MODELLING OF MILDLY RELATIVISTIC RUNAWAY ELECTRONS – DEVELOPMENT OF REDUCED-KINETIC MODEL AND VALIDATION IN KSTAR OHMIC STARTUP

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A model for mildly relativistic Runaway Electrons (REs) is developed in a reduced-kinetic form and validated in KSTAR ohmic startup. The runaway condition has been typically defined by the force-free condition [1]: an electron undergoes net acceleration if its particle momentum exceeds the critical momentum p_c (force-free). Importance of startup REs is highlighted for upcoming plasma initiation at ITER [2]. Their generation is usually governed by the Dreicer mechanism that accounts for an upward diffusive flow across p_c under the effect of an electric field [3]. This produces *mildly relativistic* seed REs. In the presence of a strong electric field, they are rapidly accelerated close to the speed of light so a current carried by them can be deduced by assuming $v_{RE} = c$. Yet, when an electric field is moderate, a mildly relativistic effect $(v_{RE} \neq c)$ may be crucial in estimating RE current density. Indeed, the critical energy corresponding to p_c can be close to the H ionization potential during an early startup [4], which implies that the light-speed assumption be invalid. Ideally, kinetic modelling can describe the mildly relativistic effect. However, a recent improvement in a startup code demands the RE model have a fluid form due to the computational cost that has increased as the code aims at designing scenarios only using control room parameters such as wave forms of coil currents, prefill gas pressure, machine information and etc [5]. Therefore, in order to follow the philosophy as well as account for the mildly relativistic correction, we develop the RE current model in a reduced-kinetic form.

Three main findings strengthen physical foundation in the model development that we build upon the established RE physical basis [1]. (1) The fluid description of RE density is appropriate during a tokamak startup but extracting the Dreicer generation rate from an electron distribution function requires introduction of the region-based runaway boundary p_V in a dynamic scenario since diffusive terms are the leading order compared to the acceleration around a narrow singular layer across p_c [6,7]. (2) The binary nature of inelastic collisions should be accounted for by the Boltzmann operator in cold weakly ionized plasmas where most of inelastic interactions can involve the large energy loss [4]. (3) Multi-fluid RE model that initializes a seed RE momentum as p_V and evolves their momentum using the test particle method at every time step shows a substantial agreement with the kinetic description and reducing it into a single fluid form still preserves accuracy comparable to the multi-fluid free-fall calculation [7]. For (3), see Fig. (1a).

The model is quantitatively and qualitatively validated in KSTAR ohmic discharge after coupled with the reliable startup code DYON [5,8] to correctly describe the plasma parameter evolutions. In KSTAR 2020 ohmic campaign, a mysterious correlation was observed between the non-thermal radiative temperature from Electron Cyclotron Emission (ECE) during early ramp-up and the maximum level of Hard-X ray intensity during late ramp-up even though the database shares similar values of prefill gas pressure [9]. The validation turns out that the early density evolution can explain the observed trend. Plasma parameters are benchmarked against the experimental measurement. Then, the synthetic ECE reconstruction reveals that a predicted RE level is sufficient to give rise to the non-thermal effect on the radiative temperature (~ 371 eV) exceeding the DYON temperature (~ 220 eV) when a measured radiative temperature (> 12 keV) far exceeds the DYON prediction; the reconstruction reproduces the radiative temperature (~ 185 eV) aligning with the DYON output (~ 200 eV) if the measured one (~ 145 eV) does not retain the non-thermal effect [7]. In addition, a statistical analysis demonstrates that the measured radiative temperature has a positive correlation with the predicted RE current density. The result is shown in Fig. (1b).

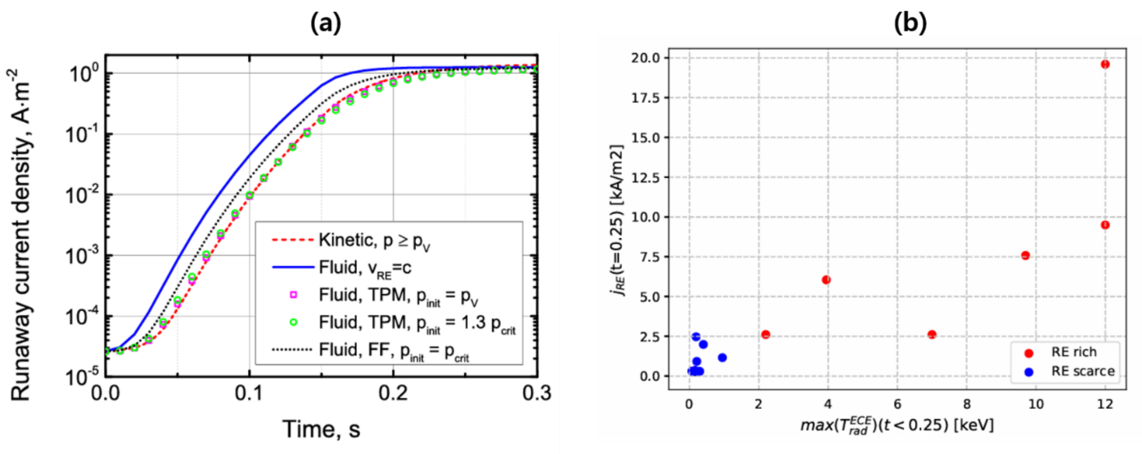

Figure 1. (a) comparison of RE current density estimated from various methods, (b) scatter plot for the RE current density predicted by DYON-RE (y-axis) and the maximum value of measured radiative temperature before 0.25 s (x-axis) [7].

Following the first trial of benchmarking of the SCENPLINT code coupled with the RE model against the JET experimental data such as the runaway current density estimated from the Hard-X ray signals [10], we validated the reduced-kinetic model with the mildly relativistic correction that is coupled with DYON by explaining the non-thermal radiative temperature aided by the synthetic ECE reconstruction in KSTAR. This work not only strengthens physical and engineering foundations of designing a runaway-free startup in fusion reactors but also improves the general understanding of RE physics. Future analysis of this study is to include the electromagnetic effect on plasma volume description [8] and consider kinetic instability [11] in interpreting the radiative temperature.

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