Radiation length of the ALICE TRD

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Abstract

In this document the best estimates for the radiation length of all parts of the ALICE Transition Radiation Detector are given. Each contributing part is described and a sum for the different logical parts of the detector and the total sum of the radiation length is calculated.

1 Introduction

The ALICE TRD covers the full ϕ range and the pseudorapidity range $-0.9 < \eta < 0.9$. The detector is segmented in ϕ into 18 super modules of 7 m length. Each super module carries 30 individual drift chambers arranged radially in 6 layers and in 5 longitudinal stacks. The TOF system which covers a similar acceptance as the TRD and is located radially outside of the TRD uses a similar segmentation into 18 ϕ-sectors and 5 longitudinal sectors. Therefore the boundaries of the detectors are aligned in a projective geometry (as seen from the interaction vertex). This enables the separation of TRD areas into areas with higher density of materials to provide the structural stability of the detector and areas with low material density to reduce interactions of particles which are to be measured in the following detectors (TRD chambers or TOF).

The super module introduces aluminum structures into the boundaries of the 18 ϕ-sectors, also some stabilizing parts will be located between the chambers of one layer in longitudinal direction. The individual drift chamber feature a frame made from Wacosit[1] and aluminum. A particle traversing this area sees a significant radiation length of $X/X_o \approx 50 - 100\%$. This note is however only concerned with the material which is found in the active area of the TRD chambers and therefore sitting before the active area of the TOF detector.

The amount of material traversed by a particle is also dependent on the angle and the origin of the particle. The radiation length calculated in this note is however only given for a particle which traverses the detector perpendicular to its plane. In the experiment this would correspond to a high-p_T particle at $\eta = 0$, traversing a chamber at its center. For the C0 chambers around midrapidity this is a reasonable description, the C1 chambers will however always see the particle at a certain θ-angle.

In cases when there is a certain amount of material given for one ROC, e.g. 6 ROBs for the C0 chambers, the relative area covered is dependent on the size of

[1] Wacosit is the brand name for glass fiber reinforced epoxy, polystyrol or polyester based pultruded profiles by Ernst Kühne Kunststoffwerk GmbH. The Material is similar to G10 or Stesalit.

Element	$X_o(g/cm^2)$	Density(g/cm^2)	$X_o(mm)$
H	67.6		
C	42.7		
N	38.0		
O	34.2		
Al	24.0	2.7	88.9
Si	21.8	2.3	93.7
Ti	16.2	4.5	35.9
Fe	13.8	7.9	17.6
Cu	12.9	8.9	14.4
Zn	12.4	7.1	17.4
Ag	9.0	10.5	8.6
Sn	8.8	7.3	12.0
Xe	8.5		
Ba	8.3	3.5	23.7
Ta	7.2	16.7	4.3
Pb	6.4	11.3	5.6

Table 1: Radiation length of some Elements calculated with the formula of Tsai.

the chamber: a L0C0 chamber is fully covered with ROBs, while a L5C0 chamber is only covered to 70% with ROBs. For such cases an 'effective thickness' is assumed, corresponding to the thickness of Material if it was distributed evenly over the 'active area'[2] of the chamber. To facilitate things the average active area of L0C0-L5C0 chambers was used which is an area of $997 \times 1060 mm^2$.

2 Calculation of Radiation Length

The radiation length was calculated with the formula from Tsai[1] described in [2]. The result for the relevant elements is shown in Table 1.

2.1 Composite Materials

Since most parts of the TRD are made of composite materials the radiation length of those has to be approximated. This is done according to

$$1/X_o = \sum w_i/X_i, \tag{1}$$

where w_i and X_i are the fraction by weight and the radiation length for the ith element[2].

3 Parts of the ALICE TRD

The TRD can be subdivided into the read out chambers (ROC) and the electronics including its services. Since in case of the TRD the front end electronics are placed directly on the detector to minimize signal path length, they are

[2]With 'active area' the part of the chamber is meant where a particle can produce a signal. Effectively it is the area which is covered by the wire grids.

