Non-linear MHD modelling of pellet injection for ELM control in ITER

Technical Specifications

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1 Purpose

The purpose of this contract is to provide the ITER Organization with computational analysis from 3D non-linear MHD simulations of pellets injected in ITER scenarios to establish the requirements for the pellet size and speed for the ITER pellet injector for ELM control. In addition, the consequences for the power fluxes at the ITER divertor during pellet triggered ELMs and the triggered ELM density losses will be evaluated and consequences for ITER operation derived. The assessment will include ITER scenarios at full field and current and scenarios foreseen in the development phase at intermediate field and current levels.

2 Scope

The standard ITER operating scenario is expected to have large amplitude Edge Localised Modes (ELMs). The resulting energy losses on a fast time scale may lead to an enhanced erosion of the divertor target and limit its lifetime. To limit the ELM enhanced erosion, the ELM energy losses need to be controlled. One of the methods for ELM control foreseen in ITER is the injection of Deuterium pellets. Present experiments [Baylor2013, Lang2013] show that ELMs can be triggered by pellets of a suitable size and injection speed. The specification of the pellets in the ITER pellet injector for ELM control must be set in consistency with these experiments. This requires an extrapolation to ITER of present results on a solid basis.
Validation of 3D non-linear MHD simulations of the ELM trigger by pellets in the DIII-D tokamak [Futatani2014] has shown that MHD simulations can provide the required basis and give estimates for the minimum pellet size and pellet speed required for ELM triggering in this device.

The objectives of the contract are to improve the prediction of the requirements on the pellet (with respect to pellet size, speed and injection geometry) for ELM control in ITER and to analyse the consequences of the injected pellets with respect to ELM energy and particle losses and divertor power loads.

The work in this contract involves the evaluation of the requirements on the minimum size of the pellets for ELM control in ITER as a function of the pellet speed and pellet injection geometry. Previous 3D non-linear MHD simulations on the requirements for pellets for ELM control in ITER have focused on the early onset of the ELM instability (due to the pellet induced pressure perturbation) without considering the ELM amplitude (energy and particle losses). In this contract, the pellet requirements are evaluated based on the 3D MHD simulations of the complete ELM cycle and the resulting ELM energy losses. The simulation of the pellet injection should at least include a moving density source at constant velocity. The pellet ablation rate integrated over space should be consistent with pellet ablation models such as the NGS model.
The pellet requirements are evaluated for a range of ITER scenarios, including the Q=10 reference scenario. Since ELM control will already be necessary at lower plasma currents [Loarte2014], the dependence of the pellet requirements on the plasma current (at given magnetic field) and as a function of q_{95} will be determined.
There are indications that the pellet requirements may depend on the MHD stability properties of the target plasma, i.e. a plasma close to the edge MHD stability limits could be easier to

destabilise by a pellet perturbation than more stable plasmas. For example, pellets injected in L-mode plasma do not trigger an ELM in experiments. In this contract the minimum pellet size for an ELM trigger will be determined as a function of the edge pedestal stability properties in ITER. The results will give an indication of the expected ELM size and possible confinement penalty due to the pellet triggered ELMs.

Recent experiments in EAST [Mansfield2012] have shown that the injection of solid (lithium) pellets can also be used for the trigger of ELMs. In ITER, the possible option of the injection of solid Beryllium pellets for ELM control should be investigated. The advantage of a solid pellet is the absence of a cryogenic system and the robustness of the pellets. The work in this contract will determine an estimate for the pellet requirement of solid Be pellets for the trigger of ELMs. This will likely be done with a simplified model for the solid pellets. The model to be used for the ablation of the solid pellets will be proposed by the contractor and discussed in detail/refined following guidance from the IO.

3 Definitions

In the following table denominations and definitions are given of all the actors, entities and documents referred to in this Specification, together with the acronyms used in this document. Other terminology used is standard in the field of ELM and MHD physics.

Denomination	**Definition**	**Acronym**
ITER Organization	For this Contract the ITER Organization	IO-
ITER Organization Responsible Officer	Person appointed by the ITER Organization with responsibility to manage all the technical aspects of this contract	IO-RO
Contractor	Firm or group of firms organized in a legal entity to provide the scope of supply.	C-
Contractor's Team	The Contractor plus all the sub-contractors/consultants working under its responsibility and coordination for the performance of the contract	C-Team
Contractor Responsible	The person appointed (in writing) by the legally authorised representative of the Contractor, empowered to act on behalf of the Contractor for all technical, administrative legal and financial matters relative to the performance of this contract	C-R
ITER Organization Task Responsible Officer	Person delegated by the IO-RO for all technical matters, but limited to one specific task order	IO-TRO
Contractor Task Responsible Officer	Equivalent to the IO-TRO in the Contractors team	C-TRO

