MEASUREMENT AND ALIGNMENT OF THE TIDVG5 SPS BEAM DUMP

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Abstract

During the Long Shutdown 2 (LS2 2018-2021) the CERN injector complex was upgraded to meet the future High Luminosity-Large Hadron Collider (HL-LHC) requirements.

One major activity was the construction and installation of a new beam dump, in the Super Proton Synchrotron (SPS), able to cope with the increasing brightness of the high luminosity beams. The challenge for survey engineers was to align the beam dump and especially the core of the component within the tolerance required by the physicists.

The measuring system had to ensure a transverse alignment tolerance of ±0.7 mm (3σ) with respect to the beam axis defined by the surrounding quadrupoles, while facing many external constraints. A 2 m thick wall, composed of steel, concrete and marble, shields the new beam dump. The estimated dose for a year of operation is 1 MGy at 35 cm from the core. In addition, a bakeout of the dump up to 150°C is required to ensure the needed vacuum quality. The system had to be reliable and failsafe as there is no manual access possible during the 20 years of service. These heavy constraints led to a complete study of the spatial measurement system for the equipment.

The paper describes in detail the design of the measurement and alignment system from the initial idea to the prototypes and the production. It also provides an overview of the tests and the first measurement results achieved.

INTRODUCTION

Beam dumps are critical equipment for running an accelerator as all accelerated particles must be stopped at some point especially during beam setup.

The SPS beam dump is called TIDVG (Target Internal Dump Vertical Graphite). The dump is internal to the machine and during normal operation, the beam goes straight through. In the event of a Dump, five kicker magnets located upstream of the TIDVG will deviate the beam to the absorbing materials of the beam dump.

Following the increase of energy of the new beam for HL-LHC, the SPS beam dump has been upgraded to the fifth TIDVG generation [1]. The new design must intercept beams from 14 to 450 GeV and dissipate up to 270 kW of energy. One other constraint is to reduce the airborne radioactivity production and improve the accessibility for interventions on the dump systems. The design takes advantage of the old experimental cavern ECX5 to get enough space to install a dump, its shieldings and services.

The dump is hidden inside a 2 m shielding structure which is the biggest constraint. The openings must be reduced to a strict minimum and any human access will be impossible during the full lifetime of the equipment. The measurement and alignment system must be robust, reliable and based on basic mechanics with simple interfaces. A maximum of this system should be outside of the dump shielding and easily interchangeable.

CNGS TARGET FEEDBACK

The CERN Neutrinos to Gran Sasso (CNGS) experiment had the same problematic in 2006. The target was hidden behind a 1.2 m thick shielding of concrete and marble and the expected positioning precision was ±0.1 mm in the global CNGS reference system [2]. The initial strategy was to measure the points on the target using a rod equipped with a centering ball at one end and a reflector on the other end. The rod was verticalized (for vertical rods) and horizontalized (for horizontal one) using mechanical spirit levels.

The three vertical rods have been used only once as the top shielding could not be opened again after the initial installation. Following the initial testing, it was decided to equip the horizontal rods with three reflectors instead of one. The horizontalization of the bars was too time-consuming in a highly radioactive area. The rigidity of the bars also appeared to be a problem even for a 2 m carbon bar.

The final system was a hidden point device. Measurements were done in two steps:

- The calibration: the system was measured while having access to all the reference and the extremity points.
- The operation: it was installed on site and the visible reference points were measured. The position of the hidden points was then calculated by a best fit of the calibration to the on-site measurements.

Figure 1 CNGS target measurement

The measurement precision was found to be acceptable with respect to the requirement. It was estimated at ± 0.1 mm for the vertical bars, and ± 0.2 mm for the horizontal bars [3]. The results have shown inconsistencies for the central point. The reason was linked to a higher extrapolation factor as the central point was further inside the shielding. With a bar of the same length the extrapolation factor increased significantly.

DEVELOPMENT STRATEGY

The measurement strategy for the TIDVG5 is based on the one used for CNGS. Based on the return of experience, it was proposed to improve the usability of the equipment and if possible, the accuracy. The results achieved in 2006 could be sufficient as the hidden points would only be twice further.

The main lessons from CNGS are the following:

- The bars should be used as hidden point device in three dimensions. Levelling the bars is a time-consuming operation that does not improve precision.
- The weight should be reduced as much as possible given that the mechanical deformation is probably the worst effect for the overall quality of the measurement.
- Extrapolation is inevitable but should not exceed a factor of 1.