	H	C	O	PMMA
composition	8	5	2	
rel. weight(%)	8.58	59.64	31.78	
$X_o(g/cm^2)$	67.6	42.7	34.2	40.8

Table 2: Composition and the resulting radiation length of PMMA (Rohacell).

contributing to the relevant radiation length. The readout chamber consist of the following major building blocks:

- Radiator
- Gas
- Amplification region
- pad plane Panel

The electronics consist of the following parts:

- Readout board PCB
- Multi Chip Module
- Active and passive components and connectors
- DCS board
- OASE board
- Cooling

3.1 Radiator

The Radiator is constructed from two sheets of Rohacell HF71, the so called window plate and bottom plate. A sheet of carbon fiber is laminated onto one side of both of these plates. The carbon sheets are each covered with aluminized Mylar foil. For stability crossbars of Rohacell are glued between the window and bottom plate to form compartments in which the fiber mats are placed. All Rohacell parts are cut from sheets of 8 mm thickness. The compartments of the radiator are filled with polypropylene fibers.

Rohacell: Rohacell is a foam of PMMA; the type used is HF71 which has a density of $0.075 g/cm^2$[3]. The radiation length is calculated based on the chemical formula for PMMA: $(C_5O_2H_8)_n$ [4]. The values are given in Tab. 2.

The thickness for the window and bottom plate are 8 mm, the crossbars have a thickness of 31.3 mm. The radiation length of 1 crossbar (31.3mm Rohacell) is $X/X_o = 0.58\%$. This compares to the radiation length of the fibre mats (of one radiator) of $X/X_o = 0.481\%$ (see next paragraph). The difference would locally add up to 0.5% of a radiation length for the full detector, assuming a particle would traverse the crossbars in all 6 layers which is virtually impossible, therefore it is neglected. For this estimate it is assumed that the radiator does not contain a frame but is completely filled with fibre mats.

	H	C	PP
composition	6	3	
rel. weight(%)	15.2	84.8	
$X_o (g/cm^2)$	67.6	42.7	45.2

Table 3: Composition and the resulting radiation length of polypropylene (fibers).

Fibers: The fibers used are of type LRP375BK produced by Freudenberg. The chemical formula of polypropylene (C_3H_6) gives the radiation length calculated in Tab. 3. The density of the fibers is difficult to measure and is also prone to fluctuations. Several measurements have been done yielding densities between 0.064 g/cm^3 [5] and 0.074 g/cm^3[6]. A realistic average value seems to be 0.068 g/cm^3 taking into account already that the fibers are slightly compressed to fit into the compartments of the radiator. This number will be further used for this estimate. The thickness of the fiber layer is defined by the Radiator dimensions to be 32 mm.

Carbon Fibers: The carbon fiber sheets of the Radiator consist of $95 g/m^2$ of the raw carbon webbing [7]. For one sheet this yields $X/X_o = 0.023\%$.

Aluminized Mylar The Aluminized Mylar on both the window and bottom plate has a thickness of 12 μm with an aluminum cover of $\approx 3 \mu m$. Mylar is a stretched polyethylene foil; the composition is similar to polypropylene and therefore the radiation length of the fiber material is taken. The density of the foil was not known, but should be close to $1 g/cm^3$. Due to the negligible contribution a further investigation was not done.

Glue There are two places where glue contributes to radiation length in the radiator:

- Glue between crossbars and window/bottom plate.
- Glue in the carbon fiber sheets.

Assuming a typical glue thickness of 0.1 mm between crossbars and rohacell plates a particle would traverse $0.06\% X_o$ in one layer. Since again it is unlikely that a particle crosses several bars in different layers, this amount of glue can be neglected.

The carbon fiber is impregnated with epoxy which is cured during the lamination process. Therefore this glue gives stability to the carbon fibers and also acts as glue to bind the carbon sheets to the Rohacell and the Mylar foil to the carbon surface. For this purpose $75 g/m^2$ of glue were used [7].