4 References

[Baylor2013] L.R. Baylor et al., Physics of Plasmas 20, 082513 (2013)
[Lang2013] P.T. Lang et al., Nucl. Fusion 53 (2013) 073010 (13pp)
[Futatani2014] S. Futatani et al., Nucl. Fusion 54 (2014) 073008 (20pp)
[Loarte2014] A. Loarte et al. Nucl. Fusion **54** (2014) 033007 (18pp)

[Mansfield2012] D.K. Mansfield, et al., 2012 Proc. 24th IAEA Fusion Energy Conf., San Diego, CA, Oct. 8-13, 2012, PD/P8-15.

5 Estimated Duration

Starting date: signing of contract.

Completion date: 24 months from the date of signature.

Number of working days required to complete the work-scope within the 24-month period: 165 days

6 Work Description

The minimum required pellet size for the trigger of ELMs will be determined by 3D MHD simulations of the pellet injection in ITER H-mode scenarios. This minimum pellet size is given by the pellet that results in a significant ELM energy loss in the MHD simulation, comparable to the expected energy loss in a steady state ITER scenario with an ELM frequency of ~40Hz. This implies a scan in the number of pellet particles.

The contract is divided in the following tasks:

1) Using this procedure, the pellet requirements will be determined for the standard Q=10 scenario for an injection velocity of 300 m/s for the 3 ITER injection geometries. To estimate the errors in the resulting prediction for the minimum pellet size, a sensitivity analysis of the modelling assumptions will be performed. This includes parameters such as the size of the modelled pellet cloud, the toroidal resolution, the resistivity, viscosity and parallel heat conduction. The plasma conditions and equilibrium for the Q=10 ITER reference plasma will be provided by IO.

2) The dependence of the minimum pellet size on the distance to the edge MHD stability limit will be determined for 2 ITER injection geometries (low field side X-point injection and high field side injection) for an injection velocity of 300 m/s in the ITER Q=10 scenario. The distance to the edge MHD stability limit of the target plasma will be varied by changing the pedestal pressure gradient and, self-consistently, the pedestal bootstrap current in a given number of steps (at 50%, 70%, 80 and 90% of the maximum stable conditions). The findings from task 1) will be used to set the optimum modelling parameters.

3) Establishment of the dependence of the minimum pellet size on q_{95}. This study will include 3 values of q_{95} (q_{95}=3.0, 4.5 and 6.0), for X-point and high-field side injection at a fixed pellet speed of 300m/s. The q_{95} variation of the target plasma will be created through a scaling of the total current (at a fixed toroidal field of B=5.3T), taking into account the current dependence of the plasma energy confinement. The distance to the MHD stability of the pedestal must be kept constant at 80% of the stability limit of the most unstable mode for the three q_{95} values.

4) Establishment of the scaling of the minimum pellet size for ELM triggering as a function of the plasma current at constant $q_{95}=3$. This study will include at least 3 values of the plasma current and toroidal field for X-point and HFS injection geometry. The distance to the MHD stability of the pedestal must be kept constant at 80% of the stability limit of the most unstable mode for the three values of plasma current.

5) Detailed analysis of the non-linear MHD simulation results with respect to the divertor power loads, the triggered ELM energy and density losses and the time scales of the ELMs. The analysis of the divertor loads will include the asymmetries in the 2D (radial-toroidal) distribution of the power and the radial width (i.e. broadening) of the power deposition, notably its dependence on the parameters (q_{95}, plasma current, ELM size, injection geometry). The density loss due to the pellet triggered ELM will also be analysed as a function of the above parameters.

6) An initial assessment of the suitability of solid Be pellet for ELM control in ITER will be performed. This study will use a simplified model for the ablation of solid pellets in the non-linear MHD simulations. The model to be used for the ablation of the solid Be pellets will be proposed by the contractor and discussed in detail/refined following guidance from the IO before application. The result of this assessment will be an estimate of the minimum solid pellet size and the required Be throughput for ELM control in the reference ITER Q=10 scenario.

7 Responsibilities

ITER:
ITER will provide the needed information and access to the adequate ITER files for executing this work when needed following the implementation plan.

