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DREAM

A fluid-kinetic framework for disruption runaway electron simulations

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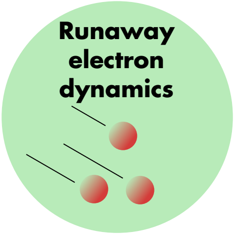
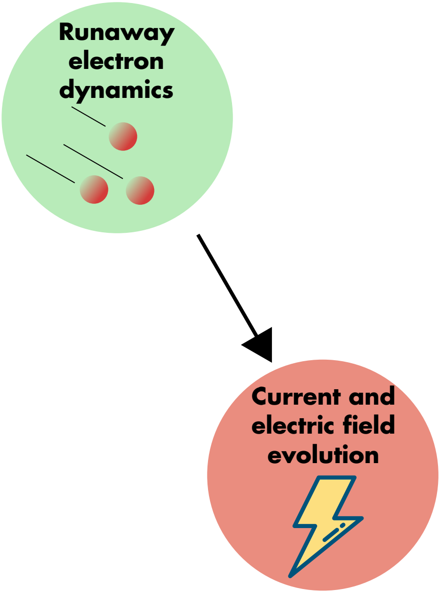
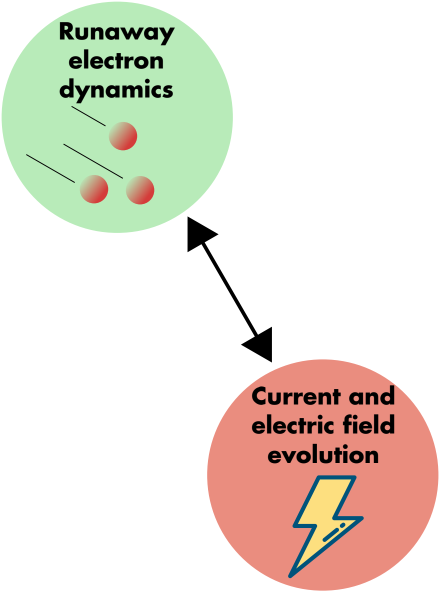

Runaway electron dynamics


Runaway electron dynamics
Current and electric field evolution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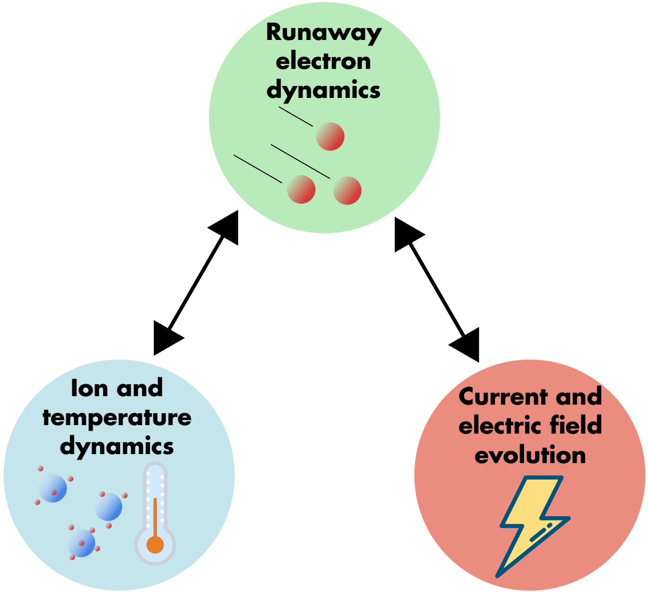
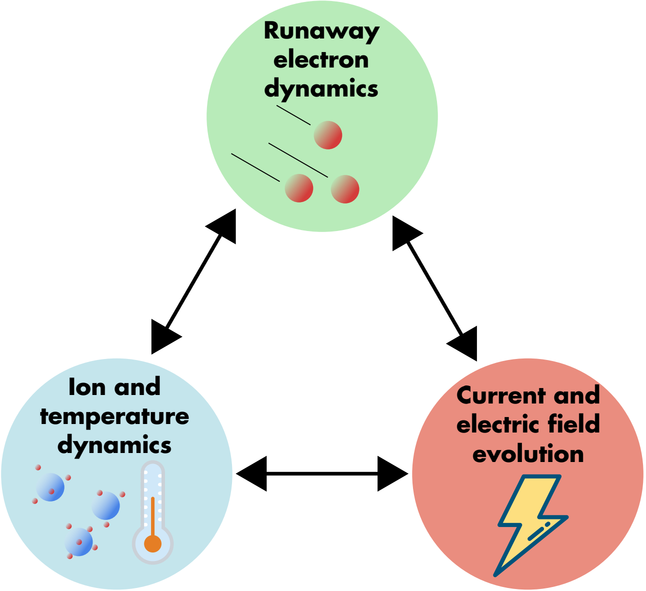

