Prospects for runaway electron avoidance with massive material injection in tokamak disruptions

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"Runaway dynamics in the DT phase of ITER operations in the presence of massive material injection",

[**Vallhagen**, Embreus, Pusztai, Hesslow and Fülöp, ArXiv 2004.12861, submitted to JPP]

- Simplified disruption modelling based on the "GO framework"
- Neon injection
- Combined deuterium and noble gas injection
  - scan over the injected densities
  - time-dependent vs equilibrium
  - current and temperature evolution in representative cases
- Estimate of the effect of
  - opacity
  - transport of neutral particles
  - non-uniform radial deposition
  - hot-tail generation

- Current density in elongated plasmas

$$\mu_0 \frac{\partial j_\parallel}{\partial t} = \frac{1}{V'} \frac{\partial}{\partial r} V' \langle |\nabla r|^2 \rangle \frac{\partial E}{\partial r}$$

where $V(r) = 2\pi^2 R\kappa r^2$ so that $V'(r) = 2\pi^2 R(\kappa' r^2 + 2\kappa r)$ and

$$|\nabla r|^2 = \frac{\cos^2\theta + \kappa^{-2}\sin^2\theta}{\left(1 + \frac{\kappa' r}{\kappa}\sin^2\theta\right)^2}$$

so that

$$\langle |\nabla r|^2 \rangle = \frac{\kappa^{-2} + \sqrt{1 + \frac{\kappa' r}{\kappa}}}{\left(1 + \frac{\kappa' r}{2\kappa}\right)\left(1 + \sqrt{1 + \frac{\kappa' r}{\kappa}}\right)\sqrt{1 + \frac{\kappa' r}{\kappa}}}.$$

[Fülöp *et al*, JPP 2020]

Sum of Ohmic and runaway current densities $j_{\|} = \sigma E + ecn_{\mathrm{RE}}$

Runaway rate

$$\frac{\partial n_{\mathrm{RE}}}{\partial t} = \left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\text{Dreicer}} + \left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\text{hot-tail}} + \left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\text{tritium}} + \left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\text{Compton}} + \left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\text{avalanche}}$$

- Dreicer seed: neural network trained on large database of kinetic simulations.
  https://github.com/unnerfelt/dreicer-nn [L Hesslow *et al*, JPP 2019]
- Tritium seed [R Martin-Solis *et al*, NF 2017]

$$\left(\frac{\partial n_{\mathrm{RE}}}{\partial t}\right)^{\mathrm{tritium}} = \ln(2)\frac{n_{\mathrm{T}}}{\tau_{\mathrm{T}}} f\left(W_{\mathrm{crit}}\right),$$

  - Fraction of the electron spectrum above the critical runaway energy W_{crit}

$$f(W_{\mathrm{crit}}) = \frac{\int_{W_{\mathrm{crit}}}^{Q} I(W)\mathrm{d}W}{\int_0^Q I(W)\mathrm{d}W} = 1 - \frac{35}{8}\left(\frac{W_{\mathrm{crit}}}{Q}\right)^{3/2} + \frac{21}{4}\left(\frac{W_{\mathrm{crit}}}{Q}\right)^{5/2} - \frac{15}{8}\left(\frac{W_{\mathrm{crit}}}{Q}\right)^{7/2},$$

where $I(W) \propto (Q-W)^2\sqrt{W}$, with $Q = 18.6\,\mathrm{keV}$.

- In DT operation γ-rays emitted by the activated walls Compton scatter electrons to runaway region.
- Gamma flux energy spectrum in ITER [R Martin-Solis *et al*, NF 2017]

$$\Gamma_\gamma(E_\gamma) \propto \exp\left(-\exp\left(z\right) - z + 1\right) \text{ with } z = \left[\ln\left(E_\gamma(\mathrm{MeV})\right) + 1.2\right]/0.8$$

(Details of the spectra will depend on the final configuration of the first wall and blanket.)

- Total Compton cross-section

$$\sigma(E_\gamma) = \frac{3\sigma_T}{8}\left\{\frac{x^2 - 2x - 2}{x^3}\ln\frac{1+2x}{1+x(1-\cos\theta_c)} + \frac{1}{2x}\left[\frac{1}{[1+x(1-\cos\theta_c)]^2} - \frac{1}{(1+2x)^2}\right]\right.$$
$$\left. - \frac{1}{x^3}\left[1 - x - \frac{1+2x}{1+x(1-\cos\theta_c)} - x\cos\theta_c\right]\right\} \quad \text{with} \quad \cos\theta_c = 1 - \frac{m_e c^2}{E_\gamma}\frac{E_c/E_\gamma}{1-(E_c/E_\gamma)}$$

