Kinetic modelling of hot-tail generation in ITER SPI disruptions

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1. Introduction

Tokamak disruptions are a major concern for next-step devices because relativistic runaway-electron (RE) beams can deposit large, localized heat loads on plasma-facing components. In ITER, disruption mitigation relies on rapid impurity delivery by shattered pellet injection (SPI), so predictive modelling of RE generation in SPI-mitigated plasmas is needed for scenario assessment. Recent ITER disruption simulations with DREAM [1, 2], included RE scrape-off during vertical displacement [3] and material deposition [4]. They show that RE suppression requires both a small seed and limited avalanche gain. Here we introduce a self-consistent fluid–kinetic hot-tail treatment for SPI simulations. A local trigger activates the isotropic kinetic equation only after the pellet ablation has created a cold electron background assumed by the reduced collision operator. To accurately account for fast radial transport, a finite-detrapping time correction to the pitch-averaged radial transport operator is also introduced.

2. Triggered isotropic kinetics during SPI

The reference kinetic model evolves the bounce-averaged electron distribution function f in radius, momentum and pitch,

$$\frac{\partial f}{\partial t} - \left\{ e\mathbf{E}\cdot\frac{\partial f}{\partial \mathbf{p}} \right\} = \{\mathscr{C}[f]\} + \frac{1}{\mathscr{V}'}\frac{\partial}{\partial r}\left(\mathscr{V}'\{D_{rr}\}\frac{\partial f}{\partial r} \right),$$

where the braces denote bounce averaging. This model inherently accounts for magnetic trapping effects and is therefore the natural reference for hot-tail generation and transport physics, but it is too computationally expensive for extensive ITER SPI scans. At the opposite end of the modelling hierarchy, the Smith–Verwichte model [5] provides an efficient analytic estimate of hot-tail generation based on the collisional relaxation of an initially Maxwellian tail. Its low computational cost motivated its use in Ref. [1]. In this work we use an intermediate model that evolves an isotropic hot electron distribution $f_0(r,p)$ numerically. It retains momentum dynamics, electric-field deformation and radial transport, while integrating over pitch to reduce complexity. The challenge is that the isotropic suprathermal equation employs a cold-target collision operator, for which the collisional friction force scales as $1/v^2$. Consequently, an initially Maxwellian distribution is not an equilibrium solution of the kinetic equation and is driven towards lower momenta even in radial regions where no injected material is present. Evolving the kinetic equation from the beginning of the simulation would therefore produce artificial cooling and deplete the hot-electron population before the pellet material reaches the corresponding radius. We instead retain the fluid description in each radial zone, with $f = f_{\mathrm{M}}$, until the material injection and/or the disruption evolution have produced a distinct local cold-electron population. The isotropic kinetic equation is activated locally when $n_{\mathrm{cold}} \geq 0.01 n_{\mathrm{hot}}$. From that point onward, it evolves the surviving suprathermal population and provides the RE generation rate $\partial n_{\mathrm{RE}}/\partial t$ to the disruption model. In this way, it identifies when the assumptions behind the isotropic hot-electron equation become valid in the evolving SPI plasma, since the kinetic stage inherits the density, temperature and electric field produced by the pellet calculation.

3. Finite-detrapping time correction to isotropic Rechester–Rosenbluth transport

A challenge with the ordinary isotropic model, as described in [2], lies in the radial-transport model. In a fully ergodic magnetic field, electrons undergo a radial random walk by following field lines, yielding the Rechester-Rosenbluth diffusion coefficient

$$D_{\mathrm{RR}} \simeq \pi q R (\delta B/B)^2 |v_{\|}|.$$

For trapped electrons, the bounce average of the $v_{\|}$ factor vanishes, preventing them from being substantially transported radially before they can be collisionally de-trapped.