For calculation of the radiation length of glue (regardless of its exact type) the formula of the epoxy group is used ($C_2H_4N_1$). There are different compositions of glue and also Oxygen is contained usually, but the effect on the radiation length is rather small. The resulting radiation length is calculated in Tab. 4. The density of epoxy glues is typically around 1.0 g/cm^3(AY103/HY991) to 1.2 g/cm^3(AW106/HV953U, AW116/HV953U). Since the type of glue used for

	H	C	N	Epoxy
composition	4	2	1	
rel. weight(%)	10.2	56.7	33.1	
$X_o(g/cm^2)$	67.6	42.7	38.0	42.6

Table 4: Composition and the resulting radiation length of Epoxy.

	N	O	Air
composition	2	2	
rel. weight(%)	76.6	23.3	
$X_o(g/cm^2)$	38.0	34.2	37.1

Table 5: Composition and the resulting radiation length of Air.

laminating the carbon sheets to the rohacell plates is not known, the higher density is assumed where needed (see Tab. 6).

Resulting from this the glue in both carbon sheets contributes $X/X_o =$ 0.035%.

Air: The air between the fibers inside the radiator also contributes a bit to the radiation length. The density of air at 20^{o}C is $0.0012 g/cm^3$, the resulting radiation length is $X/X_o = 0.01\%$.

3.2 Gas

The drift gas which will be used in the ALICE TRD is $Xe/CO_2(85\% : 15\%)$. The drift region is 30 mm long, additionally the amplification region contributes 7.2 mm. A total of 37.2 mm of the used gas mixture under operating conditions ($\approx 20^o$C) contributes a radition length of $X/X_o = 0.2\%$.

3.3 Amplification region

Two wire planes exist in the TRD, the cathode plane made of $75\mu m$ diameter Copper[3] wire with a wire pitch of 2.5 mm and the anode plane made of Gold

[3]Our wire contains 2% Beryllium

part	$X_o(g/cm^2)$	$\rho_o(g/cm^3)$	$X_o(mm)$	g/m^2	d (mm)	$X/X_o(\%)$
Rohacell	40.8	0.075	5440		16	0.294
fibers	45.2	0.068	6647		32	0.481
carbon fiber	42.7	1.8	237	190		0.045
mylar	45.2	0.9	503		0.024	0.005
Aluminum	24.01	2.7	88.9		0.006	0.007
Glue	42.6	1.2	354.9	150		0.035
Air	37.1	0.0012	318425.2		31.4	0.01
Sum						0.877

Table 6: Parts of the radiator and the resulting radiation length. Parts of the bottom and window plate are summed up.

covered Tungsten wire of $20\mu m$ diameter with a wire pitch of 5 mm. For the average C0 chamber there are 480 cathode wires with a length of 1029 mm over a width of 1060 mm (active chamber width) resulting in a average radiation length contribution of $X/X_o = 0.014\%$. For the anode plane 240 wires contribute resulting in a average radiation length contribution of $X/X_o = 0.001\%$.

3.4 Pad plane panel

Carbon fiber The carbon fiber webbing used for the pad plane panel has a weight of $328 g/m^2$ [7]. This yields a radiation length of $X/X_o = 0.154\%$ for the two used carbon sheets used in one panel.

Glue The amount of glue used to impregnate the carbon fiber sheets is $200 - 230 g/m^2$ [7], resulting in a radiation length of $X/X_o = 0.101\%$ for both carbon sheets.
When gluing the carbon sheets to the honeycomb, glue is rolled onto the honeycomb. The amount of glue used in this process is in the order of $50 g/m^2$ per side. The carbon fiber sheets are glued onto both sides of the honeycomb and then the additional 2 mm honeycomb spacer is glued to one side of this sandwich. The panel therefore contains $150 \pm 50 g/m^2$. The radiation length contribution is $X/X_o = 0.035\%$.

Honeycomb The used honeycomb material is based on Aramide fiber and has a density $\rho_o = 0.032 g/cm^3$ [7]. The radiation length of Aramide is $X_o = 40.35 g/cm^2$. With a honeycomb thickness of 20mm + 2mm (spacer) the radiation length is $X/X_o = 0.166\%$.