- Runaway rate

$$\left(\frac{\partial n_{\mathsf{RE}}}{\partial t}\right)^\gamma = n_e \int \Gamma_\gamma(E_\gamma)\sigma(E_\gamma)dE_\gamma$$

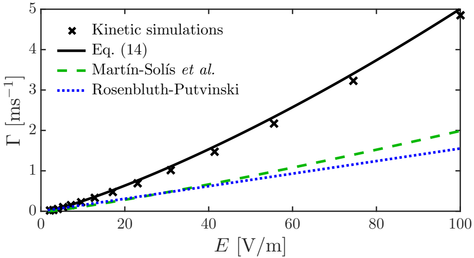
- Hot-tail generation is expected to dominate over Dreicer generation in ITER.
- Some (but probably not all) of the hot-tail runaways are expected to be lost due to the breakup of magnetic surfaces that accompanies the thermal quench.
- Recent fluid+kinetic simulations show that taking into account all the hot-tail electrons overestimates the runaway current by a factor of four in ASDEX Upgrade [Hoppe et al, submitted to JPP 2020]
- Here we neglect both hot-tail generation and losses due to magnetic fluctuations, for simplicity $\rightarrow$ runaway seed is likely to be underestimated.
- Effect of remnant hot-tail will be discussed later.

Generalization of Rosenbluth-Putvinski calculation to account for the presence of weakly ionized impurities [L Hesslow *et al*, NF (2019)]

- Asymptotic matching, valid also when $E \sim E_c^{\text{eff}}$ or $n_Z \ll n_D$:

$$\left(\frac{\partial n_{\text{RE}}}{\partial t}\right)^{\text{screened}}_{\text{aval}} = \frac{e n_{\text{RE}}}{m_{\text{e}} c \ln \Lambda_{\text{c}}} \frac{n_{\text{e}}^{\text{tot}}}{n_{\text{e}}} \frac{E_{\parallel} - E_{\text{c}}^{\text{eff}}}{\sqrt{4 + \bar{\nu}_{\text{s}}(p_\star)\bar{\nu}_{\text{D}}(p_\star)}},$$

- Stronger avalanching in the presence of weakly ionized atoms.
- Increased number of target electrons available for the avalanche process is only partially compensated by the increased friction force.



Avalanche growth rate for $n_D = 10^{20}$ m^{-3}, $n_{Ar+} = n_D$, $T = 10$ eV.

Reduction of runaway generation due to finite aspect ratio is negligible at high densities and electric fields, due to the high collisionality of electrons at the critical momentum [McDevitt&Tang EPL 2019].

- Energy loss: radial transport due to magnetic fluctuations and line radiation due to impurity influx.
- Initial part of thermal quench: $T_\mathsf{e}(t,r) = T_\mathsf{f} + [T_0(r) - T_\mathsf{f}]\, e^{-t/t_0}$ until the central temperature drops to 100 eV.
- After this, energy balance equation:

$$\frac{3}{2}\frac{\partial(nT)}{\partial t} = \frac{1+\kappa^{-2}}{2}\frac{3n}{2r}\frac{\partial}{\partial r}\left(\chi r\frac{\partial T}{\partial r}\right) + \sigma(T, Z_{\mathrm{eff}})E^2 - \sum_{i,k} n_\mathrm{e} n_k^i L_k^i(T, n_\mathrm{e}) - P_{\mathrm{Br}} - P_{\mathrm{ion}}.$$

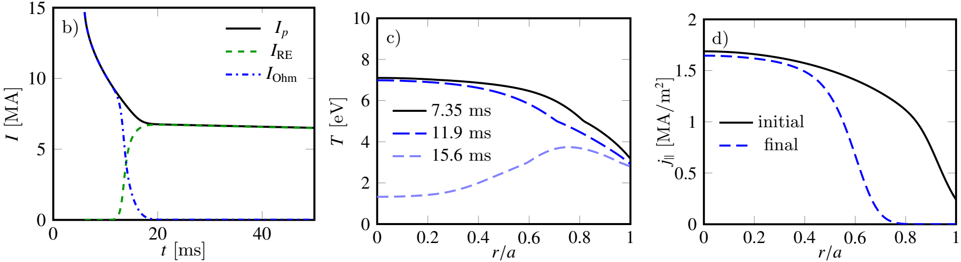
- The effect of the heat diffusion and Bremsstrahlung radiation terms are negligible.
- The density of each charge state for every ion species is calculated from

$$\frac{\mathrm{d}n_k^i}{\mathrm{d}t} = n_\mathrm{e}\left[I_k^{i-1} n_k^{i-1} - (I_k^i + R_k^i) n_k^i + R_k^{i+1} n_k^{i+1}\right].$$

