EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics
CERN – TS DEPARTMENT

EDMS Nr.: 880505 **CERN-TS-2007-004 (IC)**

Transport and installation of the LHC cryo-magnets

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Eleven years have passed between the beginning of transport and handling studies in 1996 and the completion of the LHC cryo-magnets installation in 2007. More than 1700 heavy, long and fragile cryo-magnets had to be transported and installed in the 27 km long LHC tunnel with very restricted available space. The size and complexity of the project involved challenges in the field of equipment design and manufacturing, maintenance, training and follow-up of operators and logistics. The paper presents the milestones, problems to be overcome and lessons learned during this project.

Presented at the Particle Accelerator Conference 07, Albuquerque (NM) USA
June 25-29, 2007

Geneva, Switzerland
June 2007

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INTRODUCTION

On the 26th of April 2007, the last of 1746 cryo-magnets was lowered in the LHC tunnel thereby closing the last gap in the 27 km long accelerator. Only two years had passed since the installation of the first cryo-magnet on the 7th March 2005 but several milestones had needed to be reached since the beginning of the transport and handling studies in 1996 in order to accomplish this exceptional installation. Severe space restrictions resulted from the decision to build the LHC machine in the tunnel that was designed for the smaller and lighter LEP magnets. The conceptual design, constraints and requirements for the equipment that resulted from the studies were combined into two functional specifications. They formed the basis for two calls for tender sent to suitable firms throughout the CERN member states at the end of 2000 for the transport vehicles and at the end of 2002 for the installation equipment or "transfer tables". After extensive testing at the factory, the first tunnel vehicles were delivered at the beginning of 2003, the first transfer tables at the beginning of 2004. A test campaign was started to validate the equipment and the procedures in the LHC tunnel infrastructure. A safety audit was carried out by an external, accredited company. The first operators were trained just before the installation of the first LHC cryo-magnet. The time available for the magnet installation was meanwhile reduced because of the late delivery of the cryogenic line located behind the beam lines. Moreover, the start up of the LHC cryo-magnet installation was cumbersome because of the complexity of the task at hand. The LHC magnet installation logistics chain ranged from surface handling and transport between magnet preparation sites and magnet storage with mobile cranes, road transport and overhead cranes to underground logistics with custom-made equipment. A taskforce was organised in order to coordinate the efforts of the magnet preparation, surface and underground logistics, maintenance, operator follow up and the general planning. With the joint efforts of the different fields of activities, the weekly installation rate quickly increased to up to 3 times the initially foreseen rate in order to compensate for the delays due to the other equipment on the overall LHC schedule.

CUSTOM-BUILT EQUIPMENT

The 1232 main dipoles, 424 Short Straight Section (SSS) and 90 Long Straight Section (LSS) magnets were lowered through the access shaft and then transported with the tunnel vehicles up to 17 km to the installation point. The dimensions of the tunnel vehicles produced by the consortium BNN/MAFI (Germany) needed to be highly optimised in order to transport cryo-magnets up to 16.5 m long and weighing up to 34 t through a transport volume that is very limited in both vertical and lateral directions. The hydraulic braking system and suspension were, together with the rubber tyres, required to respect the low acceleration limits for the fragile magnets. Finally, an optical guidance system and anti collision detectors were used to guide the vehicles driving up to 4 km/h next to already installed magnets and other equipment with often not more than 10 cm clearance. More than 21'000 km was driven this way without a single collision with the installed magnets.

Figure 1: Transfer of a main dipole magnet on the support jacks

At the installation point, the magnet is lifted off the vehicle by an unloading equipment. The vehicle is removed to make space for the installation equipment under the magnet. A Transfer Equipment Set TES (ZTS VVU Kosice, Slovakia) consists of two modular transfer tables that handle the magnets with six degrees of freedom and high precision (0.1 mm). This precision is needed to transfer the magnet automatically via a predefined horizontal trajectory from the unloading equipment to the magnet support jacks while passing the overlapping interconnects of the adjacent, installed magnets. The compactness of the tables was obtained with stepper motors and harmonic drives. More information about the constraints and the equipment used can be found in references [1], [2].