Since the pitch average employed in the isotropic model eliminates the distinction between trapped and passing electrons, the RR diffusion coefficient can overestimate the fast electron loss rate. To correct for the finite de-trapping time of trapped electrons, we first note that the time for electrons to collisionally deflect by $\Delta\xi_0 = \xi_T$, and thus be detrapped, is

$$\tau_{\mathrm{detrap}} = \frac{\xi_T^2}{\nu_D A_c(\xi_T)} \qquad \Rightarrow \qquad D_{\mathrm{detrap}} = j_0^2 \nu_D \frac{a^2}{\xi_T^2} A_c(\xi_T),$$

where $A_c(\xi_T)$ is the bounce coefficient

$$A_c(\xi_T) = \frac{1}{2}\left(1-\xi_T^2\right)\left\{\frac{B_{\min}}{B}\frac{\xi^2}{\xi_0^2}\right\}\Bigg|_{\xi_0=\xi_T}.$$

Since detrapping and radial escape are sequential, their times add, giving an effective transport coefficient $D_{\mathrm{FT}} = (D_{\mathrm{RR}}^{\mathrm{iso}} + D_{\mathrm{detrap}})/(D_{\mathrm{RR}}^{\mathrm{iso}} D_{\mathrm{detrap}})$ which accounts for a finite detrapping time. It

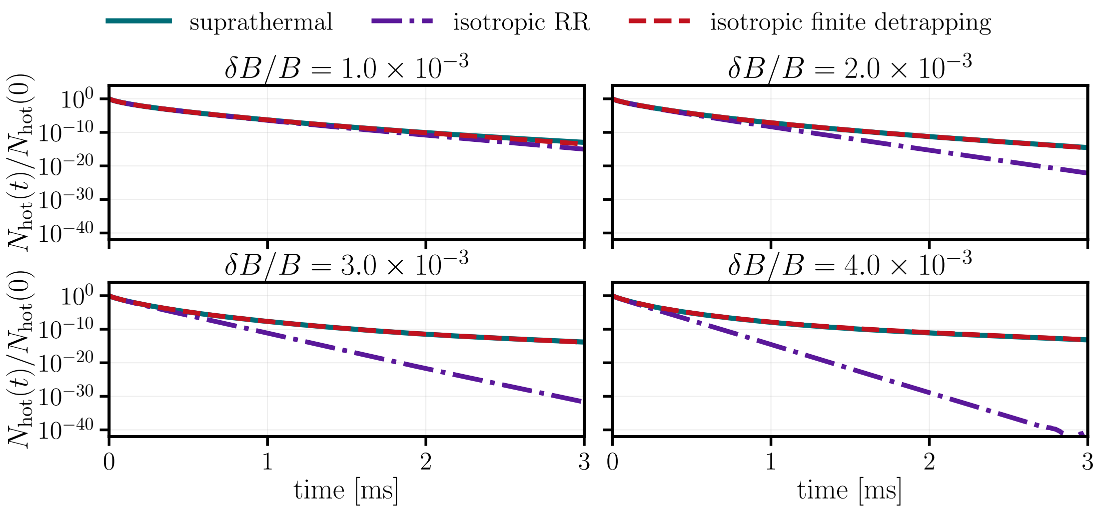

Figure 1: Normalized spatially integrated hot-electron inventory for increasing magnetic perturbation in a low temperature 15 MA L-mode ITER scenario. The pitch-resolved suprathermal model is compared with ordinary isotropic Rechester–Rosenbluth transport and with the isotropic finite-detrapping closure.

recovers ordinary isotropic Rechester–Rosenbluth transport when radial loss is slow, but saturates at the detrapping rate for strong radial transport. Figure 1 shows that the three descriptions are close at $\delta B/B = 10^{-3}$, while pure isotropic Rechester–Rosenbluth transport overestimates the hot electron loss by tens of orders of magnitude at larger perturbation. The finite-detrapping time correction follows the pitch-resolved suprathermal result across the scan because it accounts for the reduced loss rate due to the relatively slow collisional de-trapping.