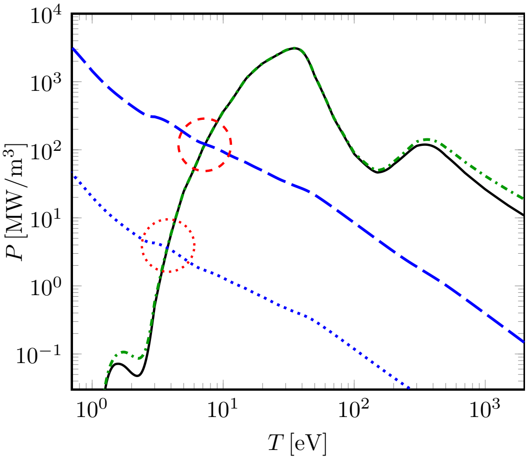
- The ionization, recombination and line radiation rates taken from ADAS.
- P_{ion} is the ionization energy loss.

Pure neon injection: $n_{\mathrm{Ne}} = 10^{20}\,\mathrm{m}^{-3}$

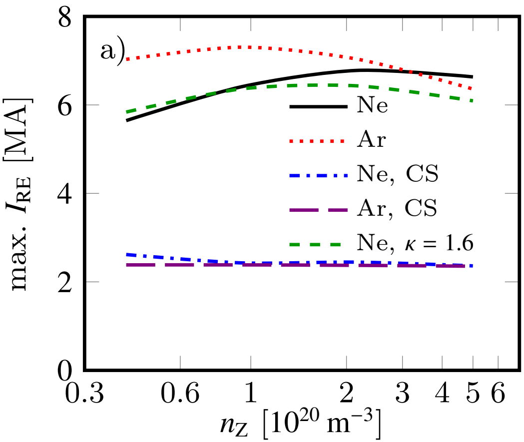
- DT plasma with initial plasma current $I_0 = 15\,\mathrm{MA}$, $j(r) = j_0\left[1-(r/a)^{0.41}\right]$
- $\langle n_e \rangle = 10^{20}\,\mathrm{m}^{-3}$, flat
- $T_0 = 20\,\mathrm{keV}\left[1-(r/a)^2\right]$, T_f flat.
- Injected material uniformly distributed at the beginning of the simulation.



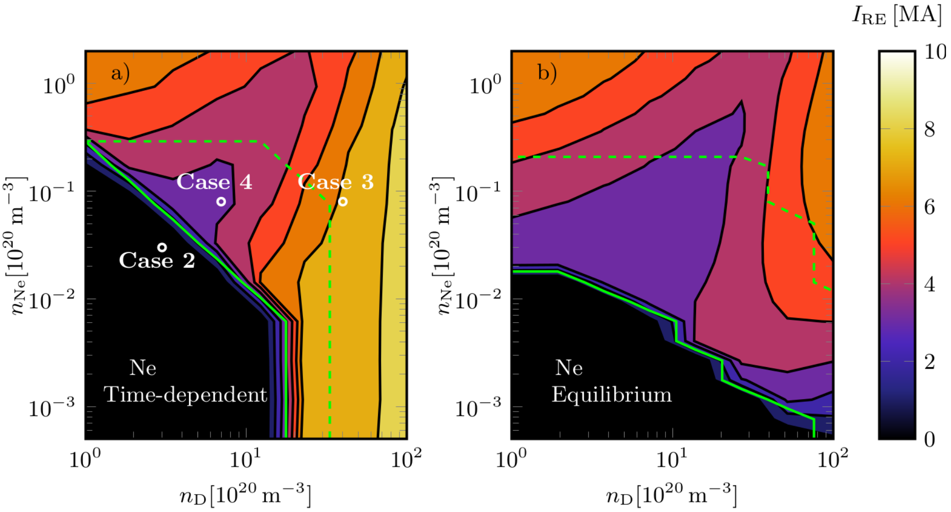
- Radiative losses (solid), radiative and ionization losses (green dash-dotted)
- Ohmic heating (blue dashed and blue dotted).
  - dashed: $j_{\mathrm{ohm}} = 1.69\,\mathrm{MA/m}^2$ corresponding to the initial on-axis current density
  - dotted: $j_{\mathrm{ohm}} = 0.2\,\mathrm{MA/m}^2$ representing a case where the Ohmic current has partially, but not completely, decayed
- The equilibrium temperatures for both current densities are in the order of a few eV.
- Large amount of partially ionized neon $\rightarrow$ large avalanche growth rate.
- Large RE conversion $\rightarrow$ 6.7 MA



- Two models for avalanche generation:
  - with partial screening
    [Hesslow *et al*, NF (2019)]
  - with complete screening (CS)
    [Rosenbluth and Putvinski, NF (1997)]
- Effect of screening increases the final runaway current for both argon and neon injections.
- Effect of elongation is very small.

