# Increasing the physics fidelity of SPI simulations with the DREAM code

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# Outline

Theme: reduced models of higher dimensional effects

- Plasmoid drift model [Vallhagen *et al* JPP 2023]
  - model summary
  - comparison with AUG experiments
  - effect in ITER
- RE scrape-off loss model
  - model summary
  - effect in ITER

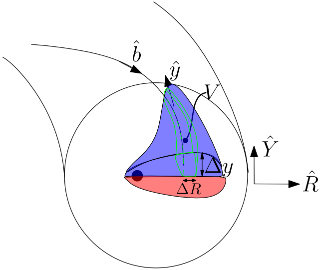
# Plasmoid drift model

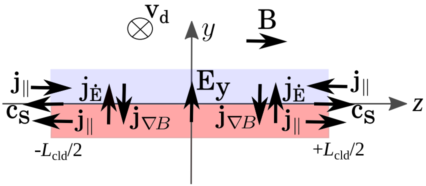
- MHD force balance equation rewritten as a current balance equation
- Integrate over upper half of the plasmoid to reduce to 1D, note $E_y \approx v_{\text{drift}} B$

$$0 = \frac{I_{\nabla B} + I_{\dot{\mathbf{E}}} + I_{\parallel}}{\Delta R} = -\frac{4(P - P_{\text{bg}})q}{B} \sin\left(\frac{L_{\text{cld}}}{2qR_{\text{m}}}\right) + \frac{\rho L_{\text{cld}}}{B^2}\frac{dE_y}{dt} + \frac{E_y}{R_{\text{eff}}}. \qquad (1)$$

  - Neglecting $y$ and $z$ dependencies, assume equal to midplane values
  - Statistical model for field lines connecting the plasmoid ends gives effective ohmic resistance

$$\frac{1}{R_{\text{eff}}} = \sigma_{\parallel} \frac{\Delta y^3}{2\pi^2 R_{\text{m}} r} \ln \frac{\pi r}{\Delta y}. \qquad (2)$$





## Simplified parallell expansion model

- Constant line integrated density $\bar{n}$ and cloud temperature $T$
- Prescribed $T$ representative of values found in e.g. measurements by Müller *et al* NF 2002 and simulations by Matsuyama *et al* PoP 2022
  - $\sim 30\,\mathrm{eV}$ for pure D pellets
  - $\sim 5\,\mathrm{eV}$ for Ne doped pellets due to radiative cooling
- $\bar{n}$ determined by ablation rate from NGS model [Parks TSDW 2017], assumed to “fill up” the cloud during the time it takes to drift a distance $\Delta y \sim 1\,\mathrm{cm}$
- Cloud expands along the field lines at the speed of sound $c_s$ inside the cloud until pressure equilibration

# Analytical solution

$$0 = -\frac{4(\bar{n}T - 2c_s t n_{\mathrm{bg}} T_{\mathrm{bg}})q}{B 2 c_s t} \sin\left(\frac{2c_s t}{2qR_{\mathrm{m}}}\right) + \frac{\bar{n}\langle m_i\rangle}{(1+\langle Z\rangle)B^2}\frac{dE_y}{dt} + \frac{E_y}{R_{\mathrm{eff}}} + 2P_A\frac{E_y}{R_A}$$

