Technical Note for the Market Survey on HTS demountable joints

In preparation for a TDP Call for Tender

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1. Introduction to F4E Technology Development Programme (TDP)

Fusion for Energy (F4E) is introducing the Technology Development Programme (TDP), a strategic initiative designed to accelerate the maturation of early-stage technologies and prepare them for integration into future fusion projects. By bridging the gap between laboratory research and industrial application in fusion field, the programme aims to strengthen Europe's technological capabilities and foster a competitive fusion supply chain.

Through this programme, F4E will support research and development in critical fusion technologies that are not yet ready for industrial deployment. Periodic calls will address diverse technical areas essential for the development, construction and operation of fusion devices. Participating organisations will advance, test, and demonstrate innovative solutions while retaining intellectual property rights, provided they commit to transforming these results into operational technologies.

In this specific case the TDP action is dedicated to the technology of demountable joints for HTS magnets.

This initiative reflects F4E's commitment to technological innovation and collaboration. By mapping relevant technologies, consulting with industry and research partners, and developing comprehensive technology roadmaps, F4E and Eni are laying the foundation for a sustainable and competitive European fusion ecosystem with industrial implications.

2. Introduction to HTS demountable joints

In the last years several studies on demountable joints have been started for the potential application in fusion magnets. Indeed, they are considered as a keystone for enhancing machine maintainability and potentially modular design of superconducting magnets. Several industries and research institutions included demountable joints within their roadmap towards fusion electricity, such as CFS, Gauss Fusion and STEP – UKAEA. Despite the increasing interest of the industrial and scientific community, the Technology Readiness Level (TRL = 2) of such technology is still quite low and thus HTS demountable joints have been identified as critical fusion technology to be supported by the Technology Development Programme.

This TDP action is delivered through a collaboration between Fusion for Energy and ENI Spa. Potential bidders shall be aware that information from this survey and the potential subsequent action will be shared with both F4E and ENI staff. Legal mechanisms will be in place during the contract execution period to ensure that the information provided by suppliers will not be shared with other parties without the explicit agreement of the supplier. Ownership of the IP of the deliverables will remain with the suppliers under the conditions described in the final call for tender.

3. Description of the HTS demountable joint

3.1 Technical description

The demountable joint concept tends to reverse the way in which the superconducting (SC) magnets are commonly manufactured. Indeed, at the time being SC magnets are manufactured by winding long conductors in the desired shape. Joints are commonly introduced only when the single length of conductor is concluded or installed on the terminations of single sub-windings to be assembled (e.g. double pancake joints). They are generally permanent and not accessible. This manufacturing approach makes the magnets a monolithic object which potentially prevents easy access to components which may be constrained by the magnet itself.

The demountable joint concept allows to avoid the winding approach. Indeed, the magnet shape is obtained by the junction of modules, each of them composed of the predefined number of conductors. This approach would in principle allow the opening of the magnet even once in its final installation location, allowing easier access to all the systems which are normally embraced by the magnet in a fusion machine (e.g. the vacuum vessel), making maintenance faster and simpler. Moreover, the coil manufacturing complexity can be reduced, avoiding the winding of very long conductors in the prescribed shape, through the modularization of the magnet itself.

This big advantage comes with several drawbacks, first of all the exponential increase of the number of joints. Indeed, if in a wound magnet, the number of joints is limited to those necessary to connect the various conductor lengths, in a demountable magnet, the number of joints is equal to the number of conductors forming the magnet cross section, time the number of segments or modules in which the magnet is divided. This easily translates in several hundreds of joints per magnet. Considering that each joint is a heat load for the magnet due to Joule heating, it is of key importance to minimize the joint resistance as much as possible to minimize the impact on the cryoplant. Moreover, the electrical performances shall be guaranteed during the operation, while assuring leak tightness compatible with the cryostat vacuum level. In addition to that, it is of key importance to make demountable joints compatible with remote handling strategies. These aspects make the design and industrialization of demountable joints for superconducting magnets a great engineering challenge which, once resolved, may accelerate the commercialization of nuclear fusion electricity.

3.2 Basic technical requirements

The basic technical requirements for the demountable joint project subject of the future call for tender are reported in this section. Companies answering to this market survey are invited to express their opinion on the proposed technical requirements, to suggest any possible improvement and to highlight potential showstoppers.

In general, the project is aiming at the development of a general working demountable joint concept. Indeed, the joint concept to be developed shall not be optimized on a specific coil

design. For this reason, the technical requirements and performances are based on the SULTAN test facility performances, where potentially the joint can be tested.

Operating conditions: the demountable joint subject of this project shall withstand the following operating conditions:

- Temperature: 5 K – 20 K
- Pressure: $\geq 15\ bar$
- Transport current: 100 kA (maximum SULTAN performance)
- Magnetic field: 10.9 T (maximum SULTAN performance)

Reference conductor design: the demountable joint shall be compatible with the stacked tapes conductor design. A different conductor design can be accepted upon demonstration of potential better suitability.