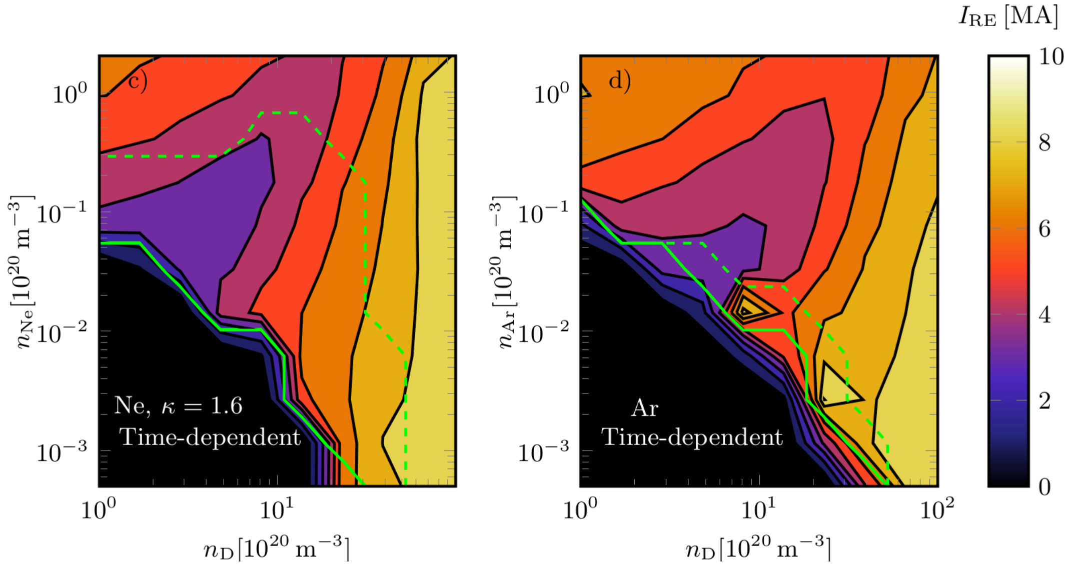


Neon + deuterium



- Below the green solid line CQ time is longer than 150 ms (insufficient material injection to induce a complete radiative collapse).
- Above the green dashed line, the Ohmic CQ time is less than 35 ms (boundary to avoid damage due to torques on the first wall).

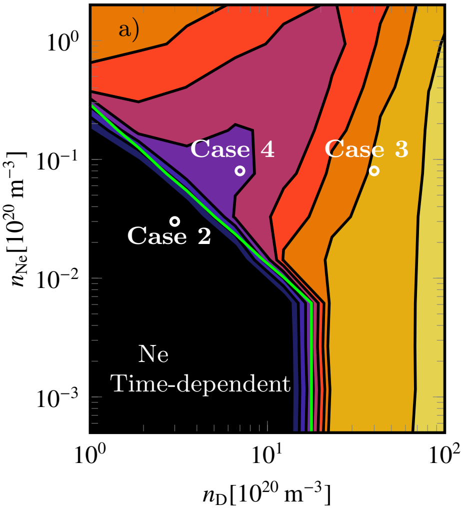
- Time-dependent leads to higher runaway currents, especially for high deuterium contents.
- In the time-dependent case:
  - It takes some time to reach the equilibrium ionization distribution.
  - Low degree of ionization $\rightarrow$ larger radiative losses $\rightarrow$ lower temperature $\rightarrow$ higher induced electric fields $\rightarrow$ higher runaway currents.
  - If the temperature drops too low, deuterium starts to recombine $\rightarrow$ increases the avalanche.
  - Ionization energy loss matters.


$I_{\rm RE}$ [MA]
10
8
6
4
2
0
c)
10^0
10^{-1}
10^{-2}
10^{-3}
$n_{\rm Ne}[10^{20}\,{\rm m}^{-3}]$
Ne, $\kappa = 1.6$
Time-dependent
10^0
10^1
$n_{\rm D}[10^{20}\,{\rm m}^{-3}]$
d)
10^0
10^{-1}
10^{-2}
10^{-3}
$n_{\rm Ar}[10^{20}\,{\rm m}^{-3}]$
Ar
Time-dependent
10^0
10^1
10^2
$n_{\rm D}[10^{20}\,{\rm m}^{-3}]$

