

DEVELOPMENT OF CATIA_2_GEANT INTERFACE FOR SIMULATION OF HIGH ENERGY PHYSICS EXPERIMENTS

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ABSTRACT

High Energy Physics (HEP) implements simulation for deep and wide range investigation of physics experiments by generating artificial events from the Monte-Carlo (MC) events generators in a format which is identical to the output of the facilities for experiment, detectors. However in some regions of detector data vs MC never match perfectly and there are discrepancies. Several reasons can cause it. Primary interest falling down on the investigations to understand how correct is detector representation in simulation. Simulation infrastructure implements GEANT for modelling of geometry. Shapes consistency and detalization is not important while adequateness of volumes and weight of detector components are essential for tracking. Geometry descriptions stored in database in general formats – XML, Oracle tables, etc. Then it is transforming in GEANT during the simulation. There are 2 main reasons of faults of geometry descriptions in simulation: 1/ Difference between simulated and as-built geometry descriptions 2/ Internal inaccuracies of geometry transformations added by simulation software infrastructure itself. For investigation of both reasons CATIA-GEANT interface was built. The aim was to use CATIA as a hub for collection of different geometry descriptions using by simulation and in same time make their comparison to find faults and analyse quality of GEANT simulation infrastructure. Paper represents results of analysis done for the ATLAS experiment at LHC – Large Hadron Collider, CERN, Geneva, Switzerland.

KEYWORDS

Large Hadron Collider, ATLAS collaboration, Geometry descriptions, CATIA, GEANT.

1. INTRODUCTION

ATLAS simulation is implemented for deep and wide range investigation of physics processes from the event generator in a format which is identical to

the output of the ATLAS detector data acquisition system. Simulation chain combines as a single job – generated events and decays, detector model and physics interactions, digitized energy deposited into voltages and currents for comparison to the detector outputs [1]. Both the simulated data and detector outputs are running through the same trigger and reconstruction packages. However LHC Run-1 data analyses shows discrepancies of simulated and real data for some regions of detector. Fig 1 illustrates example of data vs MonteCarlo (MC) discrepancy prepared by ATLAS data preparation group [3]. Several reasons can cause above mentioned discrepancies. However with high probability they caused by inaccuracies of detector geometry descriptions using in simulation. Thus, primary objective of investigation of data/MC discrepancies foresee analyses of detector geometry descriptions in problematic regions. This analyse includes 2 studies:

1. Consistency study of simulation geometry

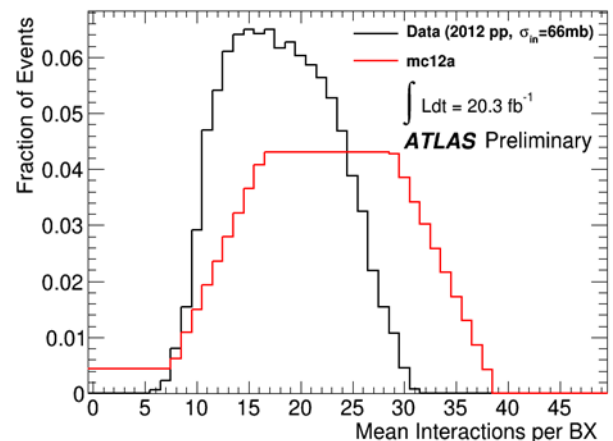


Figure 1 Data/MC discrepancy

descriptions with as-built geometry descriptions of detector

2. Study of inaccurateness of geometry transactions doing by simulation software infrastructure itself.

2. ATLAS DETECTOR GEOMETRY FOR SIMULATION

ATLAS detector is part of Large Hadron Collider - LHC at European Organization for Nuclear Research (CERN), Geneva, Switzerland. It is one of the most complex engineering facility worldwide. Detector geometry consists of simple parts like prisms, cylinders, tubes, etc. having no splines or art profiles but in same time characterized with enormous complexity [5]. Logical structure expressed by hierarchical tree with 50 units/subunits. They are corresponding to different components of detector like, toroid magnets, calorimeters, shielding, services, supports, platforms, etc. Total number of assemblies exceeds 3'700 (fig.2). Number of mechanical parts are > 10'000'000. Full "as-built" geometry of ATLAS detector occupies 61 Gb disk space.

