Contract: Development of Numerical Codes for Optimization of Runaway Electron Suppression Systems in ITER

Technical Specifications

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Table of Contents

1 Abstract

The task is to upgrade existing codes and develop new code for optimization of Runaway Electron (RE) suppression schemes in ITER. The suit of the codes shall include kinetic codes for description of RE generation and their kinetic parameters, codes for 2D evolution of background plasmas during Current Quench (CQ) of plasma disruptions, codes for analysis of plasma stability and evaluation of 3D magnetic and electrical perturbations. An important part shall be models for the actuators such as pellets and jets injection.

The duration of the contract is 12 months with possible extension for 24 more months. Bids for different subtasks can be done separately with intention to create individual codes that can run independently. Integration of the codes is expected to be accomplished at the later stages of the contract.

2 Background and Objectives

2.1. The present specification is for the provision of support to the ITER Organization in the field of Energetic Particles and Plasma Disruptions. The task is to upgrade existing codes and to develop new numerical codes for the characterization of Runaway Electrons (REs) that can be produced during the Current Quench (CQ) phase of plasma disruptions, and to apply these codes to the design of RE suppression systems in ITER.

2.2. It is expected that massive REs will be generated during plasma disruptions in ITER, which represents a serious threat to the lifetime of the Plasma Facing Component (PFC). Predictive modelling of RE formation, their effects on the PFCs, and simulation of mitigation techniques are extremely important not only for the ongoing design of the PFCs but also for the future ITER operation, planning and licensing – especially in the DT phase. It is expected that the codes shall be an essential part of the future ITER integrated modelling system to be used in a predictive mode during ITER operation.

2.3. Multiplication of high energy electrons by an avalanche process is expected to be the main mechanism of RE generation in ITER. The number of e-folds during an avalanche is very large in ITER (20-40), and hence, suppression systems in ITER must create conditions where either electron collisional slowing down or their losses are faster than the inverse growth rate of the avalanche. Three potential schemes are considered for suppression of REs in ITER:
- Massive gas or pellet injection to quickly increase the plasma electron density and slow down electrons collisionally

- Creation of magnetic perturbation by external RMP coils to enhance orbit loss of electrons
- Dense gas injection in the CQ to trigger MHD bursts and to expel REs

The numerical tools to be developed for optimization of these systems must provide an adequate description of the underlying physics phenomena.

2.4. REs are produced by acceleration of electrons in the large electric fields typical for the current quench, and can be multiplied by a collisional avalanche. These phenomena can be well described by classical collisional models which have a well proven theoretical basis and are available [1]. There are several kinetic codes which can describe the generation of REs under ITER conditions if the parameters of the background plasmas are specified [2,3,4]. These codes have to be upgraded to include all essential phenomena for multiplication of REs including seed sources specific for ITER conditions, such as high energy electrons produced by Compton scattering of gammas, tritium decay, relic tails of electron velocity distribution, etc.

REs are produced during the CQ of plasma disruptions and, therefore, numerical models for the description of CQ plasma parameters have to be developed. At this stage of a disruption the plasma is strongly contaminated by impurities produced from the walls and the plasma temperature is defined by a power balance between Ohmic heating and impurity radiation. Appropriate radiation models have to be implemented and effects of plasma opacity have to be evaluated if necessary. Validity of standard 1D transport model during CQ can be questioned. The electron temperature during a CQ is predicted to be very low in ITER (10-30 eV), and thus, electron heat conduction along the magnetic field lines could be too low to sustain constant temperatures on magnetic surfaces. Theoretical models for the 3D effects on the plasma and RE transport have to be developed and validated in experiments and 2D models must be corrected or upgraded if necessary.

Assessment of the loss of RE electrons requires the development of new effective numerical tools. It is well-known from experimental observations that their losses are defined by MHD and possibly other instabilities. Application of RMP coils, injection of dense gas jets or large pellets can create additional magnetic and electrical perturbations which will affect RE confinement. Self consistent treatment of the RE dynamics with 3D MHD perturbations is needed to adequately describe RE confinement, their loss, and wall loading. The code(s) must be able to include magnetic perturbations produced by external RMP coils including the plasma effects on these perturbations. Although, 3D MHD codes are available [6] and applied for modelling of REs [6a] they are usually very heavy and demanding on computer resources. What is needed here is a simplified code(s) which can run in conjunction with already heavy kinetic codes. For example development of a quasi-linear toroidal MHD code for calculations of magnetic islands and magnetic stochasticity could be considered as a first and practically significant step for addressing the problem.

