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Engineering and Structural Assessment for the design of the DTT Central Solenoid

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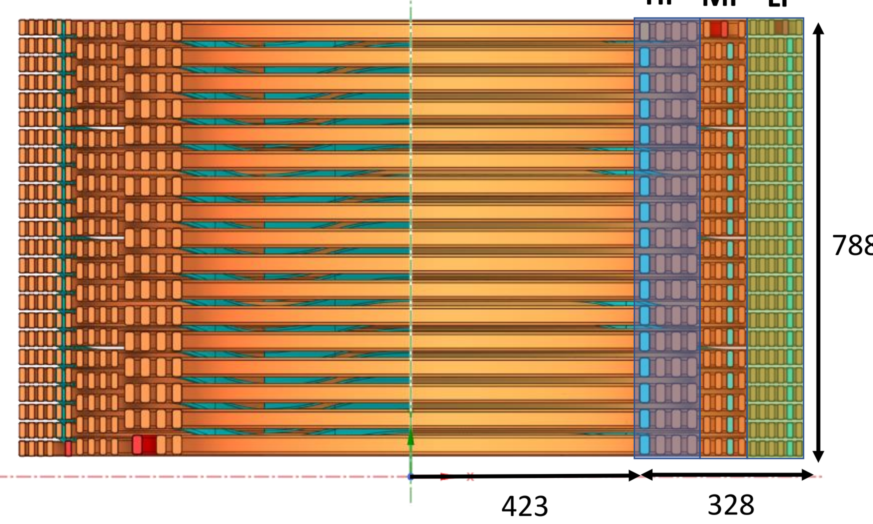
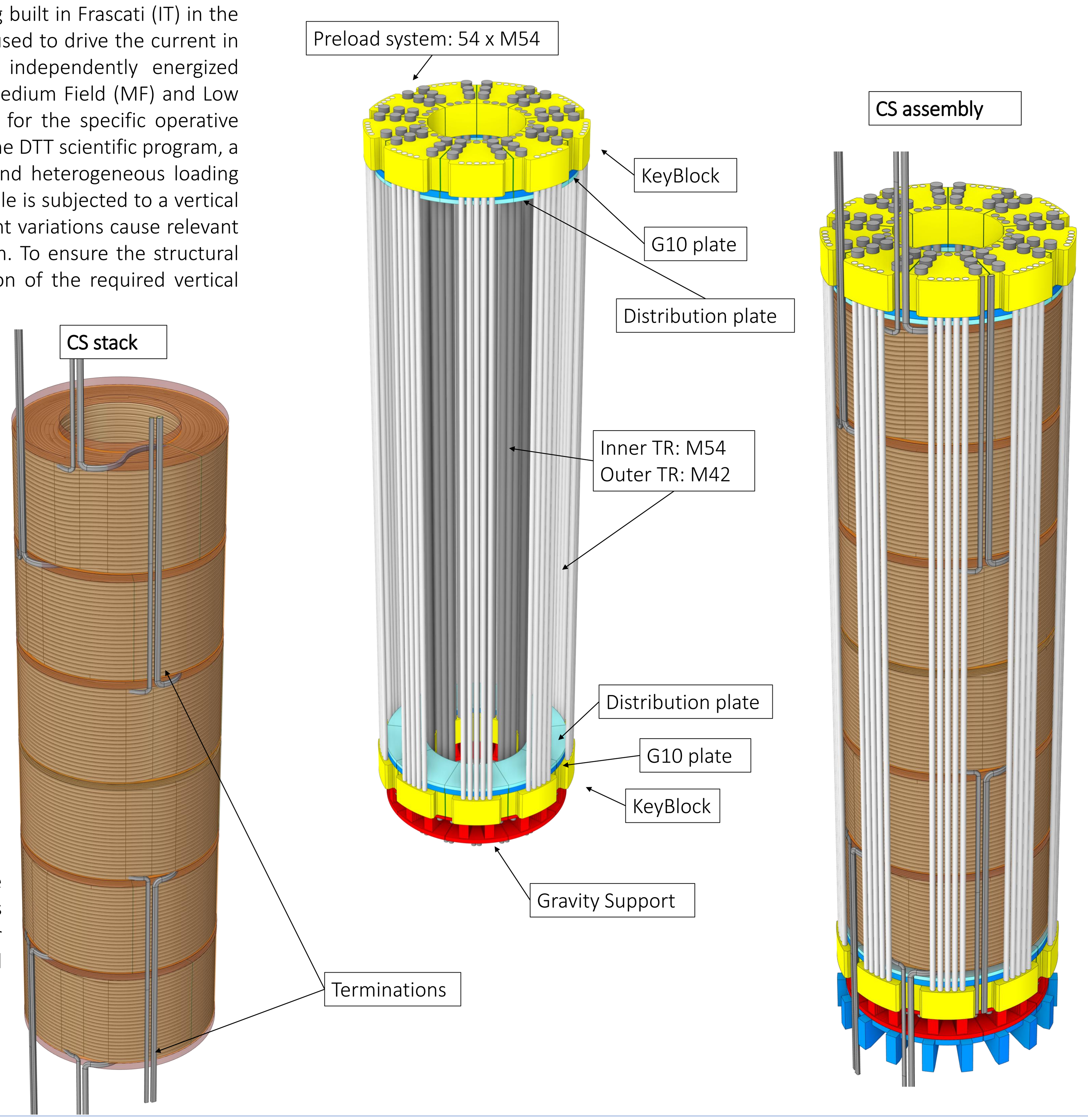
INTRODUCTION