$+$

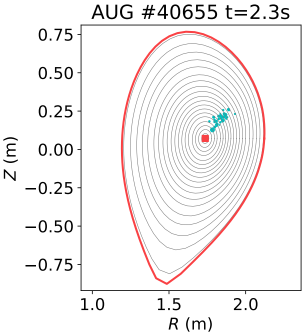
WolframAlpha

$\rightarrow$

$$\begin{aligned}
\varDelta r = {} & \frac{E_{y0}}{B}t_{\mathrm{acc}} + \frac{2(1+\langle Z\rangle)Tq}{\langle m_i\rangle c_s}t_{\mathrm{acc}} \cdot \\
& \Bigg\{\Bigg[\frac{e^{-\frac{L_c}{2c_s t_{\mathrm{acc}}}}}{2i}\left(\mathrm{Ei}\left(\left(1+i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(\frac{t_{\mathrm{pe}}}{t_{\mathrm{acc}}}+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right) - \mathrm{Ei}\left(\left(1-i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(\frac{t_{\mathrm{pe}}}{t_{\mathrm{acc}}}+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right)\right) \\
& -\frac{t_{\mathrm{acc}}}{t_{\mathrm{pe}}} e^{\frac{t_{\mathrm{pe}}}{t_{\mathrm{acc}}}} \frac{\sin\left(\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\left(\frac{t_{\mathrm{pe}}}{t_{\mathrm{acc}}}+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right) - \frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\cos\left(\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\left(\frac{t_{\mathrm{pe}}}{t_{\mathrm{acc}}}+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right)}{1+\frac{t_{\mathrm{acc}}^2}{t_{\mathrm{pol}}^2}}\Bigg] e^{-t_{\mathrm{pe}}/t_{\mathrm{acc}}} - \\
& \Bigg[\frac{e^{-\frac{L_c}{2c_s t_{\mathrm{acc}}}}}{2i}\left(\mathrm{Ei}\left(\left(1+i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right) - \mathrm{Ei}\left(\left(1-i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right)\right) \\
& -\frac{t_{\mathrm{acc}}}{t_{\mathrm{pe}}} \frac{\sin\left(\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\left(\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right) - \frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\cos\left(\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\left(+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right)}{1+\frac{t_{\mathrm{acc}}^2}{t_{\mathrm{pol}}^2}}\Bigg] \\
& +e^{-\frac{L_c}{2c_s t_{\mathrm{acc}}}}\Bigg[\frac{e^{-t'}}{2i}\left(\mathrm{Ei}\left(\left(1-i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(t'+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right) - \mathrm{Ei}\left(\left(1+i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(t'+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right)\right. \\
& \left. -e^{t'+\frac{L_c}{2c_s t_{\mathrm{acc}}}}\left(\mathrm{Ei}\left(\left(-i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(t'+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right) - \mathrm{Ei}\left(\left(i\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\right)\left(t'+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right)\right)\right)\Bigg]_0^{t_{\mathrm{pe}}/t_{\mathrm{acc}}} \\
& +\frac{t_{\mathrm{acc}}}{t_{\mathrm{pe}}}\frac{1}{1+\frac{t_{\mathrm{acc}}^2}{t_{\mathrm{pol}}^2}}\left[\frac{t_{\mathrm{pol}}}{t_{\mathrm{acc}}}\cos\left(\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\left(t'+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right) + \sin\left(\frac{t_{\mathrm{acc}}}{t_{\mathrm{pol}}}\left(t'+\frac{L_c}{2c_s t_{\mathrm{acc}}}\right)\right)\right]_0^{t_{\mathrm{pe}}/t_{\mathrm{acc}}}\Bigg\}
\end{aligned}$$

# Shattered pellet injection

- Uniform distribution of speed ($\pm 40\%$) and divergence angle ($10^\circ$)
- Statistical shard size distribution by
  [Parks GA Report 2016]
- Distribution parameters by
  [Gebhart *et al* IEEE TPS 2020]
- Ablation assuming the Neutral Gas Shielding (NGS) model
  [Parks TSDW 2017]
- Instantaneous flux surface homogenisation
  - shifted by radial drift displacement $\Delta r$ from the shard



Equilibrium reconstruction from the IDA diagnostic[a] for AUG shot 40655, used as input for AUG simulations (as in JOREK and INDEX), and illustration of the shard plume

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[a] Fischer, R. *et al.* Fusion Science and Technology 2010
Fischer, R. *et al.* Fusion Science and Technology 2020