For simulation and reconstruction simplified geometry descriptions are using because of software infrastructure performance requirements. So models have not any detalization like holes, pockets, fillets, cutouts or even small size parts. Instead all volumes are described by standard solid primitives like prisms, tubes, etc. divided mainly by materials. In same time full correspondence of simplified

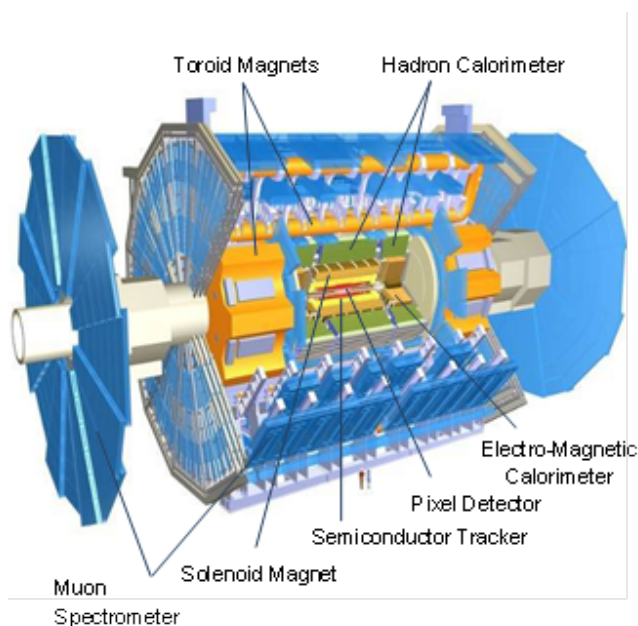


Figure 2 ATLAS Detector Structure

geometry with detailed geometry of detector in terms of volume, weight and position is extremely important. Special attention is paid for integration conflicts like overlaps and contacts. Any overlap of more than 1 picometer can lead to stuck tracks during the simulation while simulation software may not know in which part it belongs [1]. Also, some approximations are necessary for describing heterogeneous materials like electronic circuits, cables, cooling pipes and other services.

3. GEOMETRY SIMULATION LOOP

ATLAS simulation infrastructure use 3 platforms for description of detector geometry: GEANT, GeoMODEL and XML. Geometry descriptions on GEANT and GeoMODEL are generating at run-time during the simulation session, while XML descriptions stored in database. All platforms are using several methods for description of geometry:

- 1) Parametrized solid primitives – *Cube, Tube, Pyramid, Cylinder*, etc.
- 2) Combined primitives, like *Arbitrary_Polygons, Chain, Symmetric* and *Double_Symmetric_Polygons*, etc.
- 3) Boolean operations – *Subtraction, Union* and *Intersection*
- 4) Standard transactions – *Move, Rotate, Translation* and *Reflection*.

Therefore, ATLAS simulation infrastructure has several representations of same components of detector – *off-line* geometry which is XML and Oracle tables and *on-line* geometry which is GeoMODEL and GEANT. GeoMODEL is transient C++ description using as a common platform for various ATLAS software packages of simulation, digitization and reconstruction [2]. GEANT descriptions are using for Monte-Carlo simulation. As a result, simulation software doing several transformations – XML-to-GeoMODEL, Oracle-to-GeoMODEL and GeoMODEL-to-GEANT (fig.3). From the other hand each transformation cause inaccurateness because of each platform use own interpretation engine and results of geometry interpretation are different.

For the purpose of analysis of quality of geometry transformations doing by simulation software, interpretation results have to be collected and compared in order to find problematic cases of geometry description and study reasons which caused them. CATIA platform has been chosen as a hub for collection of interpretation results. Therefore several

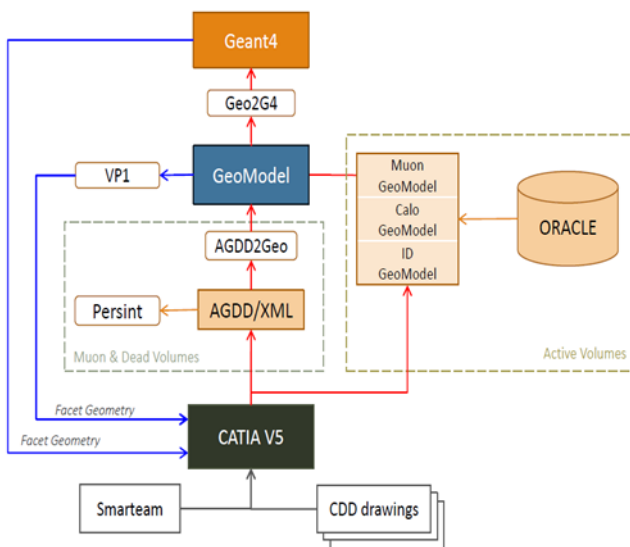


Figure 3 ATLAS Simulation loop with CATIA

chains have been developed.