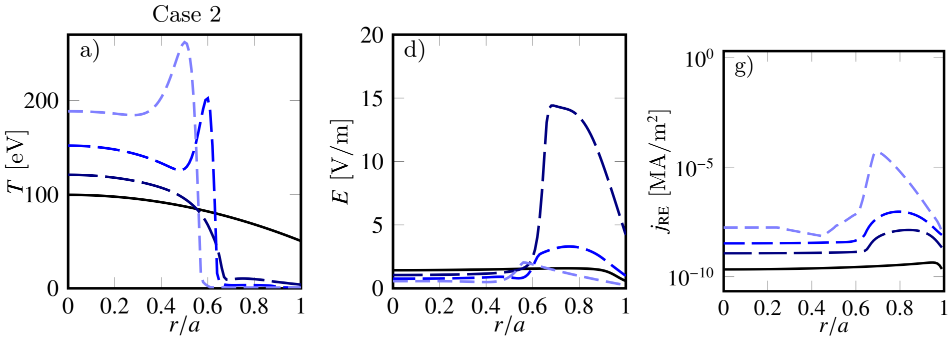
- The initial deuterium density is $n_{\mathrm{D0}} = 10^{20}\,\mathrm{m}^{-3}$.
- Injected material

Case	$n_{\mathrm{D}}/n_{\mathrm{D0}}$	$n_{\mathrm{Ne}}/n_{\mathrm{D0}}$	I_{RE} [MA]
2	3	0.03	0
3	40	0.08	7.3
4	7	0.08	3.7

- The final column shows the runaway currents right before the dissipation phase.



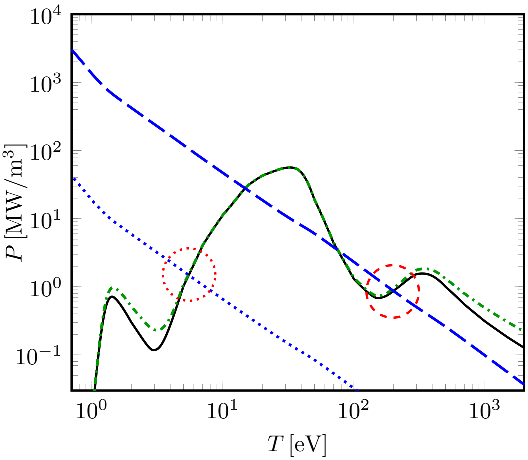
No runaways, but too long CQ time.



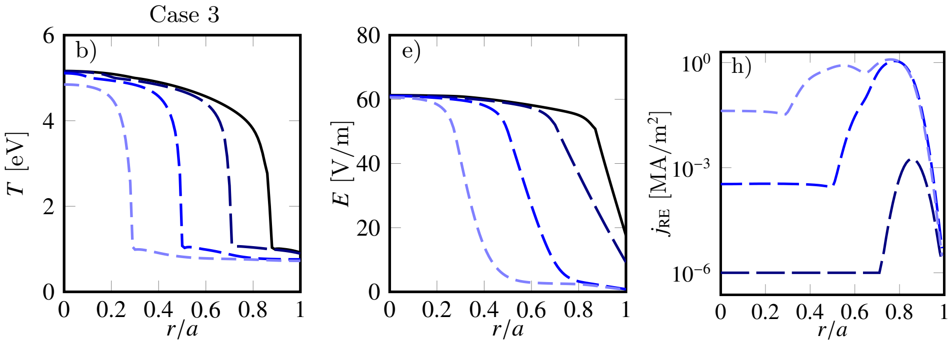
- Plasma remains hot in the centre.
- Due to the temperature drop at the edge, a strong electric field is induced $\rightarrow$ additional Ohmic heating.
- Peak in the temperature close to the boundary between the hot and cold regions.

Case 2: $n_{\mathrm{Ne}} = 3 \times 10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 3 \times 10^{20}\,\mathrm{m}^{-3}$

- Equilibrium temperature around 200 eV.
- Inner part of the plasma hot $\rightarrow$ very long CQ time.
- High temperature $\rightarrow$ weak induced electric field $\rightarrow$ negligible RE conversion.