# Particle and energy balance

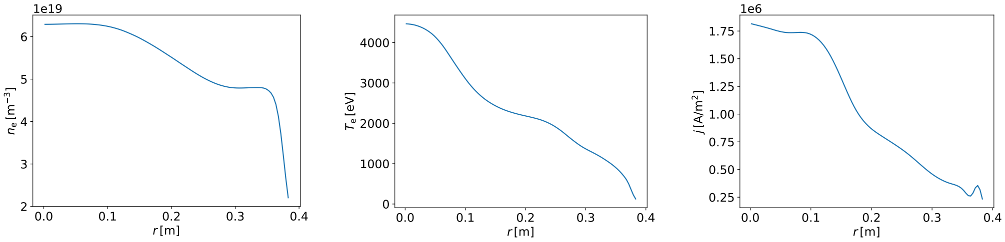
- Time dependent ionization/recombination rate equations + advection/diffusion
- Electron energy density $W_{\mathrm{M}} = \frac{3}{2} n_{\mathrm{M}} T_{\mathrm{M}}$:

$$\frac{\partial W_{\mathrm{M}}}{\partial t} = P_{\mathrm{Ohm}} - P_{\mathrm{line}} - P_{\mathrm{ioniz}} + P_{\mathrm{abs}} + \frac{1}{r}\frac{\partial}{\partial r}\left[r \frac{3 n_{\mathrm{M}}}{2} D_W \frac{\partial T_{\mathrm{M}}}{\partial r}\right] - P_{\mathrm{abl}} + P_{\mathrm{hot}} - P_{\mathrm{brems}}$$

- Radiation and ionization/recombination rates from ADAS
- Optionally AMJUEL for hydrogen species (for opacity to Lyman radiation)
  - typically relevant for ITER SPIs
  - Transparent plasma agrees better with AUG experiments (lower density)

# AUG simulation setup

- Magnetic geometry and initial profiles from AUG shot 40655
  - Representative case with high-quality (IDA) reconstruction available
- Background ion diffusion $D_{\mathrm{ion},0} = 2\,\mathrm{m}^2/\mathrm{s}$ (similar to INDEX simulations in A. Patels MCs thesis[1])
- Enhanced transport coefficients and hyperresistivity in case of a disruption
  - Max values $D_{\mathrm{ion,max}} = D_W = 100\,\mathrm{m}^2/\mathrm{s}$, $A_{\mathrm{ion,max}} = -100\,\mathrm{m/s}$, $\Lambda = 10^{-5}\,\mathrm{Wb}^2\mathrm{m/s}$, decay time $t_{\mathrm{TQ}} = 1\,\mathrm{ms}$
- Prescribed onset time to match current spike in the experiment



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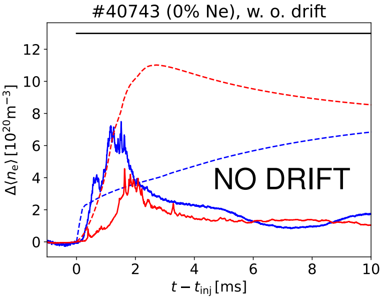
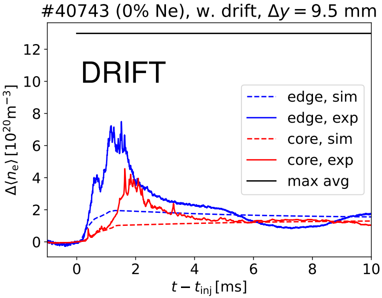
[1] `https://arxiv.org/abs/2312.03462`

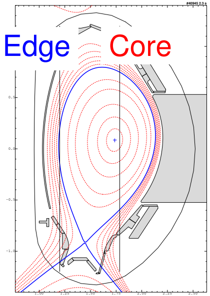
# Pure D pellet, no disruption

- AUG shot 40743: $D = 8\,\mathrm{mm}$, $L = 4.5\,\mathrm{mm}$, $v_{\mathrm{inj}} = 270\,\mathrm{m/s}$, $\theta_{\mathrm{shatter}} = 25^\circ$
  - Moderate sized (half of maximum) non-disruptive D2 injection
  - Simulation params: $N_{\mathrm{shard}} = 102$, $\Delta v / v_{\mathrm{inj}} = 40\%$, $\theta_{\mathrm{div}} = 10^\circ$
- Simulation without drift strongly overestimates line averaged densities
- Simulation with drift matches long-term behavior with $\Delta y = 9.5\,\mathrm{mm}$
  - Peak in data may be due to temporarily passing plasmoids


