TECHNICAL NOTE

NOMINAL ROUTING OF THE SUPERCONDUCTING LINK CRYOSTAT FOR THE HL-LHC INNER TRIPLETS IN THE UNDERGROUND GALLERIES AND LHC MAIN RING
DSHM

Abstract

This document defines the nominal length of the Superconducting Link cryostat for the HL-LHC matching sections (DSHM) considering the routing parameters in the HL-LHC underground areas.

In establishing the DSHM routing, fixed points were proposed for the DSHM installation process, the available space in HL-LHC service tunnels was verified with exact interface positions, and CAD routings for individual cases were developed based on the spline method.

This document also summarizes information about the interfaces of the DSHM to the DF cryostats (DFHM, DFM) and the surrounding systems, and the available space and transport situation in the tunnels.

The detailed design of the supports, protection devices and the equipment needed to transport the DSHM cryostat are outside the scope of this document, will be studied and documented separately.

TRACEABILITY

Prepared by: M. Curyło	Date: 2022-04-25
Verified by: G. Aparicio, R. Betemps, C. Bertone, M. Careil, J. Fleiter, S. C. Hopkins, J. Hurte, S. Maridor, A. Gharib, Y. Leclercq, M. Modena, E. Richards	Date:
Approved by: A. Ballarino, P. Cruikshank, P. Fessia	Date:

Distribution: G. Aparicio, A. Ballarino, R. Betemps, C. Bertone, M. Careil, P. Cruikshank, M. Curyło, A. Devred, P. Fessia, J. Fleiter, A. Gharib, S. C. Hopkins, J. Hurte, Y. Leclercq, S. Maridor, M. Modena, E. Richards, P. Schneider

Rev. No.	Date	Description of Changes (major changes only, minor changes in EDMS)
0.1	2022-01-12	First draft
0.2	2022-04-24	

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1 INTRODUCTION

1.1 Superconducting Link Design

The superconducting link (SC link, DSH) is a high-current power line housed in a semi-flexible vacuum-insulated cryostat cooled by helium gas. The Superconducting (SC) Links contain round superconducting cables (DSC) produced in multiple cabling steps from MgB_2 round wire (DSWM), see Fig. 1, which connects the current leads from the power converters to the Nb-Ti bus-bars of the magnets in the LHC main ring [1]. These electrical connections are placed in dedicated DF cryostats, where SC Links are attached. The final design of each SC link system uses a passive type of cryostat (configuration of two flexible vessels) in its construction, see Fig. 1(c).

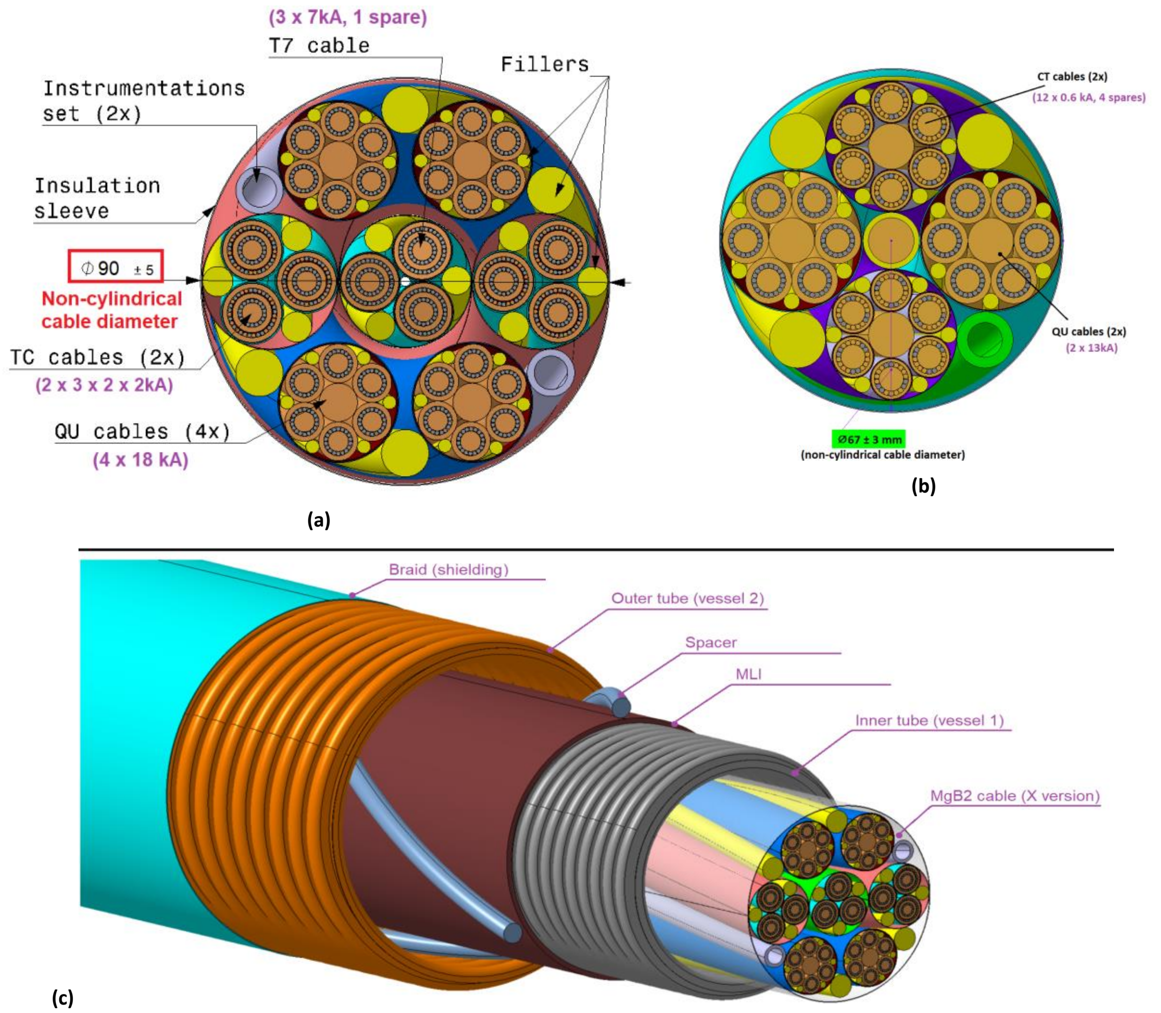


Fig. 1 Cross-section of the MgB_2 cables (a) DSCA1 for SC link type X (DSHX), for the triplets, and (b) DSCA2 for SC link type M (DSHM), for the matching sections; and (c) a cross-section of the SC link for the triplets, DSHX, away from its terminations. Circuits and current ratings are defined in [2]

There are two types of DSH, DSHX and DSHM, to be installed at each side of the ATLAS (IP1) and CMS (IP5) experiments. The DSHX (containing cable DSCA1, fig. 1(a)) provides powering for the HL-LHC inner triplets, and the DSHM (containing cable DSCA2, fig. 1(b)) feeds the HL-LHC matching section dipoles. Depending on the location of DF cryostats, these two types of DSH cryostats have a different length, routing and installation sequence.

General layouts of these systems in the IP1 and IP5 areas are shown in Fig. 2. Equipment codes [3] and functional positions [4] are shown in purple for IP1 and black for IP5.

The present document concerns only the DSHM.

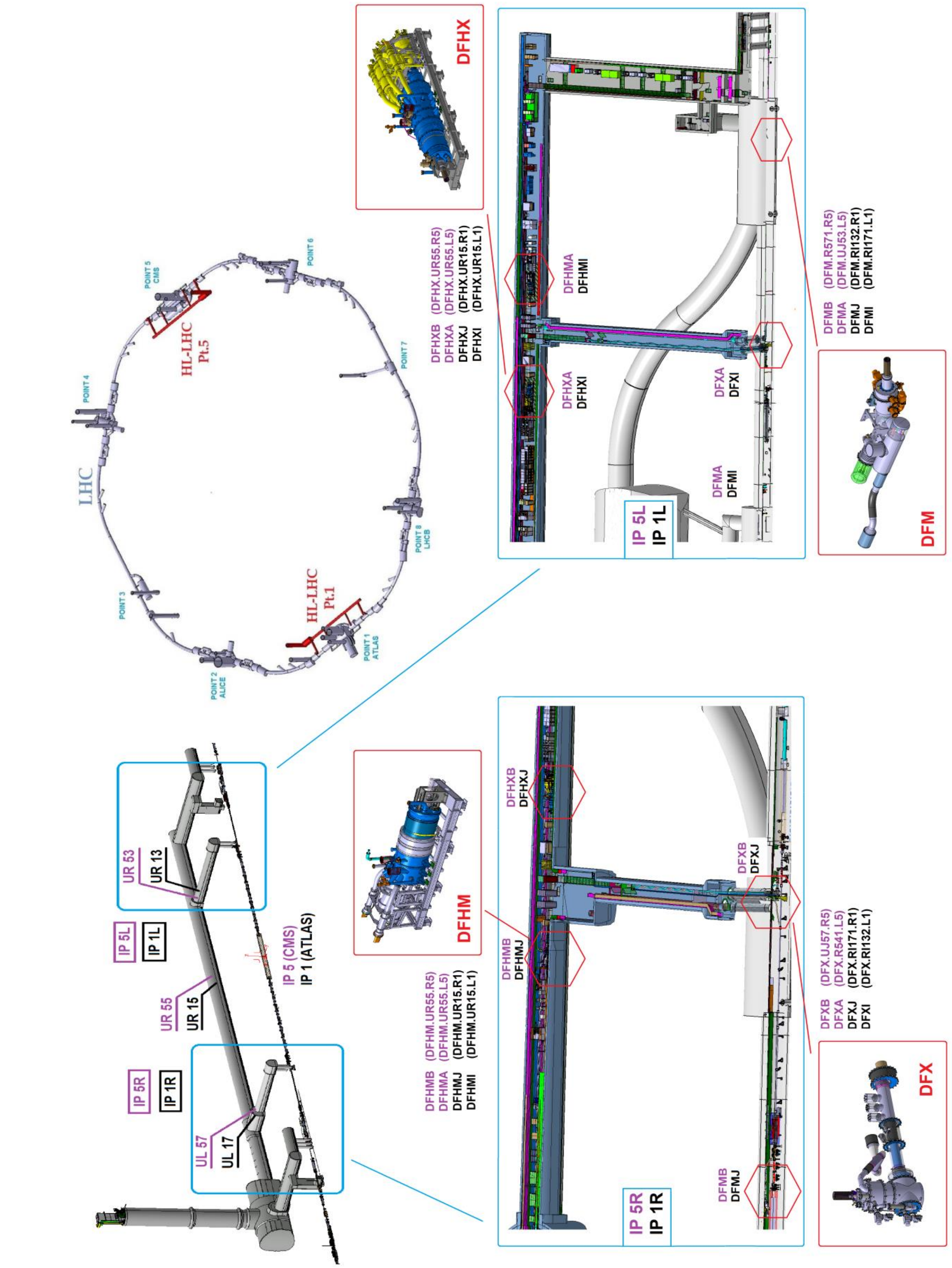


Fig. 2 DF cryostats in new service tunnels with respect to the LHC tunnel

1.2 Routing Study

Basic requirements for the routing of DSH systems are described in [5], which specifies a minimum snaking path to allow MgB_2 cable contraction at cryogenic temperature. The present document reports an analysis of the final routing configuration of the DSHX, following a study of aspects including:

- The available space for DSHM 'waves' in each tunnel section where DSHM is placed.
- The position of interfaces and surrounding devices in the tunnels.
- The tooling used to maintain DSHM in their operational configuration (fixed points).
- Limitations from transport and tunnel geometries.
- Calculation methods for estimation of nominal length.

The final design of the DSHM supports and transport equipment is outside the scope of this document and should be studied separately.