Air: About 97% of the Honeycomb volume is filled by Air. 22 mm of air have a radiation length of $X/X_o = 0.007\%$.

Pad plane: The pad plane of the TRD is made up of large printed circuit boards (PCB) consisting of the base material (halogen free FR4) and 2 layers of copper from which the pad and trace structures are formed.

FR4: The first batches of pad planes had a base material thickness of 0.36 mm, later pad planes have an increased thickness of 0.38 mm FR4 due to availability reasons. 0.38 mm thickness is used here but the difference is not very significant. The used FR4 contains 61% glass fiber and 39% resin [9] with a resulting radiation length of $X_o = 31,845 g/cm^2$. With a measured density of $2 g/cm^3$ the radiation length of the padplane base material is $X/X_o = 0.239\%$

Copper: The effective thickness of the Copper on the pad planes after all galvanic processes and etching is 0.025 mm [10]. 98% of the pad side is covered with copper, the traces and soldering pads on the other side contribute 2%. Therfore one copper layer covering the whole surface is assumed which has a radiation length of $X/X_o = 0.174\%$.

Glue When gluing the pad planes to the panel approximately $400 g/m^2$ of glue is used. The resulting radiation length per chamber is $X/X_o = 0.094\%$.

part	$X_o(g/cm^2)$	$\rho_o(g/cm^3)$	$X_o(mm)$	(g/m^2)	d (mm)	$X/X_o(\%)$
Panel:						
Carbon fiber	42.7	1.8	237	656	-	0.154
Honeycomb	40.35	0.032	12608.5	-	22	0.174
Glue (Carbon)	42.55	1.2	354.9	430	-	0.101
Glue (HC)	42.55	1.2	354.9	150	-	0.035
Glue (Cable holes)	42.55	1.2	354.9	-	0.066	0.019
Air	37.1	0.0012	318425.2	-	22	0.007
pad plane:						
FR4	31.85	2.0	159.3	-	0.38	0.239
Copper	12.86	8.93	14.4	-	0.025	0.174
Glue (PP-BP)	42.55	1.2	354.9	400	-	0.094
Sum						0.997

Table 7: Parts of the pad plane panel and the resulting radiation length.

Glue in signal cable holes: The holes in the back panel where the signal cables go from the pad plane to the PASA input are filled with glue up to the lower carbon fiber sheet, which corresponds to 2 mm height. The cutouts are $8 \times 35mm^2$, the glue usually runs a bit further into the honeycomb depending on the local geometry of the cells. It is assumed that the area covered with glue is therefore $10 \times 37mm^2$. A C0 panel has 96 holes, a C1 panel has 128 holes. For an average C0 panel the coverage of 2 mm glue is therefore 3.36%. The average radiation length is consequently $X/X_o = 0.019\%$

3.5 Readout Board

Base Material: The thickness according to specifications is: 8.5+3+3.5+3+8.5 mil =27 mil corresponding to 0.7mm FR4. It is assumed that prepreg composition (3 mil) is not very different from the FR4 base material. It is likely that the epoxy fraction is higher but this is neglected for now. It is also assumed that the used FR4 is the same material (with respect to the fraction of glass/resin) as the pad plane base material. The radiation length of 0.7 mm FR4 is $X/X_o = 0.44\%$. The size of one ROB is $299 \times 461mm^2$ with 16 cutouts of size $45 \times 10mm^2$ resulting in an covered area of $1306.4cm^2$ per board.

The effective radiation length with 6 ROBs distributed over the active area of C0 chambers would come out to $X/X_o = 0.326\%$

Signal cables: Signal cables between pad plane and readout board: The total contribution to the radiation length of the full 6 layers is in the order of $X/X_o = 0.1\%$. Locally a higher radiation length is possible depending on the angle and position of the cable and the traversing particle.