An important simplification, which may speed up the development of a code, is the negligible level of the plasma pressure. This removes a well-known technical issue related to resolving the structure of resistive MHD perturbations near the resonant magnetic surfaces. For example the existing toroidal ideal linear stability codes can be modified by introducing the quasi-linear matching conditions across the resonant surfaces and possibly non linear interaction of linear modes. As a result, a useful mixture of quasi-equilibrium and ideal matching conditions (which may mimic the effect of plasma shear rotation) with adjustable weights can be implemented in the code for better calibration against the existing experimental data.

The MHD code is considered as an essential part of code system for disruption simulations.

2.5. Theoretical models and numerical tools for massive gas and pellet injection have to be developed. It has been suggested recently that dense gas jets injected into CQ plasmas can suppress REs in ITER. An experimental program to test this new scheme is in progress on the present tokamaks. To optimize an RE suppression system for ITER and to better understand results of the experiments, new models and codes describing penetration of these gas jets are needed. Although there are several publications on penetration of gas jets in tokamak plasmas, [7] the models currently available are not applicable to the CQ conditions and/or range of gas densities of interest.

It is observed in experiments [8] that large pellets produce MHD activity and enhanced transport of the plasma which might affect pellet evaporation. Disruption mitigation in ITER will require injection of very large pellets or very dense gas jets with gas density in the jets up to 10^{25} m^{-3}. The effects of large pellets or dense jets on the background plasmas including generation of magnetic and electrical perturbations must be considered and included in the model.

Although electrons and ions of cold CQ plasmas can not penetrate deep inside the dense gas jet, REs which could be present during the CQ can produce partial ionization of the jet, and thus affect the gas dynamics of the jet in a strong magnetic field. Possible effects of REs shall be included in the models and code.

2.6 All models and codes must be validated against experiments on present tokamaks as much as practical.

2.7 The task to create code(s) for an adequate treatment of the RE electrons and background plasma during the CQ phase of a disruption is very ambitious, but it must be addressed because at stake is safe and reliable operation of ITER. Development of such a code (or package of codes) will be long-range work because of the complex nature of the code development and experimental validation. Thus, the duration of the Contract will be 12 months from the date of the signature, plus options for two 12 month extensions to be agreed and defined by both parties. However, the ITER Organization explicitly reserves the right to decide whether or not to extend the Contract.

2.8. To maximize the efficiency in performing this task, clear targets will be specified each year to promote the code development step by step. Although the code development from a zero base is not excluded from this task, further development and improvement of already existing codes, e.g. ARENA, DRIFT, KINX, DINA, M3D, NIMROD and other codes, would be highly desirable. The task is subdivided into several subtasks. Although they all are related and complimentary to each other, the individual subtasks might require somewhat different models and codes. Therefore, the subtasks can be granted to different contractors.

2.9. Those who whish to participate in the tasks must have an extensive experience in a large scale fusion experiment or other fusion projects.

3 Terminology and Acronyms

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.

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 Scope of the work

The scope of the work includes several tasks:

4.1 Improvement of kinetic code(s) for description of RE generation during disruptions to account for ITER specifics.

4.2 Development of the code for analysis of RE loss caused by magnetic perturbations

4.3 Development/improvements of the code for evolution of plasma equilibrium and energy balance in the plasma during CQ of the plasma disruption in ITER. Existing codes describing the evolution of plasma equilibrium have to be upgraded to be able to operate with codes described in section 4.1. They also have to include an appropriate model for impurity radiation.

4.4 Development of the code for evaluation of nonlinear magnetic perturbations in CQ plasmas. The code must be able to check linear stability of axisymmetric equilibria and calculate nonlinear magnetic perturbations produced either by external coils or plasma instabilities. A zero pressure approximation is acceptable.

4.5 Development of theoretical models and codes for propagation of dense gas jets in current quench plasmas. The models should be able to evaluate time-dependent parameters of gas jets propagating in CQ plasmas.

A provision has to be made for the codes to operate independently or in a mode with exchange of information between the codes. A detailed description of the codes has to be provided. It is expected that the numerical codes shall operate in the future in the frame of the Integrating Modelling system of ITER, and therefore has to comply with general requirements as much as practical [9].

