Runaway electron dynamics in ITER disruptions mitigated by shattered pellet injection

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

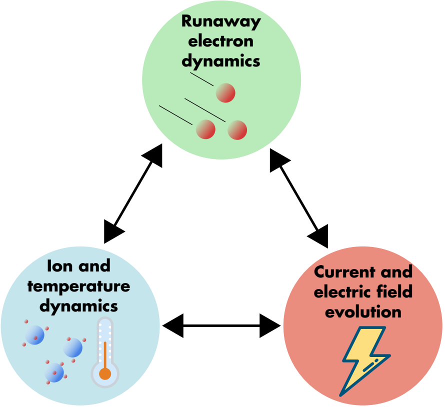
- Disruption modelling with shattered pellet injection
- Thermal quench models
- ITER scenarios
- Full current operation (15 MA)
  - Single pellet injection
  - Activated vs non-activated scenarios
  - Effect of pellet drifts
  - Two-stage injection
  - Effect of shard size
- Operation with reduced current
- Bayesian optimisation

- Disruption Runaway Electron Analysis Model

  [Hoppe et al 2021 Comp Phys Commun **268** 108098]

  https://github.com/chalmersplasmatheory/DREAM
- 1D2P bounce-averaged fluid-kinetic framework
- Accounts for
  - runaway generation in a partially ionized plasma (both fluid and kinetic models)
  - electric field evolution
  - heat and particle transport for given magnetic field perturbation
  - ionization, recombination and line radiation processes
- Shattered pellet injection

  [Vallhagen et al 2022 NF **62** 112004]



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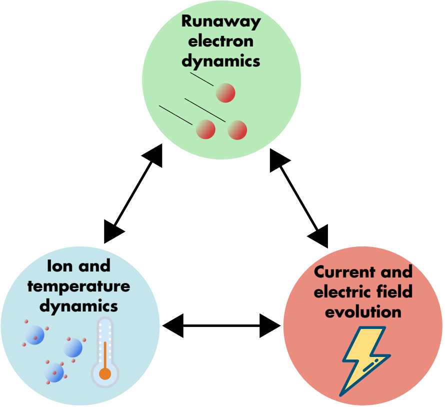
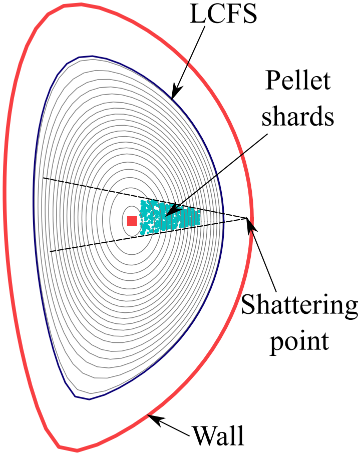


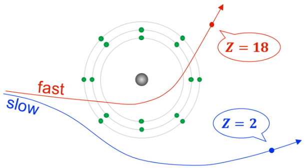
- Limitation: no vertical displacement event, no RE driven instabilities
- **Fast: allows exploration of large parameter regions**

- SPI fragment sizes follow the Parks distribution
  [Parks et al, 2017 TSDW]
- A **Neutral Gas Shielding** (NGS) model for ablation
  - Allows for H-Ne mixture and non-monoenergetic heat flux
- **Instantaneous deposition** in the form of neutrals
  - Radially shifted deposition possible to emulate drift effects
- Systematically **benchmarked** to INDEX and JOREK simulations
  [IO_IA_21_4300002402]

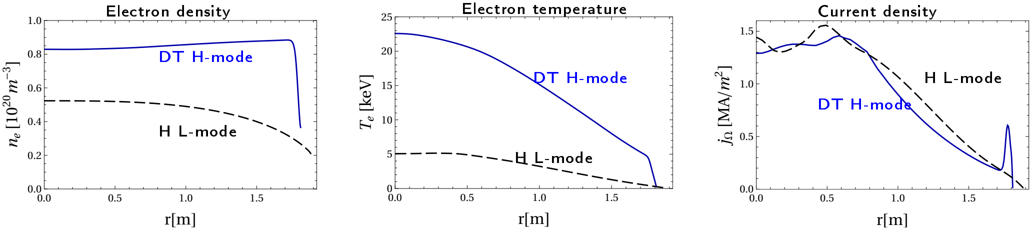


- **Dreicer:** Neural network trained on kinetic simulations
  [Hesslow et al 2018 JPP **85** 475850601]
- **Hot-tail:** Analytical expression derived for plasmas with high effective charge (overestimates the hot-tail seed if effective charge is low)
- **Compton** scattering of γ-photons from the activated wall
  - initially nominal photon flux in ITER
    [Martín-Solís et al 2017 NF **57** 066025]
  - reduced by $\times 10^{-3}$ after TQ when neutron bombardment of the wall is stopped
  - Note: photon flux from tungsten wall is much larger than from beryllium wall
    [Reali et al, PRX Energy 2023]
- **Tritium decay** emits electrons above the critical velocity

