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FÜR PLASMAPHYSIK

Modelling of shattered pellet injection in ASDEX Upgrade with DREAM

Joint REM & WPTE RT03 meeting 2025

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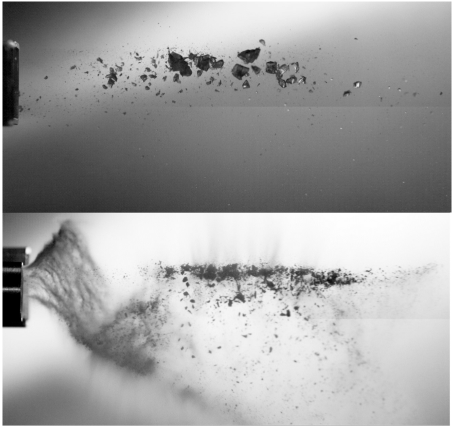
Shattered pellet injection (SPI)



(above) #694, $f_{\mathrm{Ne}} = 100\,\%$, $L(D) = 8.5(8)\,\mathrm{mm}$, $v_{\mathrm{inj}} = 127\,\mathrm{m/s}$; 25°
(below) #1136, $f_{\mathrm{Ne}} = 10\,\%$, $L(D) = 8(6)\,\mathrm{mm}$, $v_{\mathrm{inj}} = 325\,\mathrm{m/s}$; 25°

- Disruptions are a major concern for reactor-scale tokamaks
- Inject frozen material into plasma for fast controlled termination
  - $\Rightarrow$ D_2 to reduce RE generation
  - $\Rightarrow$ Ne to radiate away energy and control I_{p} decay rate
- SPI in ASDEX Upgrade
- Vast parameter space, high-dimensional optimisation

The disruption mitigation system in ITER will be based on SPI

How to model a disruption

What physics are essential?

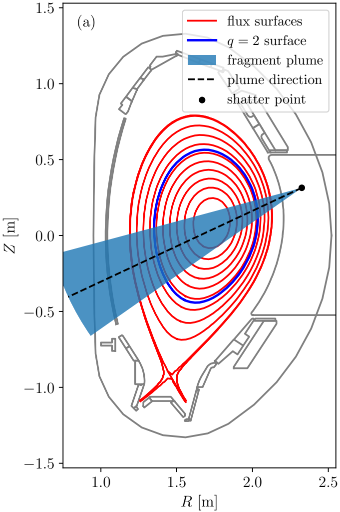
- Current evolution
- Thermal bulk of electrons
- Ion charge state distributions
- Runaway electrons?
- Magnetic field?
  - Static flux surface geometry
  - Stochastisation by enhanced transport *ad-hoc*

[M. Hoppe *et al.* Comput. Phys. Commun. (2021)]

Purpose

- Develop a 1D fluid model for simulating SPI-induced disruptions
- Validation with ASDEX Upgrade SPI experiments
- Assess the impact of statistical variation in the fragment distribution (Parks' model) has on the disruption dynamics

Magnetic equilibrium and fragment plume ⟶



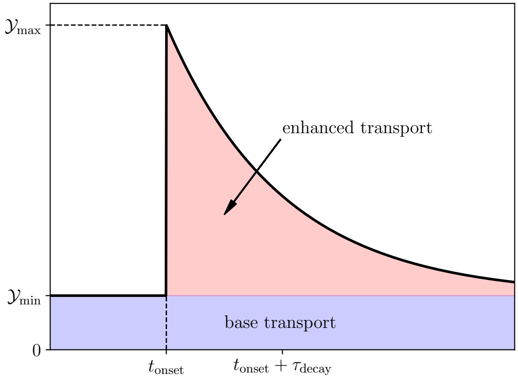
Outline

1. Summary of DREAM modelling of SPI
2. Experimental comparison
3. Simulating background tungsten in 100 % D_2 injections

