **GEM QA**: CERN, Budapest, Helsinki; **GEM framing**: Munich, Bonn, GSI, Wayne State

- All chambers thoroughly qualified in terms of:
  - Gas tightness
  - Gain and ion backflow uniformity
  - Stability (long-term irradiation with X-rays)

- Selected chambers tested at the LHC

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*Active GEM area = 0.6817 m²*
30 kHz Pb-Pb Collisions

- MC events overlaid on cluster level, using realistic bunch crossing structure
- Time is scaled linearly onto the $z$-position.
- Tracks/Clusters from different collisions are shown in different colors.
Detector Performance in Run 3 and Run 4

- New ITS
  - Improved tracking efficiency
  - Improved tracking resolution
  - Pointing resolution $\times 3$ better in transverse plane ($\times 6$ along beam)

- New TPC Readout Chambers (GEM):
  - Preserve momentum resolution for TPC + ITS tracks
  - Preserve particle identification via $dE/dx$ (arXiv:1805.03234, submitted to NIM A)
Specific Points

The data rates at FCC-ee (130kHz of collisions with about 20 tracks per collision), Trigger and DAQ will not be an issue.

TPC and gas detectors are proposed as tracking devices for ILC/CEPC/FCC-ee. We should have some principle discussions on pros. and cons. of gas detectors over silicon detectors for the FCC-ee.

We should investigate the tracking performance with basic tools and not go into full simulation/reconstruction etc. exercises to soon. This will give more flexibility for comparisons.

The low material budget (excellent momentum resolution), PID capability and low cost are claimed to be advantages of TPC/wire chambers. A detailed comparison of these points in terms of physics performance is important.

We should also discuss questions of redundancy, calibration and stability over time when comparing gas detectors to silicon detectors.

N.B. the extreme statistical precision of FCC-ee puts stringent demands on the detector stability (e.g. momentum scale etc.)
ALICE will write the 50kHz of PbPb collisions to storage without any selective trigger. The data will be ‘compressed’ and each event is written to permanent storage.

Each PbPb collision has around 6000 charged tracks.

Since the FCC-ee has a maximum collision rate of 130kHz at the Z, with only around 20 charged tracks per collision, the track rate (data rate) for FCC-ee is a factor 100 smaller than for ALICE PbPb in Run3.

→ It is clear that one doesn’t have to think about Trigger and DAQ for FCC-ee at this point, but just about the most efficient way to send the data off the detector (low mass, low power data links).

### FCC-hh Volume 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
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<td>(E_{cm}) per nucleon</td>
<td>TeV</td>
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<td>5.5</td>
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<td>26.7</td>
<td>26.7</td>
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<td>10/month</td>
<td>110/month</td>
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<td>7.8</td>
<td>8</td>
<td>9</td>
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<tr>
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<td>515</td>
<td>530</td>
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<td>(dN_{ch}/d\eta</td>
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</table>

### FCC-ee Volume 2

The rate of events to be read out and recorded by the FCC-ee detector data acquisition systems is largest at the Z pole, and is dominated by Z production (\(~100\) kHz), low-angle Bhabha’s (\(~50\) kHz), and \(\gamma\gamma\rightarrow\) hadrons events (\(~30\) kHz). While Bhabha events can be recorded in a dedicated stream, in which only the data from the luminometers are read out, the entire detector must be read out with a trigger rate in excess of 100 kHz.

With 20 tracks on average in each hadronic Z decay, about 800 readout channels are expected to
Basic formulas for tracking

An extension of the Gluckstern formulae for multiple scattering: Analytic expressions for track parameter resolution using optimum weights

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Abstract

Momentum, track angle and impact parameter resolution are key performance parameters that tracking detectors are optimised for. This report presents analytic expressions for the resolution of these parameters for equal and equidistant tracking layers. The expressions for the contribution from position resolution are based on the Gluckstern formulae and are well established. The expressions for the contribution from multiple scattering using optimum weights are discussed in detail.