- Avalanche: growth rate expression accounts for the effect of **partial screening**, i.e. the extent to which fast electrons can penetrate the bound electron cloud around the impurity ion
  [Hesslow et al 2019 NF **59** 084004]



- DT H-mode and hydrogen L-mode scenarios with $I_p^{(0)} = 15\,\mathrm{MA}$



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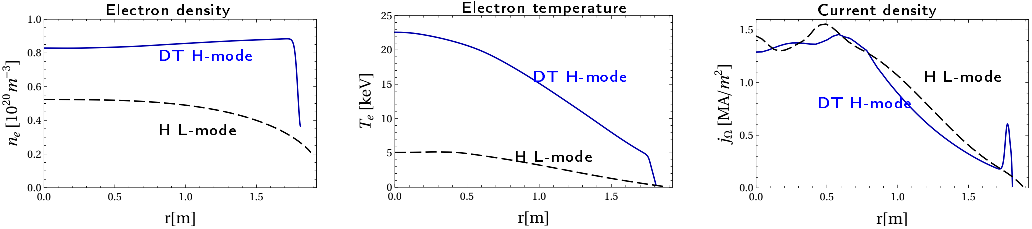
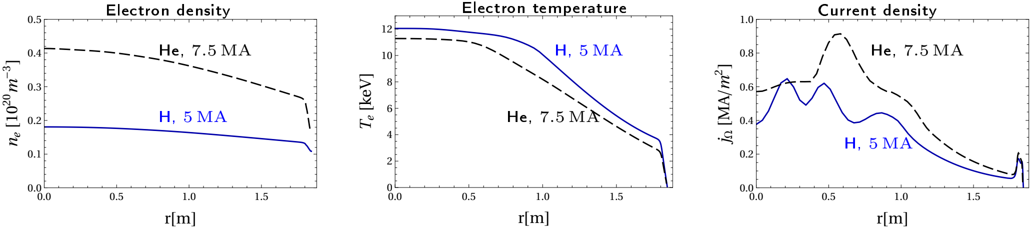


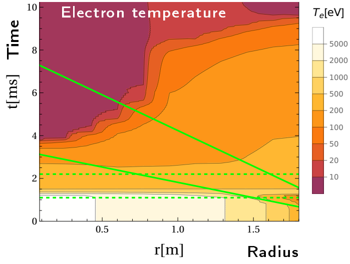
- Helium H-mode with $I_p^{(0)} = 7.5\,\mathrm{MA}$ and hydrogen H-mode with $I_p^{(0)} = 5\,\mathrm{MA}$



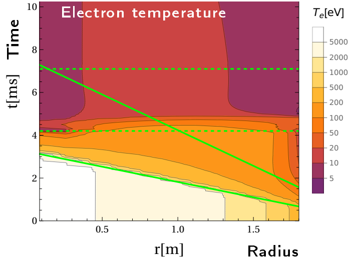
- Baseline
  - Pellet injection speed $v_p = 500\ \mathrm{m/s}$
  - Fragment velocity dispersion
    - uniform
    - with $v_p \pm \Delta v$, with $\Delta v / v_p = 0.4$
  - Injection spreading angle $10°$
  - Numerical magnetic geometry, shaping held fixed
    - wall radius $2.8\,\mathrm{m}$ (match available magnetic energy content in JOREK)
    - resistive wall time $0.5\,\mathrm{s}$
  - Single pellet injection
    - 1.8×10^{24} D atoms
    - 5×10^{22} Ne atoms
  - Shattered into 487 shards
- Variations
  - Pellet shattered into more (5185) or fewer (68) shards
  - Neon quantity (D quantity adjusted so that total number of atoms constant)
  - Injection of several pellets, simultaneously or in two stages, starting with pure D injection followed by a mixed injection

- Topology of magnetic field is modified during the TQ
- Energy loss:
  - radial transport due to MHD instabilities
  - line radiation due to impurity influx
- MHD-induced energy loss likely to dominate in the initial part of TQ
- Rechester-Rosenbluth type **heat diffusion**, **prescribed** magnetic perturbation amplitudes $\delta B/B$
- 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_{TQ} (either 1 ms or 3 ms) from transport alone

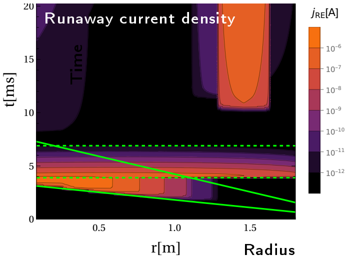
Early TQ, $t_{\mathrm{TQ}} = 1\,\mathrm{ms}$