Runaway electron dynamics
Ion and temperature dynamics
Current and electric field evolution


Runaway electron dynamics
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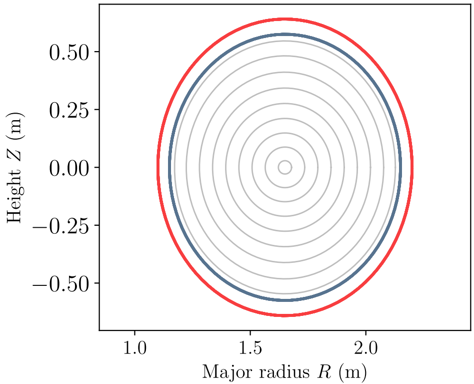
Current and electric field evolution

DREAM

Outline

1. Brief overview
2. The models
   - Electrons
   - Electric field (E), poloidal flux (ψ) and current density (j)
   - Ion and temperature dynamics
3. Model comparison

What is DREAM? (Disruption Runaway Electron Analysis Model)



- 1D transport model in tokamak geometry for
  - Electric field $E(r)$
  - Electron temperature $T_e(r)$
  - Plasma current density $j(r)$
- Fluid or kinetic (1D2P; bounce-averaged) electrons
  - Accurate treatment of transient runaway electron generation (e.g. hot-tail)
- Radial transport of electrons and heat

Electron models

DREAM separates electrons into **three populations** based on their energy:

- **Cold:** $p \sim p_{\mathrm{thermal}}$
- **Hot:** $p_{\mathrm{thermal}} < p < p_{\mathrm{c}}$
- **Runaway:** $p > p_{\mathrm{c}}$

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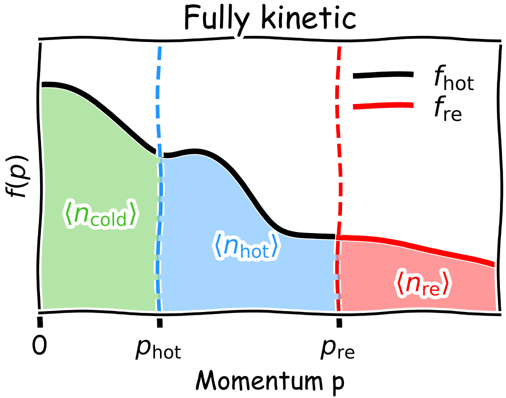
Electrons in each of these regions can be modelled either by solving the **kinetic equation** or be treated as a **fluid**



Fluid mode (one cold+hot fluid)
Both cold and hot electrons are represented by density $\langle n_{\mathrm{cold}} \rangle$ and temperature T_{cold}

[1] Aleynikov & Breizman, NF **57** (2017)

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Both cold and hot electrons are represented by the distribution function $f(r, p, \xi)$

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Superthermal mode ("Aleynikov & Breizman mode") [1]

- **Cold:** $\langle n_{\rm cold}\rangle$ and $T_{\rm cold}$ (starting at $\langle n_{\rm cold}\rangle = 0$, $T_{\rm cold} = 0$)
- **Hot:** $f_{\rm hot}$ with superthermal limit of collision operator

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Isotropic mode (reduced "Aleynikov & Breizman mode")
Same as the *superthermal* mode, but $f_{\rm hot}$ solved for using an angle-averaged equation
(Why? Performance of fluid mode, but with accurate hot-tail!)