Copper: The ROB has 6 Layers with different amount of coverage of copper as listed in Tab. 8. Per chamber the radiation length of the copper in the ROB PCB is $X/X_o = 0.404\%$

Layer	thickness(μm)	coverage (%)	X/X_o (%)
1	52	30	0.108
2	17	80	0.094
3	17	80	0.094
4	17	40	0.047
5	17	80	0.094
6	52	30	0.108
Sum			0.545

Table 8: Copper coverage, thickness and radiation length of the 6 ROB layers.

Thickness	Solder	X/X_o (%)
0.8 mm	PbSn	0.175
0.8 mm	Sn	0.125
0.5 mm	PbSn	0.043
0.5 mm	Sn	0.031

Table 9: Radiation length of different types of BGA balls per ROB.

3.5.1 Multi Chip Module

PCB: The PCB of the MCMs has 2 layers, the thickness is 1.0 mm and the size is $41 \times 41 mm^2$. There are 17 MCMs per ROB. The radiation length of one MCM PCB is $X/X_o = 0.628\%$. The contribution of 17 MCMs distributed over a ROB is effetively $X/X_o = 0.138\%$.

Copper: Copper thickness on the MCMs is $\approx 25 \mu m$. Coverage is assumed to be 30% per layer. Per MCM this gives $X/X_o = 0.130\%$, averaged over one ROB $X/X_o = 0.029\%$.

Chips: Silicon, 300 micron thickness, area of PASA+TRAP: $58.3 mm^2$. If assuming that the material is the same as the glob top, the error on the radiation length for one ROB is $< 0.001\%$. Bond wires are neglected.

Glob Top: Epoxy filled with 75% Al2O3, $\rho \approx 1.9 g/cm^3$[8], resulting in $X_o = 30.56 g/cm^2$. Size: $26 \times 26 mm^2$, thickness 1 mm. The fraction of the ROB covered with glob top is 8.8%, resulting in a radiation length per ROB area of $X/X_o = 0.055\%$.

Balls: 432 balls per MCM. Diameter: 0.8mm (Karlsruhe) or 0.5 mm (MSC), with Lead (40% Lead 60%Sn) or lead free (100%Sn). In fact lead free solder tin usually contains 4% Ag and 0.5% Cu, the effect on the radiations length is however $< 1\%$ change, therefore 100% Sn is assumed. The values are listed in Tab. 9.

3.5.2 Other components on the ROB

The remaining ROB components can be subdivided into ceramic capacitors, Tantal capacitors, voltage regulators and connectors (not included so far: board-

Part	X/X_o (%)/ROB	X/X_o (%)/chamber
PCB	0.138	
Copper	0.029	
Glob top	0.055	
Balls (0.5 mm, Sn)	0.031	
Sum	0.251	0.186

Table 10: MCM contribution to the radiation length (per ROB area and per chamber area).

Type	weight/ROB(g)	$X_o(g/cm^2)$	X/X_o (%)/ROB	X/X_o (%)/Chamber
Ceramic caps	9.3	11.16	0.064	
Tantalum caps	7.3	9.03	0.062	
Volt. regulators	17	15.22	0.085	
Connectors	24.5	34.57	0.054	
Sum	58.1	16.76	0.265	0.197

Table 11: Other components of the ROB. The radiation length is the effective radiation length per ROB.

board cable, DCS board, ORI/OASE).

Ceramic Capacitors: Ceramic capacitors consist mainly of $BaTiO_3$ plus some electrode material which is neglected here.

Tantalum Capacitors: Tantalum capacitors are made up of 50% Ta_2O_3 and 50% plastic by volume. The contribution of other components like MnO_2, Ag, Sn etc. is neglected.

Voltage Regulators: The Voltage regulators contain bas plate of copper on which the substrate sits, which is neglected here, the rest is plastic casing. It is likely that this casing is similar to glob top material. The difference in the resulting radiation length is however very small, so it is assumed that it is plastic (radiation length of epoxy was used).

Connectors: For the connectors it was assumed that they contain 90% plastic and 10% copper by weight.

3.5.3 Cables:

Board-Board cables Board-board cables are ignored for this evaluation (at least so far).

other cables? Some other cables might run over the chambers but the contribution is expected to be very small.