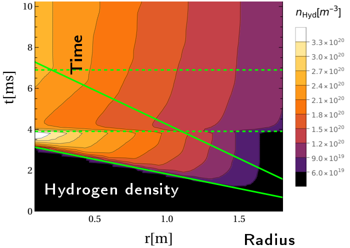


Late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$



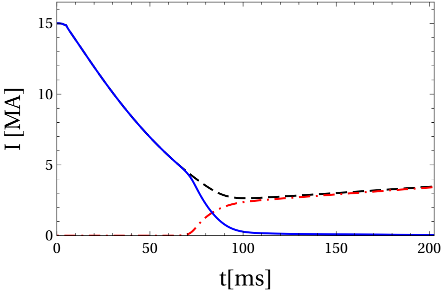
- RE transport calculated with same $\delta B/B$ as for heat diffusion [Svensson et al 2021 JPP **87** 905870207]
- Ion transport (of all ion species and charge states), with $D_{\max} = 4000\,\mathrm{m}^2/\mathrm{s}$ and $A_{\max} = -2000\,\mathrm{m/s}$, is activated at the same time as other transport channels, exponentially decaying on $0.5\,\mathrm{ms}$ timescale
- Similar form of the time evolution was used to reproduce observations in ASDEX Upgrade
  [Linder et al, 2020 NF **50** 096031]
- Diffusion and advection time-scales in the ms range $\rightarrow$ results in a substantial amount of material transported to the core over a few tenths of ms, as expected from 3D MHD simulations
  [Hu et al, 2021 NF **61** 026015]

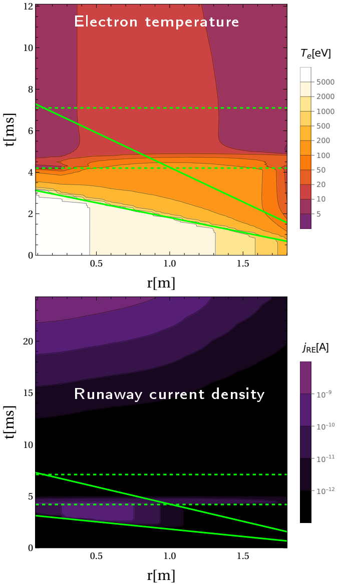




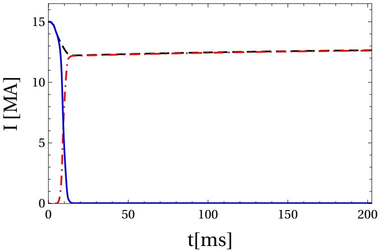
Single pellet injection - hydrogen L-mode (15 MA), best case scenario

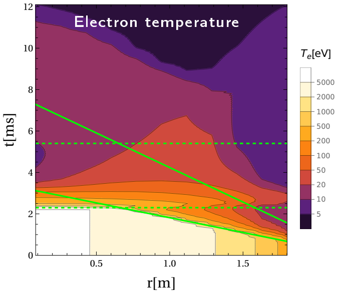
- Late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$
- 5×10^{22} Ne atoms
- Initial (mostly hot-tail) seed lost during TQ
- Tiny Dreicer seed sufficient to avalanche to $\sim$MA level
- Representative RE current $2.6\,\mathrm{MA}$

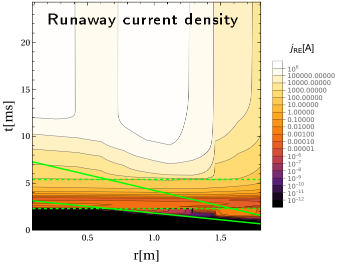




- Late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$
- 1.83×10^{24} Ne atoms
  (99% Ne concentration)
- RE current $1.5\,\mathrm{kA}$ already at the end of the transport event (Dreicer)
- Maximum of E/E_D is more than 5 times larger due to a lower electron density
- Repr. RE current $11.8\,\mathrm{MA}$ by $t \approx 15\,\mathrm{ms}$

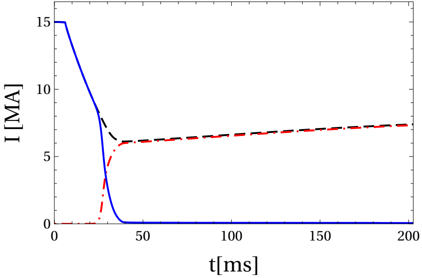






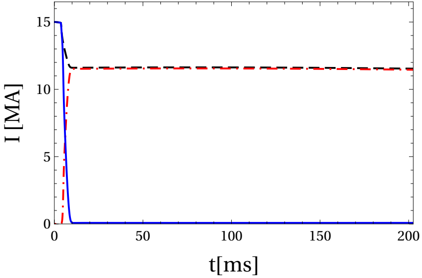
Best case

- Late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$
- Injected neon concentration 1.35%
- Tritium and Compton also active after the transport event
- Repr. RE current $5.9\,\mathrm{MA}$