Reference mechanical load: the joint shall withstand the peak mechanical load which can be obtained in the SULTAN test facility (maximum current of 100 kA and maximum magnetic field of 10.9 T). The transport current and the magnetic field are orthogonal and the Lorentz forces arising are repulsing between the two SULTAN legs. The local effect of the Lorentz forces on the demountable joints depends on the specific joint design. It is therefore the responsibility of the contractor to properly apply the mechanical load on the proposed design.

Thermal and Electromagnetic cycling: The joint performances, either mechanical and electrical, shall not degrade after 10 thermal (warm-up and cool-down) and electromagnetic cycles.

Vacuum compatibility: The joint design shall assure a maximum helium leak rate of $10^{-7}\ \frac{mbar \cdot l}{s}$ to be compatible with the SULTAN facility vacuum level.

Electrical performance: the single joint electrical resistance shall be below 1 $n\Omega$ allowing 0.1 $n\Omega$ as a target.

Electrical insulation: the joint design shall foresee an electrical insulation capable of withstanding a voltage of 1 kV (SULTAN requirement).

Maximum space occupation: the joint design shall be compatible with the aperture dimension of the SULTAN facility ($92 \pm 0.5\ mm \times 142 \pm 0.5\ mm$). According to the specific joint design the actual space occupation available shall be evaluated. It is contractor responsibility to fit the specific joint design within the allowable space occupation.

Material compatibility: the joint shall be designed without using any magnetic material ($\mu_r \leq 1.05$).

Geometrical constraints: the two legs shall be straight and parallel with a maximum overall length of 3605 mm, to allow for the proper insertion in the SULTAN opening.

4. Scope of the future Call For Tender (CFT) proposals

The future project strategy is still to be finalised, and a couple of approaches are being considered. The description of the possible project strategies is reported in this section so that potential suppliers can express their opinions and preferences on this aspect by answering to this market survey.

The project is expected to follow a phased approach to ensure effective monitoring of the results throughout its duration. All strategies outlined below should be considered as reference scenarios and may be adjusted depending on the outcomes achieved. F4E/Eni reserves the right to close the project or to reduce the number of bidders at any gate review should the results be deemed unsatisfactory, allowing the remaining contingency to be allocated either to more promising bidders or to other TDP projects.

4.1 Proposal 1: Detailed engineering design of a demountable joint

The first proposal is a fully funded approach which aims at financing two suppliers proposing their detailed engineering design of the demountable joint.

In Figure 1 the schematics of the project strategy is shown, highlighting the two foreseen phases, the intermediate gate review and the final deliverable. More details on each phase is reported below.

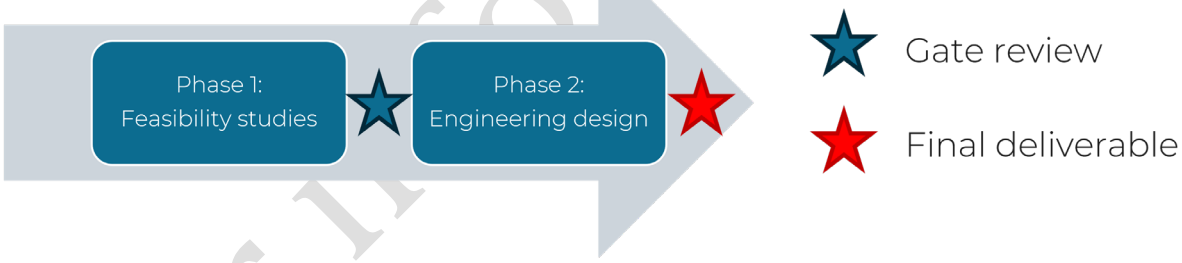

Figure 1. Project strategy proposal 1.

- ***Phase 1: Feasibility studies.***
  For this phase it is proposed to selected up to 4[1] bidders among all the participants to the cal land to pay 50 k€[1] per bidder to:
  - conduct comprehensive state-of-the-art assessments on the topic of demountable joints for HTS fusion magnets,
  - followed by a critical evaluation of the compatibility of existing designs with the defined technical requirements and operative conditions
  - identify, based on this analysis, a reference solution and develop a pre-conceptual design as reference document for the gate review.

[1] Number to be confirmed in the final call for tender documentation

- ***Gate review.***
  During the gate review, the pre-conceptual designs proposed by the selected bidders are analysed and evaluated on the basis of the technical soundness, of the preliminary results to demonstrate the potentialities to respect the technical requirements and of the overall manufacturability of the proposed concept. Among all the proposed concepts, up to two[1] of them are selected for the second phase of the call, which aims at the engineering design of the proposed concept.
- ***Phase 2: Engineering design & Small scale tests.***
  In this phase, it is proposed to pay the selected bidder(s) 400 k€[2] each to develop the detailed engineering design of the proposed concept. The effort shall be focused on the design of a SULTAN sample, thus respecting the requirements reported in this technical note, which will be furthermore detailed in the final technical specification. With the allocated budget the bidder shall:
  - Prepare detailed technical drawings
  - Support the design with suitable numerical analyses
  - Perform small scale tests on mock-ups to assess joints performances (e.g. electrical resistance, helium leak tightness, etc.)
- ***Final deliverable.***
  In the final deliverable the bidder shall include all the details of the developed engineering design of the joint, along with the technical drawings, the analyses results and the test results. The deliverable shall be submitted to Eni/F4E as a milestone document for the final payment.