Part	weight/ROB(g)	X/X_o (%)/ROB	X/X_o (%)/Chamber
Al pipes	29.69	0.095	
Al plates	21.01	0.067	
Thermal glue	12.84	0.032	
Water	8.8	0.019	
Sum		0.213	0.158

Table 12: Radiation length contribution of cooling components, averaged over the size of one ROB and one chamber.

3.5.4 Spacer Material:

Between ROBs and chamber there is a spacer material of 1 mm thickness, consisting of a polyethylene foam. The contribution is $\Delta X/X_o \approx 0.6\%$ for the full detector.

3.5.5 Mounting screws:

The ROBs are screwed to the chamber by little M3 screws with specially designed head (1 mm thickness). The weight of the screws per ROB including washers etc. is 14 g. Consequently the Radiation length per ROB area is $X/X_o = 0.083\%$, per chamber $X/X_o = 0.062\%$ and $X/X_o = 0.37\%$ for the full detector. If a particle traverses a screw through its full length (7 mm) it sees a radiation length of $X/X_o \approx 50\%$.

3.6 Cooling

Cooling consists of Al pipes glued to Al plates attached to the heat sources.

Cooling meander: Al pipes with 3.0 mm outer diameter and 0.5 mm wall thickness. Per ROB there are four cooling pipes of $\approx 700mm$ length. The cooling pipes of the adjacent ROBs are interconnected and connected to the cooling manifold by silicon tubes, whose contribution to radiation length is ignored here.

Cooling plates: On top of the MCMs the cooling pipes are attached to Al plates ($32 \times 32 \times 0.4mm^3$). On one ROB there are 17 MCMs which are cooled, additionally the voltage regulators are also covered with such Al plates. The area over the voltage regulators corresponds roughly to the area of 2 MCMs, therefore it is assumed that one ROB is covered with 19 plates of the above mentioned dimensions.

Thermal glue/paste: The way the Al plates are attached to the Al pipes is not defined yet, most likely any solution will not contribute a lot of material, so this is ignored for now. The Al plates will have to be in good thermal contact with the MCM glob top surface, so some form of thermally conductive paste or glue will be used between Al plate and glob top surface. Since this is not finalized it is assumed that the material is similar to glob top (which would be true for both thermal paste and Al filled Epoxy) and the thickness is assumed to

Part	X/X_o (%)/Chamber
Radiator	0.877
pad plane	0.506
Back panel	0.49
Wires	0.015
Chamber gas	0.207
ROB PCB (incl. Cu)	0.73
MCM (0.5 mm, Sn balls)	0.186
other ROB comp.	0.197
Spacer	0.01
Mounting screws	0.062
Cooling	0.158
Sum /chamber	3.438

Table 13: Sum of the radiation length of the components of one average C0 chamber.

be 0.5 mm. I expect that this is an upper limit. The size is chosen corresponding to the glob top size to be $26 \times 26mm^2$.

3.7 DCS board:

not included

3.8 OASE board:

not included.

3.9 Air between chambers:

The space between chambers where the electronics are placed, is mostly filled with air. The contribution from $5 \times 19mm$ air is $X/X_o = 0.3\%$.

4 Summary

All contributions to the radiation length of one average C0 chamber are listed in Tab.13. The total radiation length of the TRD without any Super module contribution is listed in Tab.14. This number is for lead-free 0.5 mm BGA solder balls. If 0.8 mm balls containing Pb are used the radiation length of the full detector is increased by 0.67% to $X/X_o = 21.3\%$

In the current design a bottom and top plate of the super module of each 2 mm Al are foreseen, which add another $X/X_o = 4.5\%$. The total including this contribution comes to $X/X_o = 25.8\%$ for the full TRD. Additionally each chamber will be equipped with one DCS board and 2 OASE boards, which are not included.

	X/X_o (%)
6 chambers	20.6
air between chambers	0.3
Sum	20.9

Table 14: Sum of the full TRD detector

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