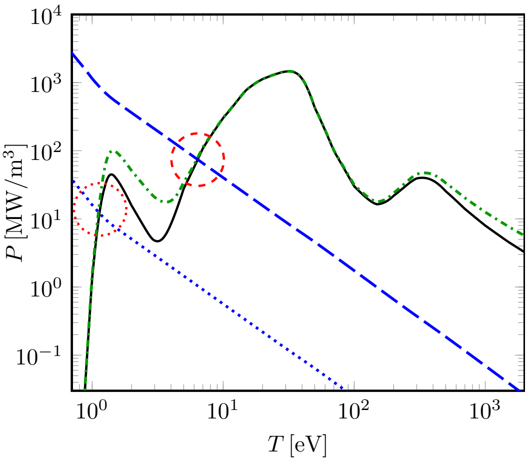


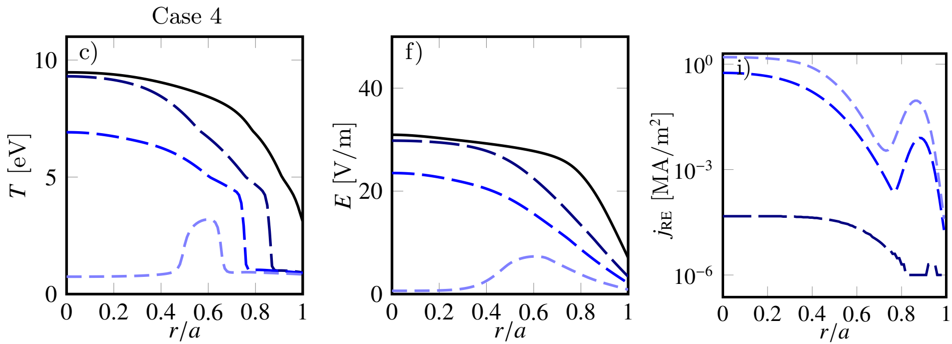
Case 3: $n_{\mathrm{Ne}} = 8 \times 10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 4 \times 10^{21}\,\mathrm{m}^{-3}$



- Radiative losses are strong, resulting in very low temperatures.
- The boundary between the two regions (5 eV and 1 eV) moves radially inward.
- Recombination → higher avalanche growth rate → large RE generation in the outer part of the plasma.
- The Ohmic current remaining in the more central part diffuses outward → a significant induced electric field is sustained in the cold region.
- Large RE conversion with an off-axis radial density profile.

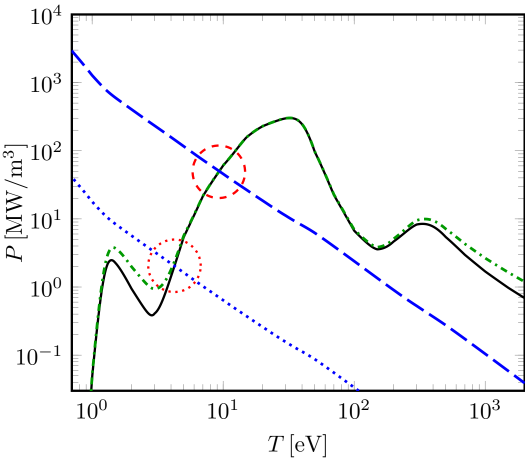
- Large amount of deuterium leads to an overall enhancement of the radiative losses.
- Ionization energy loss matters (difference between solid black and green dash-dotted lines).
- Equilibrium temperature is shifted from a few eV down to only about $1\,\mathrm{eV}$.

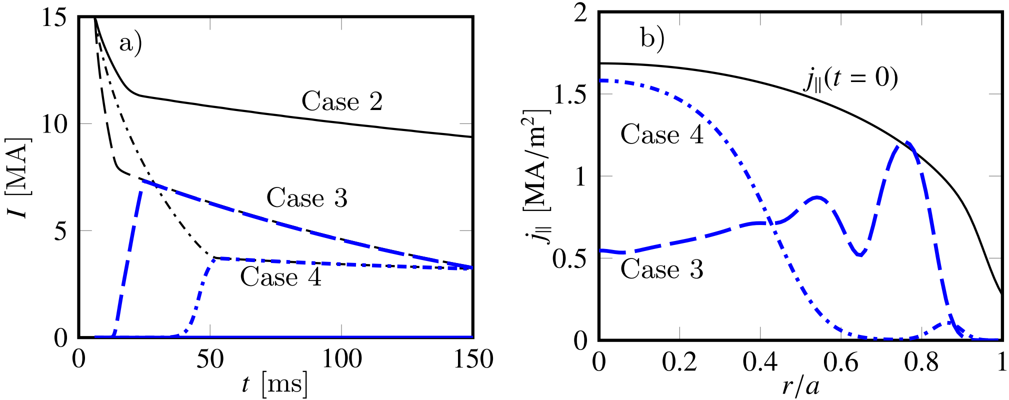




- Deuterium density is not high enough to result in temperatures low enough to make the deuterium recombine.
- But it is sufficiently high to dampen the avalanche, at least partially.