The system should correct the weak aspects of its predecessor while facing the specificity of the beam-dump detailed page 1.

The development strategy of the system is the following:

- Testing a reduced scale prototype: 3 m long with an extrapolation factor of 1
- Testing a full scale protype: 5 m long with an extrapolation factor of 1
- Production of the set that will be used for alignment in 5 pieces

Two scenarios were evaluated. In the first one, only the primary direction was used for the calculations of the dump position. In the second one, the full 3D position of the hidden target was used to calculate the position of the dump. As the longitudinal tolerance was 20 mm, it was decided to not realign this direction after the initial installation and to calculate the corresponding offset.

GEODETIC NETWORK

Another important aspect was the geometry transfer from the references to the equipment that needed to be aligned.

The installation of the dump and shielding also adds a constraint for the measurement of the SPS machine itself and becomes an enormous obstacle installed within the survey corridors. The usual horizontal measurement method in long machines is the ecartometry. That is done by measuring offsets with respect to a wire stretched along the beamline. With the installation of the new shielding in the ECX5 cavern, stretched wire measurements are not possible anymore. A new solution using an external network was developed to answer two constraints:

- Ensure the transmission of the position of the reference quadrupoles to the points that will be measured during the dump alignment.
- Ensure the alignment of the machine, especially regular alignment of quadrupoles without any loss of accuracy in the area.

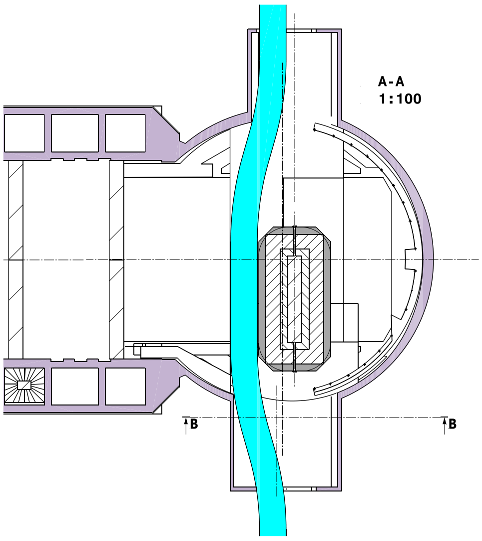

Figure 2 : ECX5, in blue the transport zone shifted by dump installation

The main tool available to perform measurements in accelerators is the laser tracker. Its efficiency and accuracy have been demonstrated for the alignment of the LHC experiments and the overall layout of the ECX5 in SPS is similar.

As the access to the area is only possible during technical stops, simulations were performed in advance to plan and verify the network prior to the installation. The network is a combination of points on the cavern wall on three different floor levels and points on the magnets. Points in the cavern are drift nests installed on the walls all around the cavern. Critical positions for laser tracker stations are materialized with wall brackets: they are located at the entry and exit of the cavern and two positions in height that allow measurements from above the dump shielding. The magnet points that are measured, by regular ecartometry and by the laser tracker, link the machine to the network.

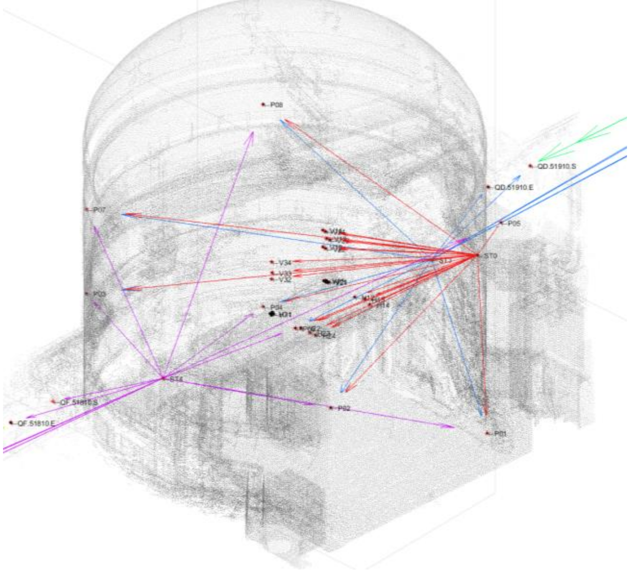

Figure 3 : Cavern and initial network layout

Two software packages were tested for the simulation:

- Logiciel General de Compensation (LGC2) [4] is the standard software for least square compensation at CERN and allows calculations with a wide choice of observation
- SpatialAnalyzer (SA) is a commercial software focused on laser tracker and metrology measurements.