1.3 Nominal Routing Definition

The nominal routing of the DSHM refers to the geometry of the cryostats in their final position after the sequence of transport and assembly with the DF terminations, before cooling down to operating conditions. The central axis of the DSHM is used in all calculations and in the CAD representation of the nominal path. A sketch with the key length data for determining nominal routing lengths is shown below (Fig. 3). The estimated linear mass for DSHM will not exceed 30 kg/m. For the full length of the DSHM, the nominal routing parameter $\mathbf{D_o}$ is taken as 160 mm, in accordance with [6].

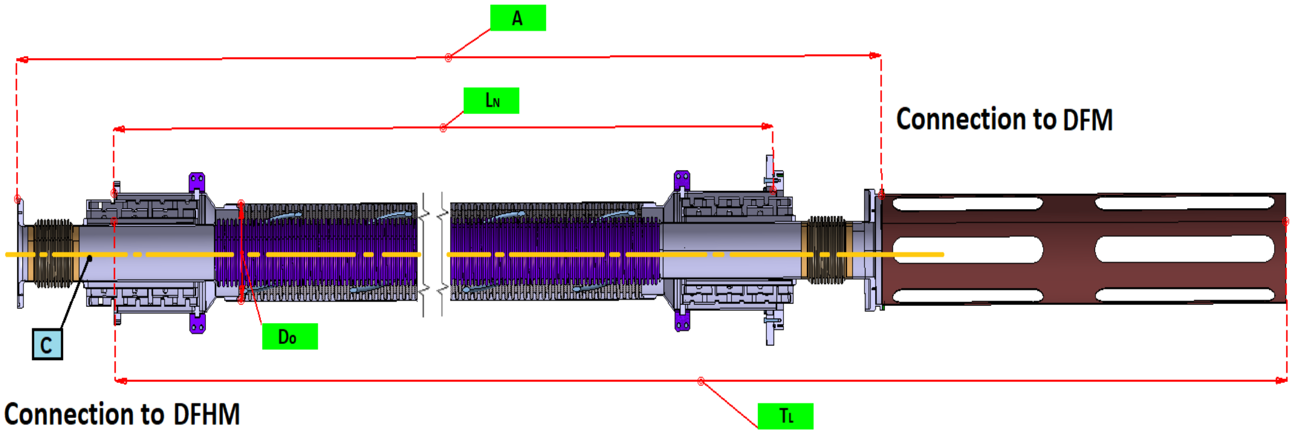


Fig. 3 DSH cryostat lengths without superconducting cable inside

A – Absolute length of DSHM cryostat, helium vessel flange to helium vessel flange [6]
$\mathbf{L_N}$ – Nominal DSHM length, vacuum vessel flange to vacuum vessel flange (reference)
$\mathbf{T_L}$ – DSHM transport length: including welded connection sleeve
C – Central axis
$\mathbf{D_o}$ – Outer diameter of DSHM flexible part (value includes braid)

2 OBJECTIVES AND SCOPE OF THE WORK

The goal of this work was to establish the nominal routing length (L_N) for DSHM cryostat.
The routing was separated into sections, and the configurations in which extra length can be stored, in addition to the minimum snaking path, were calculated.
The following tasks were executed during course of the work:

- Proposal of fixed points for the DSHM installation process
- Verification of available space in HL-LHC service tunnels
- Confirmation of interface points for DSHM

3 INPUT DATA

Integration CAD models provided by the WP15 team were used for detailed study. Integration models use simplified DF cryostat models. The main 3D geometries and 2D documents are listed below:

- New service tunnels:
  - IP1: **ST1120743_01** (P1_HL_LHC_Underground_Integration_2020)
  - IP5: **ST1120186_01** (P5_HL_LHC_Underground_Integration_2020)
- HL-LHC machine components (v.1.5):
  - IP1-L: **ST0990131_01** (HL_IP1_L_1101_INTEG. LS3)
  - IP1-R: **ST0990128_01** (HL_IP1_R_1101_INTEG. LS3)
  - IP5-L: **ST0968836_01** (HL_IP5_L_1506_INTEG. LS3)
  - IP5-R: **ST0966906_01** (HL_IP5_R_1506_INTEG. LS3)
- DFM simplified:
  - IP5-R: **ST1426476_02** (…)
- DFHM simplified:
  - IP1 and IP5 L: **ST1228847_11**
  - IP1 and IP5 R: **ST122884_12**
- Reference layout drawings of HL-LHC machine (v.1.5):
  - IP1-L: **LHCLSXH_0001**
  - IP1-R: **LHCLSXH_0002**
  - IP1-L: **LHCLSXH_0009**
  - IP1-R: **LHCLSXH_0010**
- Civil engineering drawings (WP17):
  - K3500 underground, general – trenches covers details: **LHC-PSW135003007**
  - K3100 gallery secondary structures layout and sections - sheet 3: **LHCRKS1310033049C**

The detailed design of DSHM interfaces and the adjacent WP6A devices are listed below:

- DFHM:
  - Cryostat DFHM non equipped: **ST1421552_01** (LHCDFHM_0068)
  - DSHM termination adjacent to DFHM (Welded interface SC-Link-DFHM Ø180):
    - CERN specification: **ST1356361_01** (LHCDSH_C0007, EDMS 2455692))
    - Supplier implementation: EDMS 2592800
- DFM:
  - **ST1407829_01** (DFM tunnel assembly)
  - **ST1426476_01** (DFM tunnel integration)
  - DSHM termination adjacent to DFM (DFM SC-Link Ø80):
    - CERN specification: **ST1331799_01** (LHCDSH_C0005, EDMS 2455692)
    - Supplier implementation: EDMS 2592800

3.1 Reference and Local Orientation Points

The starting point for positioning the DSHM systems is the relevant orientation of the DF cryostats in the new service tunnels and the LHC main ring. Finding orientation points for DF references in these tunnels is necessary to determine the final length of these systems and to plan the snaking (wave) configuration.

Each DF cryostat has a reference for positioning, and this is the centre point of the DF interface flange.

- **Reference for DFHM:**

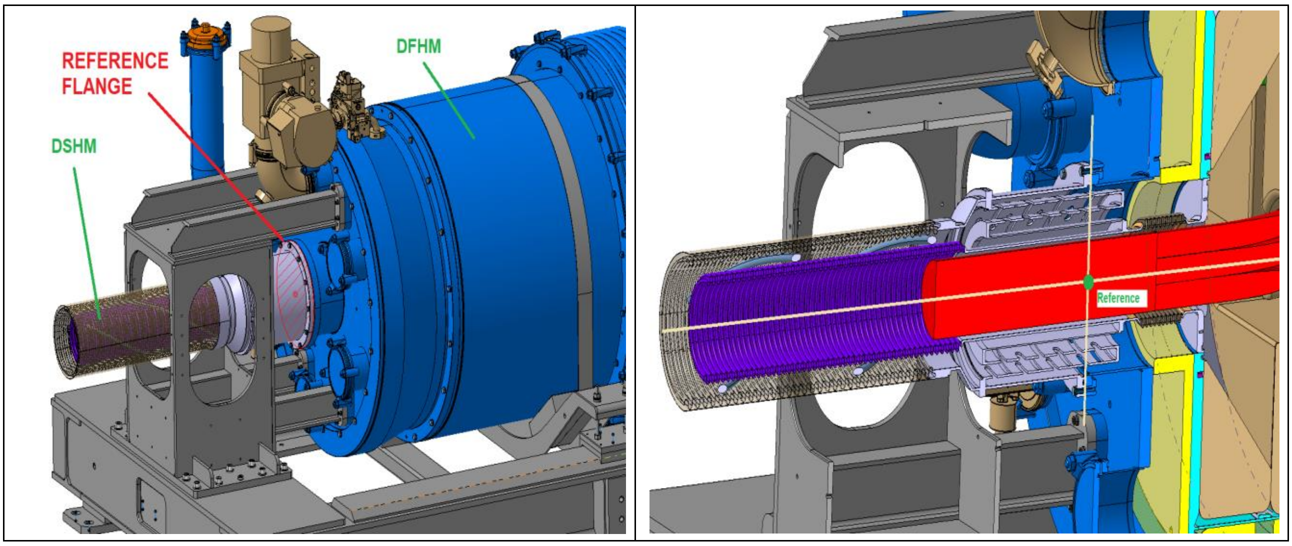


Fig. 4 DFH interface flange layout: on the right general view, on left cross section through central axis in termination area

Both types of DFH use a dedicated local coordinate system for the HL-LHC project: CERN 1102 for IP 1 and CERN 1503 for IP 5. For the installation and positioning process in the new service gallery UR, the DFH will use some orientation points related with gallery geometries in respect to these systems.

UL core symmetry in relation to the IP allows their central plane to be used as a reference for positioning.

The nominal height of 700 mm above the floor of the UR shall be obtained through adjustment of the support frame of the DFH. The tables below summarize the base point coordinates for DFH devices and the position of local orientation for installation. Fig. 5 shows the interface flange positions of both types of DFH in relation to the core plane and nominal height above the UR tunnel floor.

Table 1. Reference positions of the DFHX system.

IP # - # : AXIS SYSTEM	SIDE (L): X, Y, Z [mm]	SIDE (R): X, Y, Z [mm]
IP 1 – DFHM: CERN 1102	53200, - 102000, 8690	53200, 102000, 11210
IP 5 – DFHM: CERN 1503	53200, - 102000, 11210	53200, 102000, 8690
IP 1 – CORE PLANE: CERN 1102	NA, - 93250, NA	NA, 93250, NA
IP 5 – CORE PLANE: CERN 1503	NA, - 93250, NA	NA, 93250, NA

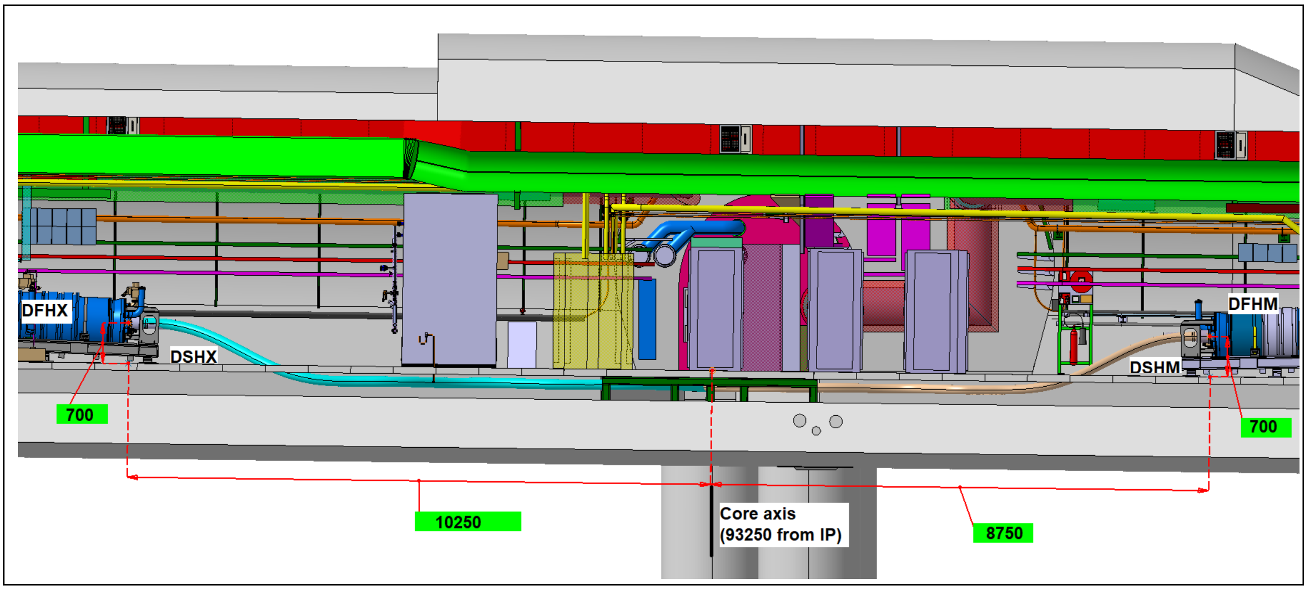


Fig. 5 Position of DFHX and DFHM base points in the UR, dimensions in mm

❖ Reference for DFM

The DFM extremity is part of the LHC machine, and the base coordinates differ between some CAD models. The LHC machine uses reference coordinates CERN 1101 for IP 1 and CERN 1506 for IP 5.

