WORK PACKAGE ENABLING RESEARCH

Scientific/technical report for mid-term evaluation

Deadline: 1 July 2016

Project title *(as in Task Agreement)*	***Kinetic modelling of runaway electron dynamics***
Principal Investigator	Yves Peysson
Beneficiary of Principal Investigator	CEA-09
Project reference number *(as in Task Agreement)*	ER15-CEA-09

Filename should be of the format: ***WPENR_AWP15_midterm_report_****Beneficiary-nn* *where* ***Beneficiary-nn*** *is, for example,* ***ENEA-01****.*

Purpose and use of report

This compact report is to describe the progress of the project, for the mid-term evaluation by STAC, and as accessible information to the EUROfusion projects,

It will also be uploaded to the Enabling Research Wiki pages (https://www2.euro-fusion.org/ERwiki/index.php?title=Main_Page), and thereby be available to the PMU and the relevant Work Package and Task Force Leaders to assist exploitation of the research and output, and possibly later adoption of the activity into the main WPs.

The reports should be as brief and clear as possible, referring to publications and other information for details. However there should be enough information to support statements that deliverables have been achieved. As an indication **the full report should not exceed 10 pages excluding this title page**. Please keep to the report format and do not attach additional information. If there are one or two particularly significant figures that are needed to demonstrate the results, these can be included in the tables.

Information from the 2015 annual monitoring report can usefully be repeated

1. Main scientific output - summary

Summarise the main achievements of the project to date

1) The physics of synchrotron radiation reaction force, which is found to limit considerably the runaway electron energy, and leads to significant modifications in the runaway electron distribution. Includes theoretical work and numerical implementation in kinetic solvers. This work is in the continuation of the previous enabling research project – 2014 – on runaway electron physics and is associated to kinetic modelling of runaway generation mechanism (CODE code, LUKE code)
2) First theoretical calculation of the bounce-averaged knock-on collision operator for describing runaway avalanches in realistic magnetic configuration of tokamaks, and implementation in kinetic solver LUKE.

2. Project deliverables

Deliverable *(deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement, and comment on status of future deliverables**
Kinetic modelling of runaway generation mechanisms : Quantify the effect of pre-existing fast electrons in the hot-tail formation and subsequent runaway production rate (2015).	Partially	*Participation to a dedicated experimental campaign on COMPASS tokamak. Ongoing simulations. Further simulations will require the full availability of METIS/LUKE scheduled for 2016. Manpower may be an issue for further work (the participant to the project has left as scheduled in the project)* *Physics of synchrotron radiation reaction force on runaway electron dynamics* *First theoretical calculation of the bounce-averaged knock-on collision operator for runaway electron avalanches*
Kinetic modelling of runaway generation mechanisms: Include the effect of finite incident runaway momentum in the knock-on collision model for more realistic calculations of the secondary runaway generation (2015).	Not	*Postponed for lack of manpower. The validation of the simplified operator is a priority before deriving and using a more refined operator*

Deliverable *(deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement, and comment on status of future deliverables**
Kinetic modelling of runaway generation mechanisms : Design specific synthetic diagnostics for characterizing the runaway dynamics, especially in the early phase of their generation (2015).	Partially	*Preliminary developments are underway. Quantitative assessment is linked to the development of the self-consistent solver of the evolution of runaways with the electric field. The synthetic diagnostic for synchrotron radiation is operational for CODE code and will be soon (end 2016 or beginning 2017) for LUKE code with spatial dependencies. Collaboration with PSFC (MIT)*
Self-consistent evolution of runaways with the electric field: Validate the self-consistent solver obtained by coupling LUKE with the equilibrium/transport code METIS/CRONOS (2015)	Fully	*Numerical implementation completed and under testing. Conditions under which self-consistency between the runaway electron distribution function and the electric field is necessary have been identified. This work has been submitted to publication in November 2015 (Nuclear Fusion).*
Self-consistent evolution of runaways with the electric field: Compare with experimental runaway observations on Tore Supra (RF power drop, shot #28340) and TCV (density ramp-up, shot # 48195) (2015).	Partially	*A detailed modelling of an Ohmic non-disruptive runaway discharge in Tore Supra (#40719) has been carried out, This work has been submitted to publication in November 2015 (Nuclear Fusion). Comparisons with experimental runaway observations on Tore Supra (RF power drop, shot #28340) and TCV (density ramp-up, shot # 48195) (2015) has been postponed to 2016, in the context of the development of the self-consistent solver.*