#40743 (0% Ne), w. o. drift

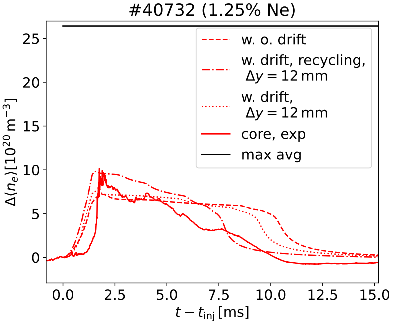

#40743 (0% Ne), w. drift, $\Delta y = 9.5$ mm

Interferometry



# 1.25% Ne, w. disruption

- AUG shot 40732: $D = 8\,\mathrm{mm}$, $L = 9\,\mathrm{mm}$, $v_{\mathrm{inj}} = 230\,\mathrm{m/s}$, $\theta_{\mathrm{shatter}} = 12.5^\circ$
  - Full sized disruptive 1.25% Ne-doped injection
  - Simulation params: $N_{\mathrm{shard}} = 13$, $\Delta v/v_{\mathrm{inj}} = 40\%$, $\theta_{\mathrm{div}} = 10^\circ$
- Sim. w.o. drift in reasonable agreement, but underestimates peak density
- Simulation w. drift and recycling/drift stopping at the edge improves agreement
  - Neutral recycling, drift breaking at rational $q$-values, shear around LCFS, other effects?
  - Measurable with Langmuir probes, He-beam diagnostic?

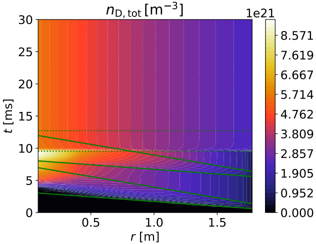


# ITER injection and TQ scenario

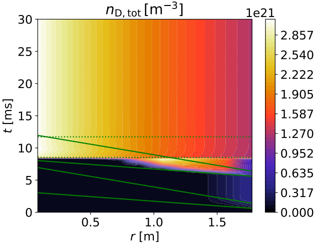
- Injection parameters: $D = 28.5\,\mathrm{mm}$, $L = 57\,\mathrm{mm}$, $N_{\mathrm{shard}} = 487$, $v_p = 500\ \mathrm{m/s}$, $\Delta v/v_p = 0.4$, spreading angle 10°
- MHD instability mimicked by Rechester-Rosenbluth type diffusion
- Two alternatives to trigger the transport event
  - Ne-doped shards reach $q = 2$ (*"Early TQ"*)
  - $T_e$ drops below $10\,\mathrm{eV}$ inside of $q = 2$ (*"Late TQ"*)
- Duration of transport event is assumed to be either $t_{\mathrm{TQ}} = 1\,\mathrm{ms}$ or $3\,\mathrm{ms}$
- $\delta B/B$ chosen so that $T_e$ reaches $200\,\mathrm{eV}$ within $t_{\mathrm{TQ}}$ from transport alone
- In transport with $D_{\mathrm{ion,max}} = 4000\,\mathrm{m}^2/\mathrm{s}$, $A_{\mathrm{ion,max}} = -2000\,\mathrm{m/s}$
  - gives a mixing on the $\sim 0.1\,\mathrm{ms}$ time scale

# Effect of drifts in ITER

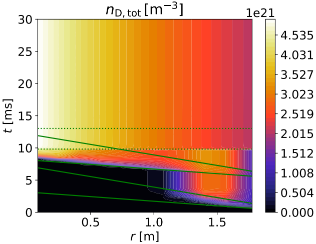
- DT H-mode, staggered SPI
  - 1 pure D pellet followed by 1 D+Ne pellet (1.35% Ne), late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$
  - Best performing case (St4 in Vallhagen *et al* NF 2024, accepted[2])
- Low assimilation of first pellet with drift, but higher for second pellet
  - extent depend on injection and model parameters, e.g. plasmoid size
- Only a minor effect on $I_{\mathrm{RE}}$
  - May depend on TQ conditions