For the purposes of this study and for better estimation, coordinates of the DFM are transformed (on each axis) to the same coordinate system as the DFH devices (CERN 1102 and CERN 1503). Moreover, due to the tilt and slope of the LHC tunnel, the position of the base points will not be symmetrical to the core plane in the IP Left and IP Right side. Depending on the DFM reference location on the Left or Right side of the IP, the difference in nominal length of the DSH is around 0.05 m.

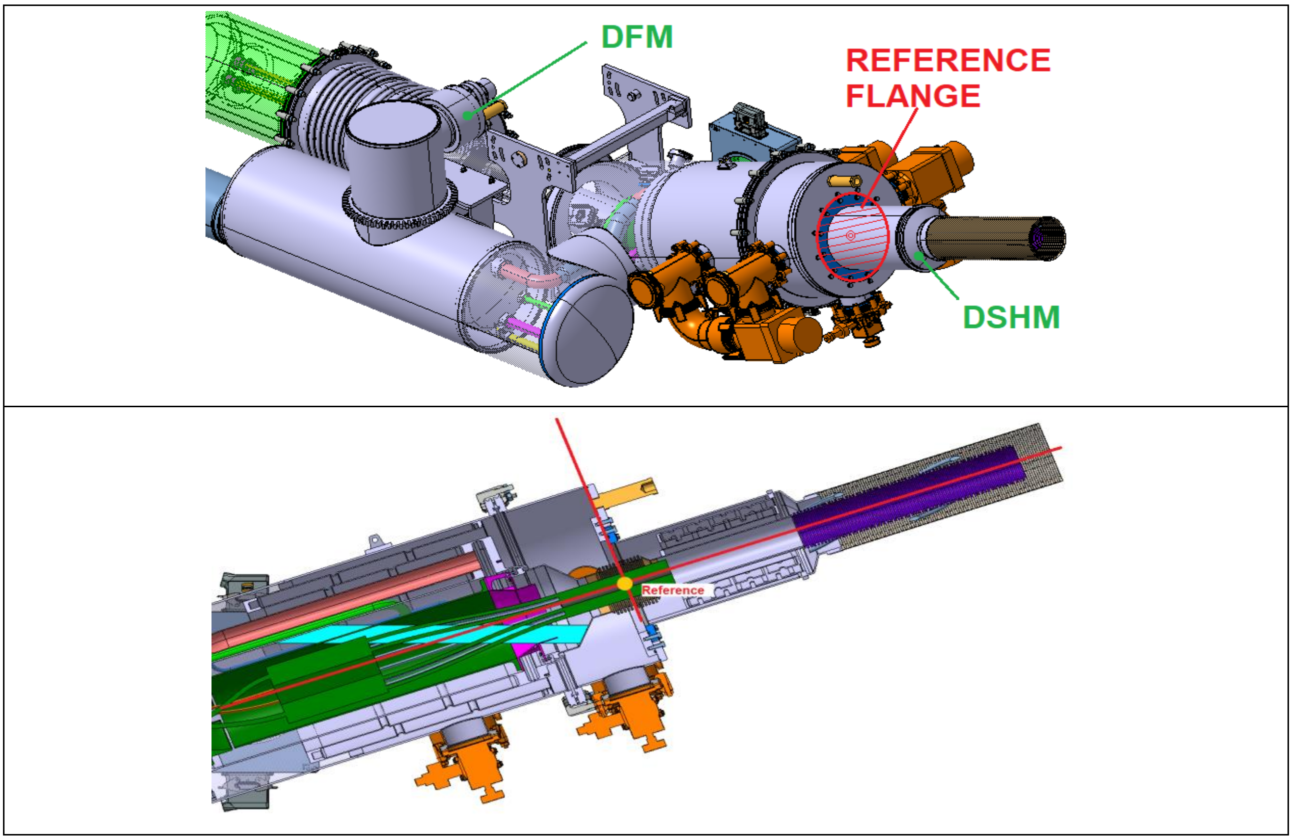


Fig. 6 DFM interface flange layout: on the right general view, on left cross section through central axis in termination area.

Table 2. Reference positions of the DFM system *

IP # - #: AXIS SYSTEM	SIDE (L): X, Y, Z [mm]	SIDE (R): X, Y, Z [mm]
IP 1 – DFM: CERN 1102	0, - 139308, -385	0, 139275, 3058
IP 5 – DFM: CERN 1503	0, - 139275, 3055	0, 139308, -382

* Reference DFM points in each variant are under review. Any minor adjustments to the position will be within the declared uncertainty of +/- 0.05 m, Table 7.

3.2 UL/UR Tunnel Integration Assumptions

For each of the two DSHM cryostats installed on both sides of IP1 and IP5, the integration environment should be considered individually. However, some general assumptions are taken for all installed systems and for the routing study:

- 40 mm distance from the outer surface of the DSHM (braid) to the side wall of the trenches and the tunnel walls.
- Due to the different depths of the trenches and sizes of their covers, a distance of 270 mm (± 5 mm) from the trench cover top surface (floor level of UR and UL tunnels) to the central axis of the DSHM was selected as nominal.

A sketch with the general assumptions mentioned above is shown in Fig. 7.

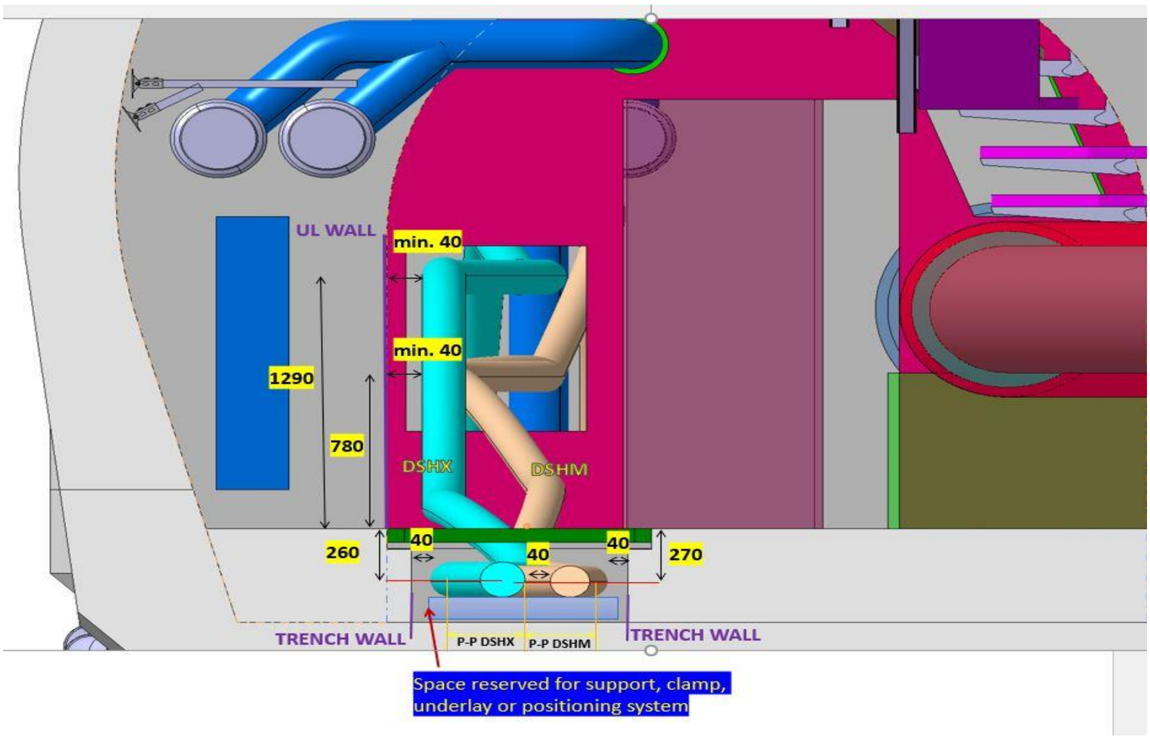
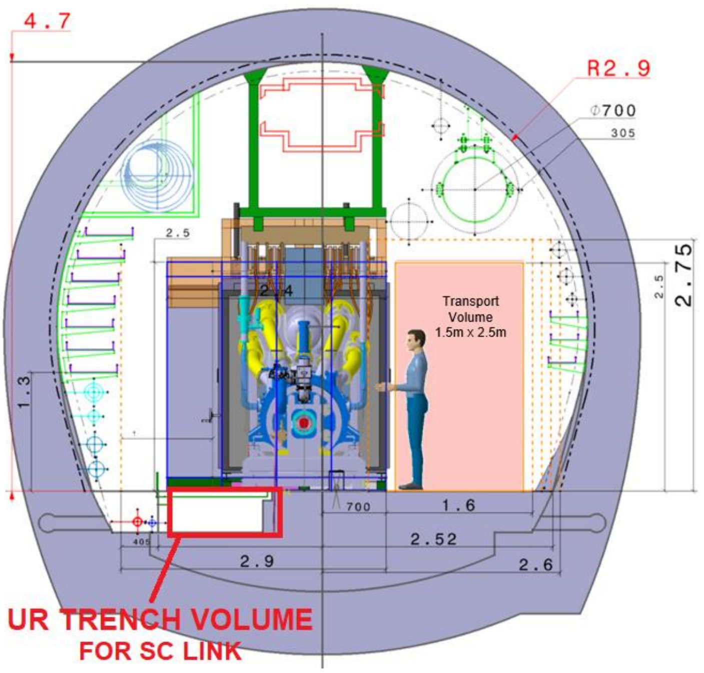
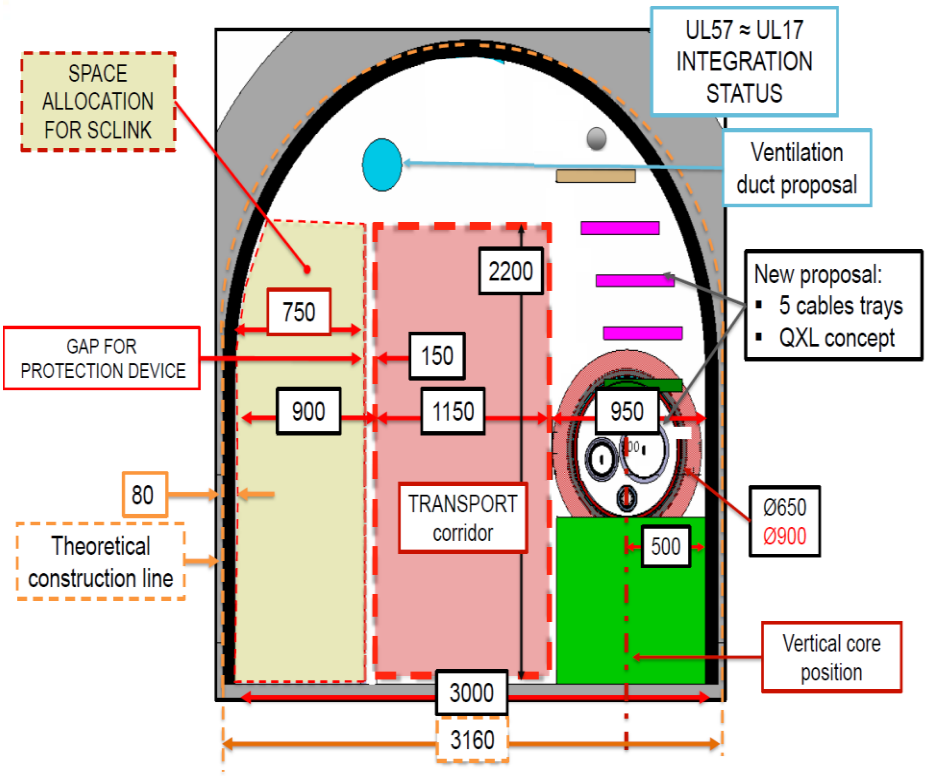