Deliverable *(deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement, and comment on status of future deliverables**
		The numerical stability of the electric field in METIS code for large electric field is underinvestigation.
Code benchmarking : A complimentary proposal named " Global non-linear MHD modeling in toroidal X-point geometry of Disruptions, Edge Localized Modes, and techniques for their mitigation and suppression " will incorporate runaway electron dynamics in the MHD code JOREK using a PIC description. A benchmark of JOREK (using the PIC model for runaway electrons) with LUKE-METIS on axisymmetric cases will be considered. This collaboration will be coordinated by Yves Peysson and Cristian Sommariva.	Partial	*The work is in progress. The PIC description is done, but comprison with METIS-LUKE remains to be done.*
Kinetic modelling of runaway generation mechanisms : Derive operators for the electric field acceleration and the knock-on collisions including finite orbit effects (2016)	Not	*Postponed because of lack of manpower in 2016.*
Kinetic modelling of runaway generation mechanisms : Orbital spectrum calculation for analytically and/or numerically given equilibria. (2016).		
Study of runaway transport processes: Implement the quasilinear model for kinetic instabilities in the LUKE code (2016)	Not	*Postponed because of lack of manpower until mid of 2016, but this objective may start in the fall of 2016*
Study of runaway transport processes: Build a radial transport operator for LUKE in the presence of MHD instabilities, magnetic turbulence or RMP (2016)	Partially	*Same as previous item*
Study of runaway transport processes: Investigate the influence of Alfvenic fluctuations on the RE transport with a	Not	*Same as previous item*

Deliverable *(deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement, and comment on status of future deliverables**
perturbative hybrid model (HAGIS/LIGKA)		
Study of runaway transport processes: Conditions for resonant electron-mode interactions and parametric investigation of synergetic effects under the presence of different types of modes in terms of RE generation and transport.	Partially	*Same as previous item*

3. Project Goals

Comment on the situation for the various goals and the expected outcome by the end of the project, with justification.

Significant progresses have been performed to reach most of the goals of the ER15-CEA-09 project. Most prominent ones concern the effects of radiations losses (synchrotron and bremsstrahlung) on the dynamics of runaway electrons. From the point of view of the electrons, this corresponds to a reaction force that may limit considerably the kinetic energies reached by this population which are lowered from hundreds of MeV down to 30-50 MeV with the possible occurrence of a bump in the distribution function, potentially able to be a free energy source for plasma instabilities. Theoretical work has been extensively done, but also numerical implementation in CODE and LUKE codes respectively which give consistent results. This outcome may change considerably the strategy for the control of runaway electrons. The experimental evidence of the bump in tail is a challenge to validate this kinetic description, and the development of accurate synthetic diagnostic is becoming urgent, which will be also an important outcome of the project.

Within the ER15-CEA-09 project, three codes have been concerned principally: GO code, CODE code and LUKE code. CODE is a local time-dependent relativistic tool allowing a refined description of the fast electron dynamics in momentum space, GO code a 0D time-dependent runaway tools particularly suited for experimental data analysis, and LUKE code a 3D bounce-averaged relativistic electron linearized Fokker-Planck solver. Both CODE and LUKE code use relativistic collision operators, avalanche effect by knock-on collisions. However, LUKE, which is also designed for RF waves interaction with the plasma (current drive), is particularly well adapted for quantitative comparison with experimental data with synthetic diagnostics. For this purpose, its coupling with the tokamak simulator METIS allows a realistic description of the runaway population with time. The METIS-LUKE coupling which is done so far but requires some tuning for a robust convergence of the electric field with the runaway current, thanks to the fast reaction of this quantity will be also a critical outcome of the project, able to simulate runaway discharges (disruptive in the recovery phase few ten ms after the thermal quench or notdisruptive) in existing machines with predictive capabilities for ITER, which is itself another critical achievement. So far, a significant part of this objective is performed.