[1] Aleynikov & Breizman, NF **57** (2017)

Runaway electrons are either treated as (independently of cold/hot electrons)

Fluid

$$\frac{\partial \langle n_\mathrm{re}\rangle}{\partial t} = \underbrace{F_\mathrm{hot}}_{\text{flux from } f_\mathrm{hot}} + \gamma_\mathrm{Dreicer} + \underbrace{\Gamma_\mathrm{ava}\langle n_\mathrm{re}\rangle}_{\text{avalanche}} + \underbrace{\gamma_\mathrm{T} + \gamma_\mathrm{compton} + \dots}_{\text{other runaway sources}}$$

$$+ \underbrace{\frac{1}{V'}\frac{\partial}{\partial r}\left[V'\left(-A_r\langle n_\mathrm{re}\rangle + D_{rr}\frac{\partial \langle n_\mathrm{re}\rangle}{\partial r}\right)\right]}_{\text{radial transport}}$$

Kinetically

$$\frac{\partial f_\mathrm{re}}{\partial t} + \underbrace{e\left\{E_\parallel \xi\right\}\frac{\partial f_\mathrm{re}}{\partial p_\parallel}}_{E \text{ acceleration}} + \underbrace{\left\{\boldsymbol{F}_\mathrm{synch}\right\}\cdot\frac{\partial f_\mathrm{re}}{\partial \boldsymbol{p}}}_{\text{synchrotron radiation}} = \underbrace{C\left[f_\mathrm{re}\right]}_{\text{collisions}} + \underbrace{S_\mathrm{re}}_{\text{fluid RE sources}}$$

$$+ \underbrace{\frac{1}{\mathcal{V}'}\frac{\partial}{\partial r}\left[\mathcal{V}'\left(-\left\{A_r\right\}\langle n_\mathrm{re}\rangle + \left\{D_{rr}\right\}\frac{\partial \langle n_\mathrm{re}\rangle}{\partial r}\right)\right]}_{\text{radial transport}}$$

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$$+ \underbrace{\frac{1}{V'} \frac{\partial}{\partial r} \left[V' \left(-A_r \langle n_{\text{re}} \rangle + D_{rr} \frac{\partial \langle n_{\text{re}} \rangle}{\partial r} \right) \right]}_{\text{radial transport}}$$

Kinetically

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$$+ \underbrace{\frac{1}{\mathcal{V}'} \frac{\partial}{\partial r} \left[\mathcal{V}' \left(-\{A_r\} \langle n_{\text{re}} \rangle + \{D_{rr}\} \frac{\partial \langle n_{\text{re}} \rangle}{\partial r} \right) \right]}_{\text{radial transport}}$$

Background plasma

Current density (Ampère's law)

$$2\pi\mu_0 \left\langle \boldsymbol{B} \cdot \nabla\phi \right\rangle \frac{j_{\mathrm{tot}}}{B} = \frac{1}{V'} \frac{\partial}{\partial r} \left[V' \left\langle \frac{|\nabla r|^2}{R^2} \right\rangle \frac{\partial \psi}{\partial r} \right].$$

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Electric field and poloidal flux

$$\frac{\partial\psi}{\partial t} = -V_{\mathrm{loop}},$$

$$2\pi\frac{\langle \boldsymbol{E} \cdot \boldsymbol{B}\rangle}{\langle \boldsymbol{B} \cdot \nabla\phi\rangle} = V_{\mathrm{loop}}.$$

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Wall coupling
(with wall time $\tau_{\mathrm{wall}} = L_{\mathrm{ext}}/R_{\mathrm{wall}}$ as free parameter)

$$V_{\mathrm{loop}}^{(\mathrm{wall})} = R_{\mathrm{wall}} I_{\mathrm{wall}},$$
$$\psi_{\mathrm{wall}} = -L_{\mathrm{ext}}\left(I_{\mathrm{p}} + I_{\mathrm{wall}}\right).$$

Ion (charge state) densities

$$\frac{\partial n_i^{(j)}}{\partial t} = \underbrace{\left(I_i^{(j-1)}\left\langle n_{\text{cold}}\right\rangle + \left\langle \sigma_{\text{ion},i}^{(j-1)} v \right\rangle\right) n_i^{(j-1)} - \left(I_i^{(j)}\left\langle n_{\text{cold}}\right\rangle + \left\langle \sigma_{\text{ion},i}^{(j)} v \right\rangle\right) n_i^{(j)}}_{\text{ionization}}$$
$$+ \underbrace{R_i^{(j+1)}\left\langle n_{\text{cold}}\right\rangle n_i^{(j+1)} - R_i^{(j)}\left\langle n_{\text{cold}}\right\rangle n_i^{(j)}}_{\text{recombination}}.$$