- Compromise:
  - injected densities are sufficiently large to avoid an equilibrium at high temperatures
  - but not too large, such that equilibrium temperature does not drop too close to $1\,\mathrm{eV}$.
- Acceptable CQ time.
- Runaway current lower than previous case.

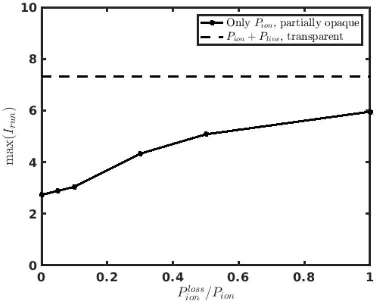




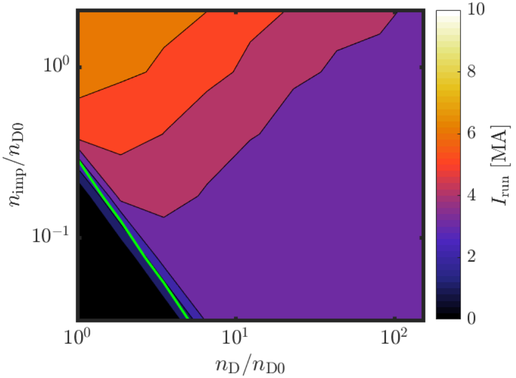
Case 2: $n_{\mathrm{Ne}} = 3 \times 10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 3 \times 10^{20}\,\mathrm{m}^{-3}$
Case 3: $n_{\mathrm{Ne}} = 8 \times 10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 4 \times 10^{21}\,\mathrm{m}^{-3}$
Case 4: $n_{\mathrm{Ne}} = 8 \times 10^{18}\,\mathrm{m}^{-3}$, $n_{\mathrm{D}} = 7 \times 10^{20}\,\mathrm{m}^{-3}$

Plasma was assumed to be transparent to radiative losses.

- But plasmas at low temperature and high density (such as Case 3) are opaque to the Lyman lines of hydrogen isotopes.
- Estimate the effect by considering the extreme case, when all the deuterium radiation is trapped.
- If only deuterium line radiation is trapped, the runaway current is reduced from 7.3 MA to 6 MA.
- Trapping also all the ionization radiation in the plasma leads to 2.7 MA.



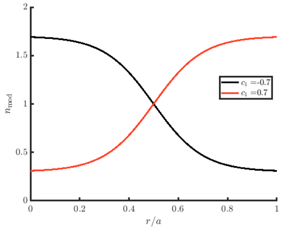
- If a fraction of the deuterium recombines, it may leave the plasma.
- Estimate the effect by removing their effect on radiation losses and runaway generation.
- The cold region in Case 3 will have less runaways, and the non-monotonic behaviour observed previously is missing.
- The resulting runaway current is similar to a case with a lower amount of injected deuterium.



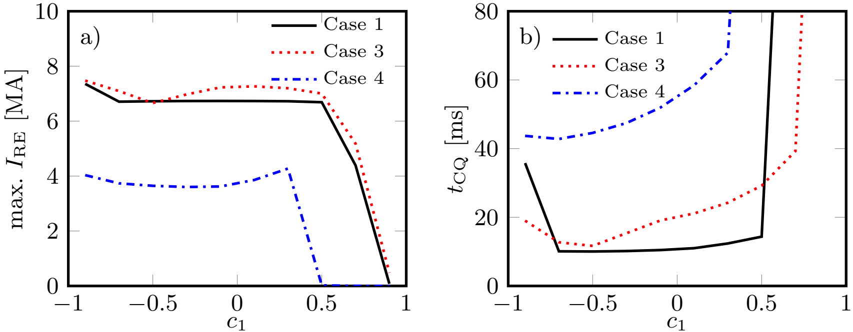
Non-uniform density deposition

Density profiles were varied from hollow to peaked.
$n \propto 1 + c_1 \tanh\left(0.5(r/a - 0.5)\right)$.

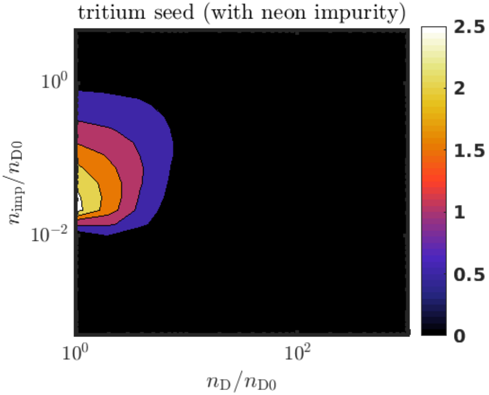
- negative c_1: density peaked at the centre
- positive c_1: density peaked at the edge

