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REVERSE ENGINEERING, A KEY AND CHALLENGING STEP BEFORE THE INTEGRATION STUDIES FOR OLD ACCELERATORS AT CERN

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Abstract

The accelerators constituting the LHC injectors chain have been gradually built and commissioned since the CERN foundation in the fifties. The operation of the Proton Synchrotron, the Proton Synchrotron Booster and the Super Proton Synchrotron started in 1959, 1972 and 1976 respectively. During the Long Shutdown 2 (LS2) of the CERN accelerator complex in 2019 and 2020, a large upgrade of these machines has been performed in the context of the LHC Injector Upgrade (LIU) Project and consolidation programme. This paper presents the process of reverse engineering performed by the Integration Office within 3D CAD environment during the preparation phase of the LS2 to allow the spatial integration studies of the upgrades and ensure the reliability of the installations. It describes the methodologies and technologies used from 2D drawings to 3D models and data consistency check processes in accordance with reality. Process remains ongoing to treat the enormous quantity of data.

INTRODUCTION

The tools and methods used by the design and integration offices for the accelerators chain at CERN evolved from 2D and 3D hand made designs in the fifties (Fig. 1) to 2D and 3D computer-aided design (CAD) starting in the eighties with EUCLID software (2D and 3D), Autodesk AutoCAD (2D) in the nineties and CATIA V5® (2D and 3D) since 2003. The LHC injectors, namely the Proton Synchrotron (PS), the Proton Synchrotron Booster (PSB) and the Super Proton Synchrotron (SPS), started operation in 1959, 1972 and 1976 respectively. Ten years ago, it was required to design these accelerators in 3D CAD environment to allow the spatial integration studies for the LHC Injector Upgrade project [1] and SPS Fire Safety Project [2] completed during the past LS2 (2019-2020). A large campaign of reverse engineering covering more than 12 km of beam lines and 20 technical buildings was launched in 2010 to build/design the 3D environment of the PSB, PS and SPS in 3D CAD i.e. CATIA V5®. to make the necessary spatial integration possible.

REVERSE ENGINEERING

Reverse engineering required the centralization of the existing documentation describing the accelerator facilities and the in-situ configuration scanning during the Long Shutdown 1 (LS1) [3] held from 2013 to 2014 and Year-End Technical Stops (YETS) held before LS2.

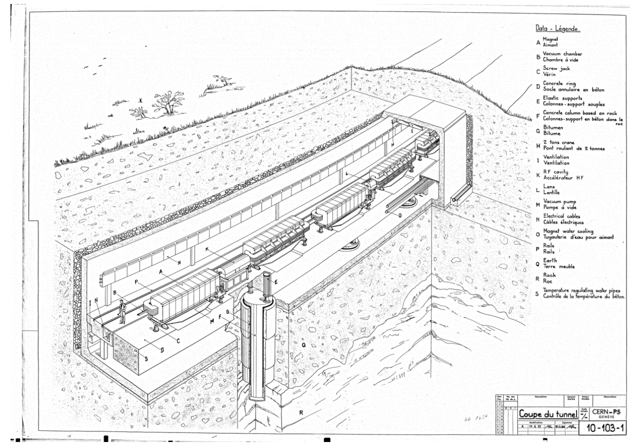

Figure 1: 3D hand made sectional view of PS tunnel - 1951

Documentation

Thousands hand made design documentation was dematerialized and referenced in the CERN Drawing Directory (CDD) to keep the link in the Product Data Management (PDM) system. Several types of documents have been treated:

- Drawings in paper format.
- Drawings in carbon copy.
- Drawings in slide film.

3D Scanning

To validate the compatibility of the documentation with reality on the field, in-situ scans campaigns were performed using laser scanning methods [4,5]. The scans are crucial for the integration office to position accurately the equipment with respect to the CERN Coordinate System (CCS) [6] and local CAD coordinates. Two types of procedures are applied:

- Geo-referenced laser scanning with high precision performed by the surveyor team for the civil engineering infrastructure and accelerator beam lines,
- Non geo-referenced laser scanning with medium precision performed by the design and integration offices for the general services.

The results of the scans are inserted in the CAD software as cloud of points or mesh model (see Fig. 2).

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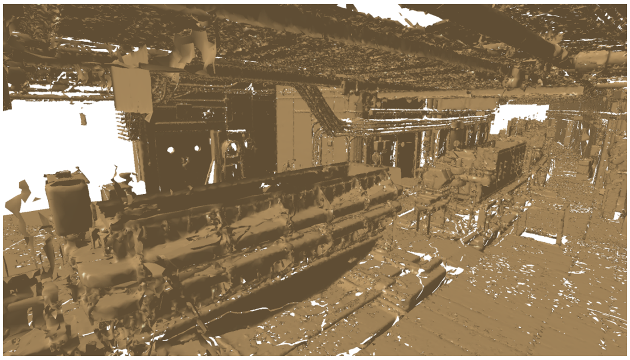

Figure 2: 3D mesh of PS ring

3D Models Design

The designers reproduced in 3D CAD the equipment as simplified volume (i.e. envelop). This was the start of the reverse engineering process performed by the various design offices, using dedicated CAD software:

Infrastructure Many design offices are involved, using different CAD software, as listed in Table 1 and providing 3D models to the integration office.