Ionization I_i^j and recombination R_i^j coefficients taken from ADAS. Kinetic ionization rates are calculated from

$$\left\langle \sigma_{\text{ion},i}^{(j)} v \right\rangle = \int \mathrm{d}p \int_{-1}^{1} \mathrm{d}\xi_0 \frac{\mathcal{V}'}{V'} v \sigma_{\text{ion},i}^{(j)} f(r,p,\xi_0)$$

according to [Garland *et al*, PoP **27** (2020)]

(Cold) electron temperature

$$W_{\mathrm{cold}} = \frac{3}{2}\left\langle n_{\mathrm{cold}}\right\rangle T_{\mathrm{cold}}$$

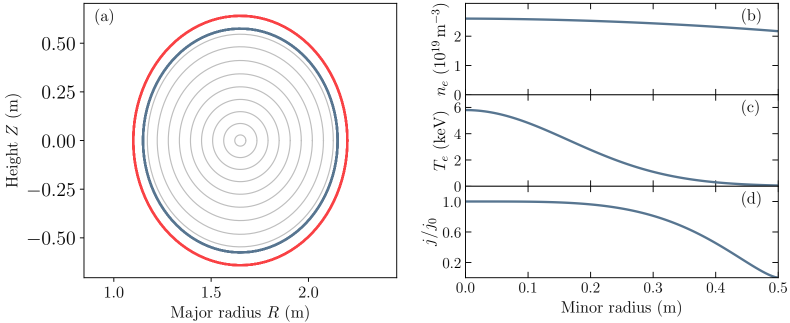
Energy balance

$$\frac{\partial W_{\mathrm{cold}}}{\partial t} = \underbrace{\frac{j_\Omega}{B}\left\langle \boldsymbol{E}\cdot\boldsymbol{B}\right\rangle}_{\text{ohmic heating}} - \underbrace{\left\langle n_{\mathrm{cold}}\right\rangle \sum_i \sum_{j=0}^{Z_i-1} n_i^{(j)} L_i^{(j)}}_{\text{line radiation}} + \underbrace{\left\langle Q_c\right\rangle}_{\text{coll. heat transfer}}$$
$$+ \underbrace{\frac{1}{V'}\frac{\partial}{\partial r}\left[V'\left(AW_{\mathrm{cold}} + D\frac{\partial W_{\mathrm{cold}}}{\partial r}\right)\right]}_{\text{radial transport}}$$

The collisional heat transfer $\left\langle Q_c\right\rangle$ includes both e-e and e-i contributions.

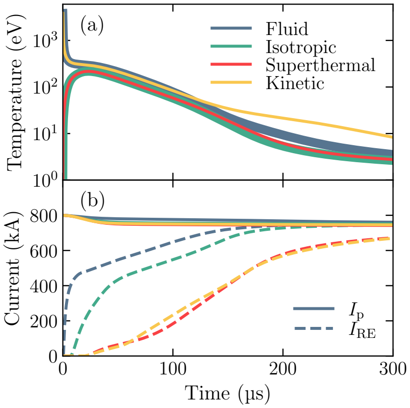
Comparison of electron models

Baseline setup: ASDEX Upgrade-like plasma



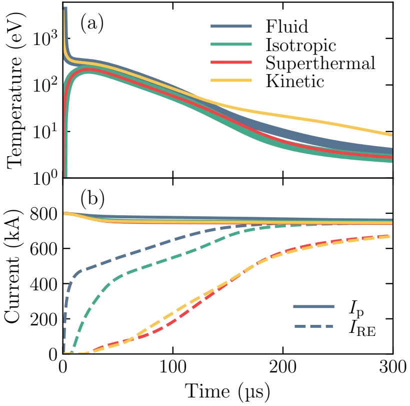
- Major radius $R_\mathrm{m} = 1.65$ m
- Plasma radius $a = 0.5$ m
- Wall radius $b = 0.55$ m
- Max. elongation $\kappa_\mathrm{max} = 1.15$
- $B_0 = 2.5$ T
- $n_{\mathrm{e},0} = 2.6 \times 10^{19}$ m^{-3}
- $T_{\mathrm{e},0} = 5.8$ keV
- $I_\mathrm{p} = 800$ kA