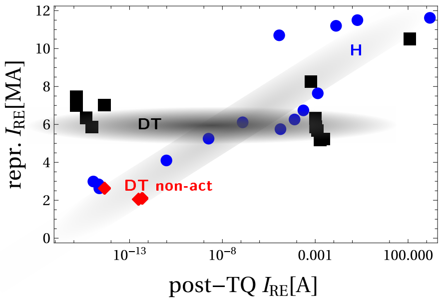
Worst case

- Early TQ, $t_{\mathrm{TQ}} = 1\,\mathrm{ms}$
- Injected neon concentration 81%
- Post-TQ RE current $131\,\mathrm{A}$, dominated by hot-tail
- Repr. RE current $10.5\,\mathrm{MA}$ (reached in $10\,\mathrm{ms}$)

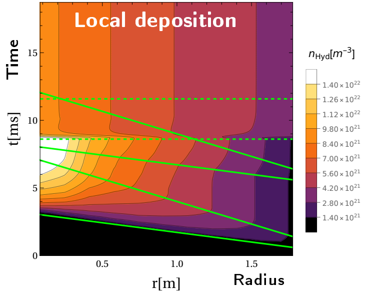


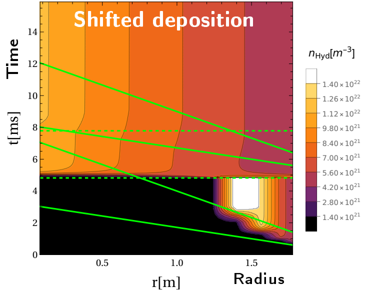
- RE current logarithmically sensitive to surviving non-activated seed
  [Vallhagen et al 2020 JPP **86** 475860401]
- DT plasma without activated seeds follows same the trend
- **Activated** seed generation active after transport event as well $\Rightarrow$ 5-6 MA floor in single stage injection cases

RE current vs RE seed surviving transport event

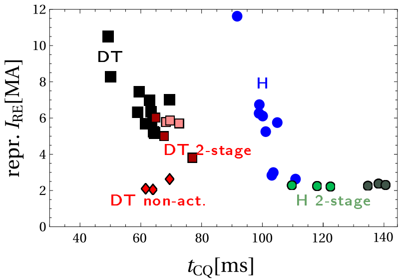


- Pure hydrogen pellet clouds are expected to **drift towards the low-field side**
- To mimic this effect, the material deposition can be **shifted outward** by $\approx 0.2\,\mathrm{m}$
- Shards unaffected by their own dilution cooling, ablate very rapidly
- **Deposition profile can be very strongly shifted**
- Large dilution cooling $(\times 1/200)$ at deposition peak
- May trigger TQ before neon-doped shards enter
- Density profiles become eventually similar due to ion transport
  $\rightarrow$ RE currents are comparable with and without shift



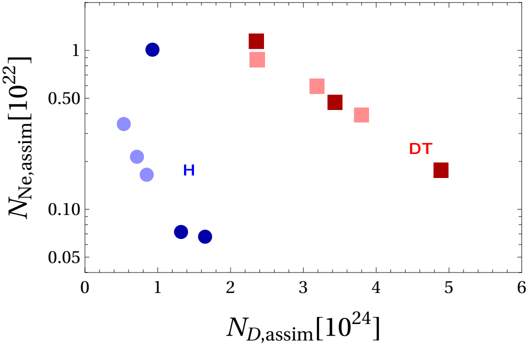


- Two-stage injection
  - First an injection of hydrogen to **cool the plasma through dilution**
  - Then a Ne-doped injection, which **radiatively dissipates** the thermal enegy
  - Leaves time for temperature equilibration to **minimize hot-tail**
- Best performing cases
  - Late TQ, $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$
  - Two-stage injection with 3 full pure H pellets followed by 1 Ne doped pellet after $5\,\mathrm{ms}$.
  - Relatively low Ne content (few $\%$)
- Two-stage injection can reduce the RE current
  - $\sim 4\,\mathrm{MA}$ in DT H-mode
  - $\sim 2\,\mathrm{MA}$ in H L-mode
- t_{CQ} can be kept within required range



Circles: H L-mode, squares: DT H-mode
Black and blue: single injection
Red and green: 2-stage
Red diamonds: DT non-activated
Dark red/green: shifted deposition
Light red/green: local deposition

- Assimilated neon quantity drops exponentially with assimilated hydrogenic quantity
- Reason: decreased temperature caused by the hydrogenic pellets



