1 Physics objectives and design considerations

1.1 The ALICE experiment

ALICE (A Large Ion Collider Experiment) [1] is an experiment at the Large Hadron Collider (LHC) optimized for the study of heavy ion collisions, at a centre-of-mass energy per nucleon pair of 5.5 TeV. The understanding is that in such high energy collisions of heavy nuclei a Quark-Gluon Plasma (QGP) will be formed. The chief difference as compared to RHIC e.g. is that gluon distribution functions at much lower values of x ($x = x_t = 2p_t/\sqrt{s} = 10^{-4} - 10^{-3}$) will be probed leading to a very high initial gluon density; values of up to 4000 gluons per unit rapidity near mid-rapidity have been quoted [2]. This is expected to lead to very fast equilibration [3] of at least the gluons on a time scale of 0.1 fm/c and hence to a very high initial energy density and temperature of the order of 1000 GeV/fm^3 and 1 GeV, respectively. ALICE aims to study the properties of this hot QGP, its dynamical evolution, phenomena associated with the phase transition of rehadronization and finally the evolution of the hadronic final state until freeze-out. To achieve this goal ALICE, as the only dedicated heavy ion experiment at LHC, is designed to measure a large set of observables over as much of phase space as achievable and thereby covering hadronic and leptonic observables as well as photons.

The ALICE experimental set-up is shown in Colour Fig. 1. The experiment will have a central barrel, housed in the L3 magnet, covering in pseudorapidity the range $-0.9 \leq \eta \leq 0.9$ with complete azimuthal coverage. This central barrel comprises an inner tracking system of Silicon detectors (ITS), a large time projection chamber (TPC), a transition radiation detector (TRD) – the subject of this technical design report –, and a time-of-flight array (TOF). In addition there will be close to mid-rapidity two single arm detectors, an array of ring-imaging Cherenkov counters (HMPID) to identify hadrons up to high momenta and an array of crystals (PHOS) for the detection of photons. This central barrel will be complemented [4] at pseudorapidities of $2.5 \leq \eta \leq 4.0$ by a muon spectrometer with its own dipole magnet. At more forward and backward rapidities detectors will be located to measure the multiplicity of charged particles and the time of an interaction, both also for trigger purposes, as well as several more specialized detectors.

1.2 Physics requirements

The chief goal of the TRD is to provide electron identification in the central barrel at momenta in excess of 1 GeV/c where the pion rejection via energy loss measurement in the TPC is no longer sufficient. As a consequence, the addition of the TRD [5] significantly expands the physics objectives of the ALICE experiment [1, 4].

1.2.1 Heavy ion collisons

The TRD will provide, in conjunction with data from the TPC and ITS detectors, sufficient electron identification capability for the following measurements:

- **In the di–electron channel**, the production of light and heavy vector–meson resonances as well as the di-lepton continuum. This measurement, centered around mid-rapidity, is complementary to the measurement of quarkonia at more forward rapidities in the di-muon channel. Also, the vertex capabilities of the ITS will allow to distinguish and measure J/ψ mesons from B-decays. This will not only permit distinction between primary and secondary J/ψ mesons but also lead to a direct measurement of the B–meson production cross section. Depending on the magnitude of thermal radiation of the QGP and the mixed phase, a measurement of the di–electron continuum between J/ψ and Υ may be sensitive to this interesting probe. We aim for a pion rejection and luminosity sampled by the trigger to achieve sensitivity at the Drell–Yan level [5].

- **Via the single–electron channel** and requiring a **displaced vertex** using the ITS information, the semi-leptonic decays of hadrons with open charm and open beauty. This will be complementary to the very difficult measurement of hadrons with open charm via identification of the displaced secondary vertex in the hadronic decay channel. While interesting in its own right the measurement of open charm and beauty is essential as a reference against which to judge effects of the QGP concerning the yields of quarkonia.
- **Via coincidences of electrons** in the central barrel and **muons** in the forward muon arm, information on the correlated production of hadrons with open charm and open beauty at a rapidity interval bridging the coverage of the central barrel and the forward muon arm. This will provide information on charm and beauty production over the rapidity range y = 0–4.