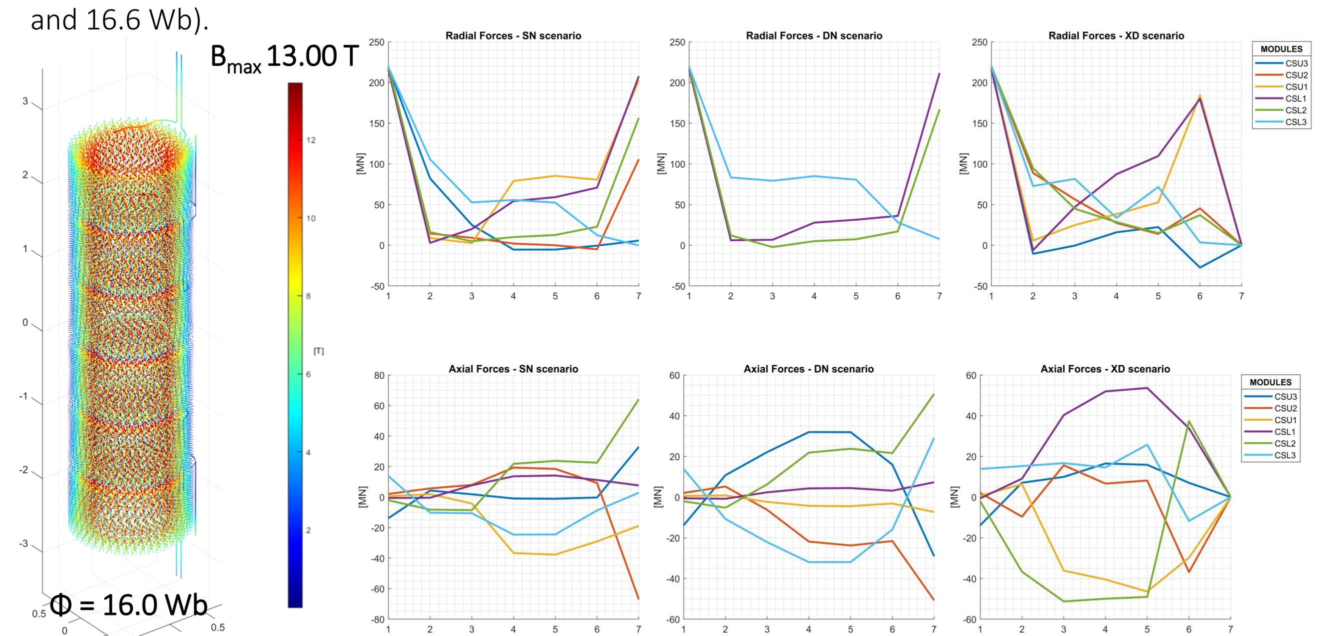
The "Divertor Tokamak Test" (DTT) is an experimental fusion reactor being built in Frascati (IT) in the framework of the European Fusion Roadmap. The DTT Central Solenoid, used to drive the current in the magnetically coupled plasma, comprises six Nb_3Sn layer-wound independently energized modules. Each module is made of three sub-modules: High Field (HF), Medium Field (MF) and Low Field (LF) grades. Each sub-module includes a different CICC, optimized for the specific operative values of magnetic field and current density. In order to meet all goals of the DTT scientific program, a variety of plasma scenarios have been designed. These cause intense and heterogeneous loading conditions for the CS stack; from the mechanical point of view, each module is subjected to a vertical expansion or compression and to a huge radial action, whereas the current variations cause relevant heat loads due to AC losses, with impact on the coil temperature margin. To ensure the structural integrity of the magnet, an external system is defined for the application of the required vertical preload to the CS modules.