GEANT-to-CATIA chain permits to dump geometry from memory into Geant-4 neutral file format *.gdml*. After it is transforming into facet *.vrml* and going to CATIA/DMU as an input. GeoModel-to-CATIA chain export GeoModel geometry into inventor neutral file format *.iv*. Then it is transforming into *.vrml* and goes as an input to CATIA/DMU. CATIA-to-XML and CATIA-to-GeoModel chains are using XML/GeoModel templates. For each particular volume templates are updating according to geometry data coming from the CATIA project tree.

Implementation of CATIA as a hub tool enables digital comparison of several geometries by powerful CATIA/DMU engine. In same time CATIA has internal links to the Enovia/Smarteam engineering databases where manufacturing drawings and as-built 3D models of detector are stored. Thus, CATIA hub can be used for another kind of analysis and investigation of adequateness of detector geometry descriptions using by simulation with as-built geometry descriptions. Paper represent results of both investigations of quality of simulation infrastructure and detector geometry descriptions using by simulation.

3. INVESTIGATION OF SIMULATION INFRASTRUCTURE

Objective is quality study of 2 geometry transformations – **T1:XML->GeoMODEL** and **T2:GeoMODEL->Geant-4**. Investigation and measurement of dimensional, form and position inaccuracies adding by T1/T2 have to be done by

analysing of test examples. Test examples should describe unique combinations of detector geometry and methods of their descriptions. Therefore formation of test examples for investigation requires typization of geometry of detector and identification of corresponding XML/GeoMODEL methods for their description.

3.1. Typization of Detector Geometry

Purpose of typization is finding groups of detector components similar by geometry and identification of typical group representatives. As it was mentioned above geometry of ATLAS detector has simple shapes and in majority of cases can be described by XML/GeoMODEL/GEANT standard primitives. There are also combined components which are constructed by joining of standard primitives and components with cuts. Therefore 3 criteria can be implemented for typization of detector geometry:

1. Correspondence of detector components to standard geometry primitives – shapes with vertex; shapes without cuts; both, regular and irregular shapes; both, convex and concave shapes
2. Grouping components with typical joining's
3. Grouping components with cuts.

After analyzing geometry of all components of ATLAS detector:

1. 22 typical primitives have been separated in 1st class of objects (fig.4).
2. 29 combined objects with typical joining's have been found for 2nd class (fig.5).
3. 33 objects with cuts were separated for 3rd class

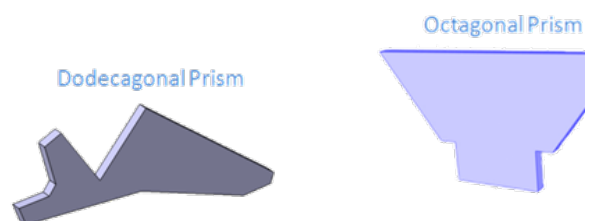


Figure 4 Examples of 1st class of objects

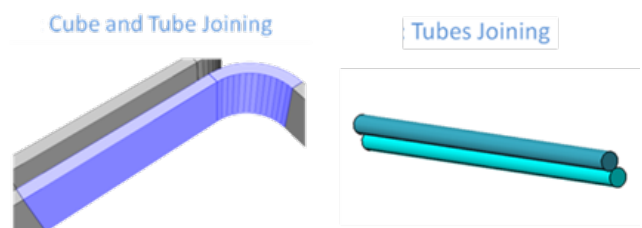


Figure 5 Examples of typical joining's in ATLAS detector



Figure 6 Examples of 3rd class of objects in ATLAS detector

(fig.6).

As a result ATLAS detector geometry can be described by 84 typical representatives of class of objects.

3.2. Selection of Methods for Description of Geometry

#04: Pentagonal Prism

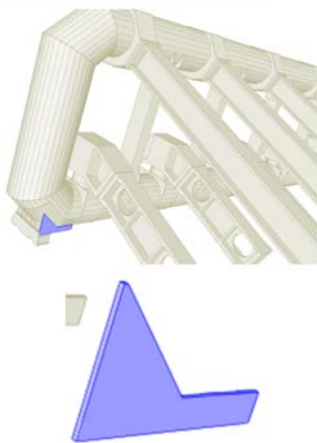


Figure 7 Pentagonal Prism primitive of ATLAS detector Coil class of objects

XML and GeoMODEL are using similar methods of description of geometry – solid primitives, polygons, Boolean operations and transformations. For each above selected typical representative of geometry several methods of description can be implemented. Fig.7 describes *Pentagonal Prism* which is one of the typical representative of ATLAS detector Coils geometry class of objects. There are several ways of description of *Pentagonal Prism*:

1. Using *Cube* method for creation of main solid -> Creation auxiliary solid for cut by *Arbitrary Polygon* method -> *Subtraction* of auxiliary solid from main solid -> *Move* created pentagonal prism into position -> *Rotation* of pentagonal prism in final position. This sequence of methods are presented on fig.8 with detailed description of