Table 1: CAD software

Desifn Office	CATIA V5®	REVIT®
Civil engineering	x	x
Metallic infrastructure	x	x
Heavy handling and transport	x	
Cooling/ventilation systems	x	x
Cryogenics systems	x	
Electrical systems	x	

Accelerators and Transfer Lines Many design offices are involved, using CATIA V5®:

- The mechanical design offices carries out the detailed design of beam lines equipment such as magnets, RF cavities, beam instrumentation, vacuum systems, etc.
- The integration design office carries out the 3D integration for teams no dedicated design offices like safety, access control, etc. and is managing reserved volumes for instance for survey measurement, transport or future installations.

3D Models Catalog

The generation of a standardized catalogue of 3D models for objects, items and articles installed on a regular/recurrent? basis in the different facilities was also considered as an advantage of laser scanning. Elements that otherwise would go unnoticed (i.e. electrical panels, racks or boxes, different types of switches or signs, lightning elements, communication objects, etc.) were 3D designed according to the scans and inserted in a standardized catalogue that is used by all design offices, avoiding creating unnecessary duplicates among the different studies.

3D Models Assembly

Once the 3D models are made available by the design offices, the integration office assembled them in 3D assembly models using CATIA v5 (see Fig. 3). The infrastructure and service models are positioned into the CCS and dedicated local coordinates while the beam line equipment is positioned according to functional references. The functional positions correspond to optical data calculated by the beam dynamic physicists and used as nominal references for the surveyors when aligning the beam line equipment. The functional positions are inserted into the 3D CAD by extracting the coordinates data (X,Y,Z) from the survey database. During the reverse engineering of the LHC injectors, the integration office strongly relied on the 360° panorama pictures provided by the configuration management team [7, 8] to virtually navigate into the accelerators while operation was ongoing (see Fig. 4).

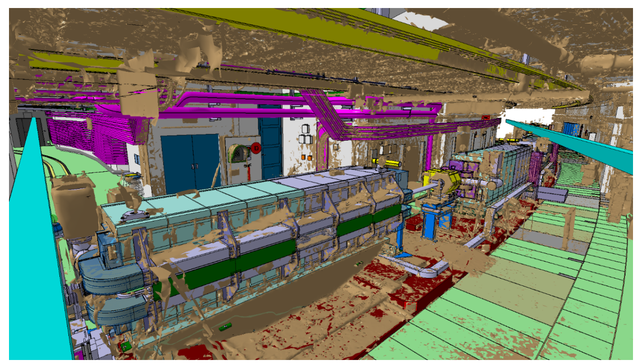

Figure 3: 3D CAD of PS ring and mesh

DATA CONSISTENCY

The integration studies for the LIU and Fire Safety Projects started when the reverse engineering phase was fully completed, checked and confirmed. The reliability of the integration models is based on the consistency of data from design documentation and nominal positions to as-built configuration.

Infrastructure

The 3D models accuracy for infrastructure and services is in the order of one centimeter. Visits on site were regularly organised during the LS1 and programmed stops to check or acquire dimensional data using simple measuring tape or laser. If necessary, additional scans were performed in localized area.

Accelerators and Transfer Lines

The 3D models accuracy for beam line is in the order of one millimeter. Visits on site were important to visualize details not visible on scans or pictures. In case of inconsistency,

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survey team performed measurements with an accuracy of 0.1 mm.

Figure 4: 360° panorama picture in PS ring 2017

Feedback from LS2

Installations during the LS2 have been performed with success [9]. In returns, several recurring issues were identified during the installation and alignment of beam line equipment. The issues had several causes; inconsistencies between as-built equipment and drawing design and inconsistencies between nominal data in databases. The data consistency is crucial considering the following source of information:

- Nominal positions of beam line equipment calculated by the physicists and inserted in the layout database [10]
- Results of surveyors alignment and measurements inserted in the survey database
- Mechanical design
- Fabrication and assembly design

A dedicated project has been put in place at CERN to improve and consolidate the process of Engineering to Alignment (E2A) during the lifetime of accelerators.

CONCLUSION

The accelerators at CERN and technical buildings have been gradually designed in a 3D CAD environment to allow reliable preparation of the machine upgrade and consolidation to be occurred during technical stops. The reverse engineering process is a key and challenging step before integration studies. The availability of virtual 3D facilities will trigger new uses for continuous improvement in the preparation and follow-up of works in the accelerators and possible virtual training for many teams like fire brigade, designers, ...

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