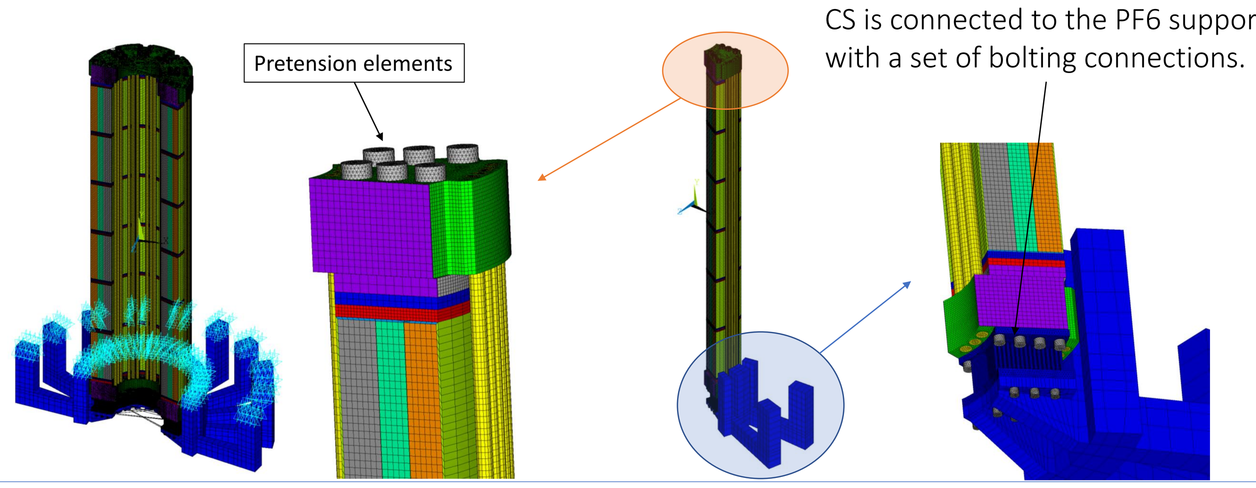
The precompression structure prevents axial repulsion and follows the shrinking of the stack preventing any detachment between modules during all scenarios. This system consists of nine sets of inner and outer Tie Rods, one upper block and one lower anchor block for the rod, as well as nine sets of six Superbolt pretensioners for the preload application.

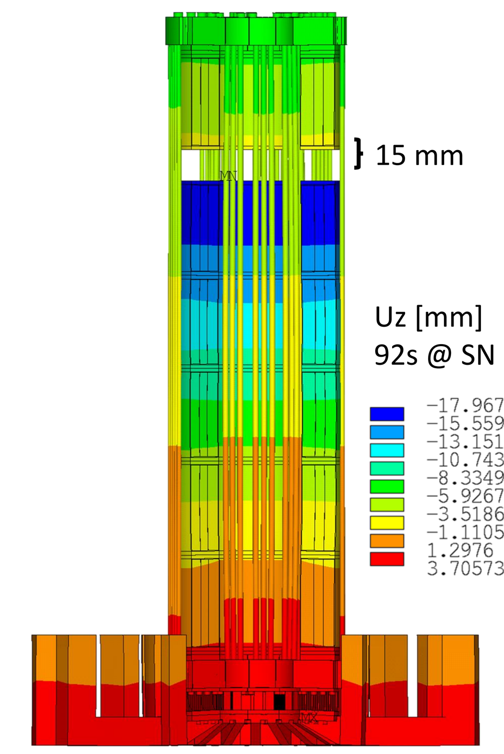
REAL WINDING ANALYSES: To evaluate the magnetic field and the Lorentz forces generated by the real winding of the CS modules a dedicated model has been defined. The peak field and the magnetic flux exhibit a reduction of 4% compared to the data obtained with the ideal model (13.5 T and 16.6 Wb).

