WORK PACKAGE ENABLING RESEARCH

2016 scientific/technical report

Deadline: 31 December 2016

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

Filename should be of the format: ***WPENR_AWP15_interim_report_****Beneficiary-nn* *where* ***Beneficiary-nn*** *is, for example,* ***ENEA-01****.*

Purpose and use of report

This compact report is to report the progress on the deliverables, to justify payment. A brief summary of the scientific highlights is also requested. While the report will be available to STAC the performance will be assessed by the PMU unless there are issues which require the advice of STAC. The mid-term evaluation of the project, where relevant, is a separate activity but can refer to these reports.

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 4 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.

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.
3) A fully non-linear kinetic-equation solver, capable of handling large electric-field strengths (compared to the Dreicer field) and relativistic temperatures has been developed. This tool allows modeling of the momentum-space dynamics of the electrons in cases where strong departures from Maxwellian distributions may arise, and was used to investigate electron slide-away.
4) The first calculation and implementation of a fully conservative large-angle collision operator, was performed. This operator accounts for the full momentum dependence of the primary distribution and avoids double counting of small- and large-angle collisions.
5) orbit-following codes such as ASCOT can be used to provide a 1D model for run-away electron transport in magnetic fields that contain both stochastic regions and islands

The effect of fast-electron bremsstrahlung emission on the momentum–space structure of the electron distribution was studied, using an improved formalism. The electrons can reach significantly higher energies than predicted by the commonly used radiative stopping–power model.

2. Project deliverables

Deliverable *(2016 deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement**
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).	Fully	Hot-tail generation has been investigated and the results were published in Stahl et al, "Kinetic modelling of runaway dynamics", Nuclear Fusion 56(2016) 112009. Participation to a dedicated experimental campaign on COMPASS tokamak. Ongoing simulations.
Kinetic modelling of runaway generation mechanisms: Include the effect of finite incident	Fully	We derived a new large-angle collision operator, as the high-energy limit of the linearized relativistic Boltzmann collision integral. This operator generalizes previous models of large-angle collisions to account for the full momentum dependence of the primary distribution and

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runaway momentum in the knock-on collision model for more realistic calculations of the secondary runaway generation (2015).		conserves particle number, momentum and energy, while also avoiding double counting of small- and large-angle collisions. The work will be submitted for publication during the first part of 2017. It was already presented at the 57th Annual Meeting of the APS Division of Plasma Physics under the title "Conservative large-angle collision operator for runaway avalanches" http://meetings.aps.org/Meeting/DPP15/Session/PP12.107 In addition, the effect of finite-incident runaway momentum has been analyzed and compared with simpler models in the paper by Stahl et al, "Kinetic modelling of runaway dynamics", Nuclear Fusion 56(2016) 112009.
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	A synthetic diagnostics for synchrotron emission is under development. Preliminary studies have been performed to reproduce synchrotron images at the Alcator C-Mod tokamak. Results have been presented at the APS conference in San Jose (2016) and a full-length manuscript is under preparation.
Kinetic modelling of runaway generation mechanisms : Finite orbit width effects on runaway electron dynamics	Partly	On the theoretical frontier, the Monte Carlo operator for small-angle collisions has been improved in efficiency. When simulating run-away electron evolution, the collision frequency can vary greatly during, e.g., Dreicer generation. Using fixed time step is computationally very inefficient, but the stochastic nature of the collisional process varying the time step cannot be done as simply as with integrating the Hamiltonian dynamics. To this end, a novel adaptive time-stepping Monte Carlo operator was developed. It is very general, allowing both test particles and background to be relativistic, and operators are given both for the guiding center and particle phase spaces.