The trigger capability of the detector (see Chapter 6 below) opens another interesting and unique possibility:

- **Jets with high** E_t can be selected at the trigger level by requiring several (3 or more) high p_t tracks in one TRD module, where the typical coverage is $\Delta\eta \approx \Delta\varphi \approx 0.35$. With individual thresholds around 3–5 GeV/c this trigger reaches full efficiency at a jet E_t of 150 GeV just where rate considerations make a trigger useful.

The theoretical uncertainties in predicting the multiplicity of produced hadrons are large since even proton-proton collisions at this beam energy have not been studied and since the gluon distribution functions at the relevant values of x have not been measured in nuclei. Moreover, first results at RHIC as a function of centrality and in comparison to pp collisions have shown [6] a scaling with the number of nucleons participating in the collision containing a linear and a quadratic term. The overall centrality dependence is a complicated interplay between collective effects and saturation of the gluon density in the initial and final state, making quantitative preditions for this completely new energy regime difficult. The theoretical estimates [7] for the rapidity density of produced charged hadrons for central Pb–Pb collisions range[1] from 2000 to 8000. Using parton saturation and classical QCD [8] a scaling function for multiplicity as a function of beam energy was derived recently which was used for a successful prediction for the full RHIC energy (200 GeV) based on 130 GeV data. Extrapolating this scaling all the way up to LHC energies would yield a multiplicity density at the lower end of the predicted range (2000 or even somewhat below). Following the general ALICE strategy to be prepared to deal with even the highest conceivable multiplicities, the detector is designed for an upper limit in the charged particle rapidity density of 8000. In the parametrization used, actually the maximum rapidity density of primary charged particles averaged over the central two units of rapidity ($-1 \leq y \leq +1$) is 8400 (called in the following 'full multiplicity'). Decays of neutral hadrons, mostly K^0_S , within 5 cm of the primary vertex increase this number to 9300. Secondary particles generated in the detectors, frames, services, and other material lead to about double the primary charged multiplicity in the TRD.

Identification of electrons in this high occupancy environment is clearly very challenging. In Chapter 11, simulations will be shown of the performance of the TRD covering the whole range of expected multiplicity densities.

As a benefit of the high gluon densities at the small x-values relevant at LHC, the cross sections for charm and beauty production as well as the semi-hard jet cross sections are more than one order of magnitude enhanced as compared to RHIC.

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[1] Early estimates based on Glauber models gave very high values of up to $dN_{ch}/dy=8000$; newer calculations based on gluon distributions or Gribov-Regge theory reduce this estimate by nearly a factor 3

All rate estimates in this document are based on an anticipated maximum luminosity for Pb–Pb collisions of $\mathcal{L} = 1.0 \cdot 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ leading to a minimum bias interaction rate of 8 kHz and a rate of 0.8 kHz for central collisions with impact parameter less than 5 fm. With past and future protection during the TPC drift time, these rates are reduced by about a factor of 4. In fact, the number of clean events in the TPC is nearly the same at a luminosity of $\mathcal{L} = 5 \cdot 10^{26} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The actual charged particle multiplicity will determine whether some overlap of intercations in the TPC is acceptable.