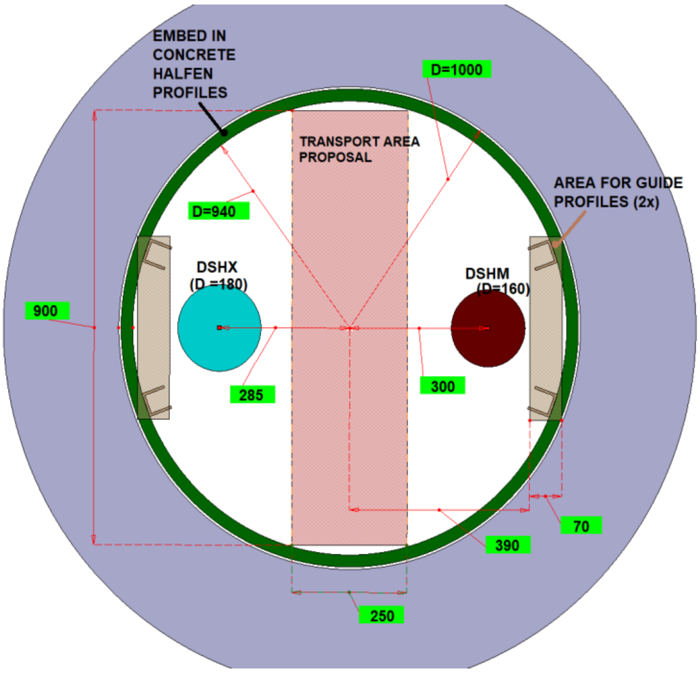
Fig. 7 General assumptions for tunnel integration

The available volume for DSHM installation in HL-LHC tunnels is partly described in [11] and for the LHC machine in [12]. Some essential cross-sections of the tunnels with key dimension data were extracted and shown in the table below.

Table 3. Overview of available space and transport volume for DSHM integration (selected cross-sections)

	Sketch with main dimensions
UR TUNNELS [13] The sketch opposite applies only for left (L) side of IP 1 and IP 5.	
UL TUNNELS The sketch opposite applies only for right (R) side of IP 1 and IP 5.	

<table>
<tr>
<td>Core (vertical shaft), cross-section, area of output to LHC tunnel

The sketch opposite applies only for left (L) side of IP 1 and IP5.
Height of 1 m above the position of the reference flange DFX.</td>
<td>
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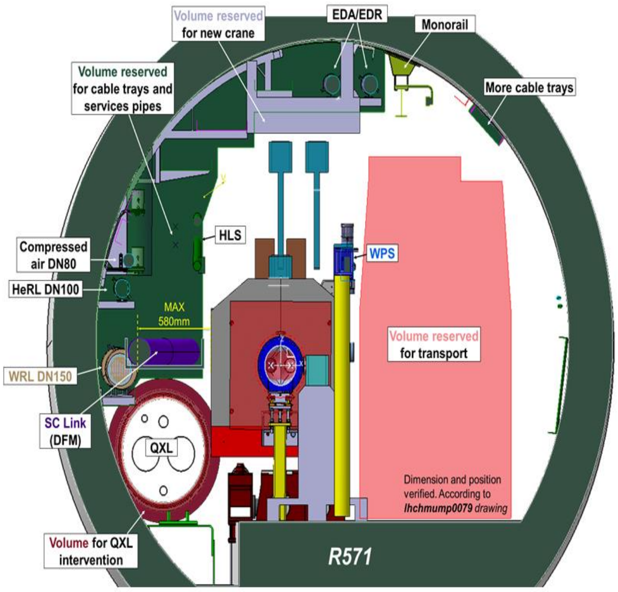
<td>
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3.3 DSHM interfaces

Most of the DSHM interfaces are placed in DF devices. A detailed description of the electrical, cryogenic, and vacuum connections can be found in the appropriate document [7-10]. Mechanical connections to the DF are shown in section 3.1, with interface drawings listed in section 3. The exact location of the DSHM systems in HL-LHC tunnels and trenches requires the installation of supporting and positioning clamping systems at fixed points. The proposed location for this interface is described in this document.

4 DSHM NOMINAL ROUTING

To find the best scenario for the DSHM routing, the entire path was divided into segments.

This allows parameterization of each segment and to manipulate the final total length of the DSHM according to the chosen parameters. Fig. 8 shows the layout with numbering of the sections (taking the example of UL 57).

Due to the slope of the service tunnels and the dimensions of trenches in UL galleries, a critical case (for storing extra lengths in a snaking pattern) has been identified for which further calculations will be performed. The selected scenario is IP5R through service gallery UL 57, core # 19 and then in the LHC tunnel: UJ57 and R571. Sections 4.1 - 4.9 present the main description for each section with the chosen nominal amplitude for the waves. In section 4.10, calculation results are presented according to the chosen methods for nominal routing and for scenarios of maximum and minimum stored length.

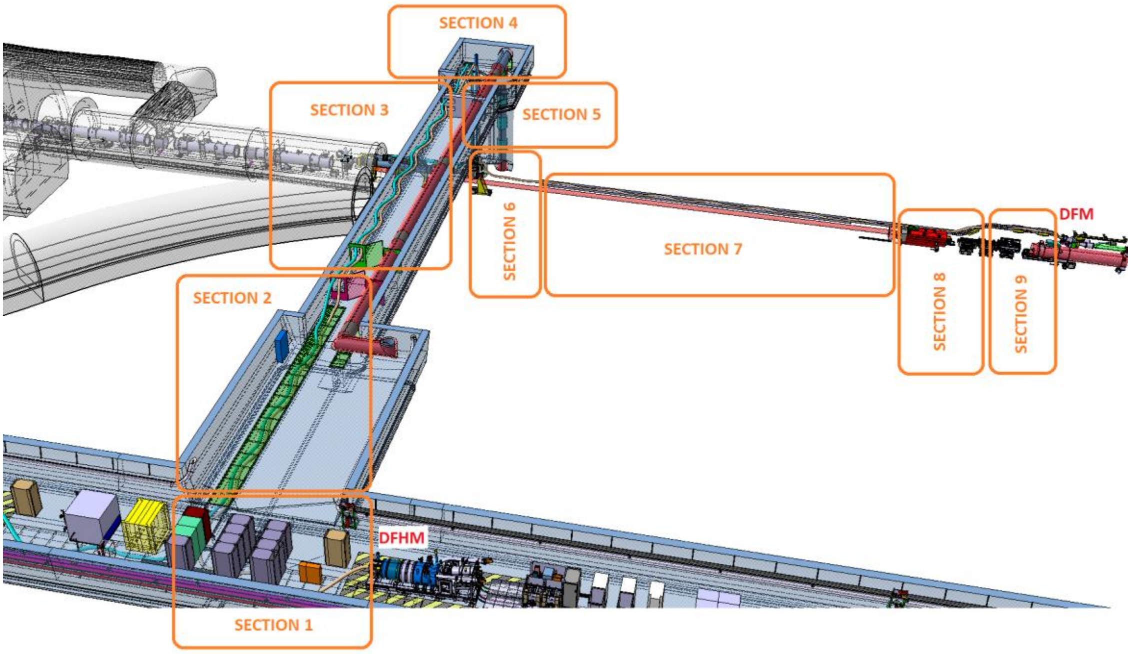

Fig. 8 DSHM nominal routing sections

4.1 Section 1

The first section is identical for all cases. Section 1 includes the connection interface to the DFHM cryostat in the UR tunnel surface, where the initial DSHM section is straight (320 mm). The path then enters the horizontal trench, this transition covers shape of wavy pattern, and it ends on the first fixed point in the UR trench. The rest of the path in this section includes routing in the UR trench, using all the available width to create wavy pattern, and a 90° transition to the UL trench, where it ends with a fixed point. Baseline studies for nominal routing assume the creation of two wavy patterns in this section with an amplitude around 250 mm. The first wave shape is obtained in the direction of descent (with the mid-point of the wave maintained by dedicated support). On the entire length of this transition (~ 4 m), an additional protection system around the DSHM is planned (in case of electrical arc). A second wave assumes a path in the horizontal direction in the UR trench. Wavy patterns in this section using bending radius locally changed. Due to limited space for wave pattern, the bending radius was reduced from 2 m nominal to 1.5m only in this zone.

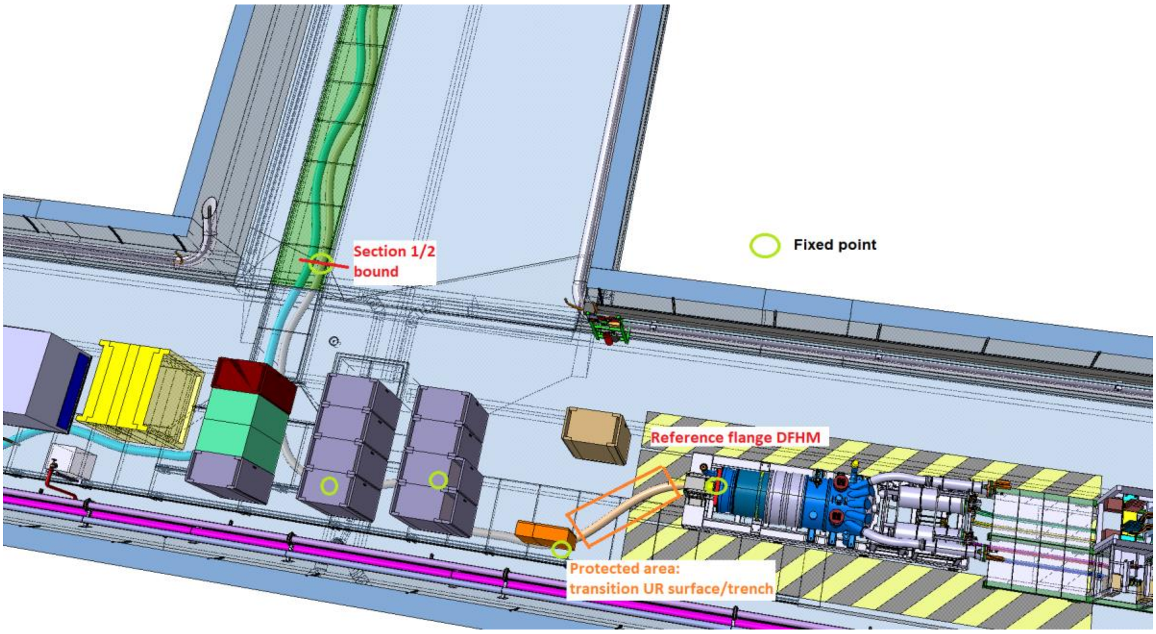

Fig. 9 Layout of section 1 of DSHM routing scenario

4.2 Section 2

The second section covers routing of the DSHM in the UL trench, bringing it to the surface of the service tunnel. In section 2, the DSHX and DSHM cryostats share the available width of the trench, significantly influencing the maximum amplitude for a wavy path (max. 390 mm). A 320 mm wave amplitude is chosen as nominal. The assumed worst-case scenario concerns the right side of IP, which includes the longest sector of horizontal trench, for which the nominal number of waves is 4 (for the left side of the IP there will be 2 waves). The last segment of this section ensures the transition to the nominal height (700 mm between the bottom surface of the cryostat and the ground level) in the UL tunnel. As in section 1, the transition area will be protected by a dedicated cover in the 5 m long sector (one cover for both type of DSH systems).