4.2 Proposal 2: Manufacturing and test of a demountable joint SULTAN sample

The second proposal is a partly co-funded by the bidder approach which aims at reaching the final objective of manufacturing and performing full scale tests on a demountable joint SULTAN sample. The advantage of this second approach is that the design would be validated through a full scale, full performance test and thus the final TRL would be higher. However, this strategy would require the financial contribution of the bidder to complete the third phase of the project as highlighted in Figure 2.

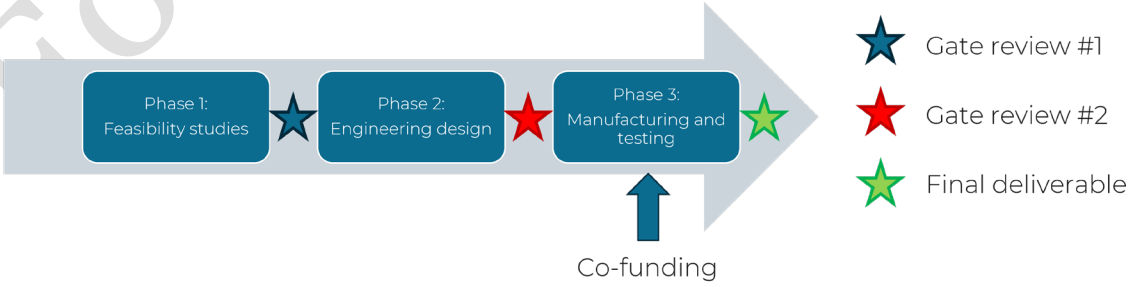

Figure 2. Project strategy proposal 2.

[2] Number to be confirmed in the final call for tender documentation

In this proposal, Phase 1 and gate review 1 are the same as in proposal 1, thus after gate review 1 demountable joint concepts will be awarded, and the engineering design phase is financed. The details from phase 2 are reported below.

- ***Phase 2: Engineering design.***
  In this phase it is proposed to pay the selected bidder(s) will be paid 300[3] k€ each to develop the detailed engineering design of the proposed concept. The effort shall be focused on the design of a SULTAN sample, thus respecting the requirements reported in this technical note, which will be furthermore detailed in the final technical specification. With the allocated budget the bidder shall:
    - Prepare detailed technical drawings
    - Support the design with suitable numerical analyses

  The details on the developed engineering design, along with the technical drawings and the analyses results, shall be included in a single final report to be delivered to Eni/F4E as reference document for gate review 2.
- ***Gate review 2.***
  During gate review 2, the engineering design proposed by the two bidders are analysed and evaluated based on technical soundness, quality of the technical drawing, completeness of the analyses results, overall manufacturability and estimated expected cost of the proposed design. Between the two proposed design, the most promising will be selected as reference design for the third phase of the project, which aims at manufacturing and testing a full-scale SULTAN sample.

- ***Phase 3: Manufacturing and full testing.***
  In this phase the awarded bidder will receive financial support (with the remaining TDP programme budget, ~200 k€[3]) to perform the following activities:
    - Perform sub-scale tests on mock-ups to assess specific joint performances (e.g. electrical resistance, helium leak tightness, etc.)
    - Perform specific manufacturing test (e.g. welding test, soldering tests, etc.)
    - Procurement of the materials
    - Manufacturing of the SULTAN sample
    - SULTAN test campaign
- Final deliverable.
  In the final deliverable the bidder shall include the manufacturing report including all joint detailed drawings, numerical analysis and the results of all the sub scale and manufacturing tests, along with the report summarizing the results of the SULTAN tests. The deliverable shall be submitted to Eni/F4E as a milestone document for the final payment.

[3] Number to be confirmed in the final call for tender documentation

5. Market survey

To establish an optimum project strategy, Eni/F4E needs to develop its understanding of the market with a comprehensive list of possible interested suppliers, along with their preferences and comments on the proposed strategies, suggestions on possible strategy improvements and their possible availability to partly co-finance the development of the project itself.

In the frame of the Market Survey, interested suppliers are invited to submit the requested information. This information will be visible to Eni/F4E only and will not be communicated to other parties, except if agreed upon by the respondent(s).

It is important to note that the content of this technical note must be considered for information only. All the data may be subject to change, also based on the market survey results. Only the tender documentation will prevail for the related forthcoming call for tender.