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Dust transport simulations for DEMO

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Outline

- Modelling strategy overview
- Simulations of W dust transport and inventory evolution in ITER-like start-up plasmas (M2.2) [Vignitchouk et al, *PPCF* submitted]
- Implementation status of DEMO plasma profiles in MIGRAINe (M2.3)

Metallic dust in fusion devices

- Safety issue due to fuel retention, radioactivity, chemical reactivity (hot dust), toxicity (Be)
- Licensing constraints are usually expressed in terms of in-vessel dust mass
- Wide range of particle sizes $(1-100\mathrm{s}\,\mu\mathrm{m})$, but large particles are particularly important
  - Contain more mass
  - Higher survivability – $t_{\mathrm{life}} \propto R_{\mathrm{d}}^2$ for $R_{\mathrm{d}} \gg R_{\mathrm{Le}} \sim 1-5\ \mu\mathrm{m}$
  - More easily re-mobilized – $R_{\mathrm{d}} \geq 5\ \mu\mathrm{m}$ appears to be required according to experimental data [Ratynskaia et al, *NME* 2017]
- Melt splashing events are a likely source for large dust [Vignitchouk et al, *NF* 2022; Ratynskaia et al, *PPCF* 2022]

Dust-plasma interaction in MIGRAINe

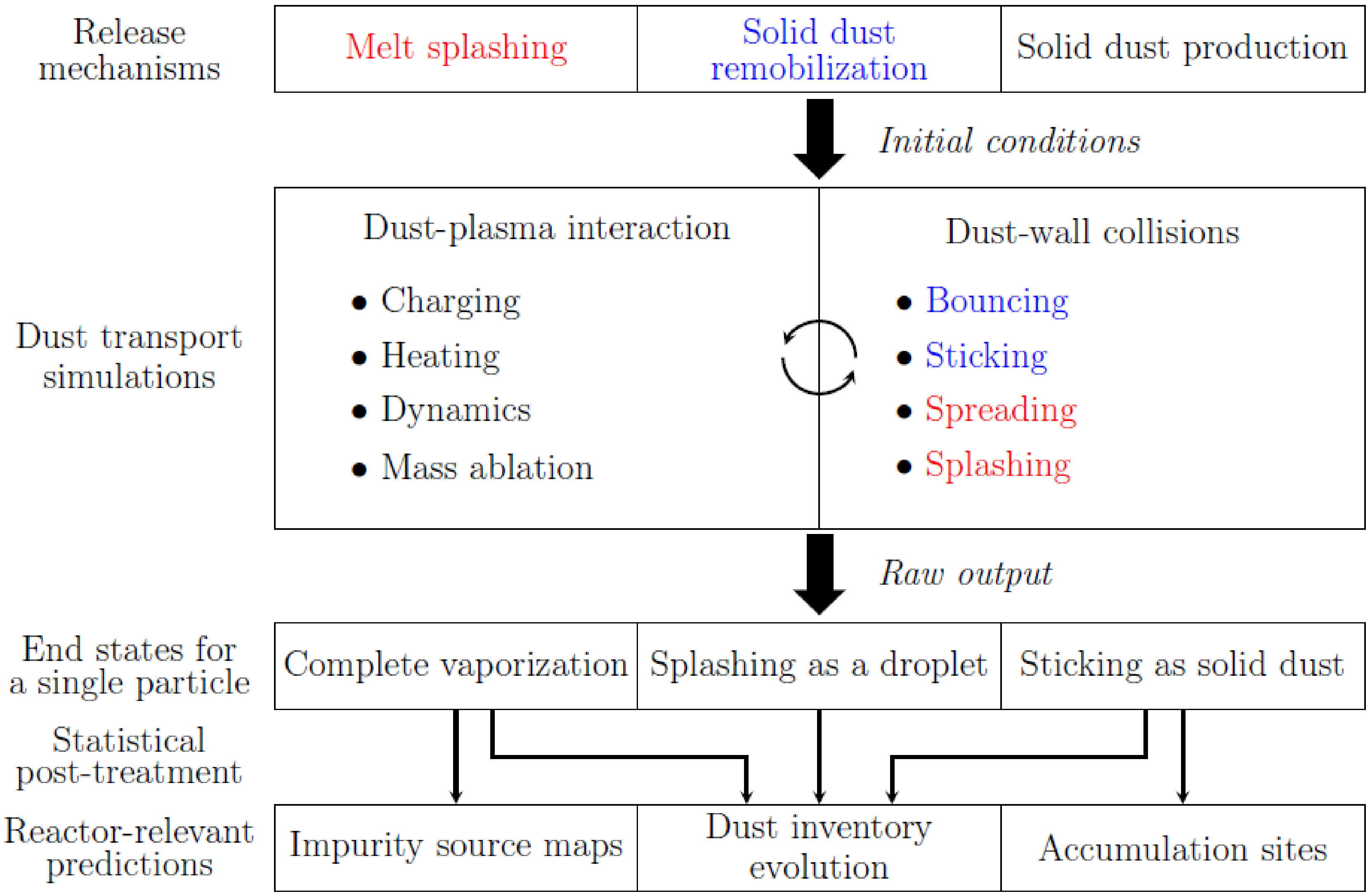
- Coupled charging, heating, dynamics and mass ablation equations for a point-like spherical particle