No drift,$I_{\mathrm{RE}} = 4.63\,\mathrm{MA}$



$\Delta y = 12.5\,\mathrm{mm},\ I_{\mathrm{RE}} = 4.90\,\mathrm{MA}$



$\Delta y = 18.75\,\mathrm{mm},\ I_{\mathrm{RE}} = 4.46,\mathrm{MA}$

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[2] `https://doi.org/10.1088/1741-4326/ad54d7`

# Scrape-off model in DREAM

- Observation in JOREK: flux at LCFS essentially constant (Wang *et al* REM 2023)
  - May be used to distinguish closed and open flux surfaces in DREAM (with otherwise constant geometry)
- Implemented as a loss term:

$$\left(\frac{\partial n_{\text{RE}}}{\partial t}\right)^{\text{scrapeoff}} = \frac{n_{\mathrm{RE}}}{t_{\mathrm{loss}}}\Theta(r_{\mathrm{LCFS}} - r), \psi_{\mathrm{p}}(r_{\mathrm{LCFS}}) = \psi_{\mathrm{p}}(a, t = 0)$$

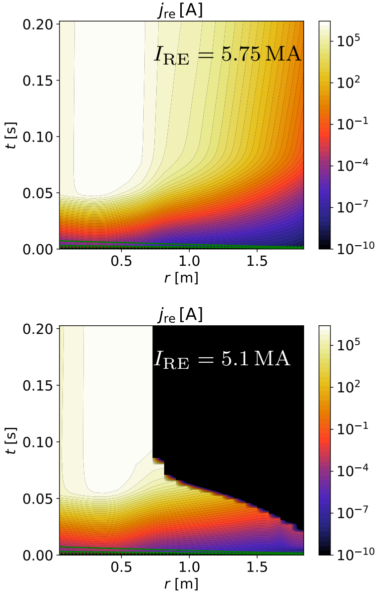
# Fluid runaway sources

$$\frac{\partial n_{\mathrm{RE}}}{\partial t} = \left(\frac{\partial n_{\text{RE}}}{\partial t}\right)^{\text{hot-tail}} + \left(\frac{\partial n_{\text{RE}}}{\partial t}\right)^{\text{avalanche}} + \left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\mathrm{tritium}} + \left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\gamma}$$
$$+ \left(\frac{\partial n_{\text{RE}}}{\partial t}\right)^{\text{scrapeoff}} + \frac{1}{r}\frac{\partial}{\partial r}\left[rD\frac{\partial n_{\mathrm{RE}}}{\partial r}\right],$$

- Analytical hot-tail model as in Appendix C in [Hoppe *et al* CPC 2021]
- Avalanche corrected for partial screening effects [Hesslow *et al* NF 2019]
- Tritium decay and Compton scattering (nuclear cases) [Fülöp *et al* JPP 2020, Martin-Solis *et al* NF 2017]
- Rechester-Rosenbluth diffusion due to magnetic field perturbations
- Hyperresistivity with $\Lambda = 0.1\,\mathrm{Wb}^2\mathrm{m/s}$ (on ohmic current) during transport event

# ITER case with moderate effect of scrape-off

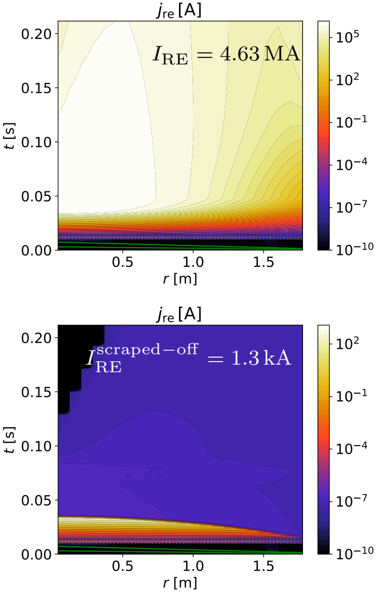
- H L-mode, single stage SPI
  - 3 D+Ne (Ne concentration 3.6%), early TQ
  - Moderately performing single stage case, (M4 in Vallhagen *et al* NF 2024)
- REs in the outer region lost
- RE plateau prevents further flux drop and scrape-off
- However, positive feedback effect expected
  - less REs ⇒ more flux drop ⇒ more scrape-off ⇒ less REs