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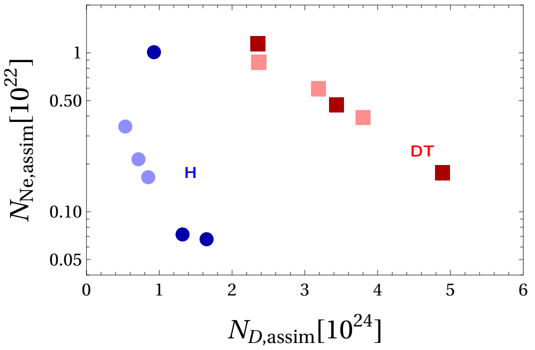
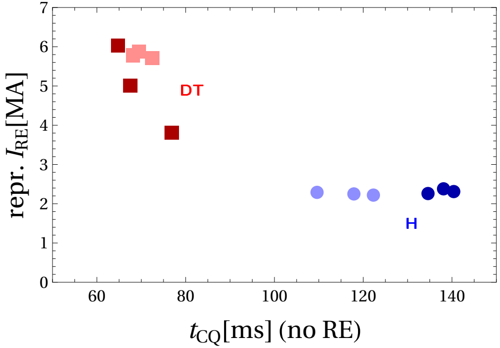


- I_{RE} and t_{CQ} do not change much



Dark red/blue: shifted deposition; Light red/blue: local deposition

Using the favourable TQ settings (late onset and $t_{\mathrm{TQ}} = 3\,\mathrm{ms}$):

- H L-mode:
  - 68 shards: assimilated fractions of 4.6% (incomplete TQ)
  - 487 shards: 5.2%, RE current $5.25\,\mathrm{MA}$
  - 5185 shards: 5.2%, RE current $6.11\,\mathrm{MA}$
- DT H-mode:
  - Increased number of shards **improves assimilation and reduces RE current**

# shards	68	487	5185
Assimilated fraction	53%	69%	80%
RE current [MA]	7	5.9	5.7

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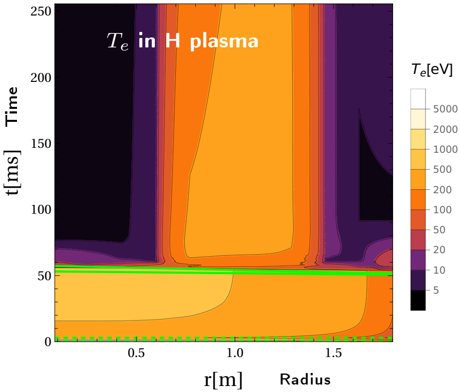
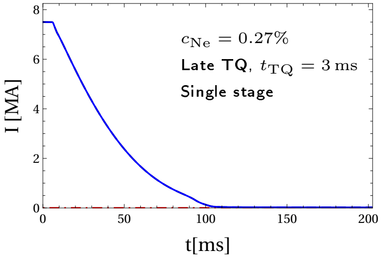
  - For the RE current the improvement between default and small shards is marginal

- If injection arrives after the TQ into a low T_e plasma, very **low assimilation rate**
- Plasma **re-heating**, long-lived ohmic current
- Larger heat transport or injection closer to TQ does not help
- Very fine shards/gas injection better for post-TQ SPI
- Current experiments do not seem to show re-heating; this needs to be validated



Significantly lower RE currents than in the $I_p^{(0)} = 15\,\mathrm{MA}$ case



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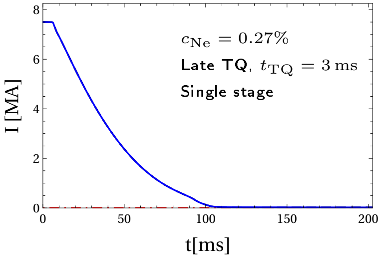

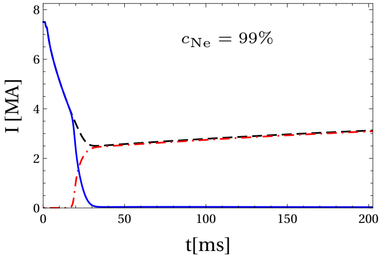

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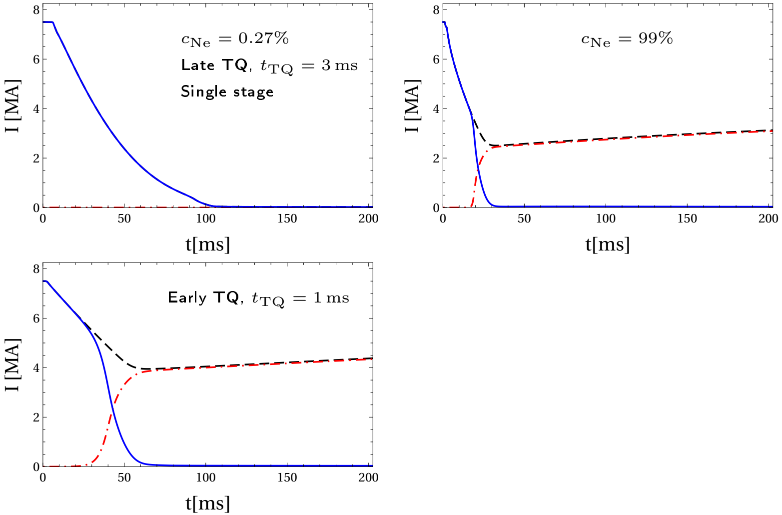

