CHALMERS
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DREAM

DREAM development and application to ITER/DEMO

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- New tool for disruption RE simulations developed at Chalmers

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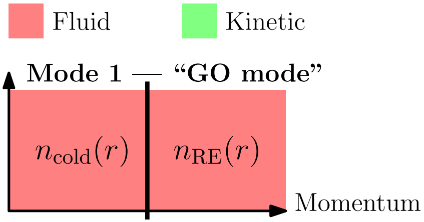
- Solves a set of transport equations

$$\frac{\partial X}{\partial t} = \frac{1}{\mathcal{V}'}\frac{\partial}{\partial z^i}\left[\mathcal{V}'\left(-\left\{A^i\right\}X + \left\{D^{ij}\right\}\frac{\partial X}{\partial z^j}\right)\right] + \left\{S\right\},$$

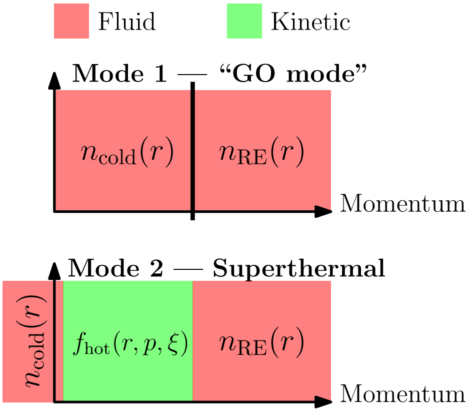
for

- $E_{\|}(r)$ — parallel electric field
- $f(r, p, \xi)$ — electron distribution function
- $n_{\mathrm{RE}}(r)$ — runaway electron density
- $n_i^{(j)}(r)$ — ion charge state densities
- $T_e(r)$ — electron temperature
- $T_i(r)$ — ion temperature
- ...and others...



DREAM allows a number of different models to be used. The main models are:

- Mode 1 – Fully fluid electrons (like GO)



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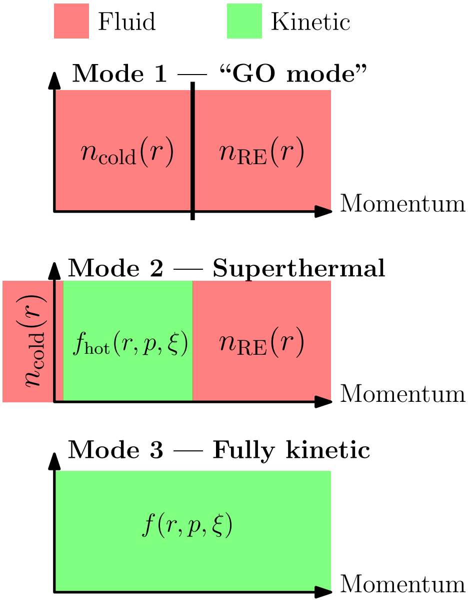
- Mode 1 – Fully fluid electrons (like GO)
- Mode 2 – Fluid RE and background; kinetic hot-tail



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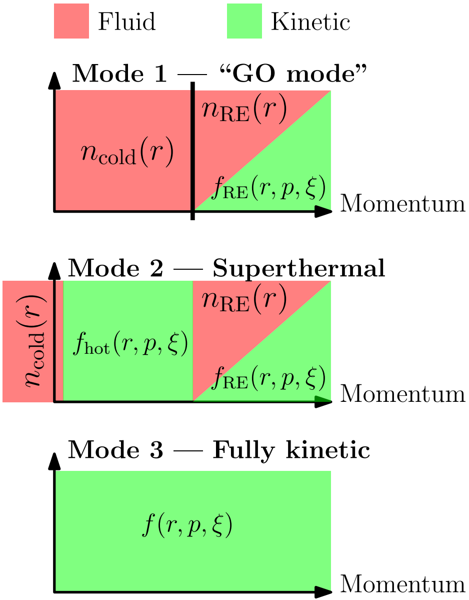
- Mode 3 – Fully kinetic