5 Estimated Duration

Starting date: Signing of contract

Completion date: 12 months from the date of signature with possible extension for up to 24 months

6 Work Description

6.1. Kinetic code(s)

The kinetic code (task 4.1) must calculate the evolution of the energy and pitch angle distribution function of the relativistic electrons during a time interval Δt on a given magnetic surface. The input parameters are the initial distribution function of REs, the toroidal electric field, the plasma 2D equilibrium, and other parameters of the background plasmas. The output shall be the final energy and pitch angle distribution function as well as the current density profile produced by RE's. Toroidal effects are essential, and correct averaging over electron orbits is necessary. Zero banana width of RE orbits is an acceptable approximation. The code must incorporate 2D geometry of magnetic surfaces, metric coefficients, and corresponding variation of the magnetic field on the surface. The kinetic module has to have a sufficiently short run time to generate the RE distribution function for a representative number of radial points and a radial profile of the RE current which will be used for modelling the evolution of plasma profiles and 2D equilibrium (Task 4.3).

6.2. The second task for kinetic area (task 4.2) is development of a code for analysis of RE loss driven by magnetic perturbations. The input parameters for the code shall be a 2D equilibrium and plasma profiles as well as 3D magnetic and electrical perturbations produced by the code described in task 4.4. The code shall use the energy spectrum and pitch angle distribution from task 4.1 to evaluate transport coefficients of the RE electrons. A drift approximation for electron orbits is acceptable. The code shall evaluate the confinement of REs in the presence of magnetic perturbations produced either by external RMP coils or by those produced by plasma instabilities and provided by the code in task 4.4. The other result of the code shall be the distribution of the loss over the wall and estimates of the heat and particle loads.

6.3. Code for evolution of 2D plasma equilibrium and plasma profiles. The code has to be equipped with the module describing evolution of a 2D plasma equilibrium with a free boundary such as the DINA or TSC codes. Evolution of the equilibrium has to account for eddy currents in the realistic ITER conducting structures and currents in PF coils and central solenoid. The current in the coils can be short circuited during plasma disruptions. This code will allow simulation of plasma evolution following the Thermal Quench (TQ) of central plasma disruptions or VDEs due to loss of PF control. Such codes are available but have to be upgraded or modified to operate in conjunction with the kinetic module described in section 4.1. The input parameters from the kinetic code shall be the radial profile of the RE current density, and the profile of plasma heating by REs. The power balance in the code has to be equipped with an appropriate model for estimation of plasma radiation produced by impurities. For this purpose, the effect of radiation opacity under massive impurity injection must be included when needed. In addition, a proper routine for position control (both vertical and radial) must be included.

6.4. Task 4.4 is for the development of a fast toroidal MHD code for calculations of 3D magnetic perturbations including magnetic islands and magnetic stochasticity. It is well known from experiments that REs are lost during MHD bursts caused by plasma instabilties. Therefore, any meaningful attempt to evaluate RE loss and wall load has to include model and codes for assessment of magnetic perturbations.

Magnetic perturbations with RE electrons can be described by MHD approximation [10,11]. However, a full 3D MHD code with appropriate boundary conditions and relatively fast run time seems to be too difficult and will require for its development time and resources which are outside of the scope of this task. Although development of effective 3D MHD codes is important for plasma research, some simplifications might be needed for assessment of perturbations during the CQ. A quasi-linear toroidal MHD code for calculations of 3D magnetic perturbations including magnetic islands and magnetic stochasticity could be a first and practically significant step for addressing the confinement of REs.

An important simplification, which may speed up the development of the code, is the negligible level of the plasma pressure during the CQ. This removes a well-known technical issue related to resolving the structure of resistive MHD perturbations near the resonant magnetic surfaces. The existing toroidal ideal linear stability codes can be modified by introducing quasi-linear matching conditions across the resonant surfaces and if possible to include non linear interaction of linear modes. As a result, a useful mixture of quasi-equilibrium and ideal matching conditions (which may mimic the effect of plasma shear rotation) with adjustable weights can be implemented in the code for better calibration against the existing experimental data. Resistive times during the low-temperature CQ plasma are very short, but could be comparable with some other phenomena such as fast loss of REs and other. An equation for evolution of the width of a magnetic island can be included in the matching condition to account for the time dependence of MHD modes during CQ.

The input parameters for the code shall be a 2D plasma equilibrium and current profile as well as external magnetic perturbations produced by RMP coils. The results of the code shall be 3D magnetic perturbations as a function of plasma parameters and time which shall be used for assessment of the RE confinement and loss pattern. The code should include a realistic geometry of the conducting structures such as the first wall and divertor plates.

Other approaches which could result in creation of fast 3D MHD code are welcome.