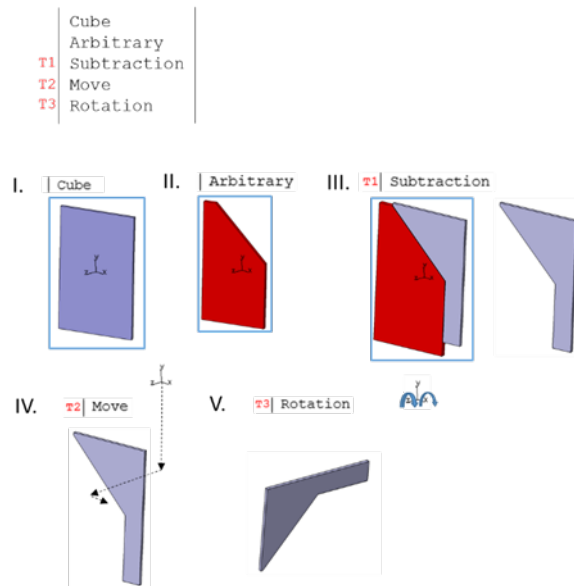


Figure 8 1st method of description of Pentagonal prism method outputs.

2) Using *Arbitrary polygon* method for creation of main solid -> *Move* Pentagonal prism in position -> *Rotation* of pentagonal prism in final position. Fig.9 describes sequence of methods and outputs.

In addition there are also several methods similar to 1st method using instead of *Cube* different methods – *Symmetric polygon*, *Trapezoid*, etc.

In same way for all above selected typical representatives of object classes of ATLAS detector, full set of possible methods was selected:

1st class of 22 objects – 4'460 methods

2nd class of 22 objects – 4'636 methods

3rd class of 33 objects – 6'579 methods

Total – 15'675 methods

However total array of methods contains some

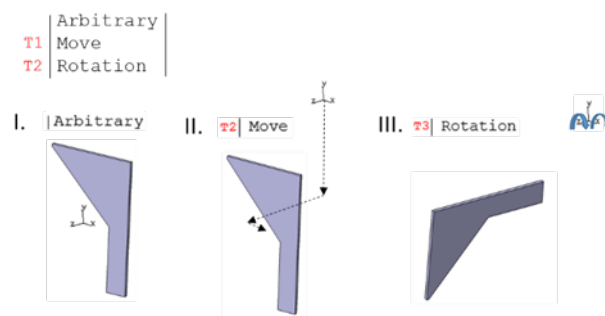


Figure 9 2nd method of description of Pentagonal prism

useless, just theoretically existing methods. Methods are different in the sense of performance and accuracy of received geometry. Thus, overall number of methods has to be separated.

First of all *Arbitrary polygon* method should be separated as a standalone method, while geometry description requires minimal number of *Boolean* operations and *Move/Rotation* transactions. Geometry can be described directly in position by only Z axis displacement and Z axis rotation.

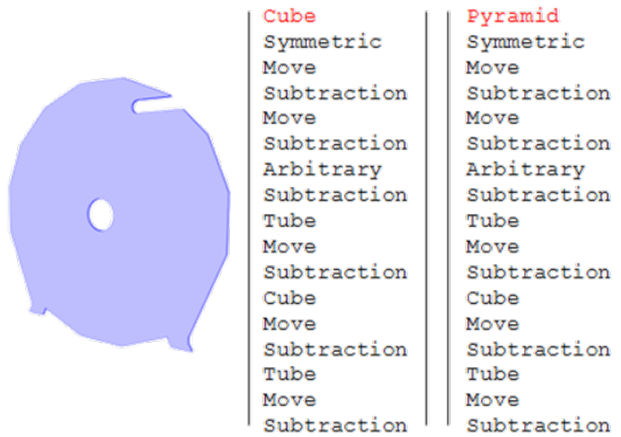


Figure 10 Description methods of Icositrahedral prism with cuts

Then many descriptions are using same methods. So there is no need to keep them for analyses. For instance fig.10 shows 2 descriptions of Icositrahedral prism with cuts. Descriptions have same structure, same sequence of transactions and differ by methods of main solid description. This is not important for analyses while inaccurateness supposed to be caused not by solid description methods but by solids transformations and Boolean operations.