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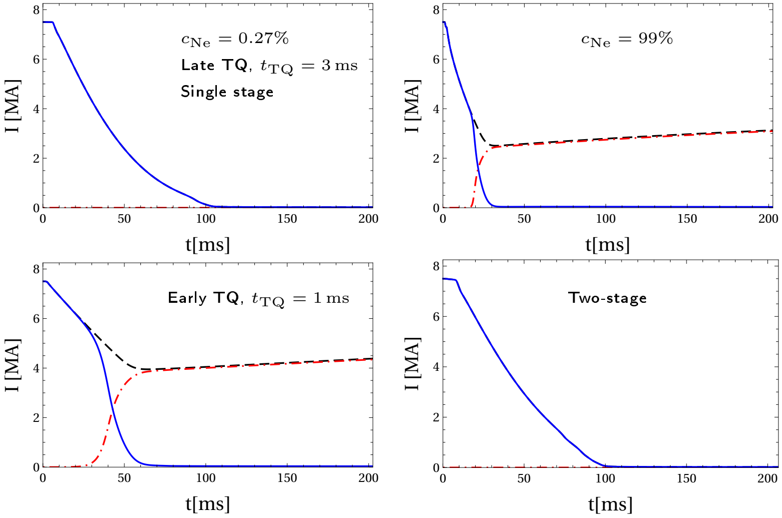
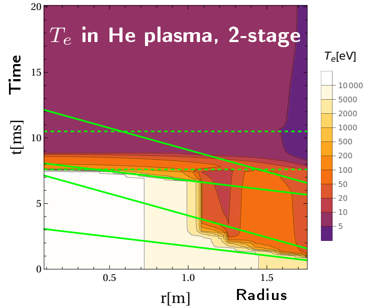


- Tolerable or negligible RE currents can be achieved
- Two-stage injection: RE current can be eliminated in both plasma scenarios
  - Intermediate cooling reduces hot-tail
- Single stage injection: not guaranteed if the TQ conditions are unfavourable
- Important factors of RE avoidance:
  - Two-stage cooling;
    sufficient even if it appears in outer half of plasma
  - High hydrogen assimilation before the TQ

Edge-localised deposition, but fast mixing during TQ



- Suitable for relatively high-dimensional global optimization of computationally expensive functions. Not gradient-based.
- Optimization for
  - low runaway and final ohmic currents ($I_{\mathsf{RE}}^{\mathsf{tol}} = I_{\mathsf{Ohm}}^{\mathsf{tol}} = 150$ kA)
  - transported fraction less than 10%: $\eta_{\mathsf{cond}} = W_{\mathrm{cond}}/W_{\mathrm{th}}^{(t=0)} < \eta_{\mathsf{cond}}^{\mathsf{tol}} = 0.1$
  - t_{CQ} between $t_{\mathsf{L}} = 25$ ms, $t_{\mathsf{U}} = 150$ ms

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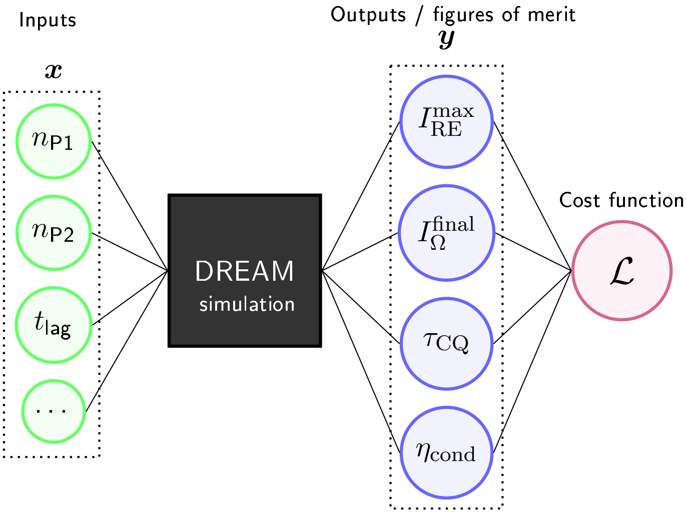
- Cost function

$$L = I_{\mathsf{RE}}^{\mathsf{max}}/I_{\mathsf{RE}}^{\mathsf{tol}} + I_{\mathsf{Ohm}}^{\mathsf{fin}}/I_{\mathsf{Ohm}}^{\mathsf{tol}} + \eta_{\mathsf{cond}}/\eta_{\mathsf{cond}}^{\mathsf{tol}} + \theta(t_{\mathsf{CQ}}),$$

$$\theta(t_{\mathsf{CQ}}) = 100[\tilde{\Theta}(t_{\mathsf{L}} - t_{\mathsf{CQ}}) + \tilde{\Theta}(t_{\mathsf{CQ}} - t_{\mathsf{U}})], \quad \tilde{\Theta}(t) = [1 + \tanh(kt)]/2$$