6.5 Task 4.5 for modelling the penetration of dense gas jets in CQ plasmas targeted on development of the theoretical models and code(s) for evaluation of gas jet parameters and effects of the dense gas jet on the background plasma.

The gas jet injected during a CQ shall propagate in a low pressure plasma. Plasma pressure, gas pressure in the jet, p_0, and magnetic field pressure are ordered as:

$$p_{pl} << p_0 << B^2/2\mu_0$$

The mean-free-path inside the gas jet is very short due to high gas density, and gas flow inside the jet can be described by continuous flow models (CFM). Interaction of the thermal plasma with the gas occurs in a relatively thin layer. Ionized particles can not move across the field lines in the strong magnetic field. The gas jet penetrates across the field by extinguishing (recombining) plasma. Models for expansion of the gas jet along the field line and across the field line must be developed to describe time evolution of the jet in the plasma.

The model must also describe electric and magnetic perturbations produced by localized dense gas jets in a current-carrying plasma with a high loop voltage typical for the CQ of ITER.

The input parameters for the model/code shall be profiles of the background plasmas. The model should describe gas jet propagation starting from the nozzle of an injector located at the edge of the first wall. The results shall be time evolution of jet parameters and evaluation of magnetic and electrical perturbations produced by the jet in the background plasma. Typical plasma parameters expected during the CQ in ITER are T ~10-30 eV, $n_e \sim 10^{20}$ m^{-3}.

7 Responsibilities (including customs and other logistics)

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(s) appoint(s) responsible person(s) for each subtask, the Contractor's Responsible (C-R) official, who shall represent the Contractor(s) for all matters related to the implementation of this Contract.

The contractor(s) will provide results according to the scope of the work outlined above and will fulfil the implementation plan and conditions of the present contract.

8 List of deliverables and due dates (proposed or required by ITER)

In each subtask, the deliverables are reports describing the statement of each problem, input data and approximations used in the models and the results obtained. For the new codes, copies of the sources of the codes with necessary instructions for installation and operation shall be provided by the Contractor. ITER shall have rights to give these codes to other individuals or groups to be further developed. For the updated or modified of already existing codes the sources of new subroutines and other modified sections and detail description of modifications shall be provided by the Contractor.

Intermediate reports will be delivered approximately every 4 months from the date of signature of the contract. Details on deliverables and priorities of the subtasks will be agreed between the PT/DA Responsible Officer and the ITER Organization Task Officer.

Progress meetings (or video-conferences) shall be organized as required to exchange information and to review the intermediate results of the task.

9 Acceptance Criteria (including rules and criteria)

A Quality plan shall provide work breakdown and list of check points at which ITER should review status of the work and make a decision for its continuation. ITER will also participate in reviewing the results of tests and analyses.

The Contractor shall submit a draft of the deliverables foreseen in the Scope at completion of the work.

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 requirements and conditions

In response to this call for tender the following shall be provided:

- Schedule of deliverables
- Cost breakdown
- Payment schedule
- Profile of key personnel involved in execution of the work activity

The official language of the ITER project is English. Therefore, all input and output documentation relevant for this Contract shall be in English. The Contractor shall ensure that all the professionals in charge of the Contract have an adequate knowledge of English, to allow easy communication and adequate drafting of technical documentation. This requirement also applies to the Contractor’s staff working at the ITER site or participating to meetings with the ITER Organization.

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.

The work shall require the presence of the Contractor's personnel at the site of the ITER Organization, Cadarache, 13108 St Paul-lez-Durance, France, for short time, for the purpose of meetings and data gathering.

For all deliverables submitted in electronic format the Contractor shall ensure that the release of the software used to produce the deliverable shall be the same as that adopted by the ITER Organization.

11 Work Monitoring / Meeting Schedule

Contractor shall also propose a list of meetings with ITER for progress monitoring in agreement with schedule proposed in § 4. At least the following meetings should be foreseen.

Scope of meeting	Point of check/Deliverable	Place of meeting
Kick-off contract	Work program	Contractor site, ITER site, or video conference
Progress meetings	Checking progress Submission of first report	Contractor site or ITER site or video conference
Semi-final progress meeting	Checking progress Submission of 2nd report	Contractor site, ITER site, or video conference
Closing contract meeting Contract completion	Checking final report	ITER site or video conference

12 Quality Assurance (QA) requirement

Prior to commencement of any work, a Quality Plan must be provided to IO for approval. 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.

13 References

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