In this context, the derivation of the bounce-averaged knock-on collision operator and its implementation in LUKE code is particularly critical, in order to describe in a realistic way the *dynamics of knocked-on electrons, which are initially highly magnetized after the Coulomb collision. With a possible large Ware pinch when the electric field is high, this mechanism contributes to concentrate the runaway electrons in the plasma core as shown in a recent publication.*

The interaction of the runaway electrons with the MHD is also extremely important, since it may affect also the distribution function of the runaway electrons, and contribute to enhance losses and reduce the upper energy limit, in addition to the reaction forces. Self-consistent calculations must be performed. The framework of LUKE is ideally suited for implementing the quasilinear diffusion operator, and it will be likely fully performed for end of 2017 as all the numerical framework is ready for this purpose.

Within the ER15-CEA-09 project, the development of numerical powerful codes has been improved, and the outcome is the deliverable of a set of tools that are able to give a consistent picture of the time-dependent runaway electron dynamics in regimes where nested magnetic flux surfaces may exist.

Besides the numerical effort, the ER15-CEA-09 project has allowed to identify numerous new physical problems like the question of the meaning of a Dreicer limit when all the electrons may runaway. Long term development involving action-angle formalism, are well incorporated also in this context. Furthermore, the existence of the ER15-CEA-09 project has deeply contributed to the settlement of a strong community for studying the problem posed by the runaway electrons, from their generation to their control.

If several deliverables are only partially achieved at mid-term, this is mainly the consequence of the great complexity of the physics that is addressed, which require subsequent time to be correctly implemented in advanced numerical tools, with a firm theoretical background. Nevertheless, the progresses from year to year are particularly visible, thanks to the remote or REM meetings. It is obvious from the present status that the runaway electron physics will require a similar support after 2017 to fully achieve the present effort and make Europe a leader in this critical domain for tokamak operation, and ITER in particular.

4. Publications/presentations

Those which have had a substantial component from the work of the project, marking those which are entirely from the work of the project. Give title, first author, journal/conference/other venue

Articles

« Kinetic modelling of runaway electron avalanches in tokamak plasmas », E. Nilsson, J. Decker, Y. Peysson, R.S. Granetz, F. Saint-Laurent and M. Vlainic, *Plasma Physics and Controlled Fusion* **57**, 09500 (2015).

« Trapped-electron runaway effect », E. Nilsson, J. Decker, N.J. Fisch and Y. Peysson. *Journal of Plasma Physics* **81**, 475810403 (2015).

« Runaway electrons in non-disruptive scenarios in the Tore Supra tokamak », E. Nilsson, Y. Peysson, J. Decker, J. F. Artaud, T. Aniel, M. Irishkin, D. Mazon and F. Saint-Laurent. Submitted to *Nuclear Fusion*, (2015).

« Effective Critical Electric Field for Runaway-Electron Generation », A. Stahl, E. Hirvijoki, J. Decker, O. Embréus and T. Fülop, *Phys. Rev. Letters,* **114**, 115002 (2015)

« Radiation reaction induced non-monotonic features in runaway electron distributions », E. Hirvijoki, Pusztai, Decker, Embréus, Stahl and T. Fülop, *J. Plasma Phys.*, **81**, 475810502 (2015)

E. Hirvijoki, J. Decker, A. Brizard and O. Embréus, *J. Plasma Phys.*, 81, 475810504 (2015)

« Numerical calculation of ion runaway distributions », O. Embréus, S. Newton, A. Stahl, E. Hirvijoki an Fülop, *Phys. Plasmas,* **22**, 052122 (2015)

« Effect of bremsstrahlung radiation emission on distributions of runaway electrons in magnetized plasma », O. Embréus, A. Stahl, S. Newton, G. Papp, E. Hirvijoki and T. Fülop, submitted to *Phys. Plasm* (2015*), arxiv.org/abs/1511.03917v1*