SA was used to confirm the quality of the simulations performed by LGC comparing two identical networks of laser tracker measurements.

The standard values for laser tracker precision in SA is 1" for horizontal and vertical angles and 8 µm +2.5 ppm for distance measurement. It corresponds to the measurement quality observed in the past years at CERN in the experimental caverns. These values associated to the layout of the network will be the input for the simulations.

Table 1 : simulated precision for quadrupoles measurement

Name	3D sigma SA (mm)	3D sigma LGC (mm)
QF.51610.E	0.244	0.338
QF.51610.S	0.227	0.313
QD.51710.E	0.017	0.169
QD.51710.S	0.017	0.161
QF.51810.E	0.077	0.081
QF.51810.S	0.047	Fixed point
QD.51910.E	0.054	0.075
QD.51910.S	0.077	0.071
QF.52010.E	0.017	0.169
QF.52010.S	0.014	0.177
QD.52110.E	0.220	0.313
QD.52110.S	0.244	0.338

Additionally, the simulated precision for network points in the ECX5 cavern and for reference points on the carbon bars was around 70 µm.

The simulations confirmed that a 3D network was sufficient to ensure the requested alignment precision for the quadrupoles and the beam dump alignment. The network was installed in the YETS 2017-2018 and measured at this time.

As most of the time, the reality was different than the simulations: there were more constraints in the field. Two aspects deteriorated the determination quality: sector doors limiting measurements on some key points and the measurement quality in long tunnels was not as good as expected in the simulation.

A second step of simulations was done based on real measurements. The main changes consisted of additional stations in front of the quadrupoles at the entry of the cavern and points along the tunnel wall at the level of the quadrupoles. These changes were tested during a 30h technical stop in 2018 and proved to be sufficient to guarantee the precision estimated in Table 1.

3 M LONG BAR TESTS

The first prototype was at a scale 0.5. Reference points were mounted at 1.5 m, 2.25 m and 3.0 m along the 3 m long bar. They were materialized by 1.5” nests supported on 20 cm aluminium brackets which were rotated by 120 ° with respect to the others around the bar axis. The extremity of the bar was equipped with a 1.5” nest allowing either a direct measurement or an installation on a point using a 1.5” steel sphere. The bar was held at its mid position by a clamp.

The goal of this test was to evaluate the impact of turning the bar around its main axis by 120°, to estimate the effect of the deformation and to get a first estimation of the precision of the measurements.

The measurement scheme was the following:

- A point was measured on a fixed nest with a 1.5’’ reflector.
- The bar was then installed on this same nest using a 1.5’’ steel sphere and measured in the 3 orientations.
- The fixed point was then checked to control the instrument stability.

Measurements were repeated twice a day and repeated the day after. All measurements were fitted together, and we used the quality parameters of the least square fits to evaluate the effect of the deformation of the bar (Table 2). The coordinate system was oriented in a way that Y is along the bar and Z is vertical.

Table 2 : 3-meter bar fit precision

Precision of fit	SX (mm)	SY (mm)	SZ (mm)
All positions and dates	3.785	0.066	5.972

First results showed that the precision depended on the axis we were looking at. The Y precision was sufficient for a beam dump alignment even degraded by extending the bar to the full size.

Another observation was that the secondary directions were much worse than expected. The first setup showed that the bar was bending by several centimetres due to the weight of the aluminium brackets and the 1.5” reflectors. This bend affected the results and especially the vertical direction by a few millimetres.

Results were then separated depending on the orientation of the bar and day of measurement as detailed in Table 3.

Table 3 : 3-meter bar fit precision sorted

Situation	SX (mm)	SY (mm)	SZ (mm)
All positions and dates	3.785	0.066	5.972
Same Orientation	0.059	0.007	0.597
Same date	3.363	0.067	6.233
Same date and orientation	0.057	0.002	0.138

Separating the fits in different categories affected the statistics but gave clear differences in the results. Bars used in the same orientation resulted in significantly improved precision. In the main direction the results were close to the tracker precision. In the secondary directions, the results were improved in a way that it could be used for alignment and especially for redundancy.