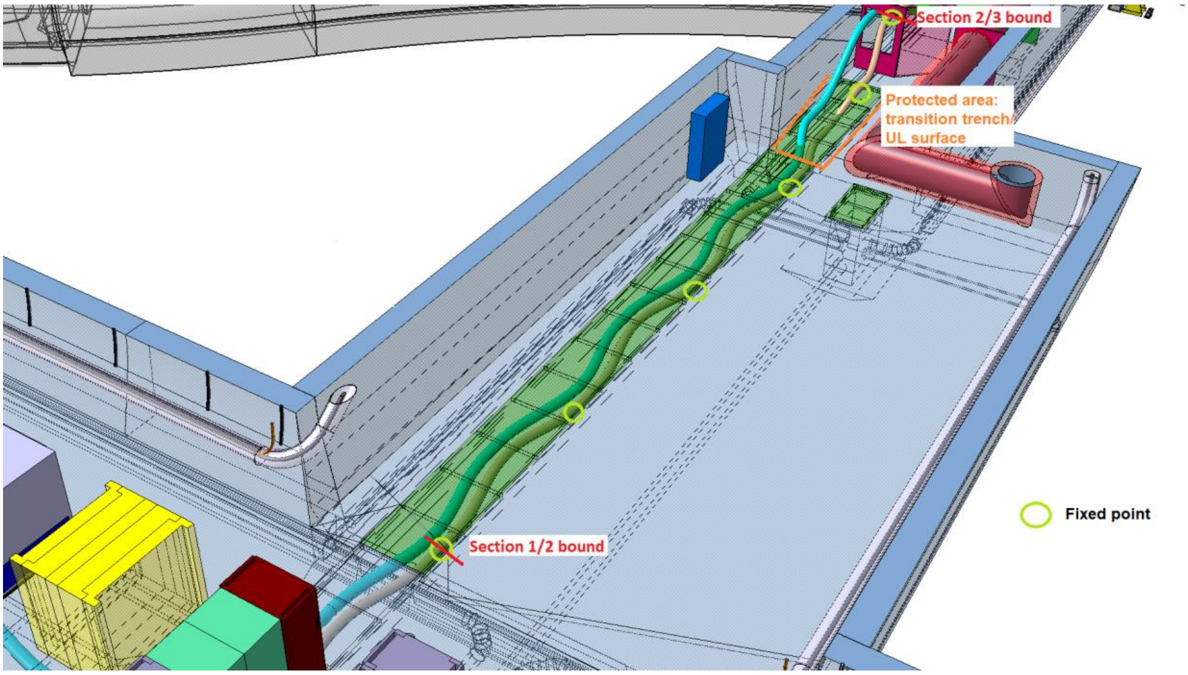

Fig. 10 Layout of section 2 of DSHM routing scenario

4.3 Section 3

The UL tunnel section provides the greatest flexibility to compensate cryostat length in the horizontal wave system in each case. The maximum amplitude under the assumed boundary conditions, and considering the available space due to transport considerations, is 530 mm. The nominal amplitude for the wave pattern in this section is 420 mm. The length of the tunnel allows 6.5 waves to be achieved in total for the right side (8.5 for the left side). Moreover, to ensure independent tray systems for both types of DSH, the nominal heights from the UL floor level to the DSHM central axis selected were 780 mm.

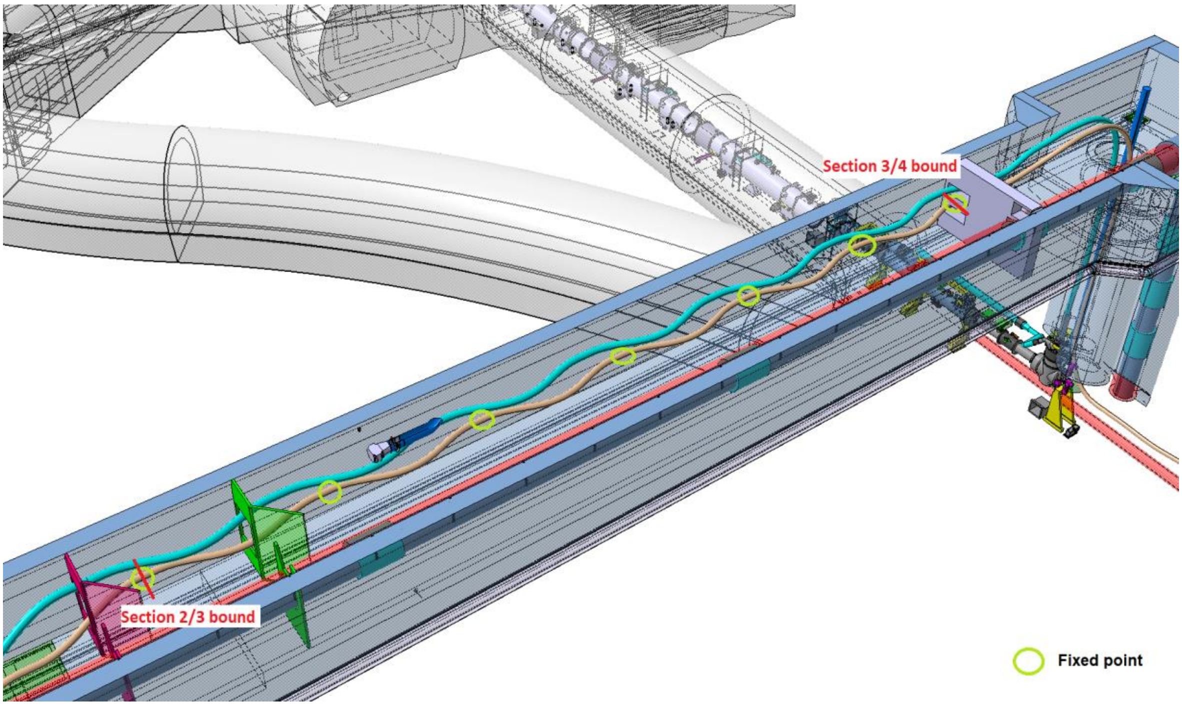

Fig. 11 Layout of section 3 of DSHM routing scenario

4.4 Section 4

The nominal path for section 4 (the blue path in Fig. 14) does not include a wavy pattern to compensate for the length of the cryostat. The nominal routing of this section takes care of the 2D transition from horizontal (section 3 in UL) to vertical position (in the core). Depending on the placement of the supporting structure, the nominal path may be either a maximum or minimum value (the orange and green curves respectively in Fig. 14). The figure below also shows the most important boundary conditions relating to the tunnel. Due to the shape of the bending, the radius was locally increased to 2.5 m. The maximum path with respect to the nominal path can accommodate 0.83 m overlength, and the minimum path with respect to the nominal path can accommodate 0.78 m under-length.

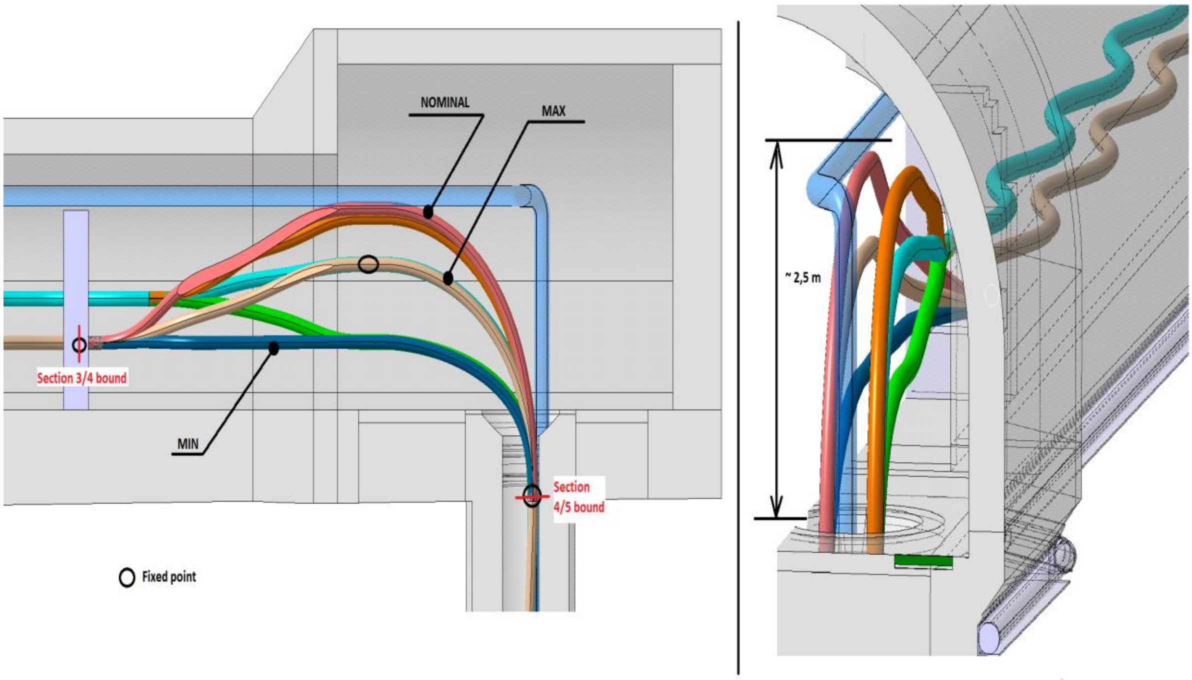

Fig. 12 Layout of section 4 of DSHM routing scenario.

4.5 Section 5

The next section of the DSHM contains the vertical region. Due to the complexity of the guiding system in the vertical section, the nominal path of section 5 does not assume the introduction of a wave system (as an option, it is believed to be a possibility to introduce one nominal wave with a minimum amplitude of 250 mm, but this should be verified on an appropriate mock-up system).