Contractor:
The contractor will propose an Implementation Plan for the execution of the contract, to be approved by the ITER Organization, to demonstrate how the work will comply with the requirements of this specification.
The contractor will provide results according to the scope of the work outlined above and will fulfil the agreed Implementation Plan and conditions of present contract.
The majority of the work will be carried out at the Contractor's site. The work may require the presence of Contractor's personnel at the site of the ITER Organization, 13067 St Paul-lez-Durance, France, for the purpose of meetings and data gathering. . The associated cost for travel and subsistence expenses for the Contractor's personnel should be included in the Contract Cost (see Section 12). The Contractor will take care of all administrative formalities required for the presence of the Contractor's Personnel at the IO site with the authorities concerned (obtaining visas, etc.).

8 List of deliverables and due dates

The deliverables of this contract are reports on the various tasks described in section 6. Three intermediate reports shall be delivered at 6 months, 12 months and 18 months from the date of signature of the contract. The Final Report shall be delivered at 24 months from the date of signature of the contract. The overall content of the deliverables in this contract are detailed below:

Deliverable	Content	Time
First Intermediate report	Reports on the results of task 1: Pellet requirements for the ITER Q=10 reference scenario, sensitivity study of modelling parameters	6 months after contract signature
Second Intermediate report	Report on the results of task 2 and task 3: Pellet requirements as a function of the distance to the edge stability limit Pellet requirements as a function of q_{95}.	12 months after contract signature
Third Intermediate report	Report on the results of task 4 and task 5: Pellet requirements as a function of the plasma current at fixed q_{95}. Detailed analysis of the divertor power loads, energy and density losses and time scales.	18 months after contract signature
Final Report	Report on the evaluation of the requirements for ELM control using solid Be pellets in ITER.	24 months after contract signature

9 Acceptance Criteria

The IO TRO shall review the deliverables and reply, within the time specified in the 15 following days, a commented version of the deliverables.

The Contractor shall perform all the necessary modifications or iterations to the deliverables and submit a revised version.

The Contract will be considered completed after ITER has accepted the last deliverable.

10 Specific Skills and Competencies

The person/team providing the service should meet the following requirements:

University PhD degree or equivalent in plasma physics,

At least 5 years of proven experience in plasma physics R&D,

At least 3 years of proven experience in non-linear MHD modelling of pellet triggered ELMs.

The official language of the ITER project is English. Therefore excellent knowledge of English is required because all input and output documentation relevant for this Contract shall be in English.

11 Work Monitoring / Meeting Schedule

The contractor will participate in a series of meetings with the ITER Organization for progress monitoring in agreement with the schedule for deliverables proposed in § 8.

At least the following meetings should be foreseen:

Scope of meeting	Point of check/Deliverable	Place of meeting
Kick-off contract	Work program	ITER site or video conference
Seven Progress meetings	Checking progress of deliverables every three months	ITER site or video conference
Closing contract meeting Contract completion	Checking final report	ITER site or video conference

12 Payment schedule / Cost and delivery time breakdown

The ITER Organization will pay per each deliverable as described in Section 8 of these Technical Specifications. Payments are subject to proper approval of the deliverables by the ITER Organization. The contractor will include the cost for each deliverable in their proposal.

The foreseen payment schedule is the following:

List of Deliverables	Estimated Schedule
Deliverable 1: Intermediate Report 1	6 months from the signature of the Contract
Deliverable 2: Intermediate Report 2	12 months from the signature of the Contract
Deliverable 3: Intermediate Report 3	18 months from the signature of the Contract
Deliverable 4: Final Report	24 months from the signature of the Contract

Prices are inclusive of all costs, including but not limited to the cost of labour, material, taxes, management, daily transport, preparation, overheads, profit and fee, and those associated with the presence of the Contractor’s Personnel at the IO site as detailed in section 7, as applicable.

13 Quality Assurance (QA) requirement

The general requirements are detailed in ITER Procurement Quality Requirements (ITER_D_22MFG4).

Prior to commencement of the task, a Quality Plan must be submitted for IO approval giving evidence of the above and describing the organisation for this task; the skill of workers involved in the study; any anticipated sub-contractors; and giving details of who will be the independent checker of the activities (see Procurement Requirements for Producing a Quality Plan (ITER_D_22MFMW)). This is a separate document which comprises:

1) a workplan with proposed time schedule and agreed preliminary dates for progress meetings,

2) a statement of those involved in the activity and their approximate role and contribution in time,

3) a statement of what work will be subcontracted and who will responsible for checking this.

Documentation developed shall be retained by the contractor for a minimum of 5 years and then may be discarded at the direction of the IO. The use of computer software to perform a safety basis task activity such as analysis and/or modelling, etc., shall be reviewed and approved by the IO prior to its use, it should fulfil IO document on calculation code for safety analysis.