Enhanced transport event

To emulate the effect of **magnetic field stochastisation** during the TQ…

- $\mathcal{Y} \in \{\Lambda,\, \chi_e,\, D_i,\, A_i\}$

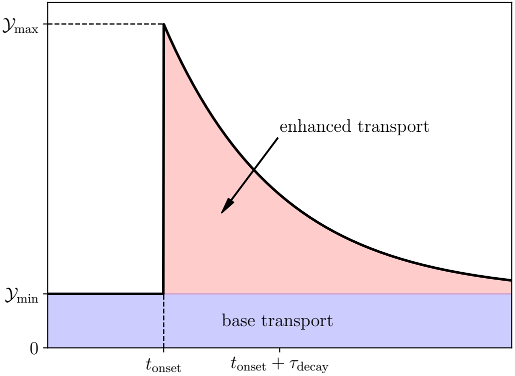


$$\mathcal{Y}(t) = \mathcal{Y}_{\min} + (\mathcal{Y}_{\max} - \mathcal{Y}_{\min}) \exp\left(-\frac{t - t_{\text{onset}}}{\tau_{\text{decay}}}\right) \Theta(t - t_{\text{onset}}).$$

Enhanced transport event

To emulate the effect of **magnetic field stochastisation** during the TQ…

- $\mathcal{Y} \in \{\Lambda,\ \chi_e,\ D_i,\ A_i\}$
- t_{onset} as $T_e < 10\,\text{eV}$ inside $q = 2$



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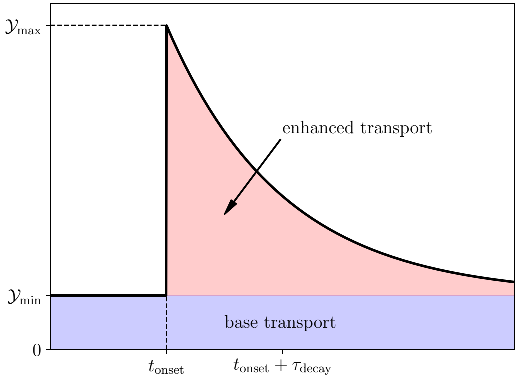
- **free parameters**
  - $\tau_\text{decay} = 1\,\text{ms}$
  - $\chi_{e,\text{min}} = 1\,\text{m}^2/\text{s}$



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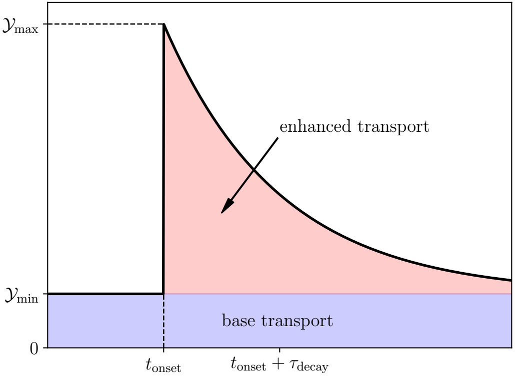
  - $\Lambda_{\text{max}} = 5 \times 10^{-7}\,\text{Wb}^2\text{m/s}$

    matching exp. I_p spikes



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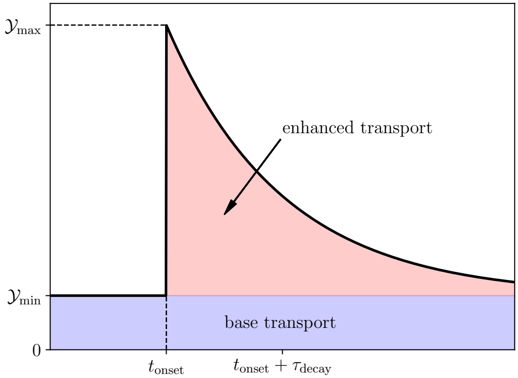
  - $\chi_{e,\text{max}},\ D_{i,\text{max}} = 10^2\,\text{m}^2/\text{s}$, $A_{i,\text{max}} = -10^2\,\text{m/s}$

    [Linder *et al.* NF 2020]