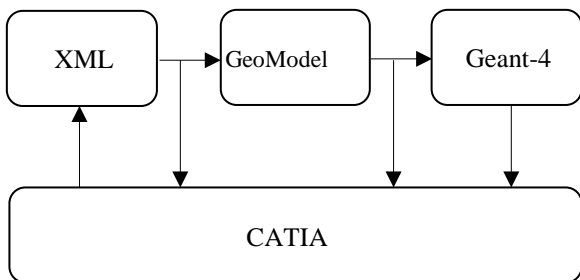


Figure 11 Simulation Loop for test runs

Total number of methods has been analyzed and just unique cases of descriptions were selected:

1st class of 22 objects – 11 methods

2nd class of 22 objects – 29 methods

3rd class of 33 objects – 38 methods.

Thus, 78 unique examples have been formed for the investigation of quality of geometry transformations doing by simulation software.

3.3. Results of Test Runs

Test examples were run in simulation loop and compare analyses of **T1/T2** transformations results were done in CATIA (Fig.11). XML geometry were compared with GeoMODEL and GEANT-4 outputs in CATIA/DMU.

For **T1:XML->GeoMODEL** transformation 44 cases, and for **T2:GeoMODEL->GEANT-4** transformation 9 cases with inaccuracies were detected

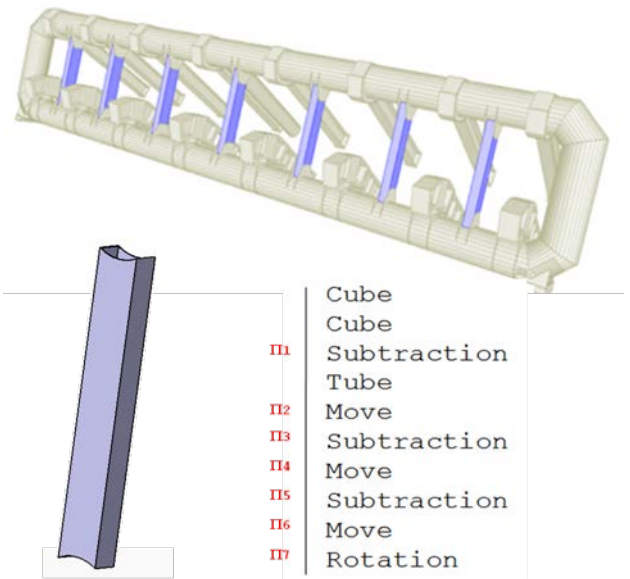


Figure 12 Test Example “Tube with cuts”

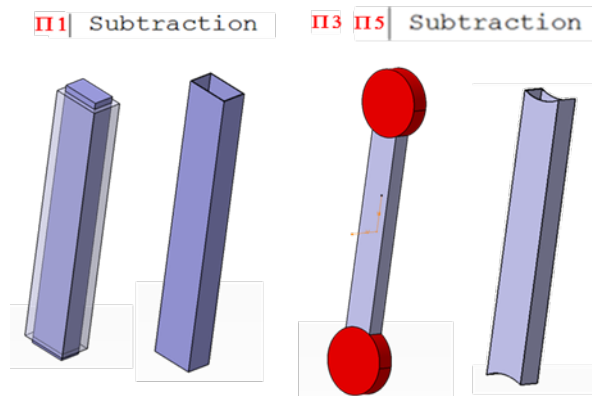


Figure 13 Boolean Subtractions of main solid

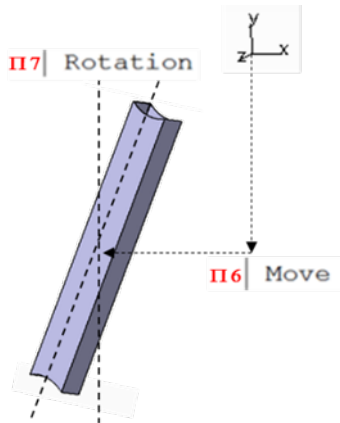


Figure 14 Move/Rotate transactions of Tube

Further investigations have done in order to understand reasons which caused inaccurateness.

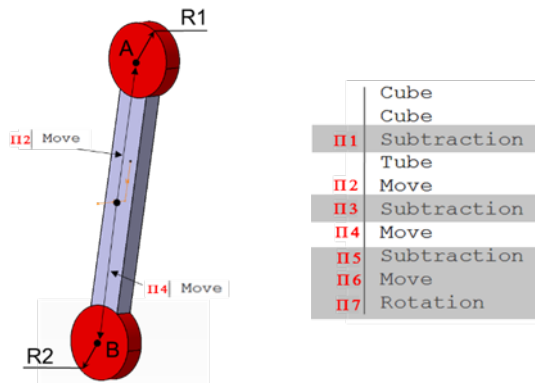


Figure 14 Sub-Case#01 with investigation of Π2/Π4 Move

Geometry transactions move/rotation and Boolean operations were considered separately and together to discover any kind of correlations between them. Fig.12 describes analyses of one of example *Tube with cuts*, where inaccuracies of **T1/T2** were detected.