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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 to Nuclear Fusion and is still in the refereeing process. Theoretical developments concerning the selfconsistency between LUKE and METIS have been carried out, and are in the implementation phase
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).	Partly	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. The numerical stability of the electric field in METIS code for large electric field is under investigation. In addition, comparisons with experimental scenarios in the DIII-D and Alcator C-Mod tokamaks were performed. The results were presented at the APS Conference, San Jose (2016).
Code benchmarking : A complementary 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	Partly	Significant progresses have been performed in 2016 either concerning code developments and physical analysis. The applications focused on calculating the orbits of relativistic electrons in a disruption simulation computed by JOREK code. These showed that part of the initial population can be confined in the region of the core of the plasma during the whole disruption. A scan according to the initial energy of the electrons also showed that the volume of confinement reduces with the increase of the initial energy. In parallel, an experimental analysis work on the ASDEX-Upgrade tokamak data was carried out. The latter has demonstrated the existence of a correlation between the energy of the magnetic fluctuations recorded by a low-field Mirnov coil at the height of the equatorial plane and the quantity of the decoupled electron current obtained after the disruption. A publication is scheduled for January 2017, while

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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.		various communications have been done in dedicated workshops like *Theory and simulation of disruption workshop* at Princeton (USA) in July 2016. A poster on the above topics has been awarded at the 43rd European Physical Society Conference on Plasma Physics and Controlled fusion.
Derive operators for the electric field acceleration and the knock-on collisions including finite orbit effects (2016)	Not	The mission initially considered has not been funded. Potsponed.
Orbital spectrum calculation for analytically and/or numerically given equilibria. (2016).	Fully	A canonical transformation to Action-Angle space is being developed for all kinds of imposed axisymmetric equilibrium (analytical, numerical or experimental). The advantages of such a transformation are clearly demonstrated especially in view of the Orbital Spectral Analysis (OSA) technique that was implemented respectively, which allows for the explicit formulation of resonance condition between REs and different types of applied perturbations. The REs are properly introduced and treated as test particles with specific initial energy, whereas pitch angle, radial position and Finite Orbit Width (FOW) are taken into account in order to derive the orbital drift frequencies of the REs; however, no collective particle effects are considered so far in our calculations. Concluding, as a result, we derive resonance charts in Action space that can allow us to identify and pinpoint the exact location of the resonances in phase space for various perturbations. Especially: i) The numerical transformation from configuration to AA space has been successfully implemented for experimental TCV equilibria (obtained in TCV-15.1.3-6 experiment) Only the scenario of the induced RMPs is currently taken under consideration in our analysis, mostly due to their importance concerning the mitigation and control of energetic particles in tokamaks, as well as the MHD induced plasma instabilities in general.

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		The results have been published in the following reference Panagiotis A. Zestanakis, Yannis Kominis, Giorgos Anastassiou & Kyriakos Hizanidis, Physics of Plasmas **23**, 032507 (2016)
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 2017
Build a radial transport operator for LUKE in the presence of MHD instabilities, magnetic turbulence or RMP (2016).	Fully	This mission has now been accomplished with ASCOT. The recent publication 'An advection–diffusion model for cross-field runaway electron transport in perturbed magnetic fields', PPCF 58 (2016) 125017, describes how orbit-following codes such as ASCOT can be used to provide a 1D model for run-away electron transport in magnetic fields that contain both stochastic regions and islands. This model is now ready to be implemented in codes like LUKE.
Investigate the influence of Alfvenic fluctuations on the RE transport with a perturbative hybrid model (HAGIS/LIGKA) [19, 20] (2016)	Partly	Postponed because of lack of manpower until mid of 2016, but this objective may start in 2017
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. (2016)	Partly	Mostly postponed because of lack of manpower until mid of 2016, but this objective may start in 2017. However a comparative study on the different waves that have been studied in the past as they interact with runaways through the anomalous Doppler resonance has been carried out.

3. 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

" Numerical characterization of bump formation in the runaway electron tail ", J. Decker, E. Hirvijoki, O. Embreus, Y. Peysson, A. Stahl, I. Pusztai, T. Fülop, *Plasma Phys. Control. Fusion, 2016, 58, pp. 025016'*

Kinetic modelling of runaway electrons in dynamic scenarios, A Stahl, O Embreus, G Papp, M Landreman and T Fülöp, Nuclear Fusion, **56**, 112009 (2016)

Effect of bremsstralhung radiation emission on fast electrons in plasmas, O Embréus, A Stahl and T Fülöp, New Journal of Physics, **18,** 093023 (2016)

Runaway-electron formation and electron slide-away in an ITER post-disruption scenario, A Stahl, O Embréus, M Landreaman, G Papp and T Fülöp, Accepted for publication in Journal of Physics: Conference Series (2016).