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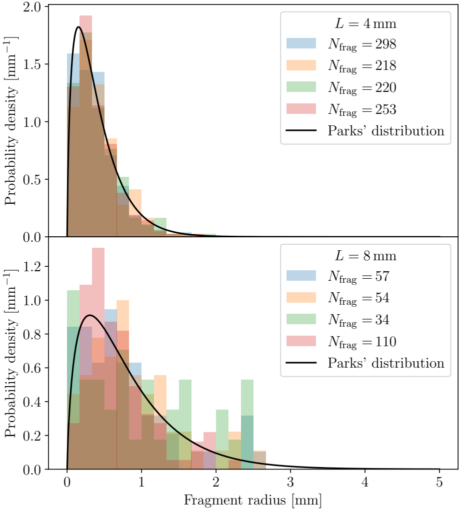
Sampling fragments

- Sizes sequentially sampled from Parks' distribution[1]
- Speeds normally distributed with mean and spread

$$\langle v_{\text{frag}} \rangle = v_{\text{inj}}(1 + \sin\theta_{\text{s}}),$$
$$\Delta v_{\text{frag}} / \langle v_{\text{frag}} \rangle = 0.2$$

- Directions uniformly within cone with spread 20°



$v_{\text{inj}} \approx 500\,\text{m/s}$, $D \approx 8\,\text{mm}$, $f_{\text{Ne}} = 0.085\,\%$, 12.5° shatter head

[1] T. E. Gebhart *et al.* TPWRS (2019)

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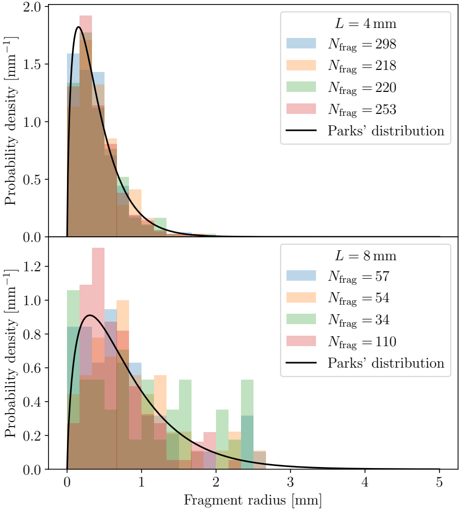
- Directions uniformly within cone with spread 20°
- **What is the impact of the statistical variation?**



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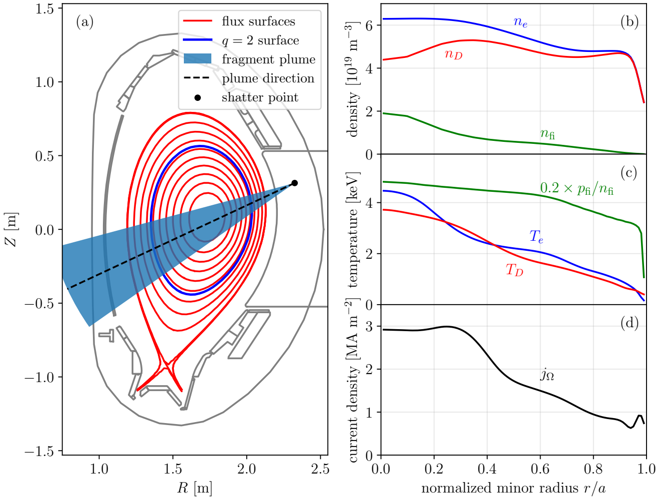
Simulation setup