Geometry represents tube which has round cuts at the

	Cube
Π1	Subtraction
Π2	Move
Π3	Subtraction
Π4	Move
Π5	Subtraction
Π6	Move
Π7	Rotation

		GeoM Δ_1	G-4 Δ_2	Total Δ
A	x	0.03	0	0.03
	y	0.02	0.2	0.22
	z	0	0	0
B	x	0.03	0	0.03
	y	-0.02	0.1	0.08
	z	0	0	0
	R1	0	-0.19	-0.19
	R2	0	0.1	0.1
Volume		-0.0005	0.0004	-0.0001

Figure 15 Sub-Case#2 with investigation of Π2/Π4 Move with Π1/Π3/Π5 Subtractions

	Cube
	Cube
Π1	Subtraction
	Tube
Π2	Move
Π3	Subtraction
Π4	Move
Π5	Subtraction
Π6	Move
Π7	Rotation

		GeoM Δ_1	G-4 Δ_2	Total Δ
A	x	0.05	0.09	0.14
	y	0.01	0.23	0.24
	z	0	0	0
B	x	0.01	0.01	0.02
	y	-0.03	0.02	-0.01
	z	0	0	0
	R1	0	-0.24	-0.24
	R2	0	0.02	0.02
Volume				-0.0001

Figure 16 Sub-Case#3 with investigation of Π7 Rotation ends. Main solid described by *Cube* solid primitive. There are 3 auxiliary solids as well *Cube-Tube-Tube* using to make cutouts on main solid in order to construct final solid. For that purpose 3 Boolean *Subtractions* Π1, Π2 and Π3 are implemented (Fig.13). Π6 *Move* and Π7 *Rotation* transactions put geometry into final position (Fig.14).

Results of transactions learned separately in order to understand reasons which cause inaccuracies. Thus, several sub-cases of compare analyse were separated. Sub-Case#01: Π2/Π4 movement of A and B center points of auxiliary tubes along Y axis from origin (Fig.14). Compare analyses shows no inaccuracies for **T1** transformation and $+0.1\text{mm}$ displacement of center for **T2** transformation.

Sub-Case#02: Π2/Π4 movement together with Boolean subtractions Π1/Π3 cause inaccuracies for **T1** in the range of $+0.03\text{mm}$ and inaccuracies for **T2** in the range of $0.3\text{mm}-0.22\text{mm}$. For **T2** radius value also fluctuated in the range -0.19mm to $+0.1\text{mm}$ which cause form deformation of final tube (Fig.15).

Sub-Case#03: Π7 rotation together with Π2/Π4 movement and Π1/Π3 subtraction adding displacements of center points $\Delta_x=0.08\text{mm}$; $\Delta_y=0.03\text{mm}$ for **T1** and $\Delta_x=0.09\text{mm}$; $\Delta_y=-0.08\text{mm}$ for **T2** transformation. For **T2** transformation radius inaccuracy is 0.05mm (Fig. 16). Displacements of

	Cube
	Cube
Π1	Subtraction
	Tube
Π2	Move
Π3	Subtraction
Π4	Move
Π5	Subtraction
Π6	Move
Π7	Rotation

		GeoM Δ_1	G-4 Δ_2	Total Δ
A	x	0.03	0.01	0.04
	y	0.02	0.2	0.22
	z	0	0	0
B	x	0.03	0	0.03
	y	-0.03	0.1	0.07
	z	0	0	0
	R1	0.01	-0.2	-0.19
	R2	-0.01	0.1	0.09
Volume				-0.0001

Figure 17 Sub-Case#4 with investigation of Π6 Move

A/B center points along *Y* axis are different $Y_A=0.23\text{mm}$; $Y_B=0.02\text{mm}$ which cause final tube asymmetry added by rotation.

Sub-Case#04: Π_6 movement together with Π_2/Π_4 and Π_1/Π_3 cause displacements of A/B center points along X and Y axis for **T1** and **T2** transformations.

Value of radius is also differ (Fig.17). Interesting to note that same *Move* transactions in axis origin without *Subtraction* (sub-case#01) cause no asymmetry. It shows correlation between Boolean operation and *Move* transaction.

Same compare analyses have been done for each of 53 fault cases founded after running of all above described test examples of ATLAS detector geometry descriptions.

For all type of detector geometries dimensional, form and positioning faults are caused by Boolean operations. For complex geometries with number of cutouts, total value of inaccuracies can cause inadequate interpretation of simulation data in Geant. So, for those cases alternative methods of geometry descriptions rather than Boolean operations should be implemented.