Basic formulas for:
• momentum resolution
• angular resolution (Θ, φ)
• Impact parameter resolution (d₀, z₀)

for N+1 equidistant measurement planes
Basic Formulas

\[ \Delta \phi_{\text{res.}} = \frac{\sqrt{12 \sigma_{\phi} \rho_{\text{res.}}}}{L_0 \sqrt{(N-1)(N+1)(N+2)(N+3)}} \times \sqrt{\frac{(16N^3 + 2N^2 - 3N)}{L_0} + \frac{60N^3 \rho_{\text{res.}}^2}{L_0^2} + \frac{60N^3 \rho_{\text{res.}}^2}{L_0^2}} \]

\[ \Delta \phi_{\text{m.s.}} = \frac{1}{\rho_{\text{res.}}} f \left( \frac{d}{X_0 \sin \theta} \right) \]

\[ \Delta \phi_{\text{opt.}} = \frac{1}{\rho_{\text{res.}}} f \left( \frac{d}{X_0 \sin \theta} \right) \]

\[ \Delta \theta_{\text{res.}} = \frac{\sigma_{\theta} \sin^2 \theta}{L_0} \sqrt{\frac{12N}{(N+1)(N+2)}} \]

\[ \Delta \theta_{\text{m.s.}} = \frac{\sin \theta}{\rho_{\text{res.}}} f \left( \frac{d}{X_0 \sin \theta} \right) \]

\[ \Delta \theta_{\text{opt.}} = \frac{\sin \theta}{\rho_{\text{res.}}} f \left( \frac{d}{X_0 \sin \theta} \right) \]
Momentum Resolution

Contribution from position resolution (res.):
Proportional to $\sigma$, $p_t$
Inversely proportional to $B_0$, $L_0^2$ and $\sqrt{N}$
Independent of $\theta$.

Contribution from multiple scattering (m.s.):
Proportional to $\sqrt{N}$ i.e. $\sqrt{\text{material budget}}$
Inversely proportional to $B_0$, $L_0$ and $\beta$
Tracker Material
11% $X_0$ Barrel
20% $X_0$ Forward
CLD Momentum Resolution

Volume 2 FCC-ee

\[ \sigma(\Delta p_T / p_{T,\text{true}}^2) \] [GeV^{-1}]

\begin{align*}
\text{Single } \mu^+ & \quad \theta = 10 \text{ deg} \\
\theta = 30 \text{ deg} \\
\theta = 50 \text{ deg} \\
\theta = 70 \text{ deg} \\
\theta = 90 \text{ deg} \\
\theta = \Phi / (p \sin \theta) \\
\end{align*}

Eq. 47, 10 deg. (mult. scattering)

Eq. 47, 90 deg., (mult. scattering)

Eq. 45, 10 deg (resolution)

Eq. 45, 90 deg. (resolution)

\[ \Delta p_T \big|_{\text{m.s.}} = \frac{N}{\sqrt{(N + 1)(N - 1)}} \frac{0.0136 \text{GeV/c}}{0.3 \beta B_0 L_0} \times \sqrt{\frac{d_{\text{true}}}{X_0 \sin \theta}} \left( 1 + 0.038 \ln \frac{d_{\text{true}}}{X_0 \sin \theta} \right) \]

\approx \frac{0.0136 \text{GeV/c}}{0.3 \beta B_0 L_0} \sqrt{\frac{d_{\text{true}}}{X_0 \sin \theta}}
At 90 degrees:
\( \Delta \frac{p_t}{p_t} \approx 0.3\% \) up to 100GeV, completely dominated by multiple scattering.
\( \rightarrow \) Material budget of the tracker is the key.

Plot \( \Delta \frac{p_t}{p_t} \) rather than \( \Delta \frac{p_t}{p_t^2} \) is more intuitive when multiple scattering dominates.
IDEA Detector

$X_0 = 1405\, \text{m}, \quad d_{\text{tot}}/X_0 = 1.6\, \text{m}/1405\, \text{m} = 0.0011, \quad \Delta p_t/p_t \text{ MS limit should be} \, 0.00026$ ?