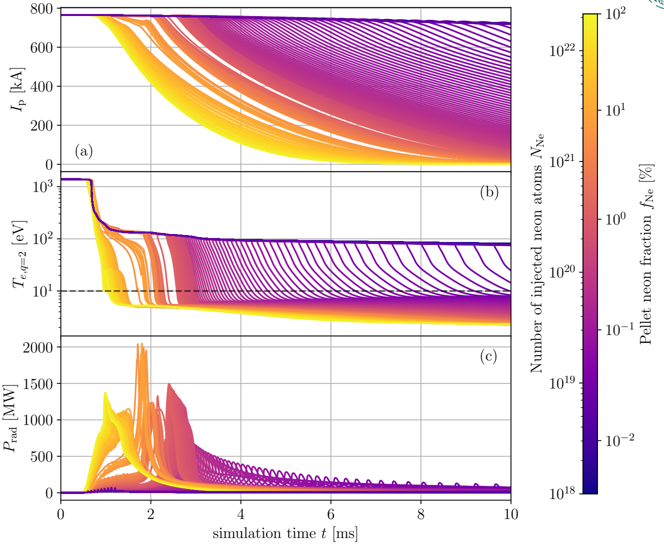


- Reference SPI H-mode discharge #40655 @$t = 2.3\,s$
- Magnetic equilibrium and initial profiles from IDA[2]
- All Ohmic current
- Adaptive time stepper $\Delta t \propto \tau_{ionis} \sim |\partial \log n_e / \partial t|^{-1}$

[2] R. Fischer *et al.* FST (2010)

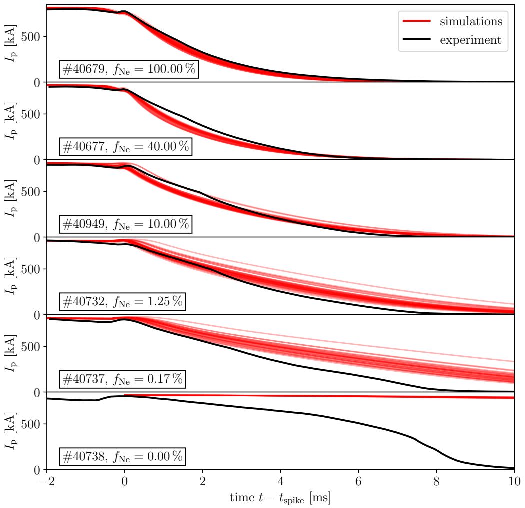
Pellet neon fraction scan

- TQ triggered near core for $f_{\text{Ne}} < 5\,\%$
- Non-disruptive for $f_{\text{Ne}} \lesssim 0.001\,\%$
- Parks' predicts $N_{\text{frag}} \sim 80$ for pure D_2, ~ 5000 for pure Ne



SPI ref. #40732 $v_{\text{inj}} \approx 230\,\text{m/s}$, $L \approx 9.7\,\text{mm}$, $D \approx 7.9\,\text{mm}$

Experimental comparison – plasma current evolution



- Nearly identical discharges, varying f_{Ne}
- 40 fragment realisations per case
- Vertical displacement event (VDE) not modelled
- No external loop voltage

- Non-disruptive at $f_{Ne} = 0$
- Negligible $j_{re} < 10\,A$ for all cases, as seen in experiment

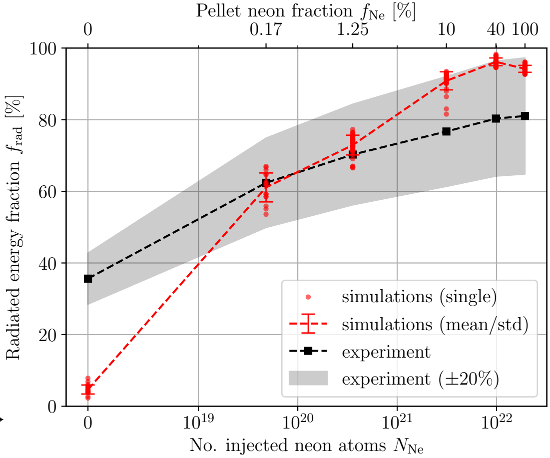
Experimental comparison – radiated energy fraction

- No external heating
- Perfectly conducting wall

$$f_{\mathrm{rad}} = \frac{W_{\mathrm{rad}}}{W_{\mathrm{th}} + W_{\mathrm{mag}}}$$

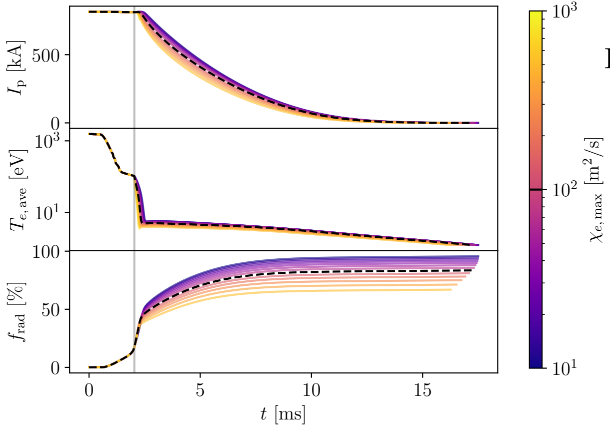
- Good agreement for $f_{\mathrm{Ne}} \geq 0.17\,\%$
- Impact of fragment sampling in intermediate f_{Ne}