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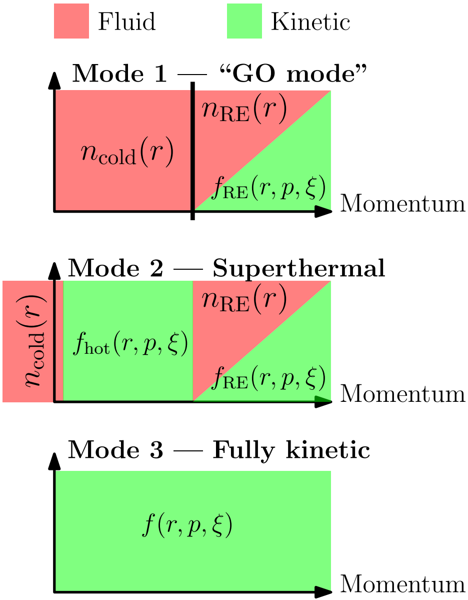

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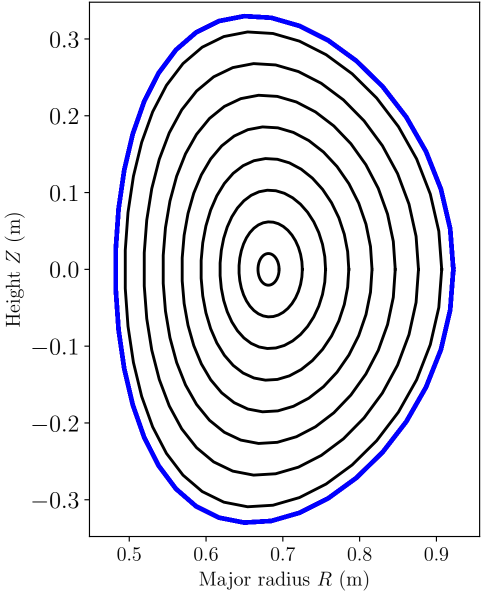
Many different combinations possible!

- Written in C++(17) and Python 3 (user interface)
  - Modular design
  - PETSc used for matrix operations
  - HDF5 for input/output
- Implicit time stepping (fully non-linear)
- Newton solver (with minor stabilizing features)
- Finite volume discretization for (r, p, ξ)
  - Automatically conserves density
  - Several robust flux limiters available (positivity conservation)

- Intensive development since March 2020 — DREAM is now ready to replace CODE and GO.
- Available on GitHub: `https://github.com/chalmersplasmatheory/DREAM`
- Five papers submitted/in preparation (incl. official DREAM paper)

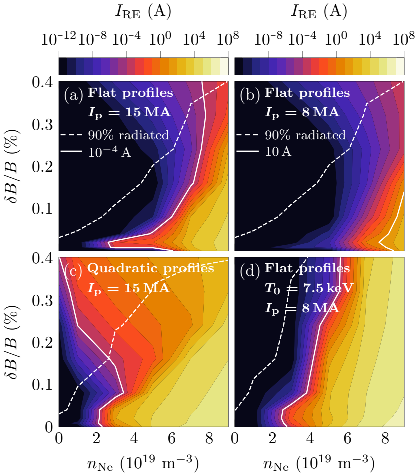
- Basic models for all quantities
- Analytical toroidal magnetic geometry
- Fast-electron impact ionization
- Fluid + kinetic radial transport of electrons and heat
- Magnetic ripple pitch scattering
- (support for using distribution function in SOFT simulations)
- . . . many others. . .



- SPI
  - First model implemented in MSc project of Oskar Vallhagen
- Hyperresistivity
  - For modelling current spike
- Non-linear electron-electron collision operator
- Numerical magnetic fields
- Ion transport

ITER & DEMO simulations

- ITER MMI scenario with hot-tail and transport
  - First results in preparation (Svenningsson *et al*)
  - More optimistic than earlier GO results
- ITER SPI scenario with hot-tail and transport
  - SPI module still under development
  - Investigate possibility of eliminating hot-tail with D + high-Z injections
- DEMO MMI & SPI studies
  - Scenarios similar to ITER scenarios, but with DEMO parameters