PROCEDURES, TRAINING AND SAFETY

About 47’000 t of magnets were installed in the underground conditions of the LHC tunnel with highly technical equipment by about 50 operators, working day and night during two years and this without accidents and with only a few minor incidents. Extensive testing was carried out at the contractor’s premises and in a mock-up in the real infrastructure in the LHC tunnel with real full weight magnets. Each step was analysed and sometimes rearranging the steps allowed to save time or to have a safer procedure. Towards the end of the testing, a safety audit of the equipment and the procedures was made by an external, specialised and accredited company. Their recommendations and the experience gained during the testing were used to validate the equipment and the procedures. The training for the operators was made with special attention for safety aspects. The services of a company specialised in the training of operators of lifting equipment were acquired to train the operators.

COMPLEX LOGISTICS

After delivery of the magnet cold mass, the magnets went through assembly, testing and tunnel preparation steps. In between the steps, the magnets were stored in intermediate surface storage places. Every week, 100 to 150 cryo-magnets were transported and handled by a team of up to 15 people with up to 4 road trucks, 3 mobile cranes and 7 electrical overhead travelling (EOT) cranes. During the summer of 2005, more than 700 cryo-dipoles and 100 SSS were stored outside because of an initial delay in availability of installation slots in the tunnel [3]. After the final preparation, most magnets were lowered through the only access shaft large enough for cryo-dipoles and were then driven by one of the six tunnel vehicles to their attributed position in the 27 km long circular tunnel where they were installed with one of the five TES. Some shorter SSS and LSS were also lowered through two other access shafts at points 2 and 6 of the eight access points that divide the tunnel in eight arcs. During each transport, the cryo-magnets were equipped with an acceleration monitoring device.

Restrictions in the logistics

One of the main complications in the magnet logistics was the fact that each cryo-magnet was allocated and prepared for a specific installation slot, based on the measured magnet performance. This means that the logistics chain was not based on “first in, first out” and that each magnet in storage had to be accessible at all times. Furthermore, the slots to which each magnet was allocated were not necessarily available for installation at the time of the allocation.

The single slot allocation of each magnet resulted in time consuming displacements of mobile cranes on the surface and transfer table sets in the tunnel that needed to be optimised.

The assembly, test and preparation factories had to run at full capacity in order to respect the schedule, i.e. no idle or empty production slots were allowed. A magnet could only be delivered if prior to that another magnet had been removed.

In the tunnel, vehicles and other equipment like the transfer tables can not pass each other. This imposed an order in the lowering of the magnets but it also had implications on the schedule. An unloaded vehicle could not pass the vehicles that arrived later at their installation slots and it waited idle until the last vehicle had finished its installation and returned. As an example, a cryo-dipole transport and installation cycle in sector 6-7 for 3 cryo-dipoles took 24 h.

Other installation activities in the tunnel like the work on the magnet interconnects with large welding machines or quality control with x-rays would also not allow the passage of the vehicles or other equipment.

Because of the length of the transport and installation cycles and the number of time and position restrictions, the installations were carried out 24 hours per day, 7 days a week by about 50 operators. An additional complexity in the logistics was to fit their shifts with the timing of the transport cycles that was changing with the place of installation.

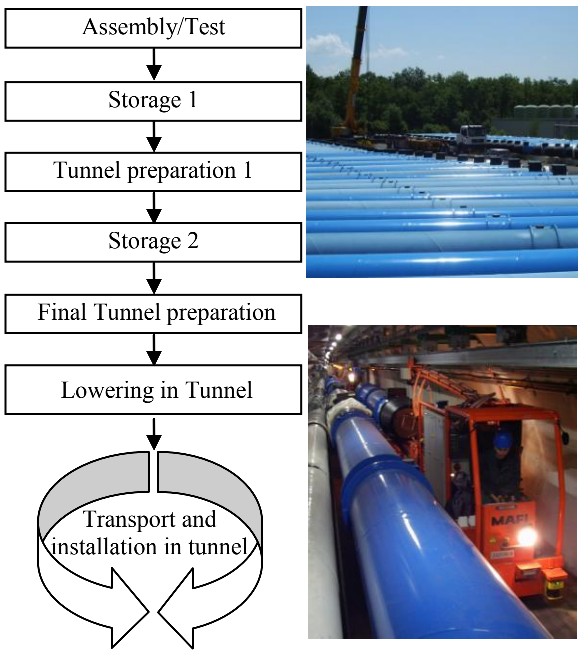

Figure 2: The logistics chain of a LHC cryo-magnet

Perturbations in the logistics chain

A detailed schedule was carried out every week and the magnets to be installed were selected taking into account the restrictions mentioned above. Nevertheless this planning could change during the week as several perturbing factors were acting on the logistics.