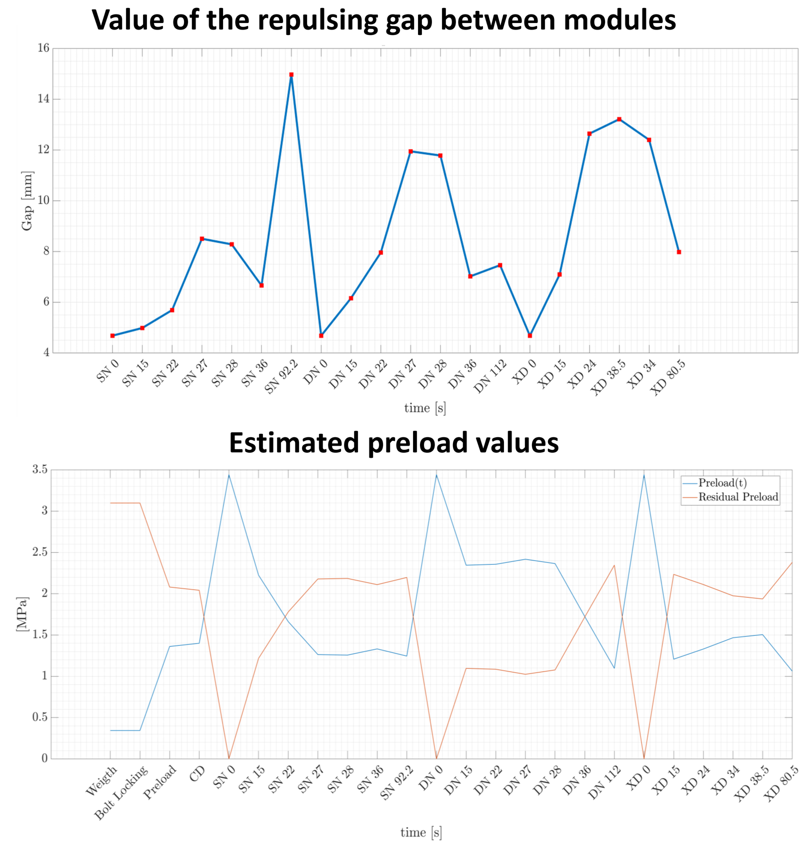


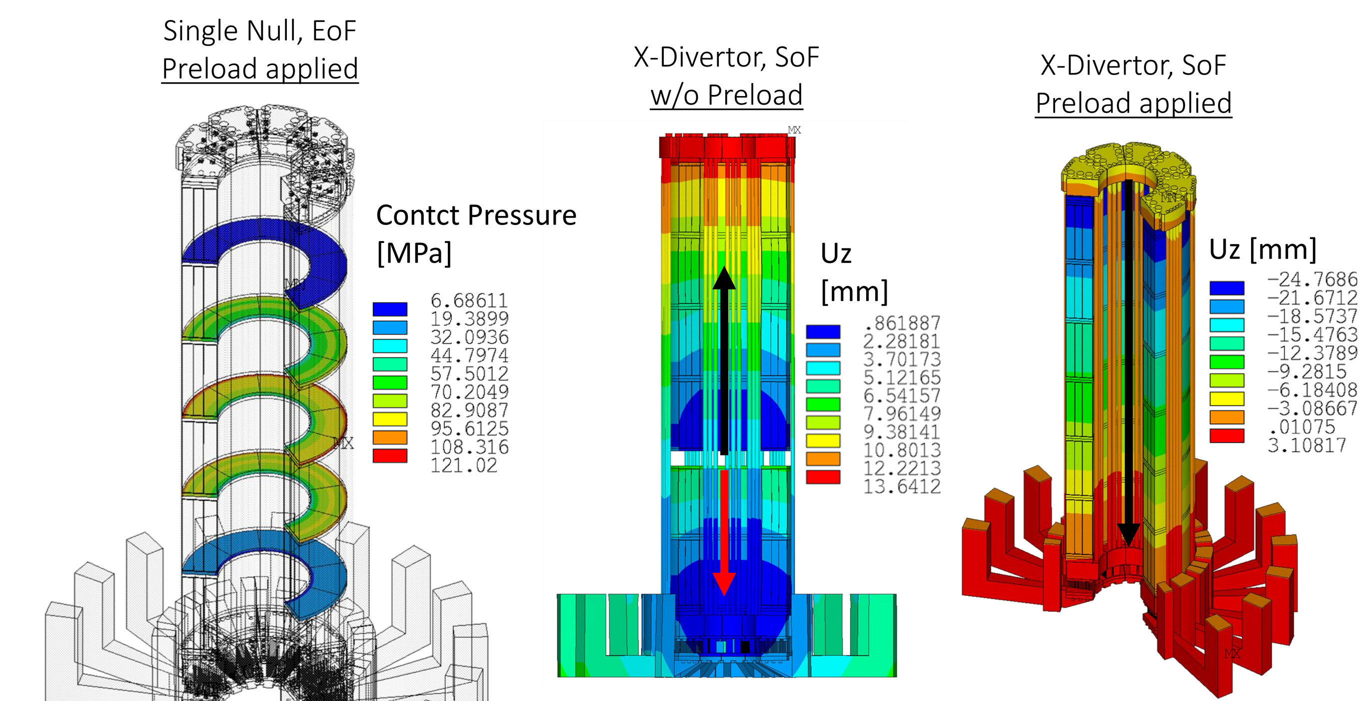
PRELOAD VALUE DEFINITION: The value to be applied during the CS assembly can be defined as the maximum required value to close all the possible gaps which occur in operation. The FEM analyses consider the Electromagnetic loads and the Cooldown for the calculation of the gap at each time point. Different components on the FEM model are connected via mechanical contacts which can reproduce bonded connections for welded interfaces or friction connection where detachment condition can occur.