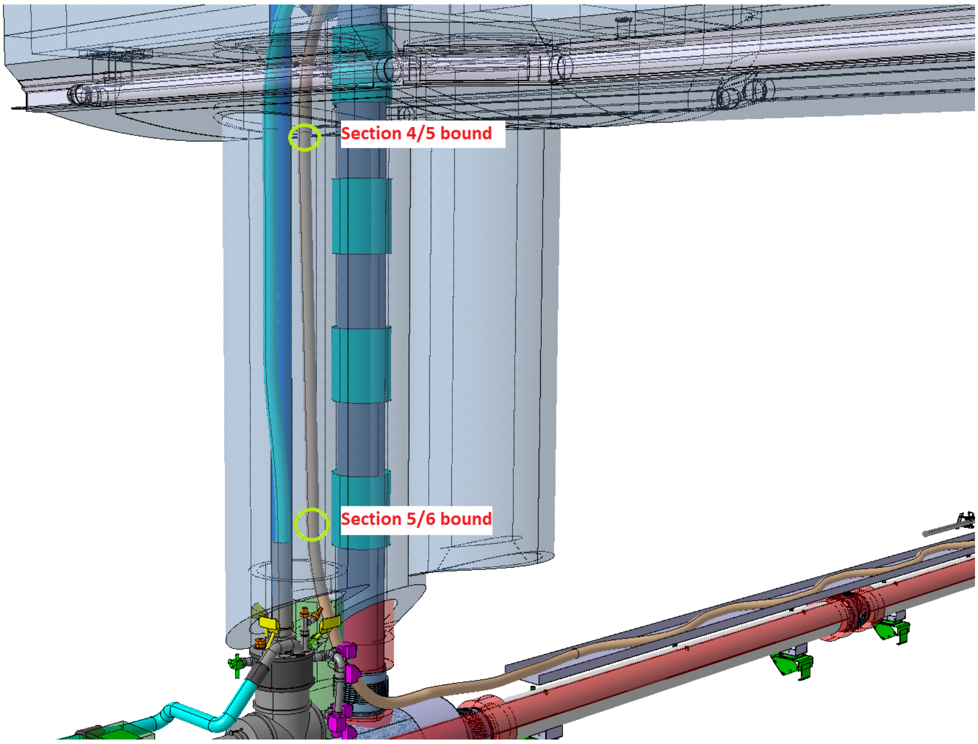

Fig. 13 Layout of section 5 of DSHM routing scenario

4.6 Section 6

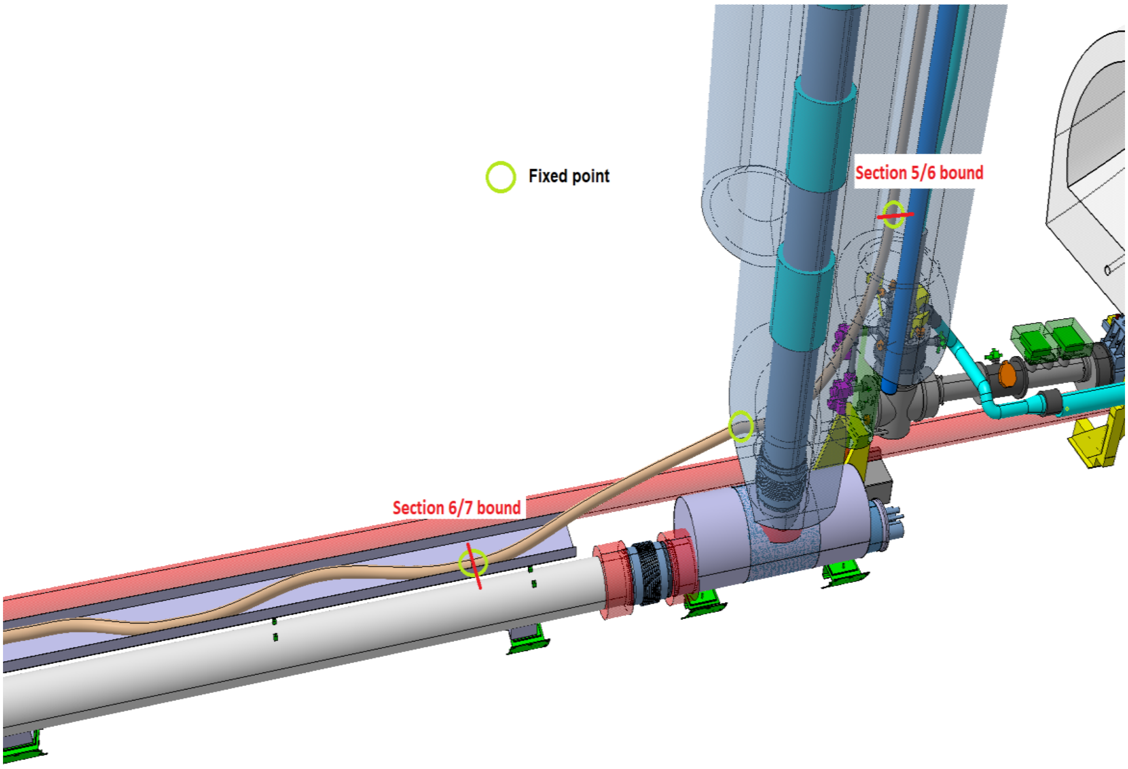

Fig. 14 Layout of section 6 of DSHM routing scenario

4.7 Section 7

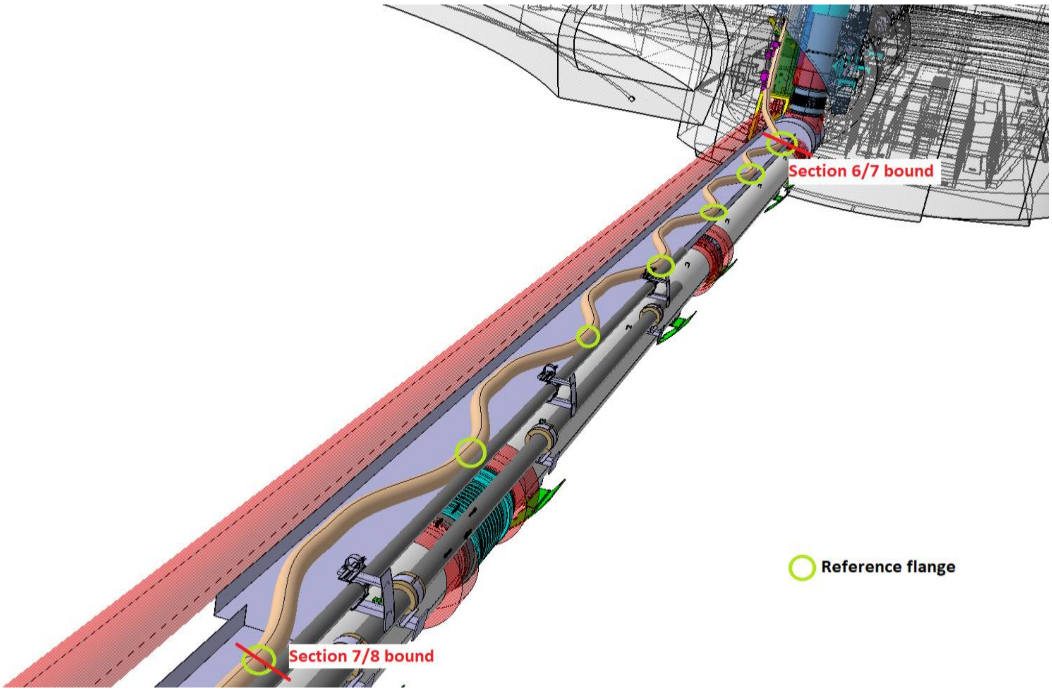

Fig. 15 Layout of section 7 of DSHM routing scenario

4.8 Section 8

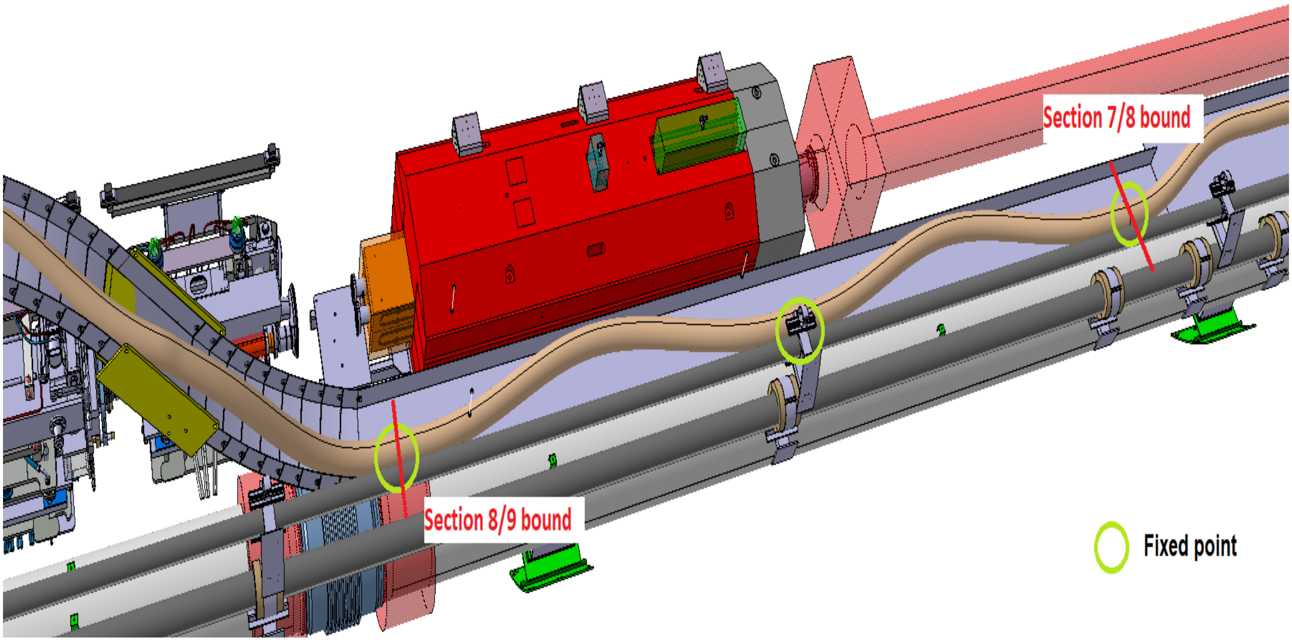

Fig. 16 Layout of section 8 of DSHM routing scenario

4.9 Section 9

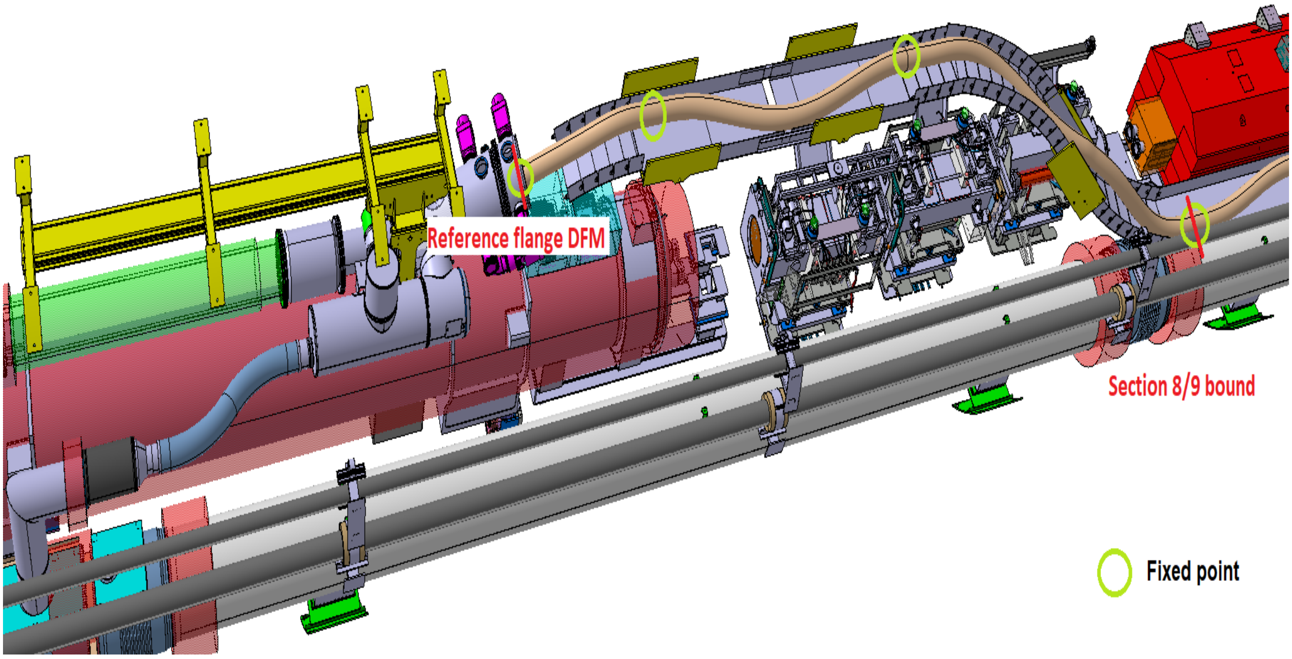

Fig. 17 Layout of section 9 of DSHM routing scenario

4.10 Summary of Calculations: DSHM

For each section, detailed calculations were performed of the length stored in the wavy pattern, using different calculation methods: the methods and the models used can be found in the Annexes (1-3). The results of all calculations have been gathered in Table 4.

