Status of the cryostat for the HL-LHC insertion magnets and modal analysis

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The “triplet” cryostat string

Ø 630 mm
~ 10.1 / 9.8 m length

Ø 570 mm
~ 7.4 m length

~ 2 ton per meter length

Ø 630 mm
6.1 m length
LHC triplet and dipole cross sections

Preference for column support posts but LHC layout cannot fit a larger cold mass plus pumping lines.

Alignment principle: The magnet position w.r.t vacuum vessel is measured (fiducialization); the cryo-magnet is then positioned in space by moving the whole assembly on support jacks. Cold supports are not adjustable.
HL-LHC insertion region cross-section

- Column support posts
  - Reinforced thickness due to high longitudinal pressure end loads
  - Conical for higher stiffness, hence better stability
  - Compression stiffness: **488 kN/mm (+ 77%)**
  - Transverse stiffness: **52 kN/mm (+ 148%)**
  - 1st Natural frequency: **8.8 Hz (+ 110%)**
- Particular vacuum vessel design allowing for larger cold mass and piping inside a cryostat of the same diameter
- Direct measurement of cold mass absolute position with frequency scanning interferometry
- Special assembly procedure
Cryostat design (ex. Q2 IR1 Right)

- Cold mass rests on 3 support posts
- Cold mass position monitoring (FSI)
- Cold mass, thermal shield and cryo-piping with central fixed point
- Tie-rod as longitudinal anchor (performs both in compression and tension)
  - Can be mounted on either side of the central support post
  - Designed to work in compression and tension
  - Functional specification [https://edms.cern.ch/document/1856323/0.1](https://edms.cern.ch/document/1856323/0.1)
    - 13 tonne on either direction
    - Adjustment range +/-10 mm
    - Resolution +/- 0.05 mm with differential screw
    - No adjustment under load
    - Not remotely operated
- Service module always on the IP side (phase separator, pumping manifold, BPM feedthroughs)
- Interconnect sliding sleeve opens towards the IP
- Survey targets
- One feedthrough for cold mass instrumentation and one feedthrough for CLIQ leads
- Pressure relief valve(s) for insulation vacuum
- Lifting points
- Phase separator can be connected to its magnet or the neighbouring magnet depending on tunnel slope
- Cryo-assembly isostatically supported on 3 jacks
Cryostat supports and vacuum vessel design

- Cryostat interface meeting 29/8/2017: decision to implement isostatic support (3 jacks instead of 4) [https://indico.cern.ch/event/661726/]
- Small difference in length between Q1/3 and Q2: same interfaces to simplify assembly tooling
- Optimisation of jack locations for minimum cold mass deformation presented at WGA#3 18/10/207 [https://indico.cern.ch/event/666376/]
  - Goal: Interface points between cold mass and vacuum vessel deform evenly
  - Total displacement of cold mass interfaces ~130 micron
  - Contribution of vacuum vessel deformation to cold bore misalignment: ~60 to 80 um
Fixed support post

Conical GFRE post

Heat intercept and termal shield support ("cost free" supporting of the termal shield)

Access door in vacuum vessel for assembly

Thermalisation straps

Top flange bolted to cold mass, bottom flange bolted to vacuum vessel

Shims for out of straigtness

NC mitigation on vertical plane

Vacuum vessel cover
Sliding support post

- Sliding thermal shield guides
- Conical GFRE post
- Heat intercept and thermal shield support (heat loads to support the thermal shield)
- Sliding surface
- **Top flange bolted to cold mass**
- Thermalisation straps
- Straightness NC mitigation in horizontal plane
- Guiding key and slot
- Shims for out of straightness NC mitigation on vertical plane
- Vacuum vessel cover
Interconnect expansion joints

- Universal expansion joints for **minimum impact on alignment**
- Specifications:
  - Design pressure (PS): from 4 to 25 bar internal relative pressure
  - Axial cyclic movements up to 46mm (500 cycles)
  - Temperature range: [1.9 K ; 300 K]
  - Nominal diameters: from Ø10 to Ø110 mm
- Quantity:
  - up to 100 bellows and flexibles per side
- Design optimisation:
  - Minimise outer diameter for integration purposes
  - Minimise axial and lateral spring rates
  - Minimise number of plies
  - Minimise the number of different bellows
- Bellows project progress status:
  - Dedicated pre-design software developed based on **European Pressure Directive** (EN13445 & EN14917+A1).
  - Most used bellows are pre-designed and loads evaluated
    - Axial rigidity up to 250 N/mm per universal expansion joint
  - Exceptional cases under study: End of Q1, Interconnection equipped with jumper, interface with DFX
## Modal analysis – Horizontal plane