In this luminosity range and assuming a data acquisition capability of 20 Hz for central collisions [9], statistics for J/ψ, open charm and open beauty is not an issue as outlined in [5]. The experiment is however statistics limited in the Υ measurement. At a luminosity of $\mathcal{L} = 1.0 \cdot 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ there will be about 13600 Υ with both decay electrons in the central barrel of the ALICE experiment in 10^6 s (a typical ALICE heavy ion year). This number refers to clean events in the TPC. Of these, 5400 will be for the 10% most central collisions. Assuming a DAQ performance of 20 Hz for central collisions and another 20 Hz for minimum bias events (without triggers this saturates the anticipated DAQ capability [9]) and 90% electron identification efficiency (the specification for the TRD), 110 and 440 Υ decays to electron pairs in the ALICE central barrel will be collected per ALICE heavy ion year for minimum bias and central collisions, respectively. These numbers do not yet include the tracking efficiency and are therefore upper limits. This demonstrates the need for a trigger. Without it there would be a marginal measurement of the Υ yield in central collisions and clearly not enough statistics to measure the centrality dependence, yields for the Υ substates (1S, 2S,...), or the spectral distributions. For a more detailed discussion and numbers including tracking efficiency for various scenarios, see Section 6.5.

- **Need for Trigger:** the Υ measurement and in particular its centrality dependence make it essential to sample the full minimum bias rate of Pb–Pb collisions of up to 4 kHz (past-protected events in TPC). The TRD is designed to provide this trigger capability. For the Υ measurement this would be a trigger on electron pairs with each electron typically having a transverse momentum above 3 GeV/c . This decision will be available on a time scale of 6 μs after the collision.

Without this trigger capability a measurement of the thermal continuum is not conceivable if it is near the Drell–Yan level. Having this trigger capability, it can also be applied to jet physics. This will be the subject of the Physics Performance Report of ALICE and here only the ideas are sketched. Requiring several (3–5) high p_t particles in a jet cone of a certain size a jet candidate can be identified. This would be effective for jet transverse energies larger then 150 GeV (see above). Then one could require two such candidates back to back, or one candidate opposite to PHOS could be combined with a high momentum photon, or two close high momentum electrons (photon jet) could be combined with an opposite jet candidate.

Another advantage this trigger provides is to identify the region of interest for the high momentum electron. This means, one could read out only the TPC sectors to which the electron candidates of the TRD point. The event size for central collisions could be reduced then to typically 3–4 out of 2×18 sectors i.e. about to 1/10 of the full size, thus relaxing the 20 Hz limitation for the acquisition of central collision events. In addition, combination of the TRD trigger with the planned high level trigger (HLT) will lead to significant improvements in the trigger efficiency and selectivity.

1.2.2 Proton proton collisons

The TRD will also contribute significantly to the ALICE proton-proton physics program. Proton-proton (pp) collisions are an integral part of the ALICE running scenario, both to collect data needed as comparison for results from heavy ion collisions and to address topics of genuine interest in elementary hadron interactions. The detailed physics arguments for including ALICE in the LHC pp running scenario are summarized in [10].

ALICE, which is designed to cover the low to medium p_t range (between 100 MeV/c and 20 GeV/c), is uniquely suited for these tasks. In addition to the physics topics which are discussed in the previous subsection and which were the original motivation for the TRD, applicable both to heavy ion and pp running, we foresee the following items specific to pp running:

- **Charm and Beauty physics**: We expect to measure transverse momentum spectra of D and B mesons down to very low p_t (essentially below 100 MeV/c). The knowledge of spectra at low values of p_t is of large interest for the extraction of the total c and b cross sections. Today's extraction of c and b total cross sections relies on large extrapolations towards low p_t because of relatively high p_t cut-off values in the acceptance. In addition, these cross sections are theoretically not well reproduced by present perturbative QCD calculations. Neither the Fermilab Tevatron experiments nor the dedicated pp LHC experiments will cover the low p_t regions for D and B mesons. Low p_t J/ψ and Υ measurements are also important since the present theoretical understanding of the production cross section is not entirely on safe ground. There are no low p_t measurements in $p\bar{p}$ and pp collisions nor will there be any in the foreseeable future.