RE current density for case M4 without (upper) and with (lower) scrape-off

# ITER case with major effect of scrape-off

- Best performing case, drift by one grid cell, (St4 in Vallhagen *et al* NF 2024)
- Positive feedback effect reduces $I_{\mathrm{RE}}^{\mathrm{scraped-off}}$
- All flux surfaces scraped off
- $I_{\mathrm{RE}}^{\mathrm{scraped-off}} = 1.3\,\mathrm{kA}$ (!)
- Disclaimer:
  - $I_{\mathrm{RE}}^{\mathrm{scraped-off}} = 2\,\mathrm{MA}$ w. $\Lambda = 0$
  - Scrape-off only applied to REs
  - Needs further validiation with higher dimensional codes
  - But a reason to be carefully optimistic...



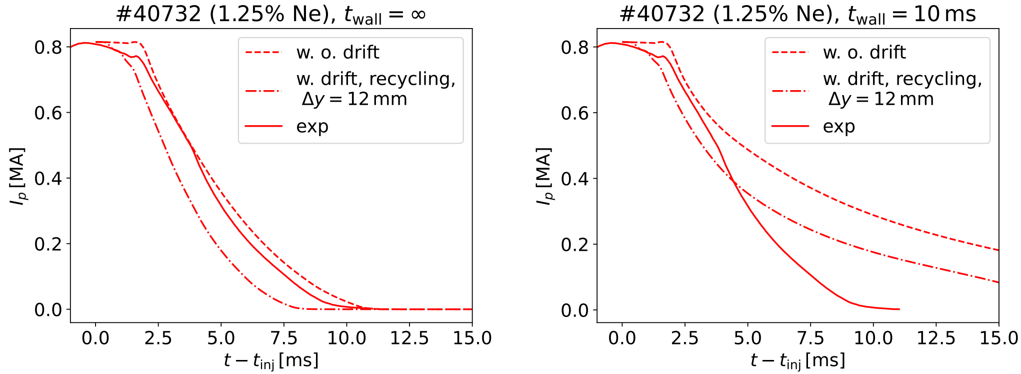
RE current density for case St4 without (upper) and with (lower) scrape-off

# Summary

- Models for plasmoid drifts and scrape-off RE losses implemented in DREAM
- Plasmoid drift model compared with AUG experiments
  - Non-disruptive pure D2 case agrees well
  - Disruptive Ne-doped case agrees if assuming recycling/drift stopping at the edge
- Low assimilation for pure D2 pellets indicated for ITER, but RE current not significantly affected (under favourable TQ conditions)
- Scrape-off model indicates all FSs may be scraped off before a large RE beam has been formed in ITER
  - Requires low enough RE current without scrape-off
  - Sensitivity to model parameters
  - Only applied to REs
  - Should be verified with higher dimensional codes

# Plasma current

- Reasonable agreement during time scale when the plasma resistivity dominates
- Accounting for finite wall resistivity makes current quench longer in simulation
- Could in reality be compensated by plasma motion and resistivity to halo current
- Kink in data could indicate an additional MHD event



#40732 (1.25% Ne), $t_{\mathrm{wall}} = \infty$

#40732 (1.25% Ne), $t_{\mathrm{wall}} = 10\,\mathrm{ms}$

# Pure D pellet, no disruption

- AUG shot 40743: $D = 8\,\mathrm{mm}$, $L = 4.5\,\mathrm{mm}$, $v_{\mathrm{inj}} = 270\,\mathrm{m/s}$, $\theta_{\mathrm{shatter}} = 25°$
  - Moderate sized (half of maximum) non-disruptive D2 injection
  - Simulation params: $N_{\mathrm{shard}} = 102$, $\Delta v / v_{\mathrm{inj}} = 40\%$, $\theta_{\mathrm{div}} = 10°$
- Sim. w. o. drift strongly overestimates line averaged densities
- Sim. w. drift matches long-term behavior with $\Delta y = 9.5\,\mathrm{mm}$
  - Also agrees reasonably well with TS data