Further geometry analyses concerns to compare study of geometry using by simulation with “as-built” geometry of ATLAS detector. Below are results of End-Cap Toroid and Coil studies – regions where data/MC discrepancies are substantial. CATIA simulation loop was implementing to collect and compare 3D models from Smarteam engineering database and XML.

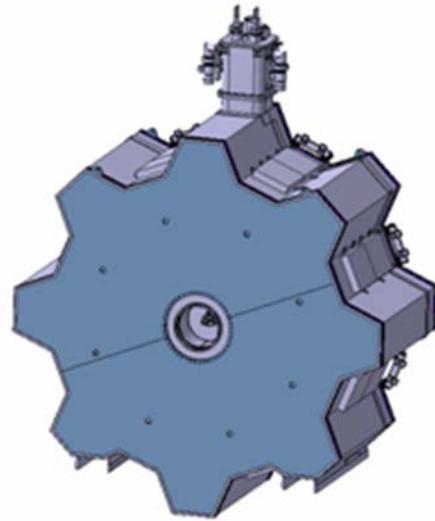


Figure 18 ATLAS End-Cap Toroid magnet

4. ATLAS END-CAP TOROID STUDY

End-Cap Toroid (ECT) is one of the biggest and heaviest (250 tonnes) part of ATLAS detector (Fig.18). According to ATLAS data preparation team estimations of simulation performance expected to become better after improvement of ECT geometry description [10]. Thus ECT geometry has been investigated. On the *1st stage* engineering descriptions on Smarteam have been analysed. Several 3D models compared and most detailed one was chosen. After comparison with several assembly drawings and photos it was concluded necessity in 3D model reproduction in CATIA, because of lot of missing parts. Manufacturing drawings for reproduction were downloaded from CDD (CERN

	CATIA	XML	Difference	Weight Coefficient
1 Cold Mass	116740 kgs	123012 kgs	5.4 %	52.7%
2 Thermal Shielding	15988 kgs	15957 kgs	0.2 %	7.2%
3 Cover	57966 kgs	57185 kgs	1.3 %	26.2%
4 Bore Tube	13433 kgs	10208 kgs	24.0 %	6.1%
5 Yoke	1820 kgs	1338 kgs	26.5 %	0.82%
6 Stay Tube	2028 kgs	2214 kgs	9.2 %	0.92%
7 JTV Shielding	4161 kgs	4510 kgs	8.4 %	1.88%
8 Turret	2476 kgs	1512 kgs	38.9 %	1.3%
9 Tie Rod	3077 kgs	1268 kgs	58.8 %	1.4%
10 Bolts/	2965 kgs		100.0 %	1.4%
11 Services	869 kgs		100.0 %	0.4%

Figure 19 Weight differences between CATIA and XML descriptions

Drawing Database). As a result detailed ECT geometry was reproduced in CATIA from 902 manufacturing drawings. On the 2nd stage full ECT description was split into 11th volumes by mechanical structure and materials and for each volume weights were calculated. On the 3rd stage 11th identical volumes have been extracted from XML geometry and calculated their weights. Compare analyses of CATIA vs XML (fig.19) shows >20% difference in volume and weight for majority of components. 2 volumes among of 11th volume are missing in XML.

Most big discrepancies were detected for BoreTube assembly – 3 tonnes; TieRod assembly – 2 tones and Turret assembly – 960 kg. Results of compare analyses were presented on ATLAS Muon and Simulation discussions. It was decided to update existing XML geometry of ECT. Therefore, on the next stage detailed CATIA geometry was simplified by keeping volume and weight of each component. Maximum scattering of volume and weight after simplification was 0.01m³ and 27kg accordingly. On the final stage baseline geometry was updated by

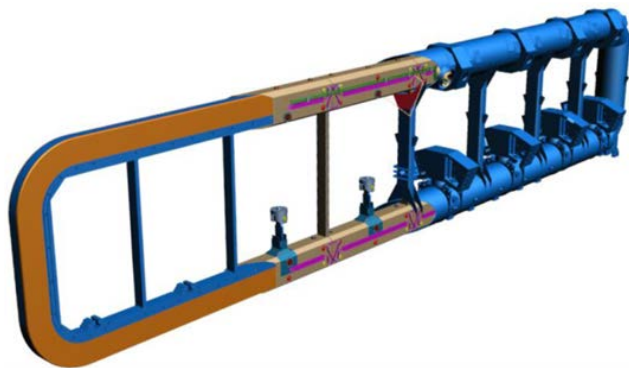


Figure 20 ATLAS coil assembly

generation of new XML descriptions from the simplified geometry.