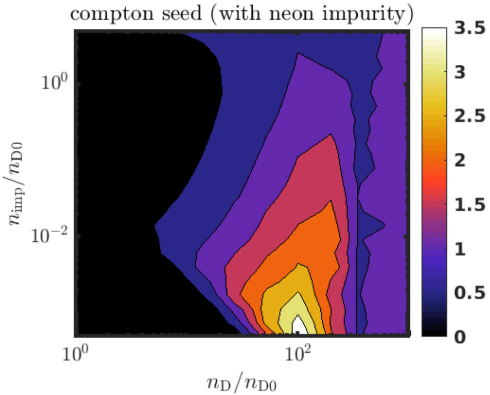


Total runaway current and CQ time are insensitive to the density profile if the number of injected atoms is constant.



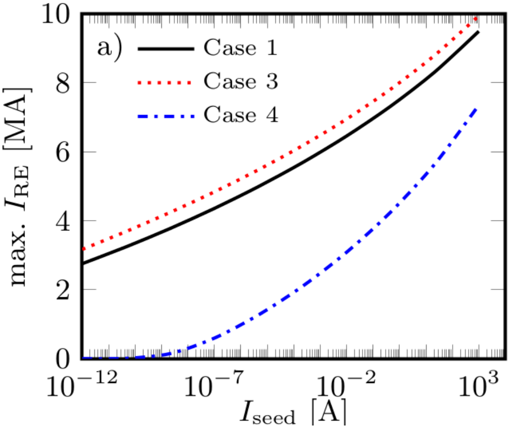
- Dreicer seed is negligible.
- Tritium seed **decreases** with increasing impurity content, due to the shorter CQ times and the increased critical energy.
- Compton seed **increases** with increasing impurity content, due to the increased number of target electrons available for Compton scattering.
- Tritium + Compton $\rightarrow$ a few amperes of seed current is obtained almost independently of the injected amount of material.





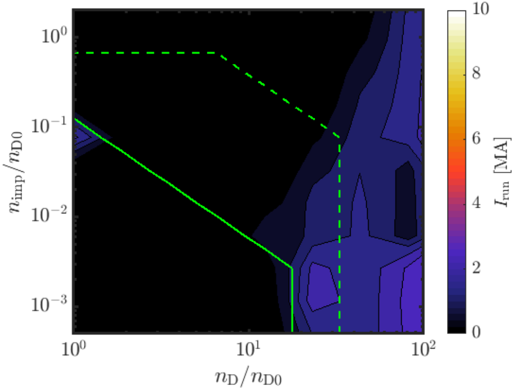
Importance of remnant hot-tail seed

- Omission of hot-tail seed is motivated with radial losses due to the breakup of magnetic surfaces during the thermal quench.
- Maximum runaway current depends logarithmically on the seed.
- A seed current of a μA gives 1 MA final runaway current even in Case 4.

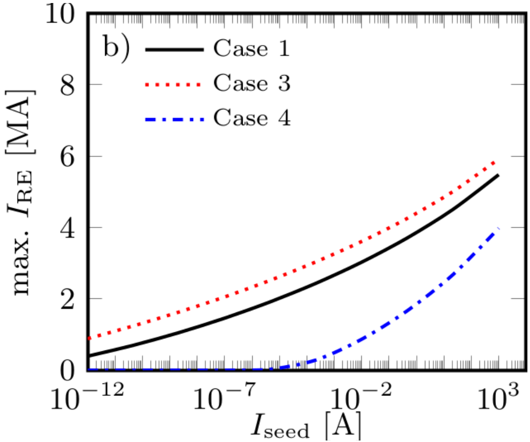


Maximum runaway current as function of seed current for Case 1, 3 and 4 (assuming a flat seed profile).

- No tritium decay or Compton sources.
- Only Dreicer: regions in the parameter space without large runaway currents



0.5 A remnant hot-tail seed is needed for a runaway current of 1 MA in Case 4.



- In the presence of partially ionized impurities, avalanche gain is higher than previously expected.
- If losses due to magnetic perturbations are neglected, impurity injection leads to high runaway currents in ITER, even if it is combined with deuterium injection.
- Large amount of injected material $\rightarrow$ low temperatures $\rightarrow$ recombination $\rightarrow$ high $n_{\rm e}^{\rm tot}/n_{\rm e}$ $\rightarrow$ large avalanche growth rate.
- Final runaway current is logarithmically weak function of seed.
- Runaway current and CQ time are fairly insensitive to the details of the density profile of the injected material (unless it peaks at the edge).
- Important to clarify details of the thermal quench, including hot-tail generation and effect of losses due to perturbations $\rightarrow$ see O Embreus' talk