Experimental values[3] ⟶



[3] P. Heinrich *et al.* Nucl. Fusion (2024)

Parameter scan in max electron heat diffusion $\chi_{e,\max}$



Diffusive heat transport

$$\left.\frac{\partial n_e T_e}{\partial t}\right|_\mathrm{transp} = \frac{1}{V'}\frac{\partial}{\partial r}V' n_e \chi_e(t)\frac{\partial T_e}{\partial r}$$

- Higher diffusion $\implies$ lower f_rad
- Theory[4]: $\chi_e \propto |\delta B/B|^2$
- Stronger MHD for higher f_Ne?

[4] A. B. Rechester & M. N. Rosenbluth, Phys. Rev. Lett. (1978)

Including background tungsten impurities

Impurities enable more radiation loss channels

- Uniform initial profile n_W of tungsten
- Tungsten charge state fractional abundance $\phi^{(j)} = n_\mathrm{W}^{(j)}/n_\mathrm{W}$
- Initialised in coronal equilibrium, depending on T_e

$$\mathcal{R}_\mathrm{W}^{(j)}(T_e)\phi^{(j+1)} = \mathcal{I}_\mathrm{W}^{(j)}(T_e)\phi^{(j)}, \quad j = 0, \ldots 73, \quad \sum_{j=0}^{74} \phi^{(j)} = 1.$$

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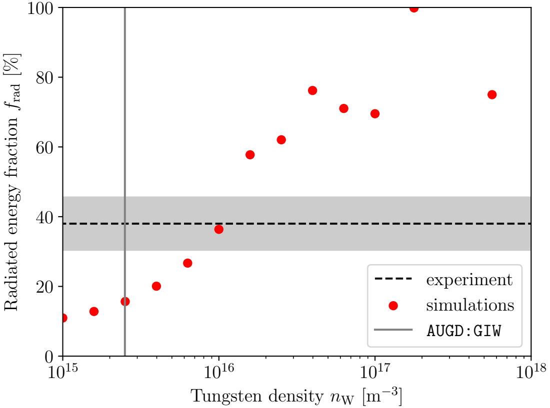
- #40738 $f_{\mathrm{Ne}} = 0$, single fragment realisation
- Fixing n_e, we adjust n_{D} when varying n_{W}
- $W_{\mathrm{th}} \approx$ const for realistic values of n_{W}

Radiated energy fraction with tungsten

scan in the pre-disruption radially uniform n_W:



- Pre-disruption $n_\mathrm{W} \gtrsim 2.5 \times 10^{15}\,\mathrm{m}^{-3}$ according to `AUGD:GIW`[5]
- At $n_\mathrm{W} \sim 10^{16}\,\mathrm{m}^{-3}$ we observe similar final f_rad as in experiment
- Other impurities e.g. Ne, B, C, N, Fe?
- Additional impurities are introduced during the disruption
- Cold impurities in SOL provide more loss channels as heated up during TQ
- Non-disruptive discharges yield $f_\mathrm{rad} \approx 20\,\%$ in experiment

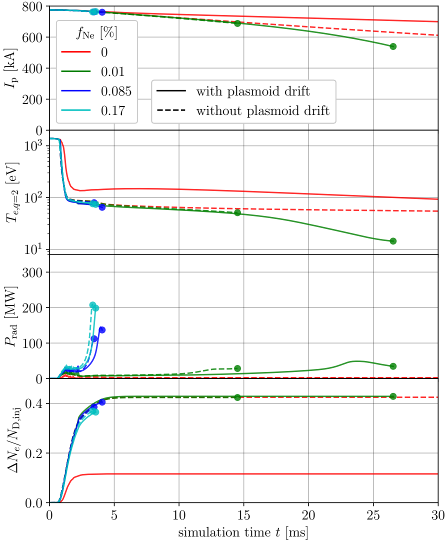
[5] T. Pütterich *et al.* Plasma Phys. Control. Fusion (2008)