« Energetic electron transport in the presence of magnetic perturbations in magnetically connected plasmas», G. Papp, Drevlak, G. Pokol and T. Fülop, *J. Plasma Phys. 81 475810503 (2015)*

« Status of research toward the ITER disruption mitigation system », E. Hollman et al, including T. Fülo and G. Papp, *Phys. Plasmas,* **22**, 021802 (2015)

« Numerical characterization of bump formation in the runaway electron tail », J. Decker, E. Hirvijoki, Embreus, Y. Peysson, A. Stahl, I. Pusztai, T. Fülop, *Plasma Phys. Control. Fusion, 2016, 58, pp. 025016*

Conference contributions:

« Kinetic modelling of runaway electrons in non-disruptive Tore Supra plasmas », E. Nilsson, J. Decker, Peysson, J.F. Artaud, T. Aniel, M. Irishkin and F. Saint-Laurent., *42nd EPS Conference on Plasma Physics* (2015). [POSTER]

« Non-monotonic features in the runaway electron tail. » I. Pusztai, E. Hirvijoki, J. Decker, O. Embréus, Stahl and T. Fülop, *42nd EPS Conference on Plasma Physics* (2015). [ORAL]

« Towards self-consistent runaway electron modelling », G. Papp, A. Stahl, Drevlak, T. Fülop, E. Lauber and G. Pokol,, *42nd EPS Conference on Plasma Physics* (2015). [POSTER]

« Numerical calculation of ion runaway distributions. » ,O. Embréus, S. Newton, A. Stahl, E. Hirvijoki an T. Fülop: *42nd EPS Conference on Plasma Physics* (2015). [POSTER]

« Kinetic modelling of runaway electron dynamics », A. Stahl, O. Embréus, E. Hirvijoki, G. Papp, M. Landreman, I. Pusztai and T. Fülop,, *IAEA Energetic Particle meeting* (2015) [POSTER]

« Coupled kinetic-fluid runaway simulations », G. Papp, A. Stahl, T. Fülop, Drevlak, G. Pokol, E. Lauber a A. Fehér,, *IAEA Energetic Particle meeting* (2015) [ORAL]

« Reaction of runaway electron distributions to radiative Processes » A. Stahl et al,, *APS conference Savannah* (2015) [POSTER]

« Conservative large-angle collision operator for runaway Avalanches », *O. Embréus et al,*, *APS confere* *Savannah* (2015) [POSTER]

« Numerical calculation of ion runaway distributions », S. Newton et al,, *APS conference Savannah* (20 [POSTER]

Thesis report:

“Dynamics of runaway electrons in tokamak plasmas”
PhD thesis (Ecole Polytechnique Paris, September, 2015)
https://pastel.archives-ouvertes.fr/tel-01212017/

5. Interface with the main EUROfusion on Work packages

Please give information of the interactions (e.g. ER presentations to project or task force meetings, or presentations to ER meetings from the main work packages)

ER15-CEA-09 project has valuably interacted with other projects, during the two ER meetings (Runaway Electron meeting 2015 and 2016) that have been organized at Pertuis (France). Some participants of MST1, task ST-16-2, MST2-9 *and JET1 workpackages have presented their results on runaway electron experiments obtained on various machines, JET (UK), ASDEX-U(Germany), COMPASS (Czech Republic) and TCV (Switzerland). The interactions were very fruitful, from the point of view of qualitative analysis and the definition of needs to simulate efficiently runaway discharges with numerical tools that have been developed or are under the responsibility of the ER15-CEA-09 project. In particular, in 2016, a reliable scenario for producing runaway electron discharges have been obtained in TCV, with extremely well diagnosed plasmas, which open the path to detailed numerical simulations in particular with METIS/LUKE codes taking into account of realistic magnetic configuration. Much in the same way such a numerical effort of discharge modelling has been also carried out for COMPASS runaway discharges with METIS/LUKE codes. Encouraging preliminary results have been obtained, but more discharges must be analysed, a task that is considered in the second half of the ER15-CEA-09 project. It is worth to note that within ER15-CEA-09 project, the importance of the self-consistency between the Ohmic electric field and the runaway current has been quantitatively estimated with METIS/LUKE for Tore Supra discharges, which allow to define the range of parameters to compare modelling and experiments.*