Table 4. DSHX length stored in nominal wavy pattern due applied method, overview for each section

SECTION NUMBER: Name (Nominal number of waves)	MIN. STORED IN WAVES [mm]	INTEGRATION BASELINE [mm]	MAX. STORED IN WAVES [mm]
1: UR surface/trench (min.1 - 1.5 – max 2 waves, not nominal: R= 1500)	Method 1: **47.58** Method 2: **55.25** Method 3: **57.15**	Method 1: **71.37** Method 2: **82.88** Method 3: **85.73**	Method 1: **95.16** Method 2: **110.5** Method 3: **114.3**
2: UL trench (4 waves)	Method 1: **137.36** Method 2: **166.16** Method 3: **162.16**	Method 1: **232.37** Method 2: **271.68** Method 3: **270.92**	Method 1: **357.73** Method 2: **402.56** Method 3: **407.68**
3: UL surface (6.5 waves)	Method 1: **223.21** Method 2: **270.01** Method 3: **263.51**	Method 1: **686.22** Method 2: **757.77** Method 3: **771.36**	Method 1: **1191.16** Method 2: **1200.62** Method 3: **1238.25**
4: Transition to the core (No waves)	Method 1: **0** Method 2: **0** Method 3: **0**	Method 1: **0** Method 2: **0** Method 3: **0**	Method 1: **0** Method 2: **0** Method 3: **0**
5: Core (No waves – max. 1 wave)	Method 1: **0** Method 2: **0** Method 3: **0**	Method 1: **0** Method 2: **0** Method 3: **0**	Method 1: **34.34** Method 2: **41.54** Method 3: **40.54**
6: Exit from Core (No waves – max. 0.5 wave)	Method 1: **0** Method 2: **0** Method 3: **0**	Method 1: **0** Method 2: **0** Method 3: **0**	Method 1: **35.26** Method 2: **40.59** Method 3: **40.77**
7: Wide segment above QXL (6 waves)	Method 1: **206.04** Method 2: **249.24** Method 3: **243.24**	Method 1: **423.12** Method 2: **487.02** Method 3: **489.24**	Method 1: **741.3** Method 2: **801.96** Method 3: **819.9**
8: Tight segment above QXL (2 waves, not nominal: R= 1800)	Method 1: **77.24** Method 2: **92.24** Method 3: **91.9**	Method 1: **77.24** Method 2: **92.24** Method 3: **91.9**	Method 1: **77.24** Method 2: **92.24** Method 3: **91.9**
9: Transition to DFM (1 wave, not nominal: R= 1600)	Method 1: **44.15** Method 2: **51.83** Method 3: **52.9**	Method 1: **44.15** Method 2: **51.83** Method 3: **52.9**	Method 1: **44.15** Method 2: **51.83** Method 3: **52.9**
TOTAL	Method 1: **735.58** Method 2: **884.73** Method 3: **870.86**	Method 1: **1534.47** Method 2: **1743.42** Method 3: **1762.05**	Method 1: **2576.34** Method 2: **2741.84** Method 3: **2806.24**
Total difference (Total baseline and min., max.) and average value	Method 1: **-799** Method 2: **-859** Method 3: **-891** AVERAGE: **-850**	AVERAGE: **1679.98**	Method 1: **+1042** Method 2: **+998** Method 3: **+1044** AVERAGE: **+1028**

In the case of the DSHM cryostat, results show a length of around 1.68 m can be absorbed in the nominal wavy path with respect to a routing path with no waves. The boundary conditions for the available space assumed due to the tunnel geometry allow for compensation of about a length difference of - 0.85 m, +1.03m from the nominal 1.68 m value. The comparison of the lengths of the individual sections can be found in Annex 4. The calculated total lengths for the entire DSHM path in IP5R for each calculation method used are presented in Table 5. Average value was chosen as the reference.

Table 5. Nominal length DSHX for I5R due to applied method.

	Nominal length L_N [m]	CAD model [ST ref.]
Geometry created with polyline function (method 1)	**119.52**	**ST1567519_01**
Geometry created with spline function (method 3)	**120.22**	**ST1522694_01**
Average value of both methods	**119.87**	**N.A.**

For the remaining DSHM cases (IP5L, IP1R, IP1L), the total path lengths were verified using the same basic assumptions and the spline method. As the considered IP5R case has the shortest path, the obtained nominal DSHM lengths (L_N) in the remaining cases should be longer and slightly different from the IP5R case. Results are presented in Table 6.

Table 6. DSHX nominal lengths in spline method

Device – IP# – Side	L_N [m] – method 3	CAD model [ST ref.]
DSHM – IP5 – R	**120.22**	**ST1522694_01**
DSHM – IP5 – L	**120.47**	**ST1571009_01**
DSHM – IP1 – R	**120.22**	**ST1570992_01**
DSHM – IP1 – L	**120.46**	**ST1571053_01**

5 CONCLUSIONS

The collected data during the study and the calculations performed gives necessary input to determine final length of the DSHM nominal routing in the HL-LHC project. Based on the average value of the calculation methods, the nominal length is L_N = 119.87 m.

All information on the min/max integration paths with respect to the nominal routing path, tunnel geometry differences and calculation uncertainties have been collected in Table 7 and summarised in Fig. 16. The DSHM integration length can be varied by - 0.85 m, +1.03m with respect to the theoretical nominal path, providing sufficient margin for link manufacturing, installation tolerances and civil engineering uncertainties.

Table 7. Integration flexibility for DSHM

	Path routing flexibility wrt nominal integration		Variations due to tunnel geometrical differences		Calculation uncertainty
Routing variables	**Section 1,2,3,5,6,7,8,9: Length variability via wave pattern**	**Section 4: Routing options above co**	**DFM flange position (non-symmetrical locations)**	**Waves in section 2-3 (L and R of IP)**	**Cal. method assumed error for length LN**
Max. [m] **Min. [m]**	+1.03 -0.85	+0.83 -0.78	+0.05 -0.05	+0.12 -0.12	+0.35 -0.35
Estimated integration flexibility: (1.86, 1.63 – (0.05+0.12+0.35)) giving + 1.34, -1.11					

For manufacturing, the length shall be rounded up from the nominal value of 119.87 m to **L_N = 120.8 m**. The resulting asymmetric integration flexibility range of +0.41/-2.04 m still accommodates the specified manufacturing tolerance of ± 0.3 m, but with additional margin against insufficient length.

For contractual purposes, the total length of the DSHM cryostat A including termination assemblies (see fig. 3) is specified instead: with the dimensions of the cryostat terminations fixed by design, the resulting length is **A = 121.3 m**.

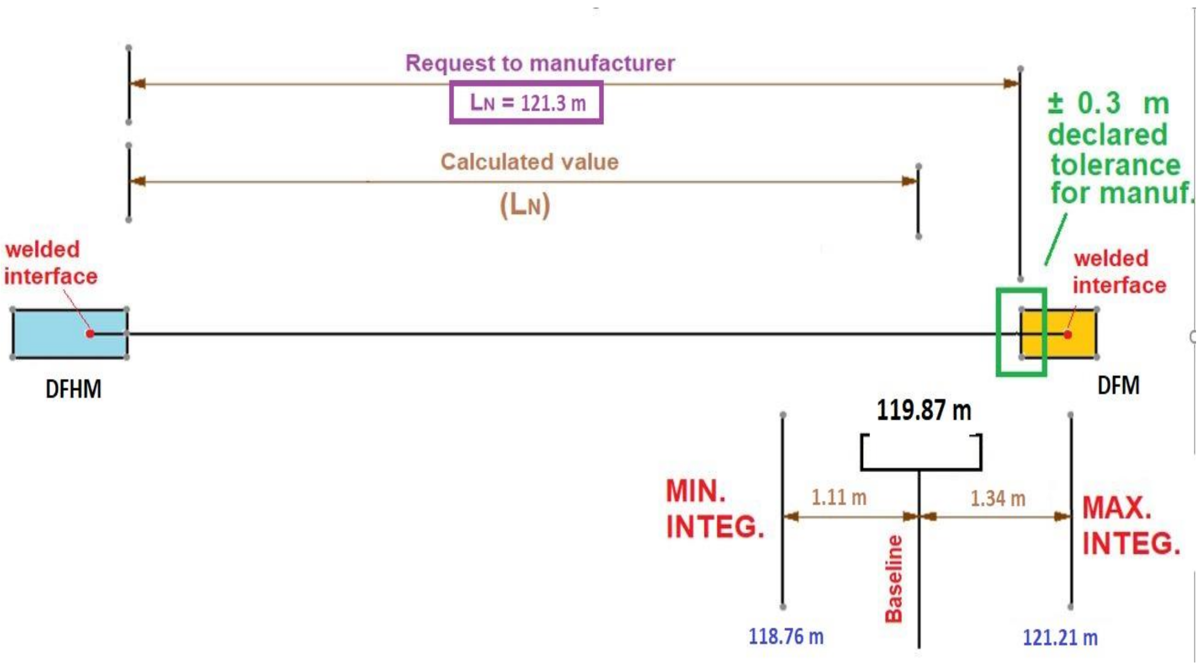

Fig. 18 Diagram with description of nominal values.

The following parameters (to be verified in future studies) may slightly influence the exact routing but are not expected to significantly affect the nominal length:

- Final accuracy of new tunnels
- Detailed design of supporting structures for DSHX and DSHM
- Length of rigid sections at fixed points (confirmed size of fixing clamps)
- Confirmed assembly sequence of WP6A components in HL-LHC project from the general planning
- Protection system due to electric arc [15]

6 REFERENCES

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7 ANNEXES

List of annexes:

- Annex 1: Calculation Method 1
- Annex 2: Calculation Method 2
- Annex 3: Calculation Method 3

7.1 Annex 1: Calculation Method 1

Calculation method 1 used a polyline function to estimate the DSH nominal routing. The polyline function allows the length of the DSH in a wavy path to be approximated. One nominal wave is represented by 4 arcs and two straight sections (Fig. 17). The path represents the central axis through the circular cross-section of the DSH. In order for the path with the assumed bending radius to pass through the amplitude (peak to peak, e.g. 250 mm), the error should be skimmed and a second polyline with an increased amplitude (for 250 mm, it will be 292.6 mm) should be created, giving the required path for the amplitude of 250 mm after declaring the bending radius (see the example in Fig. 17). As we only round corners in this method, there are straight sections that do not exist in the actual routing. For this study, the length stored in one wave was calculated for amplitudes of 250–530 mm every 10 mm, and the results are summarized in Table 8.

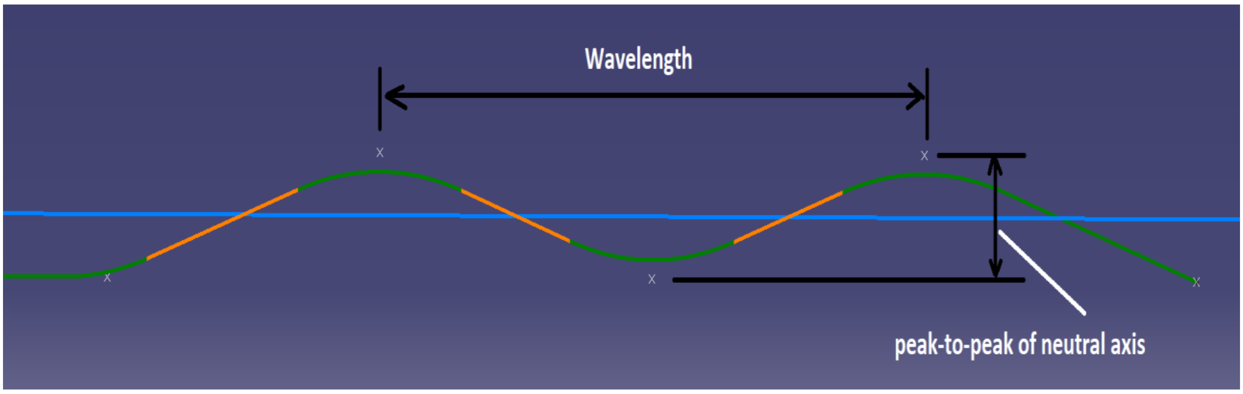

Fig. 19 Wave geometry created by polyline function.