The gravity support system of the CS is connected to the PF6 support with a set of bolting connections.





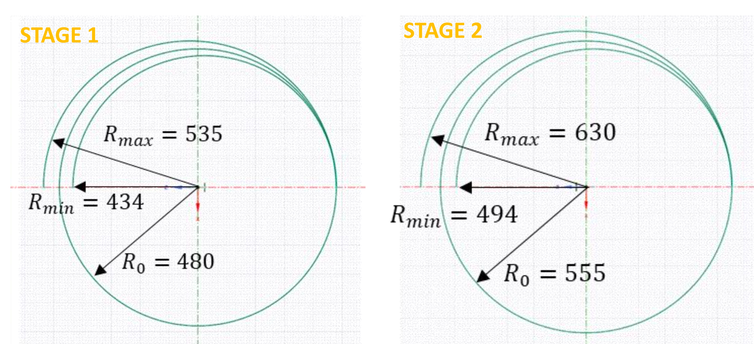




The analysis carried out demonstrates that the estimated preload value ensures the correct operation of the stack with zero-gap between modules.

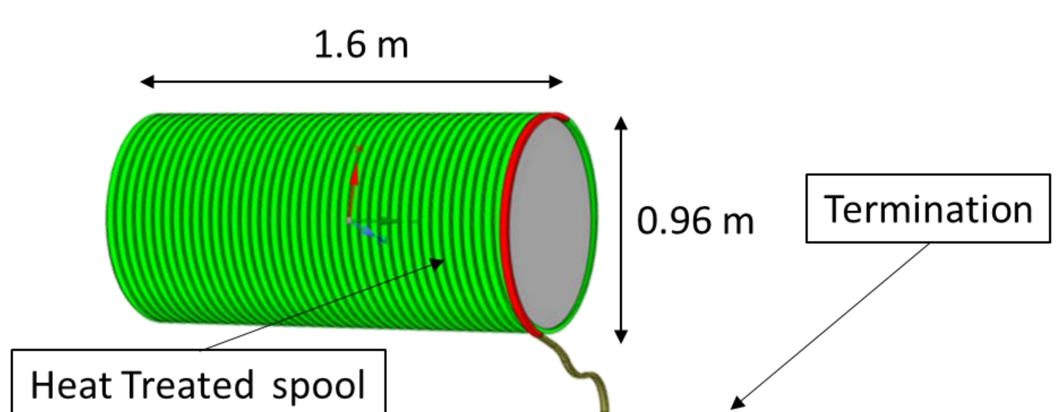
WIND, REACT & TRANSFER SPOOLING AND UNSPOOLING PROCESS

The reference design considers a Wind&React (W&R) assembly solution. To mitigate the risk of inter-turn insulation failure this study investigates "Alternative winding approaches" to include a Kapton barrier. A classical process for the Kapton application after the heat treatment (HT) is based on the complete or partial cables re-straightening. We set a limit to the bending strain that can be applied on Nb_3Sn during the spooling operations equal to 0.2%. The dimensions of the HF sub-module are particularly critical for the straightening: the dimensions of the cable are 34.54 x 9.185 with an internal radius of 434 mm. The maximum and the minimum strain can be calculated as: $\varepsilon_{max} = \frac{r}{R}\frac{(R_0-R)}{(R_0+r)}$ and $\varepsilon_{min} = \frac{r}{R}\frac{(R-R_0)}{(R_0-r)}$, r is the cross-section radius, R_0 and R the initial and the final curvature radius. By reversing this formula, we get the maximum and the minimum achievable radii. An initial winding radius has been selected for the heat treatment of each sub-module to remain below the strain limit reaching the needed final Rmin and Rmax. The HF sub-module has been divided into two stages to stay within the 0.2% limit:

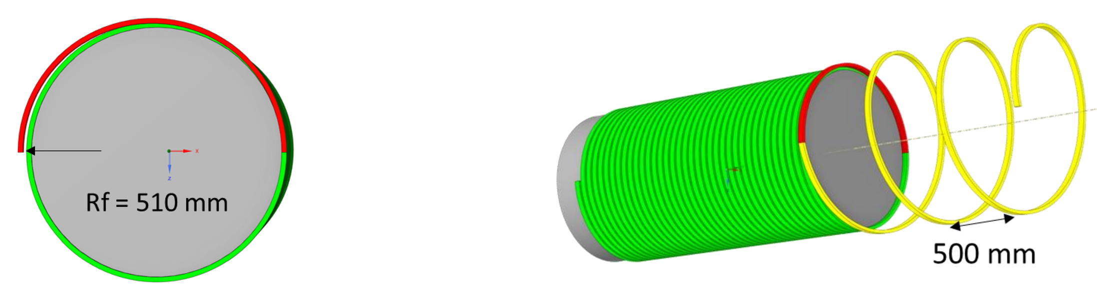


unit [mm]	HF stage 1	HF stage 2
r	9.185	9.185
ε	0.20%	0.20%
Inner Radius 1st layer	434	495
Outer Radius 2nd layer	483	544
Radius HT spool	480	555
$R_{min}(\varepsilon)$	433.8	494.3
$R_{max}(\varepsilon)$	534.8	629.9
Turns HT spool	34	29
Height of HT spool	1508	1287

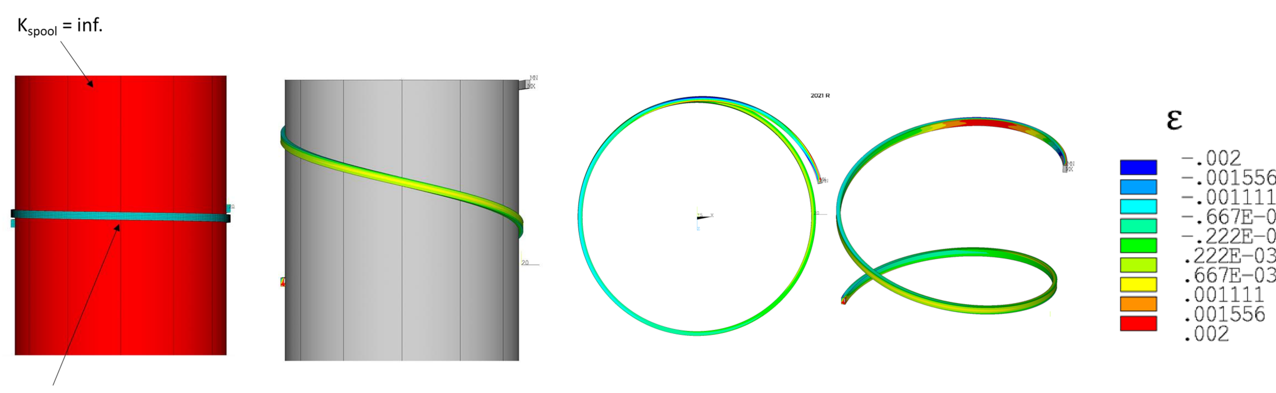
OPTION 1: This first analysed option opts for a combined radial and mainly axial reopening of the cable and considers four different spools for the HT, two stages for the HF sub-module, one for the MF and one for the LF sub-module. To analyse the process, the transfer of the first stage of the HF cable is described. This phase leads to complete the first two layers of a CS module starting from the heat treatment spool:



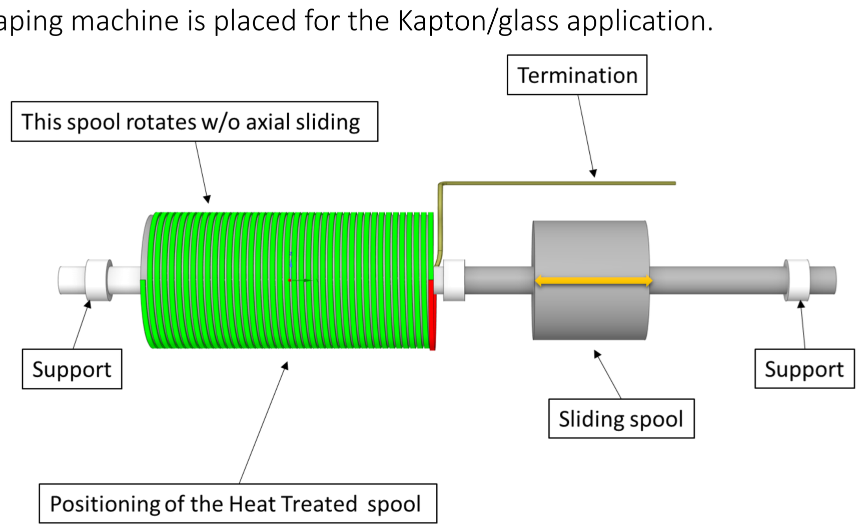
Strain phase A1, to obtain an outer radius of the cable greater than the radius of last layer. The cable wound on the final spool must be able to slide axially in the internal envelope of the reopened cable **Strain phase A2**, to obtain the needed space for the taping machine and the sandblasting.



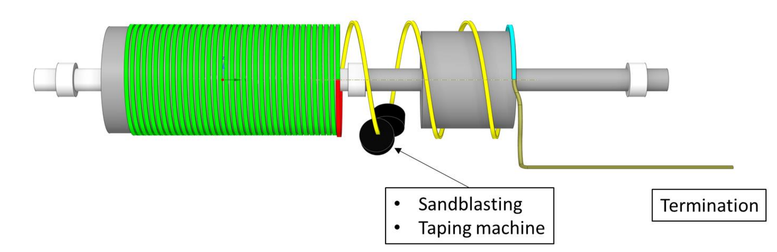
To validate the phases A1 and A2, a FEM model has been defined to evaluate the maximum longitudinal strain. The model comprises a complete turn and a half, and a cylindrical target surface to simulate the spool. One end of the cable is constrained in all directions, while at the other end a radial displacement to 33 mm, and a vertical displacement of 0.75 m are applied.



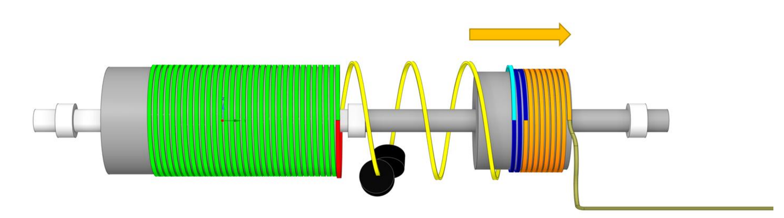
The system provides for an axial unwinding and rewinding of the cable on the final spool. The HT spool rotates on an endless screw while the final coaxial spool forces the cable by rotating and sliding in an axial direction. All cables are wound and HT on a dummy spool and then by imposing a bending strain are transferred to the final winding spool. In the space between the two spools a taping machine is placed for the Kapton/glass application.



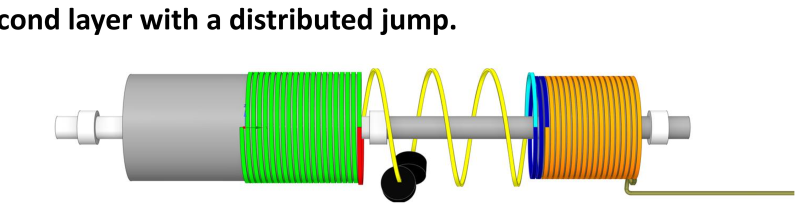
1. **Application of the strain phases A1 and A2. The taping machine is placed on the line and the deformed cable rotates and advances to the entry point of the final spool.**



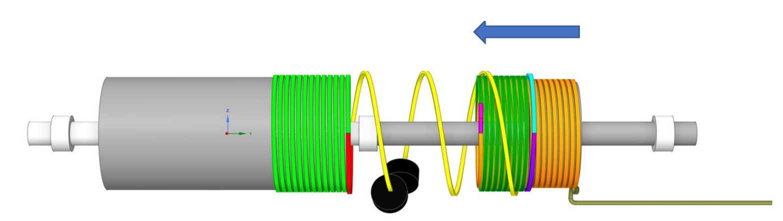
2. **The spool rotates and slides axially forcing the cable on the inner radius of the CS.**



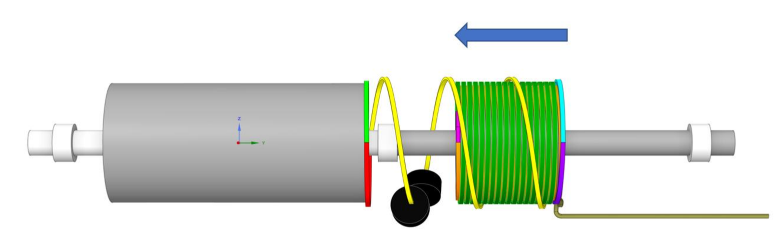
3. **Once the first layer is complete a transition zone with a different pitch switch to the second layer with a distributed jump.**