The highly technical and high duty, custom-made equipment that was only built in a very small series, needed a high level of maintenance support during the operation to solve break-downs. A maintenance team was available 24 hours per day, 7 days per week. Preventive maintenance was also carried out on a regular basis in a way that limited the temporary unavailability of the equipment to the minimum. Spare parts were acquired based on a failure modes and effects analysis to reduce machine down-time [4].

Magnets could be unavailable or would arrive too late because of non conformities or problems during magnet preparation. Magnets arriving too early for installation would block a production slot. Also the installation slot or a certain passage in the tunnel could be unavailable.

Flexibility

Such perturbations propagated through the logistics chain and could create more than one magnet delay. A magnet that was not installed would stay on a vehicle; the next magnet would hence stay in a magnet preparation slot reducing the capacity of the factory. The sensitivity of the logistics chain to such perturbations was decreased by introducing short time buffer storage places between one to five magnets in between certain steps.

The influence of perturbations was also smaller and the planning could be more optimised when more installation possibilities were available. More allocated magnets made it easier to optimise mobile crane and transfer table displacements. More available installation slots reduced the sensitivity to delayed magnets or non allocated magnets and allowed spreading the installation fronts, even over different sectors. The idle waiting time of an unloaded vehicle after an installation described above disappears when the distance between two installation fronts is high enough.

The activities at other working places in the tunnel would stop during the night or during the weekend. At such times the installations would be concentrated on sectors that were otherwise not accessible for the tunnel vehicles.

Information flow

An important issue of having different shifts working underground day and night is the flow of information. People arriving in the morning or evening needed to know the current situation. Reports were sent by email after each shift with the list of magnets installed, the position of the vehicles and transfer tables and problems that occurred. The maintenance staff would send similar reports about their interventions. The operators would fill in a “flight book”. This included times and positions of different operations which was useful for planning but it also included check lists that encouraged the operators to inspect their equipment. Finally, the operators could mention things that needed improvement.

Installation rate

After a difficult start of the LHC cryo-magnet installation, the coordination between the different participants was improved by the end of 2005. The installation rate then stabilised at 20 magnets with the introduction of the night shifts and rose to 25 magnets per week with the shifts during the weekend. The logistics chain reached its optimum during the second half of 2006 with a maximum of 35 magnets per week. The rate decreased only during March 2007 when the activity was run down gradually. During the optimum period, magnets were installed simultaneously in six different sectors.

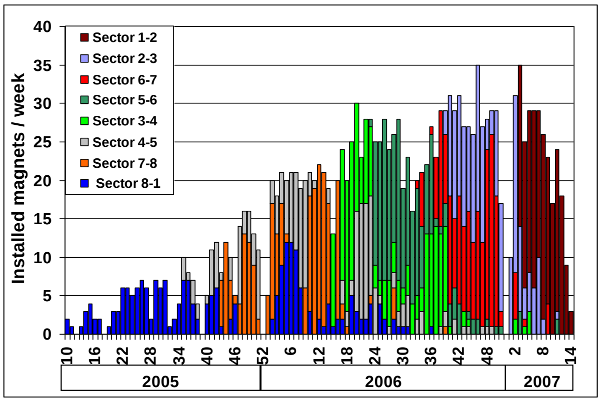

Figure 3: The LHC cryo-magnet installation rate

CONCLUSION

The LHC cryo-magnets were installed on schedule in the LHC tunnel despite the technical difficulties, reduced time available and the numerous restrictions for the logistics. A taskforce coordinated the efforts of all participants to reach an installation rate 3 times higher than the initial baseline rate of 10 magnets per week.

ACKNOWLEDGEMENTS

The authors wish to acknowledge all the people that are not in the author list that made a huge effort throughout the LHC installation to make it all happen.

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