Would be very interesting to understand which contribution comes from multiple scattering and which comes from position resolution ...
Particle Identification, TOF, dE/dx

For the future we can expect detectors with excellent time resolution, 10ps seems a realistic goal.

For TOF path of 2m a time resolution of 10ps we have $3\sigma \pi-K$, $K-p$, $\pi-p$ separation up to $5/8.4/9.8$ GeV/c

→ What is the momentum range of interest ?
→ How important is it ?
In addition to the questions of momentum and dE/dx resolution there are a few principle points.

Having several layers of silicon sensors provides significant redundancy. If one module in a single layer fails there is only a very small impact on the tracking performance.

For the TPC there is zero redundancy. If a chamber fails there is a hole in the acceptance. Stable TPC operation was achieved in the past, but 100% operational efficiency for all chambers is a significant requirement.

Also wire chambers with very large numbers of wires have been built and operated, but still, the breaking of a single wire can cause significant downtime and needs some tools for wire replacement.

Calibration is also a significant effort for gas detectors due to changing temperature and pressure conditions. This should be specifically taken into consideration when talking about the extreme requirements on measurement precision.

For silicon detectors there is very good experience with long term alignment stability from the LHC ...

With outer tracker radius of 1.8 m, achieved **transverse momentum resolution** $\sim 8 \times 10^{-5}$ GeV$^{-1}$ for 45 GeV muons at normal incidence (still within 100-200 MeV accuracy on muon momentum) required for point-to-point energy error in Z width measurements in Z scan.

→ Stability of the momentum scale ??
Transverse impact parameter resolution $d_0$

Contribution from position resolution (res.):
Proportional to $\sigma$
Inversely proportional $\sqrt{N}$

Contribution from multiple scattering (m.s.):
Proportional to $\sqrt{\text{material budget}}$
Inversely proportional to $p_t$

How many layers of a given thickness should one put into an available space of $L_0$ to minimize the contribution from multiple scattering?

$\rightarrow$ There is an optimum of $N=2+L_0/r_0$ layers!
Transverse impact parameter resolution $d_0$

$L_0 = 30\text{cm}$

$R_0 = 30\text{mm}$

$0.3\%$ of $X_0$ per layer

$p_t = 1\text{GeV/c}$

$\sigma = 5\mu\text{m}$

There is a number of layers where the multiple scattering contribution has a minimum, it is however very ‘shallow’ and the difference between having 3 layers or the optimum number of 13 layers is small ($20.3\mu\text{m}$ vs. $19\mu\text{m}$).

$\Rightarrow$ The distance of the first layer to the beamline (proportional) and material budget of the first (first two) layers are crucial!!
Also the multiple scattering contribution to the phi resolution has a minimum, which is however again quite shallow.

The multiple scattering contribution to the theta resolution and z resolution are both strictly independent of the number of layers.
Muon Systems

The ILC/CEPC/CLIC detectors feature very large muon systems.

It’s not clear whether these are needed.

The calorimeters probably have excellent muon id capability, and in principle one can put a single layer of muon stations outside the muon yoke for effective muon identification.

Since the Magnet return Yokes are very expensive one might think about a detector without any yoke like the reference detector for the FCC-hh?
FCC-hh reference detector
Very easy way to calculate tracking performance

\[
\sigma_{a_i} = \frac{0.0136 \text{GeV/c}}{\beta p} \sqrt{\frac{d_i}{X_0}} \left( 1 + 0.038 \ln \frac{d_i}{X_0} \right)
\]

\[
(C_y)_{mn} = \sigma_n^2 \delta_{mn} + \sum_{j=0}^{\text{Min}[m,n]-1} \sigma_{a_j}^2 (x_m - x_j)(x_n - x_j)
\]

\[
f(x) = \sum_{i=0}^{M} a_i g_i(x) \text{ with } M + 1 \text{ unknown parameters } a_m
\]

\[
G_{mn} = g_n(x_m)
\]

Covariance Matrix for the parameters:

\[
C_a = (G^T C_y^{-1} G)^{-1}
\]

• Very easy way to find all track parameter resolutions for any geometry.
• For g(x) one can also use a template track shape calculated from numerical integration in a non-uniform magnetic field e.g. muons through the yoke ...
• Dead material in between layers can be included by assuming a tracking layer with very large (infinite) spatial resolution such that it does not enter the fit.