$$I_{\mathrm{tot}}(\varphi_{\mathrm{d}}) = 0 \qquad \frac{\mathrm{d}H_{\mathrm{d}}}{\mathrm{d}t} = Q_{\mathrm{tot}} \qquad M_{\mathrm{d}}\frac{\mathrm{d}\boldsymbol{v}_{\mathrm{d}}}{\mathrm{d}t} = \boldsymbol{F}_{\mathrm{tot}} \qquad \frac{\mathrm{d}M_{\mathrm{d}}}{\mathrm{d}t} = \Gamma_{\mathrm{tot}}$$

- Source terms written as the sum of contributions from many physical processes, such as
  - Plasma absorption (kinetic and chemical contributions)
  - Electron emission (thermionic, secondary, backscattering, etc)
  - Thermal radiation, vaporization

- Two main categories of input
  - Initial conditions (location, size, speed, temperature)
  - Environmental data (plasma background, wall geometry)

Dust modelling methodology



Release mechanisms

Melt splashing | Solid dust remobilization | Solid dust production

Initial conditions

Dust transport simulations

Dust-plasma interaction

- Charging
- Heating
- Dynamics
- Mass ablation

Dust-wall collisions

- Bouncing
- Sticking
- Spreading
- Splashing

Raw output

End states for a single particle

Complete vaporization | Splashing as a droplet | Sticking as solid dust

Statistical post-treatment

Reactor-relevant predictions

Impurity source maps | Dust inventory evolution | Accumulation sites

[Ratynskaia et al, *PPCF* 2022]

Dust inventory evolution studies

Basic scenario

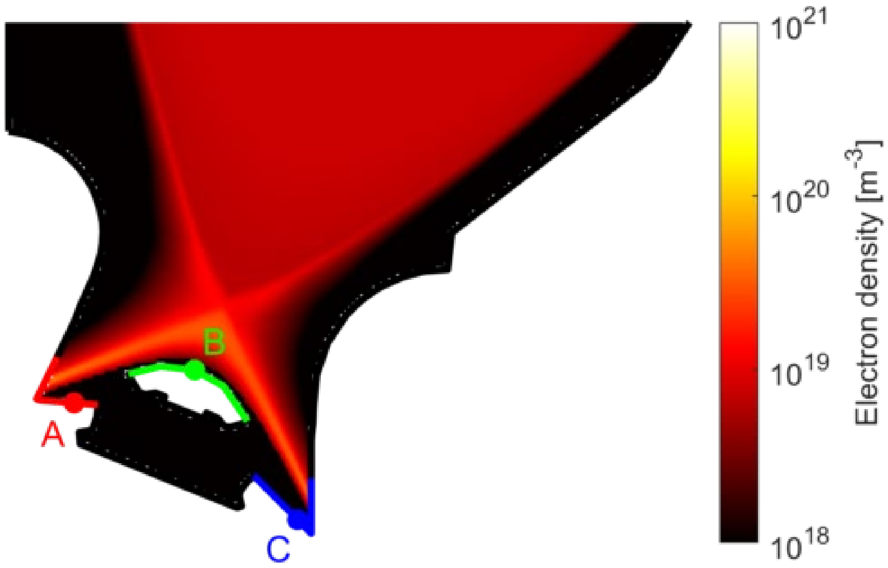
- Assume an initial dust distribution (from past melt event)
- Remobilizable particles (to be defined) are mobilized during discharge start-up
- Repeat identical discharges until dust inventory reaches a steady state
- No production of new particles