- **Topological trigger function for the HMPID**: The behaviour of the particle composition in pp collisions as a function of p_t and multiplicity is of large interest. The HMPID which is dedicated to extend the PID to momenta of 3.5 GeV/c for kaons and 5 GeV/c for protons covers only a small part of the central barrel acceptance. Therefore, it is important to be able to use the TRD to trigger on high momentum tracks pointing towards the HMPID. Otherwise the HMPID, due to the low track multiplicity, would be empty most of the time during pp running.

- **Measuring Jets in pp running**: The segmentation of the TRD modules allows to trigger on jets (monojets, dijets) as sketched above for heavy ion operation; in pp collisions the trigger on jets might be useful at much lower jet energies. In this context a topological trigger pointing toward PHOS could be useful. A trigger on the hard tracks of the charged particles pointing to PHOS could yield more detailed information about the total energy of the jet and the fragmentation functions, not achievable with charged particles only.

1.3 TRD design considerations

The physics requirements outlined in the previous section have driven the following design considerations:

- **The pion rejection capability** required is driven mostly by the J/ψ measurement and its p_t dependence. As outlined in the Addendum to the ALICE proposal [5] a factor 100 in pion rejection for electron transverse momenta above 3 GeV/c is the goal. While the requirement for the Υ is less stringent, the light vector mesons ρ, ω, ϕ as well as the di–electron continuum between the J/ψ and the Υ are only accessible with this performance.

- **The required momentum resolution** is primarily driven by the matching to the TPC. The momentum resolution requirements for the central barrel are fulfilled by combining TPC and ITS reaching e.g. a mass resolution of 100 MeV/c^2 at the Υ for B = 0.4 T (see Chapter 12) and the function the TRD needs to fulfill is to add the electron identification. This goal can be reached by having a pointing capability from the TRD to the TPC with an accuracy of a fraction of a TPC pad. The TRD will provide a momentum resolution of 5% at 5 GeV (see Chapter 11) leading to a pointing accuracy of 30% of the padwidth allowing unambiguous matching with exception of very close hits. At the trigger level good momentum resolution leads to a sharper threshold and a smaller probability of fake tracks but no strict requirement can be derived from this.

- **The thickness of the TRD** in radiation lengths has to be kept to a minimum. Any unnecessary material provides additional background dominantly due to photon conversion and increases the pixel occupancy. Also, electron energy loss due to bremsstrahlung removes electrons from the sample useful for reconstruction of resonances.

- **The granularity** of the TRD, i.e. of the cathode pads in the readout chambers, is driven in bend direction by the required momentum resolution (see before) and along beam direction by the required capability to identify (see above) and track electrons efficiently at the highest envisioned multiplicity. To not affect the reconstructed pair signal drastically we designed the detector to achieve 80% tracking efficiency (single track) for this case driving the design to pads of about 6 cm^2 .
- **Occupancy:** This maximum assumed charged particle multiplicity density of 8000 leads in the TRD to a readout pixel occupancy in central collisions of about 34% (including secondary particles) for the pad size given above. The detector is designed to function at this occupancy.

1.4 General description of the TRD

The physics requirements and design considerations listed above have led to the present design of the TRD. Central aspects of the design are summarized in the text below and detailed in the following chapters. For a quick overview there is also a synopsis in Table 1.1. For the overall description of the TRD in the ALICE experiment we use cylindrical coordinates with the origin at the intersection of the beams and with the positive z-axis pointing towards the muon arm. The angle φ is then also the deflection angle in the magnetic field. Since the TRD chambers are flat and not on a cylindrical surface it is often more convenient, when discussing processes and resolutions inside a given chamber, to use cartesian coordinates. In this case we keep the same z-axis, y is the direction of the wires and of the deflection in the magnetic field, x is the direction of electron drift.