4. **The final spool moves backward spooling the second layer.**

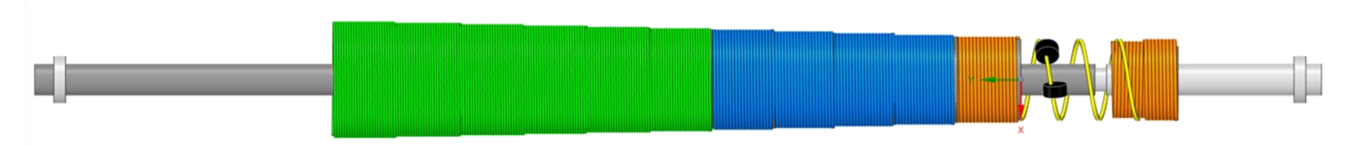


5. **The winding proceeds to complete the process.**

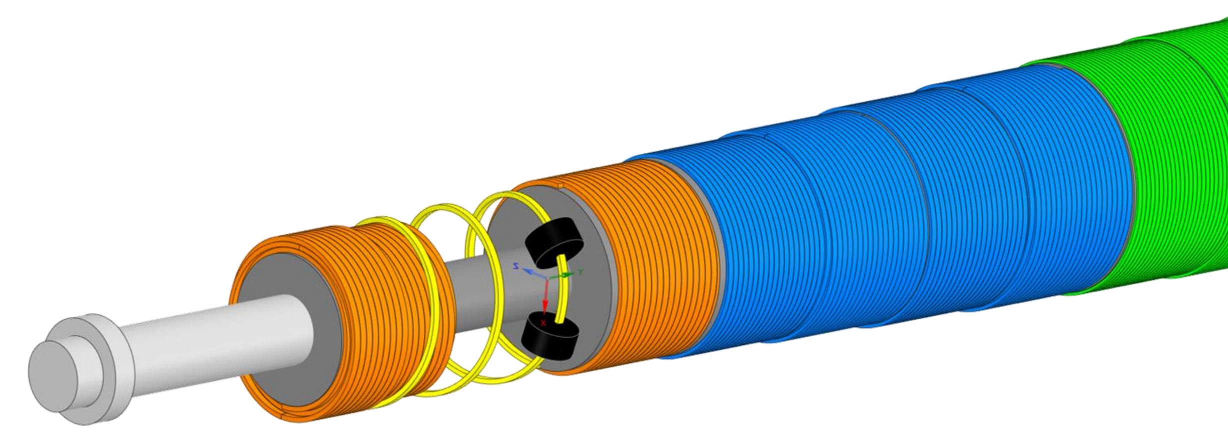


The internal joints required to connect the different unit lengths shall be either prepared before the heat treatment, for example in the form of a curved twin box, or joints to be realized after the reaction heat treatment should be developed.

OPTION 2: A different way to complete the transfer considers a single spool, 11 m long, for the simultaneous HT of all conductors. Each of the 14th layers is wound on its final diameter and then transferred to the final spool essentially without any radial strain imposition. In this option each joint must be prepared and placed in position before the heat treatment and all the layer jumps must be distributed over 180-degrees sectors. The system described for the axial reopening of the cable is the same of the Option 1, but in this case only the axial strain is needed as each cable is already placed on its final radius. Once the HT is completed, the whole cable system must be transferred on a telescopic spool, capable of rotating as endless screw and proceeds axially shortening over the first HF diameter.



SCHEMATIC VIEW: the final spool slides axially forcing the cable on the final winding.



Starting from the spool corresponding to the 1st layer of the grade HF (L1), each spool following in the winding system contains a core identical to L1 and n-1 coaxial cylinders of thickness:
$t = d_r(L_i + 1) - d_r(L_i)$.
With each rotation of the final spool, the entire winding system moves forward at the same time rotating on an endless screw. The core of each spool remains stationary, the coaxial cylinders run each on the one of $d_r(L_i - 1)$.
At the end of the transfer of the 1st HF layer, the last stage (6th LF layer) of the HT spool will be completely empty. Once also the last layer is completed, the entire lengths have been transferred. The empty winding spool has a mirrored pattern with respect to the original spool.

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