Summary

- Good agreement with $I_{\mathrm{p}}(t)$ compared to experiment for $f_{\mathrm{Ne}} \gtrsim 0.17\,\%$
- Small impact of the statistical variation in the shard size distribution on f_{rad}
- Good agreement with experimentally measured f_{rad} for $f_{\mathrm{Ne}} \geq 0.17\,\%$
- Negligible amount of RE current, as seen in experiment
- W impurities play an important role for 100 % deuterium injections
- With $\sim 10^{16}\,\mathrm{m}^{-3}$ background tungsten, simulated f_{rad} would compare well with experiment
- Ongoing work with impurities other than W

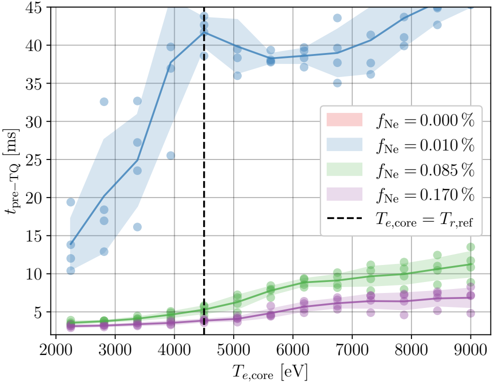
Plasmoid drift suppression

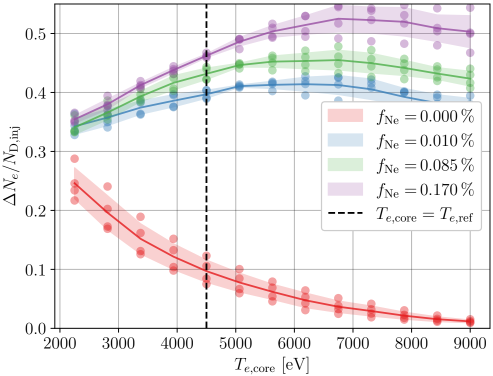
- pressure build-up $\implies$ $E \times B$-drift
- analytical plasmoid drift model[6]
- $L = 4\,\mathrm{mm}$, $v_{\mathrm{inj}} = 500\,\mathrm{m/s}$, $\theta = 12.5°$
- drift negligible for neon doped pellets
- reduced assimilation for pure hydrogenic pellets



[6] O. Vallhagen *et al.* J. Plasma Phys. (2023)

Plasmoid drift suppression, f_{Ne}-scan





Radiated energy fraction

Fraction of the available energy (initial stored energy $W_{\text{th}} + W_{\text{mag}}$, external heating W_{heat}) that is dissipated via radiation W_{rad}, accounting for some of the magnetic energy being coupled to surrounding conducting structures $W_{\text{c}} \approx 0.5\, W_{\text{mag}}$.

$$f_{\text{rad}} = \frac{W_{\text{rad}}}{W_{\text{th}} + W_{\text{mag}} + W_{\text{heat}} - W_{\text{c}}} \tag{1}$$

- Radiated energy during disruption

$$W_{\text{rad}} = \int \mathrm{d}t\, P_{\text{rad}}$$

- Initial thermal energy

$$W_{\text{rad}} = \frac{3}{2} n_e T_e + \frac{3}{2} \sum_i n_i T_i$$

- Initial poloidal magnetic energy

$$W_{\text{mag}} = \frac{1}{2} \int \mathrm{d}r\, \frac{\partial \psi_{\text{p}}}{\partial r} I(r)$$

- External heating during disruption

$$W_{\text{heat}} = \int \mathrm{d}t\, (P_{\Omega,\text{ext}} + P_{\text{NBI}} + P_{\text{ECRH}}) \tag{2}$$