The coverage in pseudorapidity matches the coverage of the other central detectors ($| \eta | \leq 0.9$). In radius the TRD fills the space between the TPC and the TOF detectors. As shown below, for quality of electron identification the TRD consists of 6 individual layers. Following the segmentation in azimuthal angle φ of the TPC there are 18 sectors. For practical considerations there is a 5-fold segmentation along the beam direction (z). The 5 detector modules have similar but not identical length in z to match the areas in between modules with more material (in particular in the space frame) with boundaries of detectors at larger radii in a projective geometry. The dimensions of the active area of each detector module are given in Table 2.2. In total there are $18 \times 5 \times 6 = 540$ detector modules.

Each module consists of a radiator of 4.8 cm thickness, a multiwire proportional readout chamber, and the front-end electronics for this chamber. The signal induced on the cathode pads is read out. Each chamber has 144 pads in direction of the amplification wires ($r\varphi$) and between 12 and 16 pad rows in z direction. The pads have a typical area of 6–7 cm^2 and cover a total active area of about 736 m^2 with $1.16 \cdot 10^6$ readout channels.

The gas mixture in the readout chambers is Xe/CO_2 in a ratio of 85/15. Each readout chamber consists of a drift region of 3.0 cm separated by cathode wires from an amplification region of 0.7 cm. The drift time for the drift region is 2.0 μs requiring a drift velocity of 1.5 cm/μs. The nominal drift velocity will be reached with an electric field of 0.7 kV/cm. In this gas mixture a minumum ionizing particle liberates 275 electrons per cm. The gas gain will be of order $5 \cdot 10^3$. The induced signal at the cathode pad plane will be sampled in 15 time intervals spaced 2 mm or 133 ns over the drift region. Diffusion is negligible (see Table 1.1), and at the nominal magnetic field of 0.4 T the Lorentz angle is 8°.

At full multiplicity the pixel occupancy will be 34%. As shown in Chapter 11 a space point resolution in bend direction of 400 μm can be achieved for low multiplicity at p_t = 1 GeV/c . For full multiplicity this is degraded to 600 μm with some unfolding. The momentum resolution of the TRD in stand-alone mode is determined by a constant term of 2.5% and a linear term of 0.5% per GeV/c . The linear term is degraded to 0.8% for full multiplicity.

Table 1.1: Synopsis of TRD parameters.

Pseudorapidity coverage	$-0.9 < \eta < 0.9$
Azimuthal coverage	2π
Radial position	$2.9 < r < 3.7$ m
Length	maximal 7.0 m
Segmentation in φ	18–fold
Segmentation in radius	6 layers
Segmentation in z	5–fold
Total number of modules	540
Largest module	120×159 cm^2
Detector active area	736 m^2
Detector thickness radially	$X/X_0 = 14.3\%$
Radiator	fibres/foam sandwich, 4.8 cm per layer
Module segmentation in φ	144
Module segmentation in z	12–16
Typical pad geometry	$0.725 \times 8.75 = 6.34$ cm^2
Time samples in r (drift)	15
Number of readout channels	$1.16 \cdot 10^6$
Number of readout pixels	$1.74 \cdot 10^7$
Detector gas	Xe,CO$_2$ (15%)
Gas volume	27.2 m^3
Depth of drift region	3 cm
Depth of amplificaton region	0.7 cm
Nominal magnetic field	0.4 T
Drift field	0.7 kV/cm
Drift velocity	1.5 cm/μs
Diffusion, longitudinal	$D_L = 250$ μm/$\sqrt{\text{cm}}$
Diffusion, transversal	$D_T = 180$ μm/$\sqrt{\text{cm}}$
Lorentz angle	8°
Occupancy (for full multiplicity)	34%
Typical space point resolution at 1 GeV/c	
in $r\varphi$	$400(600)$ μm for low (high) multiplicity
in z	2.3 cm (without tilt)
Momentum resolution	$\delta p/p = 2.5\% \oplus 0.5\%(0.8\%)p$ for low (high) multiplicity
Pion suppression at 90% electron efficiency and $p_t \geq 3$ GeV/c	better than 100