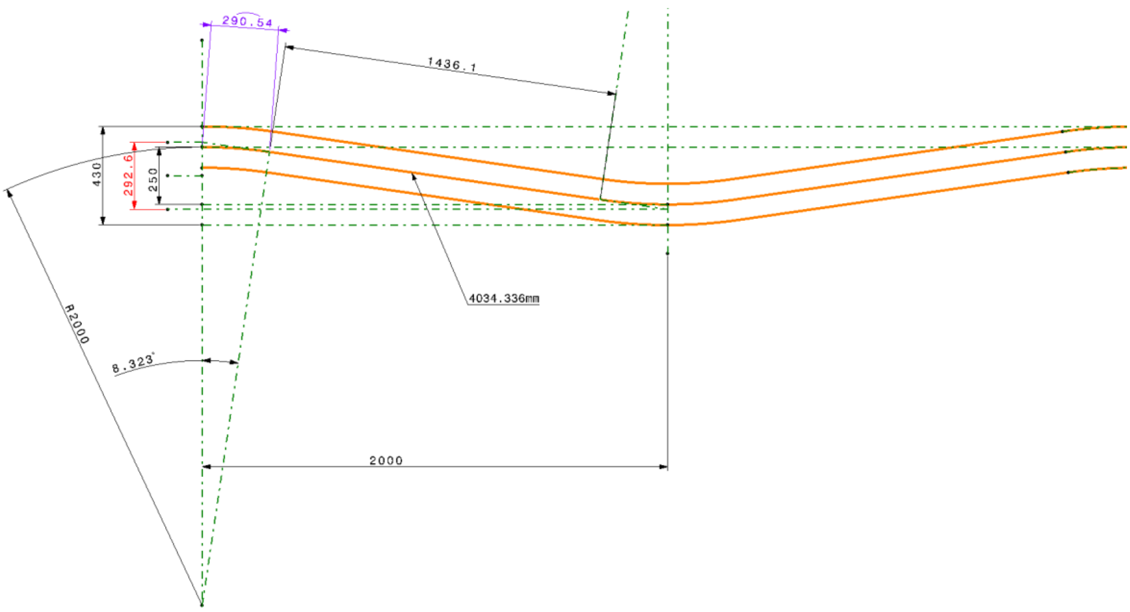

Fig. 20. Parameters used in polyline function (on example of theoretical p-p 250 mm amplitude), source: ST1403154_01.

Table 8. Received results: method 1

Theoretical P-P (Tp) [mm]	Polyline method P-P (Pp) [mm]	L [mm]	Δ [mm]
250	292.6	4034.336	34.34
260	306.8	4037.297	37.3
270	321.4	4040.421	40.42
280	336.1	4043.643	43.64
290	351.3	4047.047	47.05
300	366.7	4050.566	50.57
310	382.5	4054.241	54.24
320	398.8	4058.094	58.09
330	415.4	4062.074	62.07
340	432.5	4066.225	66.23
350	450	4070.516	70.52
360	468.2	4075.015	75.02
370	486.8	4079.641	79.64
380	506.1	4084.459	84.46
390	526.1	4089.458	89.46
400	546.9	4094.651	94.65
410	568.5	4100.02	100.02
420	591	4105.572	105.57
430	614.7	4111.355	111.35
440	639.7	4117.362	117.36
450	666	4123.553	123.55
460	694	4129.973	129.97
470	724.1	4136.644	136.64
480	756.8	4143.581	143.58
490	793	4150.836	150.84
500	833.4	4158.341	158.34
510	880.5	4166.213	166.21
520	938.5	4174.47	174.47
530	1022	4183.256	183.26

7.2 Annex 2: Calculation Method 2

To verify a borderline case (max. stored length in one nominal wave), a theoretical calculation was performed. This second calculation method assumes the ideal case in which there are no straight sections and uses basic mathematical relationships related to the segments of a circle. The transition from one arc to the next takes place immediately assuming a wavelength of 4 m (chord × 2).

The wavelength consists of 4 equal sections of arcs that can be grouped into 2 pairs. In this calculation method, a variable parameter was adopted: peak to peak value (arc height: (f) × 2), which translates into the value of the bending radius (R) and the obtained wavelength (L).

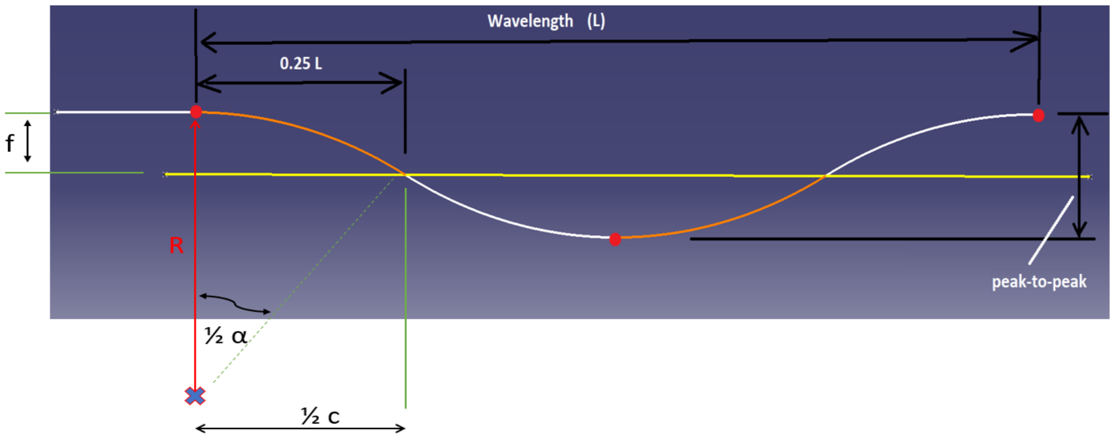

Fig. 21 Wave geometry assumptions used in method 2

$$R = \frac{4f^2 + c^2}{8f} \ [mm]$$

$$\propto = 2 \cdot \sin^{-1}\left(\frac{c}{2R}\right) \ [°]$$

$$L = 2 \cdot \frac{\alpha \cdot R \cdot \pi}{180} = 2 \cdot 2 \cdot \frac{4f^2 + c^2}{8f} \cdot \sin^{-1}\frac{4 \cdot c \cdot f}{4f^2 + c^2} \ [mm]$$

The obtained values were collected in the table below. In this method, the maximum p-p parameter is 530 mm (above this value we get a radius below 2000 mm).

Table 9. Received results: method 2

P-P [mm]	f [mm]	R [mm]	∝ [°]	L [mm]	Δ [mm]
250.00	125.00	4062.50	28.50	4041.54	41.54
260.00	130.00	3911.15	29.63	4044.92	44.92
270.00	135.00	3771.20	30.75	4048.42	48.42
280.00	140.00	3641.43	31.88	4052.06	52.06
290.00	145.00	3520.78	33.00	4055.83	55.83
300.00	150.00	3408.33	34.12	4059.73	59.73
310.00	155.00	3303.31	35.24	4063.76	63.76
320.00	160.00	3205.00	36.36	4067.92	67.92
330.00	165.00	3112.80	37.48	4072.21	72.21

340.00	170.00	3026.18	38.59	4076.63	76.63
350.00	175.00	2944.64	39.70	4081.17	81.17
360.00	180.00	2867.78	40.82	4085.85	85.85
370.00	185.00	2795.20	41.92	4090.65	90.65
380.00	190.00	2726.58	43.03	4095.58	95.58
390.00	195.00	2661.60	44.14	4100.64	100.64
400.00	200.00	2600.00	45.24	4105.83	105.83
410.00	205.00	2541.52	46.34	4111.14	111.14
420.00	210.00	2485.95	47.44	4116.58	116.58
430.00	215.00	2433.08	48.54	4122.15	122.15
440.00	220.00	2382.73	49.63	4127.84	127.84
450.00	225.00	2334.72	50.72	4133.66	133.66
460.00	230.00	2288.91	51.81	4139.61	139.61
470.00	235.00	2245.16	52.90	4145.68	145.68
480.00	240.00	2203.33	53.98	4151.87	151.87
490.00	245.00	2163.32	55.07	4158.19	158.19
500.00	250.00	2125.00	56.14	4164.64	164.64
510.00	255.00	2088.28	57.22	4171.21	171.21
520.00	260.00	2053.08	58.30	4177.90	177.90
530.00	265.00	2019.29	59.37	4184.71	184.71
540.00	270.00	1986.85	60.44	4191.65	191.65
550.00	275.00	1955.68	61.51	4198.71	198.71

7.3 Annex 3: Calculation Method 3

The final calculation method used a spline function. The nominal wave pattern in this method is described by the position of control points and routing geometry properties associated with these points (tangent direction, tangent tension, curvature direction and curvature radius). To describe the nominal path even more precisely, straight sections were used at the fixed points (in the intended place of the clamp or cleat, 300 mm as nominal). The geometries used in the nominal wave are shown in the Fig 18.

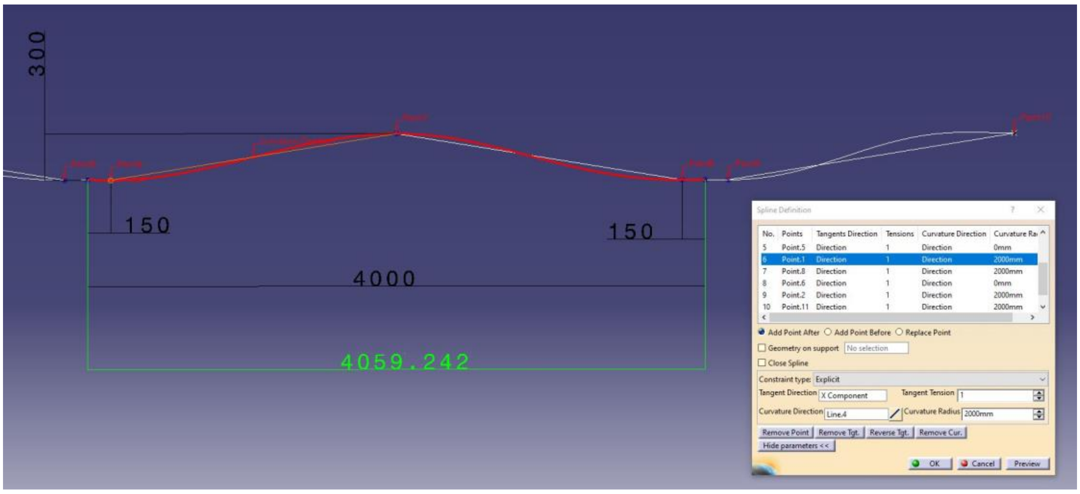

Fig. 22 Method 3 – control points for spline function, source: ST1503563_01

Table 10. Received results: method 3

P-P [mm]	L [mm]	Δ [mm]
250.00	4040.54	40.54
260.00	4044.00	44.00
270.00	4047.59	47.59
280.00	4051.33	51.33
290.00	4055.21	55.21
300.00	4059.24	59.24
310.00	4063.42	63.42
320.00	4067.73	67.73
330.00	4072.20	72.20
340.00	4076.79	76.79
350.00	4081.54	81.54
360.00	4086.42	86.42
370.00	4091.45	91.45
380.00	4096.62	96.62
390.00	4101.92	101.92
400.00	4107.36	107.36
410.00	4112.95	4112.95
420.00	4118.67	118.67
430.00	4124.53	124.53
440.00	4130.52	130.52
450.00	4136.65	136.65
460.00	4142.91	142.91
470.00	4149.31	149.31
480.00	4155.85	155.85
490.00	4162.52	162.52
500.00	4169.32	169.32
510.00	4176.25	176.25
520.00	4183.31	183.31
530.00	4190.50	190.50
540.00	4197.83	197.83