One should make it mandatory to superimpose these analytic results to all simulation plots!
Muon system performance estimate

Three ways to measure the muon momentum

1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil

We assume a constant magnetic field inside the coil radius \( L_1 \).

The measurement points in the tracker of radius \( L_0 \) are equidistant and have all the same resolution \( \sigma_0 \).

The measurement point at \( L_1 \) has a position error \( \sigma_1 \) that is given by the multiple scattering inside the calorimeters (\( \sigma_y \) in the following).

The formula for the momentum resolution is given in the next slide.
Muon system performance estimate

Muon System standalone by measuring the angle of the muon when exiting the coil

\[ \frac{\Delta p}{p} = \frac{2p}{0.3L_1B} \sqrt{\theta_0^2 + \sigma_{\text{theta}}^2} \]

\[ \theta_0 = \frac{0.0136}{\beta p [\text{GeV}/c]} \sqrt{\frac{L_{\text{Calo}}}{X_{0\text{Calo}}} \left(1 + 0.038 \log \frac{L_{\text{Calo}}}{X_{0\text{Calo}}} \right)} \]

Inner Tracker of radius \( L_0 \) with \( N+1 \) equidistant layers of resolution \( \sigma_0 \)

\[ \frac{\Delta p}{p} = \frac{p}{0.3B} \frac{\sigma}{L_0^2} \sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{p}{0.3B} \frac{\sigma}{L_0^2} \sqrt{\frac{720}{N+5}} \quad N \gg 1 \]

Combined

\[ \frac{\Delta p}{p} = \frac{p}{0.3B} \frac{\sigma_0}{L_0^2} \sqrt{\frac{720N^3(c_1\sigma_0^2 + c_2\sigma_0^2)}{(N+1)(N+2)(c_3\sigma_0^2 + c_4\sigma_0^2)}} \]

\[ c_1 = 2[2N(L_0^2 - 3L_0L_1 + 3L_1^2) + L_0^2] \]
\[ c_2 = L_0^3(N+1)(N+2) \]
\[ c_3 = 3[L_0^2(3N^3 - N - 2) - 12L_0L_1(2N^3 - N^2 - N) + 12L_1^2(7N^3 - N^2 - N)] + 60N^3 \frac{L_1^4}{L_0^4} - 120N^3 \frac{L_1^3}{L_0^3} \]
\[ c_4 = L_0^3(N-1)(N+1)(N+2)(N+3) \]

\[ \sigma_y = \frac{1}{\sqrt{3}} \frac{L_{\text{Calo}}}{X_{0\text{Calo}}} \theta_0 \]
CMS muon resolution at $\eta=0$

The lines represent the formulas from the previous pages.

```
In[2]:= (* ----------------------------- *)
In[3]:= NO = 10;
In[4]:= L = 1.1;
In[5]:= sig0 = 23*10^(-6);
In[6]:= L1 = 3;
In[7]:= (* sigl=50*10^(-6); *)
In[8]:= B0 = 4;
In[9]:= XOTracker = 0.7;
In[10]:= sigtheta = 170*10^(-6);
In[11]:= XOCalo = 100;
In[12]:= LCalo = 2.1;
```
Tracking performance of FCC-hh reference detector

Analytic formulas as important crosschecks ...
The high granularity of ECALs proposed for $e^+e^-$ detectors results in significant cost, e.g. almost 50% of the entire detector cost for the CLIC detector:

<table>
<thead>
<tr>
<th>System</th>
<th>Cost fraction</th>
<th>Cost [MCHF]</th>
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<td>Silicon Tracker</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0</strong></td>
<td><strong>397</strong></td>
</tr>
</tbody>
</table>

What is the performance impact for a larger granularity, more standard e.g. scintillator based ECAL ?

