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Runaway seed formation during the thermal quench and the effects of radial transport of fast electrons

Ola Embreus

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EUROfusion

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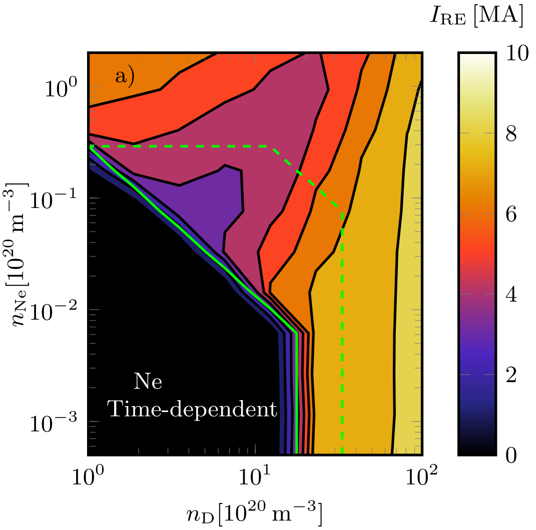
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Recent modelling suggests unsuccesful RE mitigation in ITER (15 MA nuclear phase), if:

- The entire hot-tail seed is lost during the TQ,
- All RE's created during the CQ are confined.



Green boundary encloses tolerable CQ times

[O Vallhagen *et al.* (2020), submitted to JPP]

[See presentation by T Fülöp for further details]

- Survival of hot-tail seed can further exacerbate the problem... (Part 1)
- ...but transport of relativistic electrons may help us. (Part 2)
- Model kinetic equation:

$$\frac{\partial f}{\partial t} + eE_{\parallel}\frac{\partial f}{\partial p_{\parallel}} = C[f] + \frac{1}{\sqrt{g}}\frac{\partial}{\partial r}\left(\sqrt{g}D\frac{\partial f}{\partial r}\right)$$

$$C[f] = \frac{\nu_D}{2}\frac{\partial}{\partial \xi}\left[(1-\xi^2)\frac{\partial f}{\partial \xi}\right] + \frac{1}{p^2}\frac{\partial p^3 \nu_s f}{\partial p}$$

- Resolving full phase-space dynamics sometimes infeasible:
  $\Rightarrow$ develop reduced models to capture these effects.

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Expansion in strong pitch angle scattering: $f = f_0 + \delta f_1 + ...$
[Rosenbluth & Putvinski, NF (1997), Hesslow *et al.* NF (2019)]

$$\frac{\partial}{\partial t} \sim \nu_s \sim \delta^2, \quad E_\parallel \sim \delta, \quad \nu_D \sim 1,$$
$$\frac{\partial f_0}{\partial t} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{(eE_\parallel)^2}{3\nu_D}\frac{\partial f_0}{\partial p} + p\nu_s f_0\right)\right] = \frac{1}{\sqrt{g}}\frac{\partial}{\partial r}\left(\sqrt{g}D\frac{\partial f_0}{\partial r}\right)$$

- Previously used in RE avalanche theory
- Current carried by f_1 term:

$$j_{\mathrm{RE}} = \int e v_\parallel \delta f_1 \, \mathrm{d}\mathbf{p} = -\frac{e^2 E_\parallel}{3}\int \frac{v}{\nu_D}\frac{\partial f_0}{\partial p}\, \mathrm{d}\mathbf{p}$$

allows self-consistent evolution of fields $\nabla^2 E = \mu_0 \partial(\sigma E + j_{\mathrm{RE}})/\partial t$

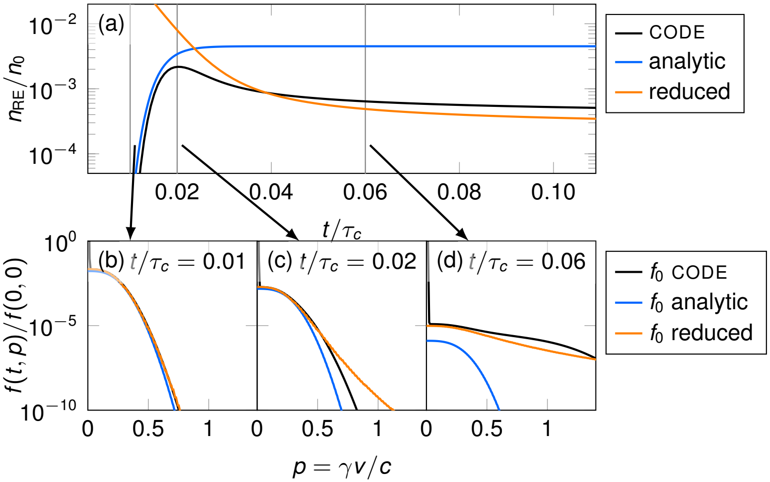
Performance of reduced theory compared with:

- CODE (2D kinetic solver: `https://ft.nephy.chalmers.se/retools/`)
- analytic theory [Smith & Verwichte, PoP (2008)] amended with j_{RE}

Test case with high Z:

$$n_0 = 10^{20}\,\mathrm{m}^{-3},\quad T_{\mathrm{initial}} = 6\,\mathrm{keV},\quad T_{\mathrm{final}} = 5\,\mathrm{eV},\quad \tau_{\mathrm{TQ}} = 0,\quad Z_{\mathrm{eff}} = 20,\quad \sigma E + j_{\mathrm{RE}} = j_0,\quad j_0 = 1\,\mathrm{MA/m^2},$$

No transport ($D = 0$)

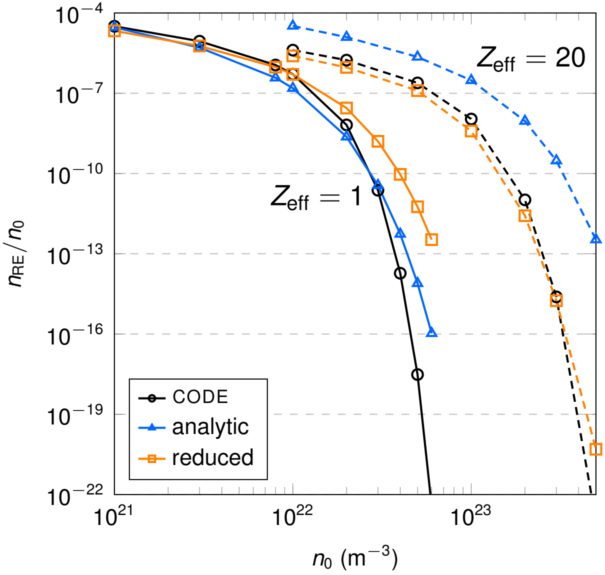


Density scan: suppression of hot-tail formation by raising collisionality

$$n_{RE} = \lim_{t\to\infty} n_{RE}(t)$$

Best performing model Z_{eff}-dependent:

- Low Z_{eff}: analytic model better
- High Z_{eff}: reduced kinetic better



Reduced hot-tail model roadmap:

- Assess validity in more realistic TQ simulations
  - Self-consistent temperature evolution
  - Screening effects in collision frequencies
- Explore effects of stochastic radial losses during TQ
  - Can we meet 90% radiated fraction and simultaneously deconfine the hot-tail seed?
  - How does faster-than-resistive current flattening influence seed formation?
- Attempt a modified reduced theory to extend validity to low Z_{eff}

Further details on the hot-tail models is published at:

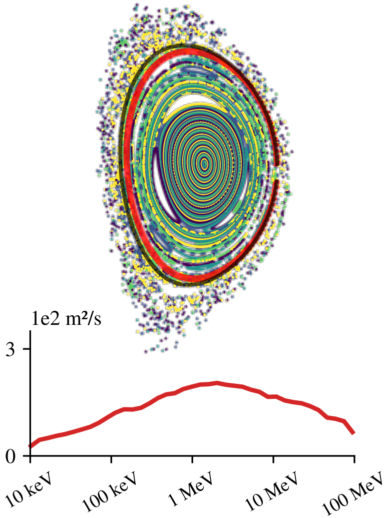
I Svenningsson, MSc thesis (2020)

`https://hdl.handle.net/20.500.12380/300899`

- Fast electrons lost along open field lines
- Most realistic model: orbit following
- Alternative approach: advection-diffusion model

$$\frac{1}{\sqrt{g}}\frac{\partial}{\partial r}\left[\sqrt{g}\left(-A(r,p,\mu)f + D(r,p,\mu)\frac{\partial f}{\partial r}\right)\right]$$

- Challenge: Find self-consistent f for net transport
- Question: Level of perturbation required to suppress the runaway avalanche?



Perturbed ITER-like field with corresponding radial diffusion coefficient

More details: K Särkimäki pres. + publication
`https://arxiv.org/abs/2006.03726`

Revisit and generalise previous study [P Helander *et al.* PoP 7 (2000)]:

$I_p \gg 1\,\text{MA} \Rightarrow$ RE avalanche faster than CQ

$$\tau_{\text{ava}} \sim \ln\Lambda \frac{m_e c}{eE_{\|}} \ll \tau_{\text{CQ}},$$

$$\frac{\partial f}{\partial t} \mapsto \Gamma f.$$

Average over pitch angles:

(*New terms)

$$\Gamma F + \frac{\partial U(p)F}{\partial p} = \frac{1}{\sqrt{g}}\frac{\partial}{\partial r}\left[\sqrt{g}\left(-A(r,p)F + D(r,p)\frac{\partial F}{\partial r}\right)\right]$$

$$U = eE_{\|} - p\nu_s - F_{\text{rad}}(p)$$

$$U(0)F(0) = \Gamma_{\text{ava}} n_{\text{RE}} = \Gamma_{\text{ava}} \int F(p)\,\text{d}p \qquad \text{(Boundary condition)}$$

Solution: $n_{\text{RE}}^{-1}\partial n_{\text{RE}}/\partial t \equiv \Gamma = \Gamma(r;\ A,\ D,\ \Gamma_{\text{ava}})$

Test case:

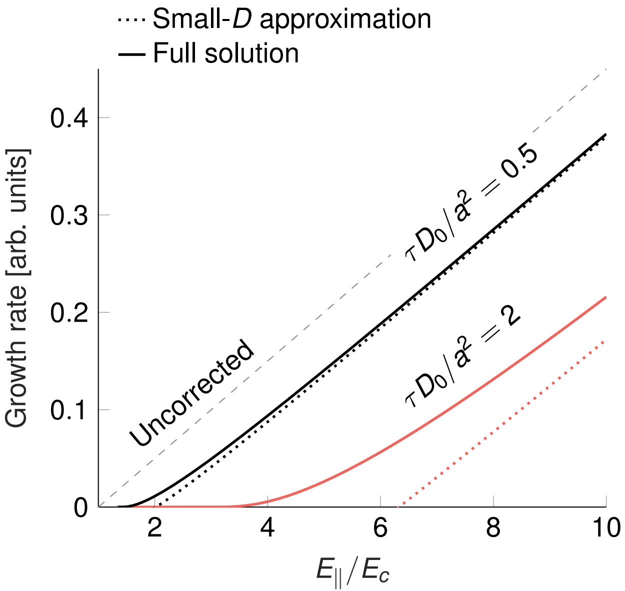
- Radially uniform diffusion:

$$D = \frac{D_0}{\sqrt{1 + p^2/m_e^2 c^2}},$$
$$A = 0$$

- Γ given by integral equation:

$$1 = \Gamma_{\text{ava}} \int_0^\infty \frac{\mathrm{d}p}{U(p)} \times$$
$$\times \exp\left(- \int_0^p \mathrm{d}p' \frac{\Gamma + D(p')/a^2}{U(p')} \right)$$

$a \sim$ minor radius



Test case:

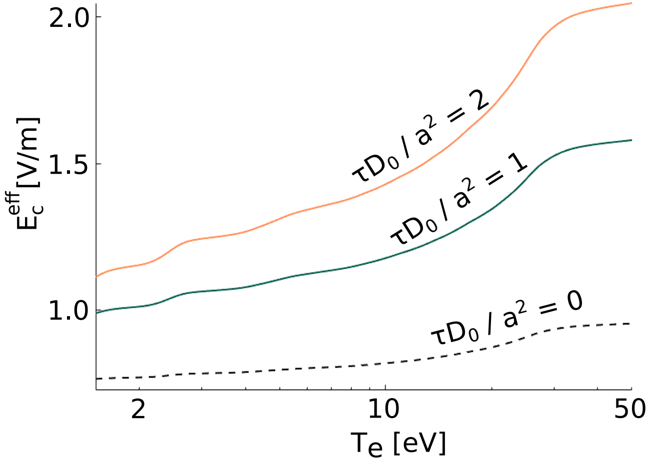
- Threshold electric field E_c^{eff}:

$$\Gamma(E_c^{\text{eff}}) = \frac{\partial n_{\text{RE}}}{\partial t} = 0$$

- Current decay rate in runaway plateau [B N Breizman NF (2014)]

$$\frac{\partial I_p}{\partial t} \propto -E_c^{\text{eff}}$$

- Root-finding algorithm implemented to solve $\Gamma = 0$ for given $D(p)$



$n_D = 1 \times 10^{20}\,\text{m}^{-3}$, $n_{\text{Ar}} = 0.3 \times 10^{20}\,\text{m}^{-3}$, $B = 5.3\,\text{T}$.

Roadmap for reduced model of RE transport:

- Determine domain of validity by comparing with kinetic simulations
- Study A, $D(r, p, \xi)$ from particle following in realistic fields
- Assess $\delta B/B$ needed to obtain tolerable avalanche multiplication

Further details on the growth rate model with radial transport is published at:

P Svensson, MSc thesis (2020)

`https://hdl.handle.net/20.500.12380/300784`

- Kinetic runaway physics expensive to resolve within integrated models
- Ongoing effort to improve reduced kinetic modelling of
  - Hot-tail seed formation during thermal quench
  - Suppression of avalanche by radial transport during current quench
- Upcoming research: explore consequences in realistic disruption simulations