- $n_{\mathsf{P}1}$ number of pellets[a] 1st injection, $n_{\mathsf{P}1} \in [0.2, 3]$
- $n_{\mathsf{P}2}$ number of pellets 2nd injection, $n_{\mathsf{P}2} \in [0.2, 3]$
- c_{Ne} neon concentration in the 2nd pellet, $c_{\mathsf{Ne}} \in [0.001, 1]$
- t_{lag} time between injections, $t_{\mathsf{lag}} \in [0, 10]$ ms
- v_1 speed of 1st pellet $v_1 \in [100, 800]$ m/s
- v_2 speed of 2nd pellet $v_2 \in [100, 800]$ m/s



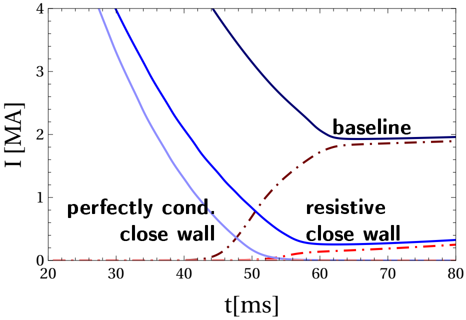
[a] *injected atoms normalized to that in a standard ITER pellet*, $1.85 \cdot 10^{24}$

- **Early TQ** and $t_{\mathrm{TQ}} = 3$ ms
- Previous simulations
  - $v_1 = v_2 = 500$ m/s
  - 5 ms lag between injections
- **Optimum**: $L = 38$
  - $n_{\mathsf{P1}} = 2.18$, $n_{\mathsf{P2}} = 0.47$
  - $c_{\mathsf{Ne}} = 0.0013$
  - $t_{\mathsf{lag}} = 3.6$ ms
  - $v_1 = 754$ m/s, $v_2 = 379$ m/s
  - $I_{\mathsf{RE}}^{\mathsf{max}} = 4.7$ MA, $I_{\mathsf{Ohm}}^{\mathsf{fin}} = 77$ kA, $\eta_{\mathsf{cond}} = 0.6$ and $t_{\mathsf{CQ}} = 131$ ms
- Higher speed of first injection
- Low neon concentration in second injection
- Slightly lower RE current than in “manual” optimization, but still MA-level

- Wide range of plausible scenarios and phases of operation were studied
- **Two-stage injections help** hydrogen assimilation and reduce hot-tail, providing the best performing cases
- Strong avalanche leads to **MA-scale runaway currents** in 15 MA ITER discharges, even in non-activated scenarios
- Runaway current is likely to be overestimated as the vertical displacement, kinetic effects and RE transport during the CQ are not included
- Emulating **drift of hydrogen pellet cloud** can lead to edge-localized deposited densities
  - this is counteracted by ion transport; **performance unaffected** (for short drift displacements)
- **Pellet must arrive before the TQ**, otherwise poor assimilation leads to re-heating and long current quench time
- **RE current can be eliminated in low initial plasma current scenarios** using two stage injection

Spare slides

- Without activated sources, previous SPI modelling predicted elimination of REs at high injected deuterium quantities
- **Reproduced only with a tightly fit perfectly conducting wall.**
- **Higher wall radius** chosen to match available magnetic energy inside the first toroidally closed conductor
- **Assimilation is poorer** in H plasma ($\leq 12\%$) due to lower initial temperature than in high performance DT discharge ($\leq 80\%$)



DT H-mode, without activated sources, single injection of 3 Ne doped pellets.

- Magnetic perturbations during CQ neglected; what level would be needed to suppress the RE current?
- Radial losses reduce the number of runaway electrons participating in the avalanche $\rightarrow$ can reduce the growth rate of the exponentiation
- Take advantage of the separation of the time-scales [Helander et al, PP 2000]
- Generalized calculation, includes radiation and momentum-space-dependent diffusion [Svensson et al, JPP 2021]
  - Assume rapid pitch-angle dynamics $\rightarrow$ solve for the pitch angle distribution
  - Integrate the kinetic equation over pitch-angle $\rightarrow$ reduced kinetic equation
  - Find lowest-order solution, neglecting transport and radiation effects. Use this to evaluate the transport term to next order
  - Integrate over momentum to find the runaway density
  - Couple with the evolution of the electric field