Would LArg be an effective alternative ? There is some R&D on lightweight cryostat materials such that the impact of this additional material in front of the calorimeter might be significantly reduced (see talk by M. Aleksa).

Possibly even a thin coil in front of the ECAL would not even pose a problem, as proposed for the IDEA detector (see presentation by Herman Ten Kate).
Summary

Let’s take the next 5 years to think about principle concepts with basic formulas, Toy MonteCarlo and fast simulation. Our newcomers should get a ‘clue’ about principles and not get lost in full simulation technicalities.

At this stage, full simulation should be used to benchmark some geometries, but not for detector optimization ...

Physics studies should be done with fast parametrized detector performance.

Silicon sensors with ultra low material budget are clearly a key element for and FCC-ee detector due to the low momenta of the decay particles.

Timing detectors with <10ps time resolution might be very useful for PID.

We should re-think the muon systems.

We should explore LAr calorimetry and other alternatives ...
Figure 4.15: Point resolution in the magnetic bending plane $\rho\phi$ as a function of $z$ for (blue) GEM and (red) MWPC amplification, with (left panel) $4 \times 7.5 \text{ mm}^2$, (middle panel) $6 \times 10 \text{ mm}^2$, and (right panel) $6 \times 15 \text{ mm}^2$ pads, respectively.

Figure 4.3: Dimensions (mm) of the ALICE TPC readout chambers.

Detector gas: Ne-CO$_2$-N$_2$ (90-10-5)

Gas volume: $90 \text{ m}^3$

Drift voltage: 100 V/cm

Drift field: 400 V/cm

Maximal drift length: 290 cm

Electron drift velocity: 2.58 cm/µs

Maximum electron drift time: 97 µs

$\alpha (\beta = 0.5)$: 0.32

Electron diffusion coefficients: $D_T = 209 \text{ µm}^2/\text{cm} \cdot \mu\text{s}, D_R = 221 \text{ µm}^2/\mu\text{s}$

Ne$^+$ drift velocity: 1.532 cm/µs

Maximum Ne$^+$ drift time: 151 µs

Readout chambers:

- Total number: $2 \times 2 \times 18 = 72$
- Readout technology: 4-GEM stack, single mask, standard (140 µm) and large (280 µm) hole pitch
- Gas gain: 2000
- Ion back flow: $< 1%$
- Energy resolution at 5.9 keV: 12%}

**Inner (IROC):**

- Total number: $2 \times 18 = 36$
- Active range: $848 < r < 1321$ mm
- Pad size: $4 \times 7.5 \text{ mm}^2 (\rho \times \phi)$
- Pad plane: 63
- Total pads (IROC): 5904
- S/N: 20.1

**Outer (OROC):**

- Total number: $2 \times 18 = 36$
- Active range: $1366 < r < 2461$ mm
- Pad size (inner): $6 \times 10 \text{ mm}^2 (\rho \times \phi) (1346 < r < 2006 \text{ mm})$
- Pad plane (inner): 70
- Total pads (inner): 6656
- Pad size (outer): $6 \times 15 \text{ mm}^2 (\rho \times \phi) (2086 < r < 2461 \text{ mm})$
- Pad plane (outer): 35
- Total pads (outer): 3200
- Total pads (OROC): 9856
- S/N: 33.1
The radiation length $X_0$ of a mix of different materials with volume fractions $v_i$, radiation length $X_0^i$ and density $\rho_i$ is given by

$$\frac{1}{X_0} = \sum_i \frac{v_i}{X_0^i} \quad \sum_i v_i = 1$$  \hspace{1cm} (254)

The density of this mix is given by

$$\rho = \sum_i v_i \rho_i$$  \hspace{1cm} (255)

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**Gas choice:** The baseline gas mixture is Ne-CO$_2$-N$_2$ (90-10-5), see Chap. 3.

$X_0 = 345\text{m}$

$X_0 = 1405\text{m}$