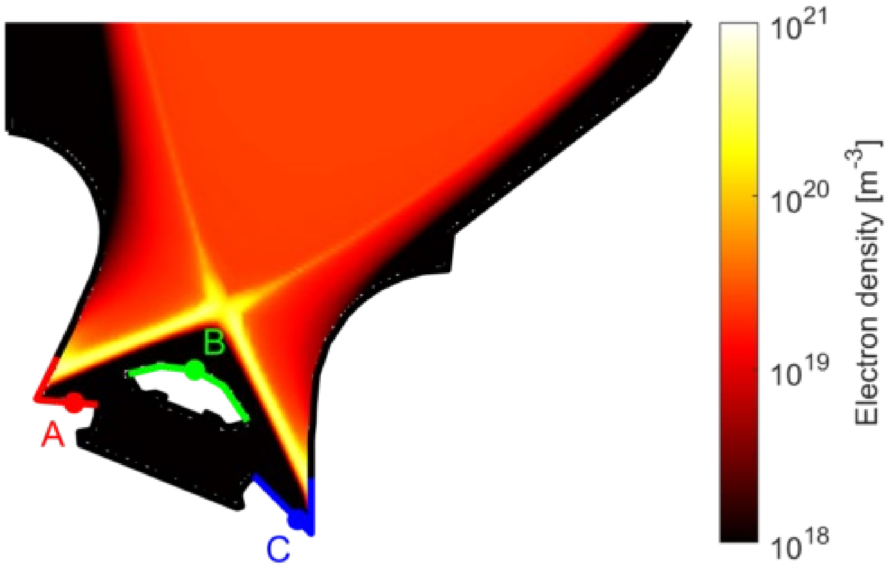
Main questions

- How many discharges does it take?
- What kind of particles are left? Where in the vessel?
- Where do vaporizing particles tend to deposit impurities in the start-up plasma?

W dust in ITER-like start-up plasmas

- Remobilizability criterion: $R_\mathrm{d} \geq R_\mathrm{min} = 5\ \mu\mathrm{m}$
- 2 plasma backgrounds: low and high recycling, translates to low and high n_e and conversely for T_e
- 3 initial size distributions: modal radius $10, 25, 40\ \mu\mathrm{m}$
- 2 size-velocity correlations: $R_\mathrm{d} v_\mathrm{d} \leq R_\mathrm{min} v_\mathrm{max}$ with maximum initial speed $v_\mathrm{max} = 2, 10\ \mathrm{m/s}$





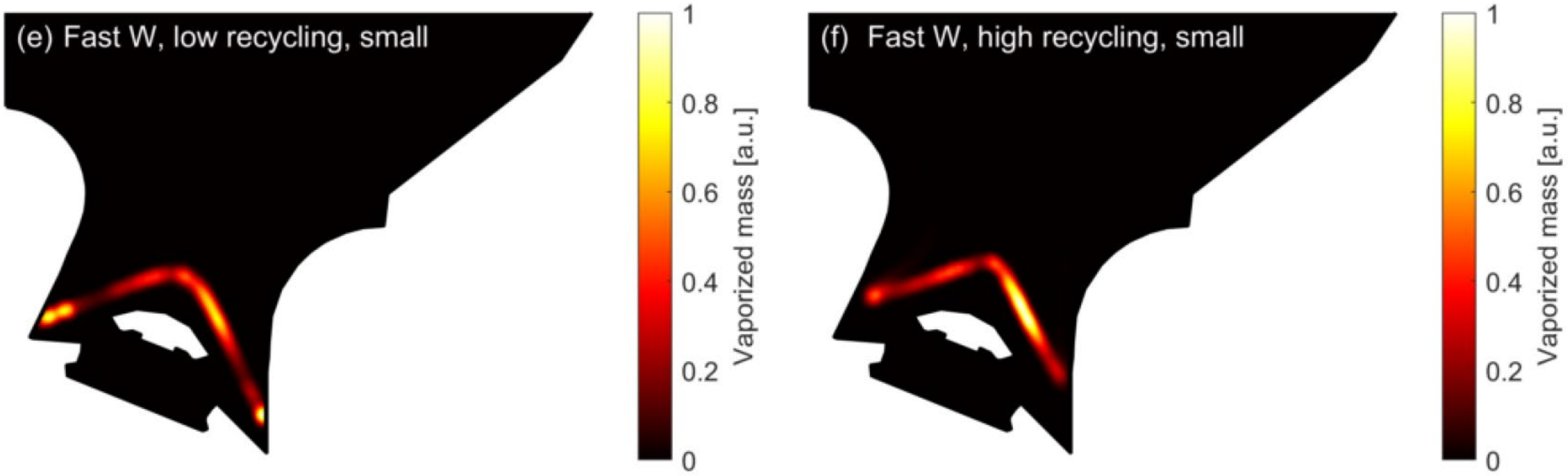
- 3 dust injection points, each attached to a neighborhood

