Development of the runaway electron modelling capabilities of the European Transport Simulator

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Introduction The relativistic runaway electron beam formed in disruptions is one of the most critical problems of reactor-size tokamaks. Despite the decades of modelling efforts we still miss a self-consistent simulation tool that could simultaneously capture all aspects of this phenomenon. This paper presents a step towards the development of such modelling capabilities.

Integrating simulation tools for different physical phenomena can be cumbersome. The EUROfusion Code Development for integrated modelling project (WPCD) facilitates this by providing an Integrated Modelling framework (EU-IM), implemented in Kepler [1], and a standard data structure for communication that enables relatively easy integration of different physics codes [2], so called "actors". Interchangeability of the actors is a main feature that allows easy benchmarking, which is extremely useful for the verification of the workflows. A three-level modelling approach was adopted to runaway electron simulation within the EU-IM [3]. The first level of modelling (Runaway Indicator) is limited to the indication if runaway electron generation is possible or likely. The second level (Runaway Fluid) adopts a similar approach to the GO code [4], using analytical formulas to estimate changes in the runaway electron current density. The third level is foreseen to be based on the solution of the full electron kinetics (like LUKE [5]), that will eventually be the ultimate – but computationally expensive – tool.

This paper presents the integration of the first two modelling steps into the European Transport Simulator (ETS) workflow [6] of EU-IM, consequent benchmarking with the GO code, and testing of the extensions of the modell.

Runaway electron actors in ETS Runaway Indicator has two functions: It generates a warning message if the E parallel electric field is higher than the E_c critical field for runaway generation [7] anywhere inside the $x = r/a = 0.95$ normalized minor radius. It gives a second warning if the toroidal electric field in this region is expected to produce a non-negligible runaway

*See http://www.euro-fusionscipub.org/EU-IM.

current according to the primary generation formula (67) of [7]. This is expected to exclude false indications of flattop runaways [8]. Runaway Indicator is integrated into the Instantaneous Events module of ETS, and by default it runs in every time step.

The purpose of Runaway Fluid is to provide an estimate of the non-inductive current due to runaway electrons using computationally cheap analytical estimates of runaway electron growth rate. It is integrated into the "Heating & Current Drive Workflow" which will allow simple benchmarking with more advanced kinetic models, and which itself is part of the Convergence Loop of ETS. By default, Runaway Fluid is switched off in ETS, and it allows exact specification of modells to be used when enabled by an expert user. For primary generation it takes the Dreicer generation into account by either to most general formula (63) of Connor and Hastie [7] or formula (66) valid for high E/E_c normalized electric field or even the simplest formula (67) constrained to relatively low temperatures, but providing a systematic overestimation of runaway generation in the whole domain. For realistic aspect ratio tokamaks a correction factor for the effect of toroidicity is to be applied as suggested by Nilsson et.al. [9].

Runaway Fluid uses the classical formula for avalanche generation by Rosenbluth and Putvinski [10]. Their formula can optionally be modified by a E_a threshold at low electric field obtained using a momentum-conserving approach to the knock-on collisions and approximated by formula (8) of the paper by Aleynikov et.al. [11]. Studies with LUKE showed that the avalanche growth rate can also be significantly reduced at toroidal magnetic surfaces with high mirror ratio due to the trapping of the high energy electrons generated in the knock-on collisions. For this purpose formula (A.4) of the paper by Nilsson et.al. [9] is implemented.

Even with the extensions, the Runaway Fluid approach does not provide reliable modelling for slightly critical electric field cases, yet it can still be used to extend the validity of ETS to scenarios having just a little bit of runaways: The modelling can be first run by neglecting the effect of runaways, which is the default setting. Then if the Runaway Indicator gave warnings, the modell can be re-run with Runaway Fluid set to use the growth rates without the corrections. This case, Runaway Fluid gives a conservative over-estimation of the runaway current. If the comparison of the two cases show no significant difference, the user can be sure that runaway electrons are not a significant factor in the studied simulation scenario.

Benchmark of ETS and GO Having tested the growth rates and the newly developed actors in separate test workflows, as the next step benchmarking of ETS with Runaway Fluid against the GO code was proposed. The difficulty with this task is that the simple runaway modells of GO were shown to be relevant for large electric field cases with self-consistent electric field diffusion, like disruptions [4], but they are not valid for quasi-steady state conditions, which is the usual operation scenario for ETS. For the purpose of the benchmark a new actor was implemented in ETS that produces an energy sink for electrons and ions with a power proportional

Table 1: *Effect of the more advanced models of Runaway Fluid with respect to the simple modell analogue to GO in case of two scenarios. Percentages mark the changes in peak runaway current density with respect to the simplest modells.*