<table>
<thead>
<tr>
<th>N.</th>
<th>Mode direction</th>
<th>Modal shape</th>
<th>LHC Dipole</th>
<th>HL-LHC Triplets</th>
<th>Additional Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>Lateral swing</td>
<td><img src="image1" alt="Modal Shape" /></td>
<td>4 Hz</td>
<td>8.8 Hz</td>
<td>--</td>
</tr>
<tr>
<td>2)</td>
<td>Lateral</td>
<td><img src="image2" alt="Modal Shape" /></td>
<td>8 Hz</td>
<td>13 Hz</td>
<td>Different cold mass deformation</td>
</tr>
<tr>
<td>3)</td>
<td>Lateral</td>
<td><img src="image3" alt="Modal Shape" /></td>
<td>8 Hz</td>
<td>14 Hz</td>
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<tr>
<td>4)</td>
<td>Lateral</td>
<td><img src="image4" alt="Modal Shape" /></td>
<td>14 Hz</td>
<td>26 Hz</td>
<td>--</td>
</tr>
<tr>
<td>5)</td>
<td>Lateral swing</td>
<td><img src="image5" alt="Modal Shape" /></td>
<td>26 Hz</td>
<td>27 Hz</td>
<td>Different cold mass deformation</td>
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<tr>
<td>6)</td>
<td>Lateral</td>
<td><img src="image6" alt="Modal Shape" /></td>
<td>26 Hz</td>
<td>48 Hz</td>
<td>Vessel vibration</td>
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<tr>
<td>7)</td>
<td>Lateral</td>
<td><img src="image7" alt="Modal Shape" /></td>
<td>42 Hz</td>
<td>76 Hz</td>
<td>Vessel vibration</td>
</tr>
</tbody>
</table>
Horizontal plane modes

1) Lateral swing at 8.8 Hz

2) Lateral at 13 Hz

3) Lateral at 14 Hz

5) Lateral swing at 27 Hz
## Modal analysis – Vertical plane

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<tr>
<td>1)</td>
<td>Vertical</td>
<td><img src="image1" alt="Modal shape" /></td>
<td>8 Hz</td>
<td>16 Hz</td>
<td>Vessel vibration</td>
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<tr>
<td>2)</td>
<td>Vertical &amp; longitudinal</td>
<td><img src="image2" alt="Modal shape" /></td>
<td>14 Hz</td>
<td>30 Hz</td>
<td>--</td>
</tr>
<tr>
<td>3)</td>
<td>Vertical</td>
<td><img src="image3" alt="Modal shape" /></td>
<td>18.5 Hz</td>
<td>28 Hz</td>
<td>Slightly different modal shape</td>
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<tr>
<td>4)</td>
<td>Vertical</td>
<td><img src="image4" alt="Modal shape" /></td>
<td>20 Hz</td>
<td>20 Hz</td>
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<tr>
<td>5)</td>
<td>Vertical</td>
<td><img src="image5" alt="Modal shape" /></td>
<td>28 Hz</td>
<td>47 Hz</td>
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<tr>
<td>6)</td>
<td>Vertical</td>
<td><img src="image6" alt="Modal shape" /></td>
<td>46 Hz</td>
<td>68 Hz</td>
<td>Vessel vibration</td>
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</tbody>
</table>

Experimental modal analysis of LHC dipole by K. Artoos et al. EDMS 348871, 2002
Vertical plane modes

1) Vertical at 16 Hz

2) Vertical & Longitudinal at 30 Hz

4) Vertical at 20 Hz
Modal analysis – Longitudinal & Others

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<td>1)</td>
<td>Longitudinal</td>
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<tr>
<td>2)</td>
<td>Vertical &amp; longitudinal</td>
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<td>14 Hz</td>
<td>30 Hz</td>
<td>--</td>
</tr>
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- **Torsional** cold mass deformation at 46 Hz
- First **vacuum vessel** modes at 35 Hz, 60 Hz, 63 Hz

**Reference LHC cryodipole modal analysis:**

A concept of cryostat and cold mass that...

- **Fits in the tunnel** (same width as other LHC cryostats) and encloses all the cryogenic piping running along the string, including phase separators.
- Interconnects based on all welded seals (LHC solution), including space required for **cutting and welding** machines.
- Minimises work in the **tunnel**, by design.
- **Cold mass supports** based on LHC dipole and SSS concept. Sledge on rails cryostating principle.
- **Isostatic support** of the cryo-assembly, designed to accommodate pressure end loads (vacuum and quench) and allow remote alignment.
  - Aims at **alignment stability** requirements comparable to those of the LHC SSS and cryo-dipole.
  - Minimises the number of component and assembly **variants**.