Discharge iteration scheme

- Sample the space of initial parameters
- Run MIGRAINe simulations on the sample to obtain a correspondence between initial and final parameters
- Assign initial statistical weights $w_k^{(0)}$ to each particle k
- Project the final parameters of remobilizable particles back onto the initial sample to get an evolution map $\left\{w_k^{(n)}\right\} \mapsto \left\{w_k^{(n+1)}\right\}$ which advances by one discharge
  - Move particle position to the nearest injection site
  - Distribute final particle mass $M_{\mathrm{i}1} \leq M_{\mathrm{f}} < M_{\mathrm{i}2}$ into initial mass values $M_{\mathrm{i}1,2}$ present in the sample
- Initial weights can be changed at will without any need to re-run MIGRAINe

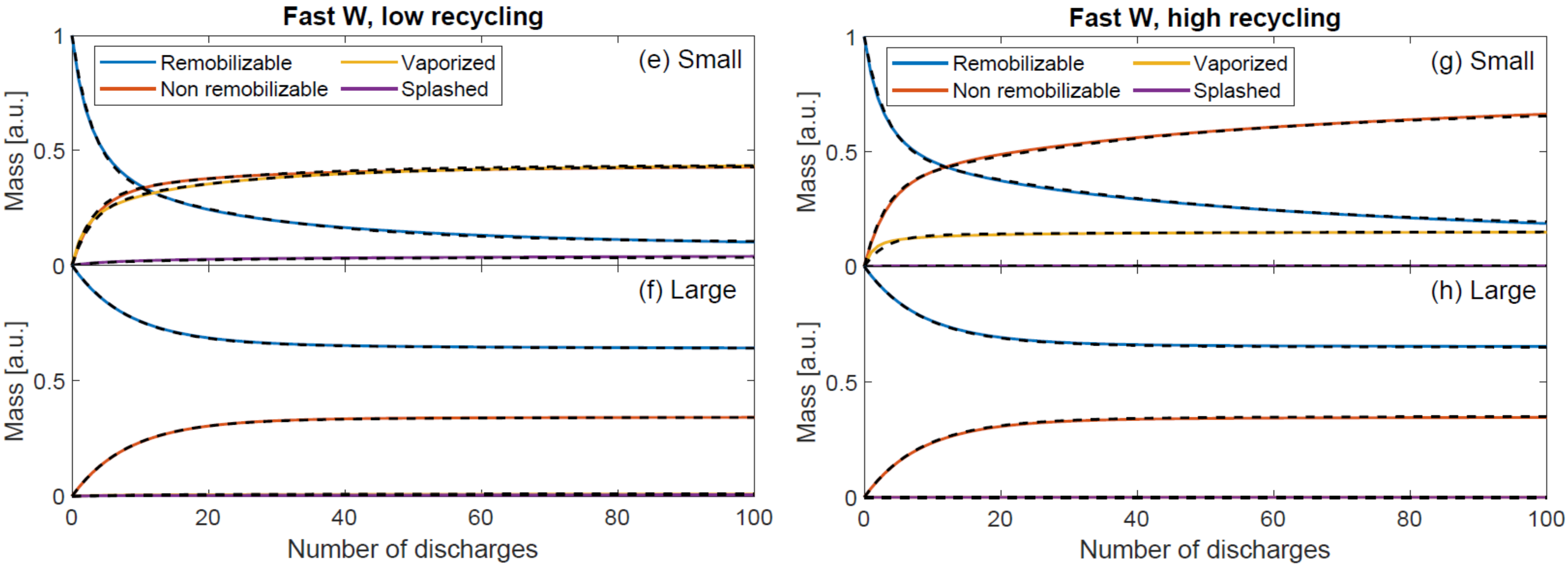
Impurity deposition maps

- Track vaporization mass loss from moving particles to get maps of the corresponding impurity neutral source
- May be used as input in plasma simulation codes to assess the risk of early discharge termination



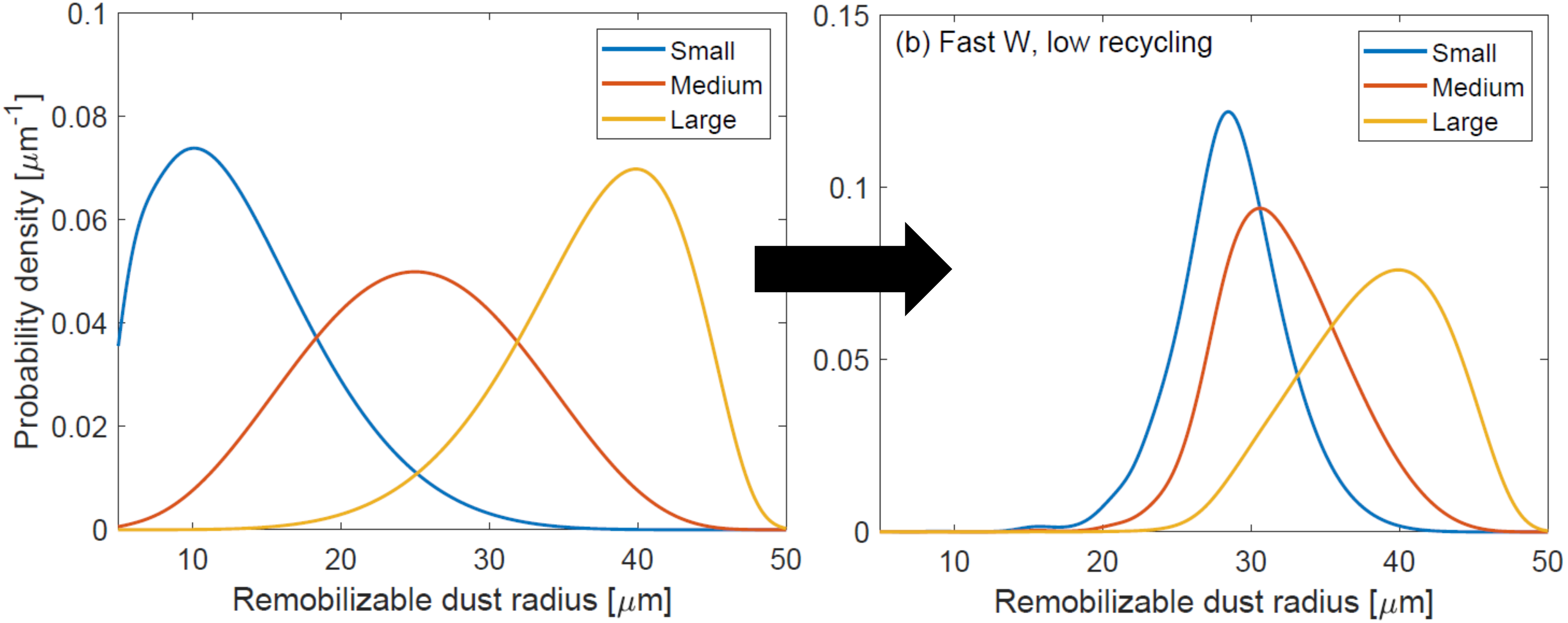
Inventory evolution – in-vessel mass

- “Slow” cases with $v_{\max} = 2\ \mathrm{m}/s$ yield essentially no evolution: particles don’t enter hot/dense plasma regions
- Vaporization is more effective in the low recycling case, expected from thermal heat flux scaling $\propto n_{\mathrm{e}} T_{\mathrm{e}}^{3/2}$
- Steady-state reached within 20 discharges
- Good fits by Markov models assuming 2 sub-populations