DREAM: Equation system

$$\mathcal{D} = \frac{1}{\mathcal{V}'}\frac{\partial}{\partial r}\left[\mathcal{V}'\left(A + D\frac{\partial}{\partial r}\right)\right], \qquad \text{(Radial transport)}$$

$$\frac{\partial f}{\partial t} = \frac{1}{4\pi p^2}\frac{\partial F_p}{\partial p} + \mathcal{D}_f f, \qquad \text{(Fokker–Planck)}$$

$$F_p = 4\pi p^2\left(p\nu_s f + \frac{1}{3}\frac{(eE)^2}{\nu_D}\frac{\partial f}{\partial p}\right), \qquad \text{(Momentum flux)}$$

$$\frac{\partial n_{\mathrm{RE}}}{\partial t} = -F_p\left(p_{\mathrm{max}}\right) + n_{\mathrm{RE}}\Gamma_{\mathrm{ava}} + \gamma_{\mathrm{Dr}} + \gamma_{\mathrm{tritium}} + \gamma_\gamma + \mathcal{D}_{\mathrm{RE}}n_{\mathrm{RE}}, \qquad \text{(RE fluid)}$$

$$F_p(0) = \frac{(n_{\mathrm{cold}} - \sigma_i n_{\mathrm{Zi}} Z_i)}{\partial t}, \qquad \text{(hot-cold sink)}$$

$$W_c = \frac{3}{2}n_{\mathrm{cold}}T_{\mathrm{cold}} + W_{\mathrm{binding}},$$

$$\frac{\partial W_c}{\partial t} = E_\parallel j_\Omega + \int \frac{p^2}{2m_e}\nu_{E,ee} f\,\mathrm{d}\boldsymbol{p} + n_{\mathrm{RE}}ceE_{\mathrm{c}}^{(\mathrm{cold})} + n_{\mathrm{cold}}\sum_{ij} n_i^{(j)}L_i^{(j)} + Q_c + \mathcal{D}_c W_c,$$

(Energy balance)

$$\frac{\partial n_{Z_i}}{\partial t} = R_{i+1} - R_i + I_{i-1} - I_i + \mathcal{I}_{i-1} - \mathcal{I}_i, \qquad \text{(Ion rate equation)}$$

$$\mathcal{I}_i = 4\pi n_{Z_i} \int \mathrm{d}p\, p^2\, v\sigma_{Z_i,\mathrm{ionize}} f + I_i^{(\mathrm{RE})} n_{\mathrm{RE}} n_{Z_i},$$

(RE impact ionization)

$$2\pi\mu_0 \frac{j_\parallel}{B} \langle \boldsymbol{B} \cdot \nabla\varphi \rangle = \frac{1}{V'}\frac{\partial}{\partial r}\left[V' \left\langle \frac{|\nabla r|^2}{R^2} \right\rangle \frac{\partial \psi}{\partial r} \right], \qquad \text{(Current diffusion)}$$

$$\frac{\partial \psi}{\partial t} = V_{\mathrm{loop}} + \frac{\partial}{\partial \psi_t}\left(\psi_t \Lambda \frac{\partial^2 I}{\partial \psi_t^2} \right), \qquad \text{(Poloidal flux)}$$

$$\frac{\partial \psi_{\mathrm{w}}}{\partial t} = R_{\mathrm{w}} I_{\mathrm{w}}, \qquad \text{(Wall current)}$$

Fokker–Planck equation

$$\frac{\partial f}{\partial t} + \underbrace{\sigma\Theta\frac{e\left\langle \boldsymbol{E}\cdot\boldsymbol{B}\right\rangle}{\left\langle B/\sqrt{1-\lambda B}\right\rangle}\left[\frac{1}{p^2}\frac{\partial p^2 f}{\partial p} - \frac{2}{p}\frac{\partial \lambda f}{\partial \lambda}\right]}_{\text{electric field acceleration}}$$

$$= \underbrace{\frac{1}{p^2}\frac{\partial(p^3\nu_s f)}{\partial p}}_{\text{slowing−down}} + \underbrace{\frac{2\nu_D}{\mathcal{V}'}\frac{\partial}{\partial\lambda}\left(\mathcal{V}'\left\{\frac{1-\lambda B}{B}\right\}\lambda\frac{\partial f}{\partial\lambda}\right)}_{\text{pitch scattering}}$$

$$+ \underbrace{\frac{1}{\mathcal{V}'}\frac{\partial}{\partial r}\left[\mathcal{V}'\left(-\{A\}f + \{D\}\frac{\partial f}{\partial r}\right)\right]}_{\text{radial transport}}$$

$$+ \underbrace{\{S\}}_{\text{source terms}},$$