4. ITER 15 MA L-mode application

The triggered isotropic model with finite-detrapping time transport was then applied to low temperature 15 MA L-mode ITER SPI simulations [1]. Figure 2 shows early/late thermal-quench onset and 1–3 ms thermal-quench durations. Red curves are fully fluid calculations, while dashed curves use the triggered isotropic kinetic model. Across cases spanning about ten orders of magnitude in $I_{\rm RE}$, the kinetic model predicts a two order magnitude increase in the runaway seed compared to the fluid model. High-temperature H-mode simulations, resolution studies and $\delta B/B$ convergence scans are ongoing and will be presented in a future study. The comparison also tests the triggering procedure. In these runs the kinetic model is not initialized at a fixed global thermal-quench time; it is started where and when the SPI simulation has generated enough cold electrons. This preserves the delayed material-deposition physics while still allowing the surviving hot population to be evolved kinetically.

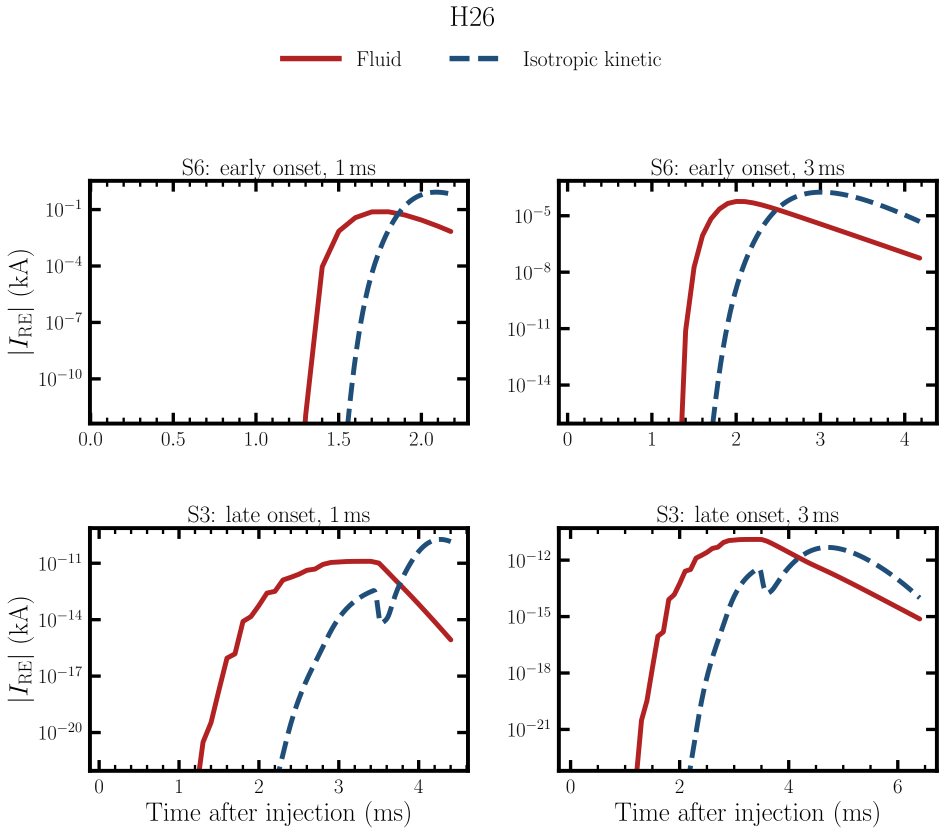

Figure 2: Runaway current in ITER 15 MA L-mode (H26) SPI cases evolution until the end of the TQ. Solid red: fluid model; dashed blue: triggered isotropic kinetic model with finite-detrapping time transport.

5. Conclusions

We have introduced a local trigger for using the isotropic kinetic hot-tail equation inside self-consistent SPI simulations: each region is switched from fluid to kinetic evolution only once pellet-induced cooling has produced the required cold electron background population. Once activated, the reduced description is not the ordinary isotropic model with Rechester–Rosenbluth transport, but the triggered isotropic model supplemented by finite detrapping effects. This avoids excessive depletion of the trapped hot reservoir, reproduces pitch-resolved hot-electron losses and substantially improves the predicted RE seed scale in the tested cases.

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