Moreover, from the interaction between ER15-CEA-09 and MST1 projects, it is important to note that a nested magnetic configuration is rebuild few ten ms after the thermal quench of the disruption, in agreement with the further good confinement of the runaway electrons during the current plateau phase. Such a point is particularly important, as it indicates, at least in the central region of the plasma, that existing simplified codes like METIS or LUKE assuming non-stochastic magnetic configuration may be nevertheless used to some extent, *while the very complex phase just after the thermal quench is restricted to MHD codes, able to describe the full transient ergodization of the plasma. In this context, the ER15-CEA-09 project keeps contact with participants of the CfP-WP15-ENR-01/IPP-05 project ("Global non-linear MHD modeling in toroidal X-point geometry of disruptions, edge localized modes, and techniques for their mitigation and suppression), in particular concerning developments with JOREK code. Recent presentations of JOREK results during REM meetings have shown the dynamics of runaway electrons in the ergodized phase post thermal quench, leading to the loss of 95% of the electrons, the 5% remaining becoming runaway and being rapidly confined. This is an important input for simulations with the tools under the responsibility of the ER15-CEA-09 project.*

Therefore, the interaction between ER15-CEA-09 and other work package projects is very fruitfull to pave the use of operational numerical codes that can catch the experimental observations, and with which quantitative extrapolations to ITER post-disruptive runaway regimes may be performed.

In addition, the PI of ER15-CEA-09 project has been invited to present a review of ER15-CEA-09 activity on a meeting on MHD and runaway particles in mid of July 2016, and also to a meeting on the same topics at PPPL (Princeton). It is important to note that the REM meetings organized under the auspice of the ER15-CEA-09 project have attracted several US physicists from PPPL and MIT, and ITER organization. Sharing knowledge as it is investigated in the project in a sign of attractiveness of activities in ER15-CEA-09 project.

6. Proposals for exploitation by the main WPs

Please give suggestions on how the output might be used by, or the activities taken up in, the main WPs, and indicate which WP(s) and when the exploitation might begin.

Thanks to the already active existing collaborative environment between the ER15-CEA-09 project and the work packages, the suggestion is to increase the link in the design of relevant experimental scenarios, well diagnosed with refined time resolution, such that quantitative modelling can be performed easily. At present time, the numerical tools useful for that purpose (Go code, CODE code, METIS/LUKE codes) are already available in the different labs participating to studies on runaway electron physics. Such tools must be routinely operated as a support of experiments, which is foreseen on several machines, TCV, COMPASS, likely ASDEX-U, and WEST when this machine will be operational. The goal is to develop a large database of well documented simulated experiments on runaway electrons, which can be potentially obtained in the coming years, thanks to the collaborations that have been developed in the context of ER15-CEA-09 project and the other work packages. The mobility of physicist is particularly crucial, in order to share the knowledge.

7. Managerial aspects (optional)

If you think there are any major managerial issues for your project (*changes to personnel, cost issues, etc*.), beyond any mentioned in the annual report, which might affect the outcome of the project and should be brought to the attention of STAC, please mention them here. (*1 page maximum*)

There is a need to do some changes in the personnel resources compared to the original plan.

The changes we would like to ask you to do are the following and concerns principally Chalmers university and CCFE, but also BME (Hungary). The total amount is unchanged compared to the original version for Chalmers University.

1) Newton Sara moved from CCFE to Chalmers University.
2) Eero Hirvijoki left Chalmers University and ER project on runaway electrons
3) For 2015, the budget (constant) is the following
   - Fülöp Tünde, 0.1 ppy *144 = 14.4 k€
   - Stahl Adam, 0.7 ppy * 61.6 = 43.12 k€
   - Newton Sarah, 0.16 ppy * 70.8 = 11.3 k€
   - Embreus Ola, 0.8 ppy * 56 = 44.8 k€

4) Newton Sarah is no more involved in the ER Project on runaway electrons for 2016 and 2017

5) For BME (Hungary), Roland Lohner has been replaced by Mátyás Aradi