4. ATLAS COIL STUDY

ATLAS detector have 8 identical coils. Coil is complex engineering facility which consists of lots of various parts inside and outside (Fig.20). Initial analyses of Smarteam model on completeness shows necessity for model reproduction in CATIA. 255

		Material	Density kg/m ³	Volume m ³	Weight tones	Difference tones
XML	Outside Assembly	Steel	7'870	3.887	30.6	5.1
CATIA		Steel	8'000	4.458	35.7	
XML	Voussoir Structures	Aluminum Steel	2'700/7'870	4.56	13.2	-0.9
CATIA		Aluminum Steel	2'650/8'000	4.416	12.3	
XML	Tie Road	Aluminum	2'700	0.42	1.1	1.8
CATIA		Steel/Titan Aluminum	8'000/4'480/ 2'705	0.5193	2.9	
XML	Thermal Shielding	Aluminum	2'700	13.138	35.5	5.6
CATIA			Aluminum	2'740	0.7517	
	Coil Casing	Aluminum	2'650	12.033	31.9	
	Coil Covers	Aluminum	2'660/2'650	1.898	5	
	Services	Aluminum Steel	8'000/8'000/ 2'650	0.59	1.9	
					Difference:	11.6

Figure 21 Weight differences between CATIA and XML of Coils

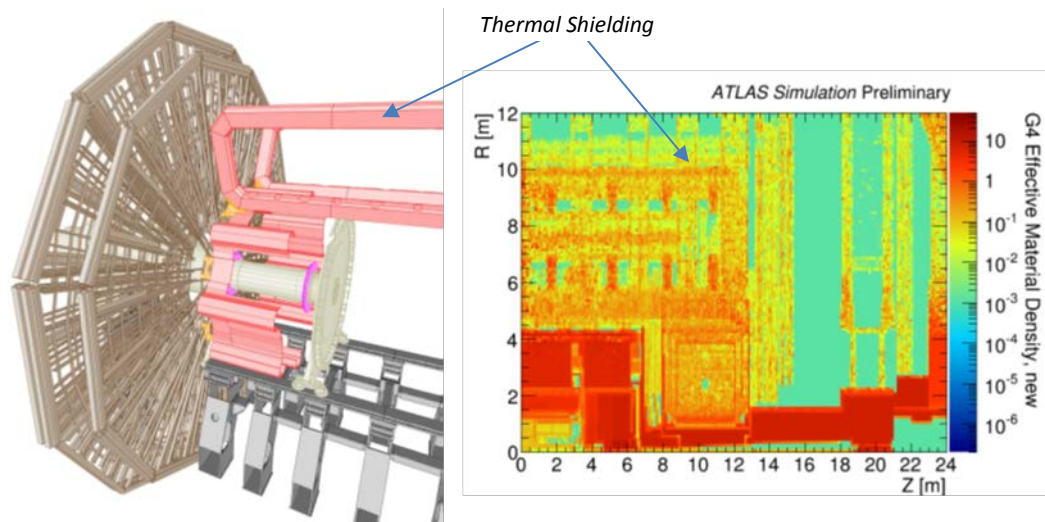


Figure 22 Simulation results with updated geometry of coils

CDD drawings have been considered and added as a 3D parts to Smarteam model of coil. After, coil assembly was split into 7 volumes according to mechanical structure and materials [7]. Then weight for each of volume were calculated. On the next stage identical 7 volumes were extracting from XML geometry and also weights were calculated. Compare analyses shows big differences in volume and weight between CATIA and XML descriptions (fig.21). Also it was found missing assemblies in XML, like thermal shielding which is situated inside coil and has major influence on simulation data. Compare analysis results were presented on ATLAS software & Computing week and on Muon week at CERN, Geneva, Switzerland. It was concluded necessity for XML geometry update. Later, XML baseline geometry was updated by ATLAS simulation team. Fig.22 illustrates different simulation results by adding thermal shielding to XML descriptions.

5. CONCLUSIONS

1. Improvement of geometry modelling software infrastructure is actual task for ATLAS simulation
2. Creation geometry hub on the base of CATIA brings unique possibilities for several geometry crosschecking and investigation of simulation tools
3. For all type of detector geometries dimensional, form and positioning faults are caused by Boolean operations
4. Boolean operation correlated with Move/Rotation transactions in GEANT. Once Boolean operation is implemented

transactions generating inaccuracies of geometry displacements

5. For complex geometries with number of cutouts, total value of inaccuracies can cause inadequate interpretation of simulation data in Geant
6. ATLAS End-CAP Toroid geometry study shows 5% - 58% deviation of weight between XML and as-built geometry volumes
7. ATLAS Coils geometry study shows 11.6 tones missed materials in XML baseline geometry.

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