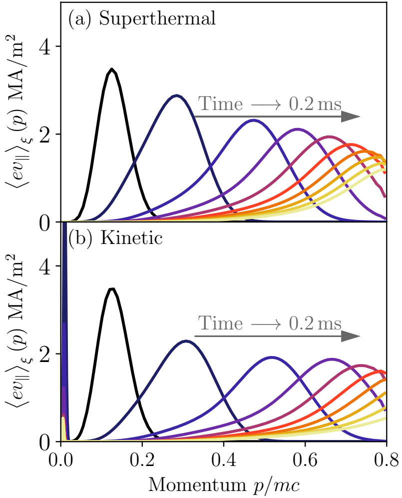
Scenario 1: Full conversion



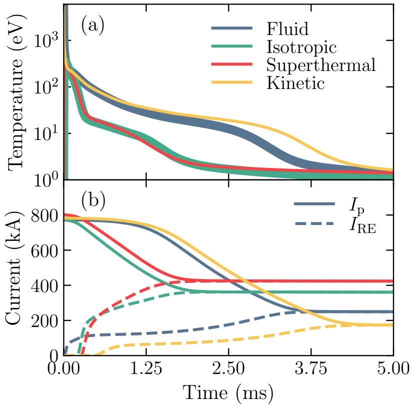
- Mixed D and Ar injection
- $n_D = n_{Ar} = 2.6 \times 10^{19}$ m^{-3}
- Almost full conversion $I_p \rightarrow I_{re}$
- Good agreement between electron models

Scenario 1: Full conversion



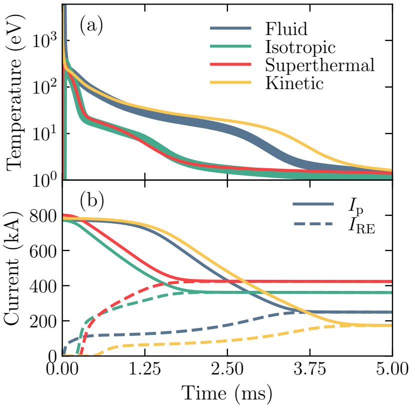


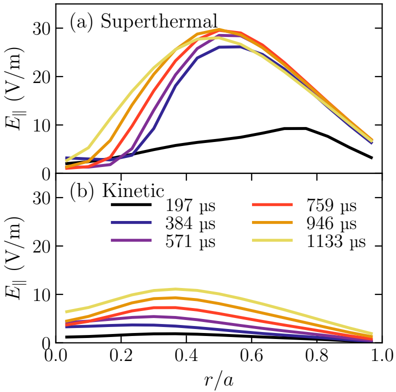
Scenario 2: Slow disruption



- More D, less Ar
- $n_D = 5.2 \times 10^{20}\,m^{-3}$, $n_{Ar} = 5.2 \times 10^{18}\,m^{-3}$
- I_{re} between 200-400 kA
- Major differences between electron models: due to the very different starting temperatures + less hot-tail

Scenario 2: Slow disruption

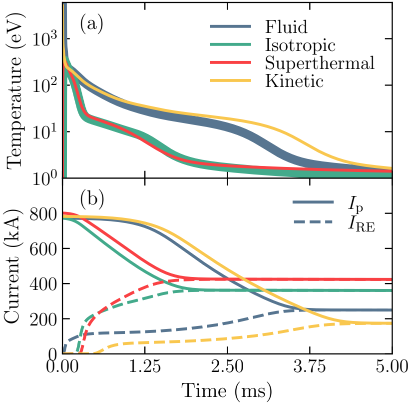




DREAM is a fluid-kinetic (1D2P) framework for self-consistent runaway electron simulation.

What's new with DREAM?

- Background plasma and runaway evolution with **kinetic hot-tail**
- Radial transport of electrons
- Kinetic ionization
- Tokamak geometry (bounce and flux-surface averaged)



On arXiv: 2103.16457

https://github.com/chalmersplasmatheory/DREAM

Benchmark

Comparison to Fig. 4 of GO simulations in ITER-like scenario [Vallhagen *et al*, JPP **86** (2020)].

- Mixed D and Ne injections
- Good agreement in I_p and $j_{\mathrm{re,max}}(r)$
- Some models have been upgraded in DREAM $\Longrightarrow$ agreement not perfect