The conclusion of this test was that the solution seems viable, with a sufficient precision for measurements in the main direction and with a rather acceptable precision for the secondary direction. The plastic deformation of the bar affects the repeatability of the measurement so the weight of the system and the constraints in the bar must be reduced to the minimum. The rotation of the bar around its main axis into 3 steps appears to be counterproductive: it increases the error caused by the deformation of the bar. The mass distribution of the three positions is too different to give consistent results. The bar needs a stable and repeatable position to give consistent results.

DESIGN IMPROVMENTS

The first prototype led us to a more detailed mechanical study. We reduced the weight by changing the reference reflectors from 1.5” to 0.5” (from 170 g to 6 g per reflector) and the brackets from aluminium to carbon fibre. The other point was to check that the supporting system guarantees the holding of the bar inside the cone while minimizing its deformation.

The simulation confirmed almost 50 mm of bend for the model of the first bar. This was drastically reduced by lowering the weight to a few hundred grams.

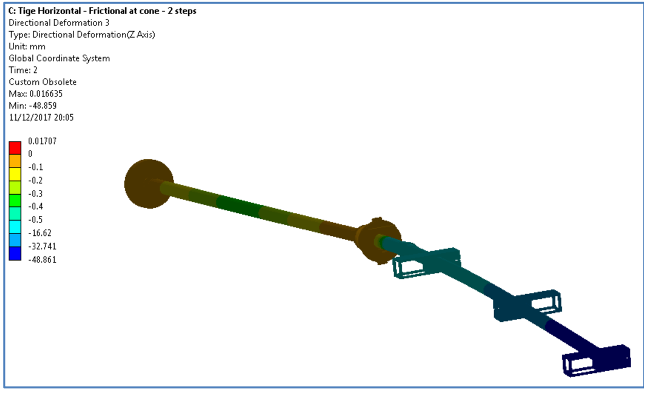

Figure 4 : deformation of the bar under weight

The main part of the simulation was to determine the required force to hold the bar inside the reference cone and check the deformation. The result was that a force of 72 N keeps the extremity sphere of the bar inside the cone with an axisymmetric contact while minimizing the deformation in the first part of the bar below 0.3 mm. The simulations also showed the vertical bar deformation would be far below 0.1 mm for the same force.

In parallel, a full design of the holding system was performed in order to maintain the bar in place, minimizing the deformation and allowing a small angular movement for the relative position of the support point and the dump fiducial.

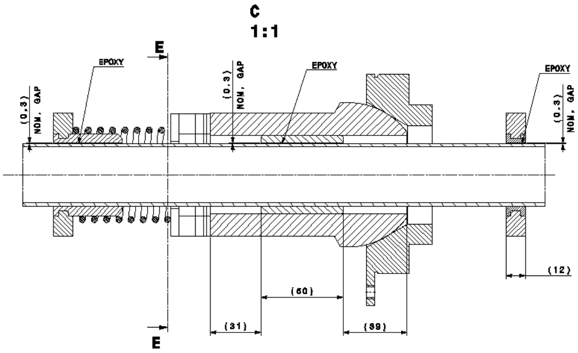

Figure 5 : Holding system of the carbon rods

5 M LONG BAR TESTS

After encouraging results on the 3 m bar, a full-scale prototype was ordered. At this point we took a bit of margin by reducing the extrapolation from a factor of 1 to a factor of 2/3. Four reference points were installed on a 5 m long bar, spaced by 1 m, and the holding point was set at 2 m as expected for the final tool. This setup allowed us to test a potential gain using four reference points instead of three and to assess the quality of results according to the extrapolation factor. As we were getting closer to the final object, we were testing it on both orientations, horizontal as well as vertical.

Figure 6 : Vertical test setup

The tests were like the ones from the 3 m bar. For each measurement, we carried out 5 iterations in vertical position and 5 in horizontal orientation. We measured 4 times separated by several months. The coordinate system was oriented as before: the main axis Z was along the local vertical, the secondary axis Y was along the horizontal bar and X was perpendicular to the two others.

This time we compared the position measured with a 1.5” Corner Cube Reflector (CCR), considered as reference, to the position calculated via a 3D best fit.