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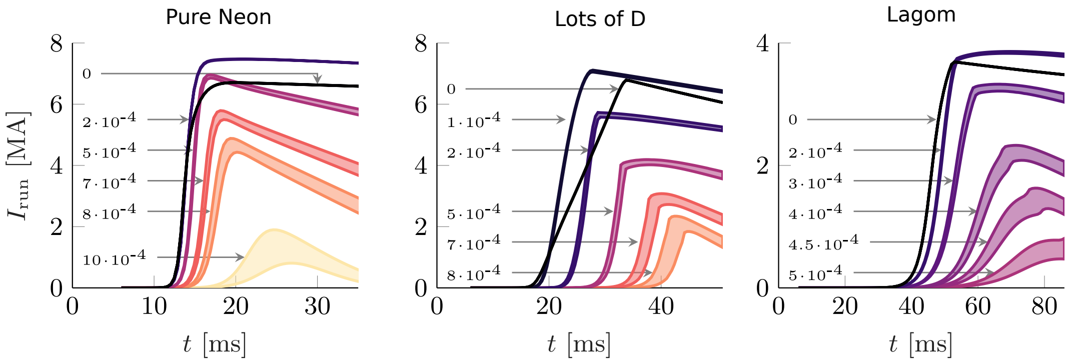
Use a momentum-space dependent diffusion coefficient

$$D(p) \propto (\delta B/B)^2 \, \frac{p}{1+p^2}$$

and calculate the runaway current for ITER-like current quench with material injection

Initial parameters: $I_p = 15$ MA, $T_e = 20(1-0.99(r/a)^2)$ keV, $n_{e0} = 10^{20}\ \mathrm{m}^{-3}$ (flat), $j_{\|} = j_0(1-(r/a)^2)^{0.41}$

Material deposited uniformly at the start of the simulation. TQ modelled by an exponential drop in temperature until 100 eV. After that, temperature is determined by energy balance.

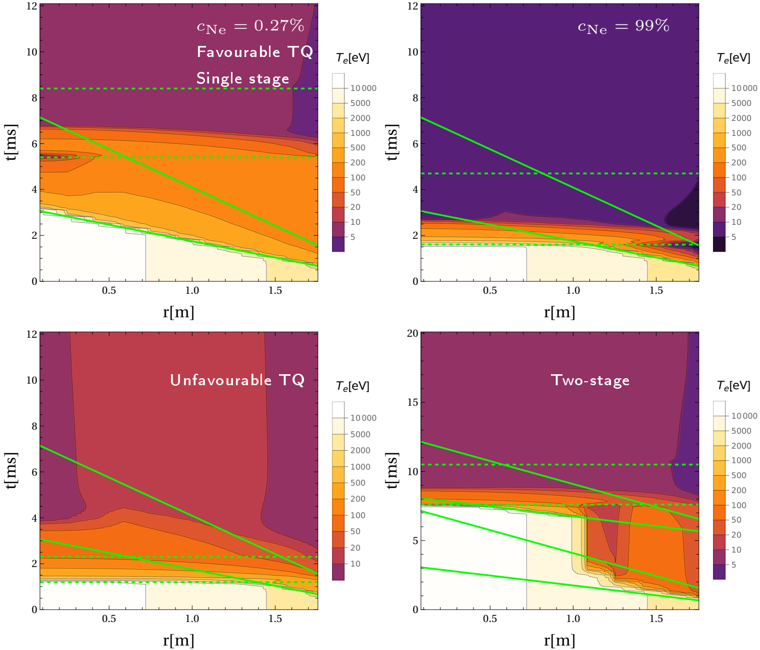


- Pure Ne: $n_{\mathrm{Ne}} = 10^{20}\,\mathrm{m}^{-3}$;
- Lots of D: $n_{\mathrm{Ne}} = 8\times10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 4\times10^{21}\,\mathrm{m}^{-3}$;
- Lagom: $n_{\mathrm{Ne}} = 8\times10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 7\times10^{20}\,\mathrm{m}^{-3}$

- For small $\delta B/B$ the maximum runaway current increases, but for larger perturbation levels it is reduced.

[Svensson et al, JPP 2021]

Electron temperature evolution, helium H-mode, 7.5 MA



- Thermal quench models: heat transport
  - S6 - H26 scenario, unfavourable TQ conditions (early, $1\,\mathrm{ms}$), 2.7% Ne.
  - S3 - H26 scenario, favourable TQ conditions (late, $3\,\mathrm{ms}$), 2.7% Ne.
- Thermal quench models: particle transport
  - S9 - H26 scenario, favourable TQ conditions, large shard size, 10.8% Ne.
- The effects of displaced material deposition
  - St6_NoShift - DTHmode24 scenario, local deposition, two-stage: 3 pure H pellets followed by 1 doped pellet with 1.35% Ne, favourable TQ conditions.
  - St6 - Same as previous one, but with shifted deposition.
- Reheating when injection arrives after TQ
  - C23 - H26 Scenario, Single 99% Ne pellet injected $50\,\mathrm{ms}$ after the TQ. Remnant transport with $\delta B/B = 4 \cdot 10^{-3}$.
- RE current can be eliminated by 2-stage injection
  - C12 - He56 scenario, two-stage, favourable TQ conditions, 1 hydrogen pellet followed by one doped pellet with 0.27% Ne.