Correction term	**High E disruption case** *Parameters:* $t_d = 0.5$ ms, $T_{min} = 15$ eV	**Moderate E transient case** *Parameters:* $t_d = 10$ ms, $T_{min} = 100$ eV
Dreicer formula valid for **high temperature** [7] (66)	0.1% decrease in j_r	23% decrease in j_r
Dreicer formula valid for **low electric field** [7] (63)	0.1% decrease in j_r	21% decrease in j_r
Threshold for avalanche generation [11]	No change	No change
Toroidicity corrections [9]	25% decrease in j_r	15% increase in j_r (decrease in total current)

to the energy content of the corresponding population, thus producing an exponential drop in temperature with a specified t_d decay time. It also has a feature to smoothly stop the temperature drop at a specified T_{min} minimum temperature. Having introduced this drastic change in energy content on the timescale of milliseconds, we switched off all other transport modells and sources. A common choice for the boundary condition on the curent diffusion equation was the perfectly conducting wall just at the plasma boundary.

The benchmark was performed with $t_d = 0.5$ ms and $T_{min} = 15$ eV starting from an ASDEX-Upgrade simulation as initial condition. Qualitative and order of magnitude correspondence was found between GO and ETS, but there was also a significant difference in the evolution of the electric field and as a result there was a factor of 2 difference in the runaway current. This can probably be explained by the different assumptions on magnetic geometry, which needs further study.

Extended capabilities of ETS with Runafluid The Runaway Fluid modells were constrained to the simplest Dreicer and avalanche generation formulas for the purpose of the benchmark with GO, but afterwards the effect of the correction factors was explored also using a more moderate electric field scenario with $t_d = 10$ ms and $T_{min} = 100$ eV, as well.

Table 1 shows the effect of switching on the more advanced corrections that aim to extend the range of validity of Runaway Fluid. As expected, the effects are more significant for the lower electric field scenario. There, it is clearly necessary to use one of the more generally valid Dreicer generation formulas, whereas in case of disruptions it is not needed. The avalanche threshold gives practically no difference in either case due to both still having quite high electric field compared to the threshold electric field. In real flattop or runaway ramp-down scenarios this might still be significant. A study of this correction will require the development of other types of runaway scenarios in ETS. The toroidicity correction, on the other hand, appears to give a significant contribution to already the high electric field scenario, and it influences not just magnitude of the runaway current but the shape of the beam as well in the moderate electric field case.

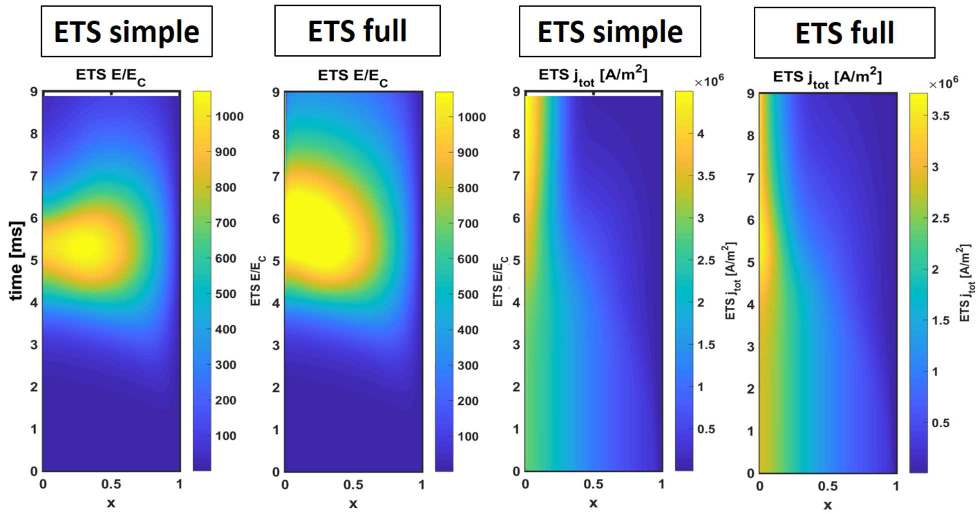

Figure 1: *Evolution of the electric field profile and of the total current density comparing ETS with simple models in Runaway Fluid to the case of applying all the corrections.*

Figure 1 details of the time evolution of the high electric field case of Table 1. It shows that the magnitude ot the electric field produced is quite similar, but the resulting runaway production is significantly reduced for the modell with the toridicity correction.

Conclusions This paper presented the development of the first two runaway electron modelling steps and their integration into the European Transport Simulator (ETS) workflow of EU-IM. We discussed the results of this extension of ETS in terms of modelling capabilities, and we described a method to safely draw conclusions. A benchmark with the GO code was presented, along with some tests highlighting the extensions of the analytical models in the EU-IM implementation that allows simulating for moderate electric fields. The next step in the development of runaway electron capabilities of ETS will be to integrate a Fokker–Planck solver for the purpose.

Acknowledgements This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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