NORSE: A solver for the relativistic non-linear Fokker-Planck equation for electrons in a homogeneous plasma, A Stahl, M Landreman, O Embréus and T Fülöp, Accepted for publication in Computer Physics Communications (2016).

Panagiotis A. Zestanakis, Yannis Kominis, Giorgos Anastassiou & Kyriakos Hizanidis, Physics of Plasmas **23**, 032507 (2016)

K. Särkimäki, E. Hirvijoki, J. Decker, J. Varje, T. Kurki-Suonio, 'An advection–diffusion model for cross-field runaway electron transport in perturbed magnetic fields', PPCF 58 (2016) 125017

-- K. Särkimäki, E. Hirvijoki, J. Terävä, 'Adaptive time-stepping Monte Carlo integration of Coulomb collisions', submitted to Computer Physics Communications on December 13th, 2016

Conference contributions:

"Running away and radiating" T Fülöp et al, Workshop on "Solved and Unsolved Problems in Plasma Physics", Princeton, (2016) [ORAL]

"Effect of bremsstrahlung radiation emission on fast electrons in plasmas", O Embréus et al, EPS conference on plasma physics, Leuven (2016) [ORAL]

"A non-linear solver for runaway-electron dynamics" A Stahl et al, Varenna Fusion Theory Conference (2016) [POSTER}

"Kinetic modelling of runaways in fusion plasmas" T Fülöp et al, IAEA Fusion Energy Conference, Kyot (2016) [POSTER}

"Analysis of runaway electron synchrotron emission in Alcator C-Mod", A Tinguely et al (incl Hoppe, St Embréus), APS Conference San Jose (2016) [ORAL]

"Synchrotron and collisional damping effects on runaway electron distributions" C Paz-Soldan et al (inc Wilkie, Stahl, Embréus, Fülöp), APS Conference San Jose (2016) [ORAL]

C. Sommariva et al., 'Simulating Runaway Electrons during disrnptio11.1 with test particles in

the JOREK code', Proceedings of the 43'd European Physical Society conference on plasma physics,

Leuven, Belgium, 2016

G. Papp et al., 'Runaway electron generation and mitigation on the European medium sized tokamaks

ASDEX Upgrade and TCV', 26111 IAEA Fusion Energy Conference, Kyoto, Japan 2016

(to be submitted to Nuclear Fusion)

J. Mlynar et al., 'Losses of Runaway Electrons in MHD-active plasmas of the COMPASS tokamak',

26111 IAEA Fusion Energy Conference, Kyoto, Japan 2016 (to be submitted to Nuclear Fusion)

K. Särkimäki, E. Hirvijoki, J. Decker, J. Varje, T. Kurki-Suonio, 'An advection–diffusion model for cross-field runaway electron transport in perturbed magnetic fields', presentation at the Theory and Simulation of Disruptions Workshop, PPPL, U.S.A., 20.7.16-22.7.16

K. Särkimäki, an oral presentation on run-away electrons for general audience at the FinnFusion Annual Seminar, Lappeenranta, Finland, 23.-24.5.2016

Y. Peysson , "A european effort for kinetic modelling of runaway electron dynamics" presentation at the Theory and Simulation of Disruptions Workshop, PPPL, U.S.A., 20.7.16-22.7.16

Y. Peysson , "A european effort for kinetic modelling of runaway electron dynamics" presentation at the JET disruption/run-away Workshop, Abingdon,UK, 11.7.16-13.7.16

Y. Peysson: organization of the Runaway Electron Meeting at Pertuis (France) 6-8th June 2016 + two oral presentations

Thesis:

"Kinetic modelling of runaways in plasmas" Licentiate Thesis (Chalmers University of Technology, June 2016) http://ft.nephy.chalmers.se/publications/Embreus_Licentiate_thesis.pdf

"Effect of screened nuclei on fast electron beam dynamics" MSc Thesis (Chalmers University of Technology, February 2016) http://ft.nephy.chalmers.se/publications/Thesis_Linnea_final.pdf

4. Managerial aspects (optional)

If you think there are any managerial issues to you project (*changes to personnel, cost issues, lack of communications and etc.*), which STAC and PMU shall take care of, please mention them here. (*1 page maximum*)

None