Table 4 : 5-meter bar point determination

Situation	X RMS (mm)	Y RMS (mm)	Z RMS (mm)
Hz	0.756	0.099	0.405
Ve	0.259	0.277	0.074
Hz same day	0.624	0.071	0.239
Ve Same day	0.083	0.070	0.042

First results showed that the accuracy in the main direction was better than 0.1 mm which is clearly sufficient. We also saw that it was improved when comparing measurements from the same day. As before, the statistics were reduced but the results were significantly improved. We could confirm that the system fulfils the requirements when calibrated on site before the measurements.

A second conclusion was that we could use only the vertical bars for a complete alignment of the dump as the secondary direction is accurate enough to do so.

One last concern was the maximal error of the system in realistic use. Results were within the statistics with maximum errors around 3 sigmas.

Table 5 : Maximum error for measurement using a 5-meters bar

Situation	X Max error (mm)	Y Max error (mm)	Z Max error (mm)
Hz	1.40	0.25	0.70
Ve	0.25	0.20	0.15

As we got good results with the 5-meter long, we wanted to test if a 4-meter bar could be sufficient. We removed from the calculation the last reference point which reduced the effective part to 4 m. Results were very close, so we decided to keep the 4 m long bar for the production: it eases the manipulation of the system inside the ECX5 as the main risk is a loss of the calibration by a collision.

4 M LONG FINAL BAR TESTS

The 5 final bars (3 vertical and 2 horizontal) were tested in real conditions with the final supporting system.

Table 6 : Final 4-meter bar accuracy determination

Situation	X (mm)	Y (mm)	Z (mm)
Hz RMS	0.084	0.014	0.214
Ve RMS	0.114	0.093	0.013
Hz max error	0.21	0.04	0.42
Ve max error	0.35	0.28	0.04

The main improvement concerned the holding system. The previous one was compressing the bar, adding mechanical constraints, contrarily to the new one that maintains it by applying a defined and constant force along the bar while allowing a small rotation at the supporting point.

The tests confirmed that the requested precision is reached by the system. The calibration must be done on site right before the measurements and as close as possible to the equipment. Each calibration was performed with the same orientation and the same tension. The handling of the bar is difficult due to its length even if the weight reduction is a major advantage. For redundancy and controls, the device was calibrated twice to confirm the results before use.

FIRST USE IN REAL CONDITIONS

At the end of LS2 (fall 2020) the beam dump was installed in the SPS.

The fiducialisation, the determination of the fiducial points position with respect to the axis of the equipment, was performed on surface prior to the installation, using a laser tracker with a measurement uncertainty below ±0.1 mm.

The first alignment was carried out with direct lines of sight to compute a first position before closing the shielding. Once fully covered with the shielding, the position was checked with the carbon bars as shown on Figure 7.

Figure 7 : On site measurement of the TIDVG5

The calculation of the dump axis based on the determined network gave a precision in the range of +/-0.1 mm in vertical and +/-0.2 mm in radial. Offsets calculated from the secondary direction were consistent with the ones from the primary direction, i.e., within the accuracy determined in the final 4 m bar test.

CONCLUSION

The design of the measurement system for the SPS beam dump is based on the experience of the CERN survey team. Similar problems in the past provided a starting point since radioactive areas and equipment require efficiency and robustness.

A solution based on vertical and horizontal rods measured by a laser tracker was proposed.

First tests on a reduced-scale prototype confirmed the concept to be promising, however some problems from the previous system were more important than expected. We had to improve the mechanics of the system to reduce the influence of deformations.

The second prototype was key to validate the requirements and confirm the accuracy of the system including maximal errors that could affect the future alignment.

Once the series were produced, we tested the different bars in their future conditions. The accuracy on the position of the hidden point was better than ±0.1 mm for the radial measurement of the horizontal bars and for the vertical measurement of the vertical bars. Secondary orientations were within a ±0.2 mm accuracy, providing enough redundancy to detect any error during the calibration process or any deformation of the equipment.

In parallel to the design of the carbon bars, the measurement of the network confirmed the simulations on the second error budget. The accuracy of the network points in the cavern is better than ±0.1 mm.

The full calculation including fiducialisation, network measurement and hidden point measurement resulted in a precision of determination of the dump axis in the range a ± 0.25 mm, within the initial tolerance of ±0.7.

As a conclusion, the system developed for the SPS dump proved to be better than initially expected considering the CNGS results. There is no active part and all pieces can be reproduced outside of the radioactive environment. The system can be used for decades as there is no electronic involved and it is maintenance free. It is not a sophisticated piece of technology, but it is robust, failsafe and it fulfils the alignment requirements.

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