Plasma current

- Ohmic current $j_\Omega \sim \sigma E_\|$ from **Ohm's law** using Sauter-Redl conductivity[7]
- Runaway electron current $j_{\mathrm{re}} = ecn_{\mathrm{re}}$ calculated from generation rates
  - Dreicer generation[8], Hot-tail generation[9]
  - Avalanche growth rate accounting for partial screening effects in non-ideal plasmas[10]
- Total current density $j_\| = j_\Omega + j_{\mathrm{re}}$ from poloidal magnetic flux ψ_{p} via **Ampère's law**
- **Faraday's law of induction** – includes a *hyperdiffusive* term[11]

$$\frac{\partial \psi_{\mathrm{p}}}{\partial t} = -2\pi \frac{\langle \boldsymbol{E} \cdot \boldsymbol{B} \rangle}{\langle \boldsymbol{B} \cdot \boldsymbol{\nabla} \varphi \rangle} + \mu_0 \frac{\partial}{\partial \psi_{\mathrm{t}}} \psi_{\mathrm{t}} \Lambda \frac{\partial}{\partial \psi_{\mathrm{t}}} \frac{j_\|}{B} \tag{3}$$

[5] A. Redl *et al.* Phys. Plasmas (2021)
[6] L. Hesslow *et al.* J. Plasma Phys. (2019b)
[7] I. Svenningsson MSc. thesis (2020)
[8] L. Hesslow *et al.* Nucl. Fusion (2019a)
[9] A. Boozer J. Plasma Phys. (1986)

Thermal electrons

- Electron density n_e from **quasi-neutrality**
- **Energy balance** governing the evolution of electron thermal energy

$$\frac{3}{2}\frac{\partial n_e T_e}{\partial t} = \frac{j_\Omega}{B}\langle \boldsymbol{E}\cdot\boldsymbol{B}\rangle + \frac{j_{\rm re}}{B}E_{\rm c}\langle B\rangle - n_e \sum_i \sum_{j=0}^{Z_i-1} L_i^{(j)} n_i^{(j)} \tag{4}$$

$$+P_{\rm ion} + \sum_i Q_{ei} + \frac{1}{V'}\frac{\partial}{\partial r}V'\frac{3n_e}{2}\chi_e\frac{\partial T_e}{\partial r},$$

→ Ohmic heating
→ Radiative cooling, deuterium opaque to Lyman radiation (ADAS, AMJUEL)
→ Collisional heat exchange
→ Diffusive heat transport, with free parameter $\chi_e(t,r)$

Ions and neutrals

- Thermal energies $3/2 n_i T_i$ are evolved via collisional heat exchange
- Charge state distributions evolve in time (ion species i, charge state $j = 0, 1 \ldots Z_i$)

$$\frac{\partial n_i^{(j)}}{\partial t} = \mathcal{I}_i^{(j-1)} n_i^{(j-1)} n_e - \mathcal{I}_i^{(j)} n_i^{(j)} n_e + \mathcal{R}_i^{(j+1)} n_i^{(j+1)} n_e - \mathcal{R}_i^{(j)} n_i^{(j)} n_e \tag{5}$$

$$+ \delta_{0j} \sum_{k=1}^{N_{\mathrm{frag}}} \mathcal{G}_k \frac{\delta(r - r_k)}{4\pi r^2 R_0} + \frac{1}{V'} \frac{\partial}{\partial r} V' \left(A_i n_i^{(j)} + D_i \frac{\partial n_i^{(j)}}{\partial r} \right).$$

→ Ionisation
→ Recombination
→ Deposition of material as neutrals, ablation rate $\mathcal{G}_k \propto n_e^{1/3} T_e^{5/3}$ per the NGS model[12]
→ Advective and diffusive particle transport, with free parameters $A_i(t, r)$ and $D_i(t, r)$

[10]Neutral Gas Shielding model [P. Parks & R. Turnbull Phys. Fluids (1978)]

Tungsten mean charge number

- Mean charge number

$$\bar{Z}_{\mathrm{W}} = \sum_{j=1}^{74} j\phi^{(j)} \qquad (6)$$

- For $T_e \approx 4\,\mathrm{keV}$ and above, why the difference between the two?