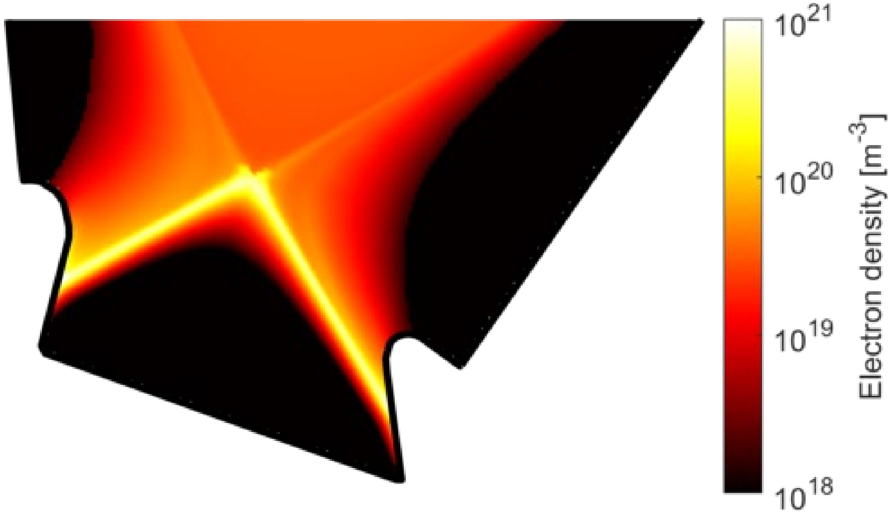
Inventory evolution – distributions

- Possibility to track the evolving particle distributions (size, in-vessel location)
- Shift towards large sizes as time evolves since smaller particles are more likely to vaporize



DEMO plasma profiles

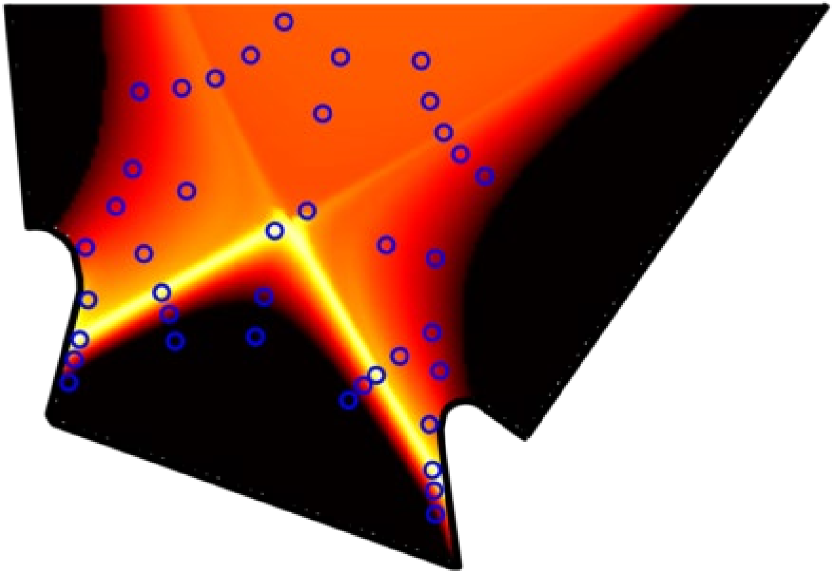
- Similar to ITER high-recycling discharge



- Many impurity species (all charge states for He and Ar)
- Effect of impurities on dust hard to assess a priori, surface neutralization heating can be non negligible (stored ionization energy U_i can reach $100\mathrm{s\,eV}$) – in previous ITER disruption simulations with Ne mitigation, neutralization heating represented up to 15% of the total heat flux

Pre-implementation testing

- Separate implementation of charging and heating assuming uniform plasma, fixed dust size and electron emission yield
- Plasma conditions sampled from DEMO profiles



$$1 \leq R_\mathrm{d}/R_\mathrm{Le} \leq 50$$

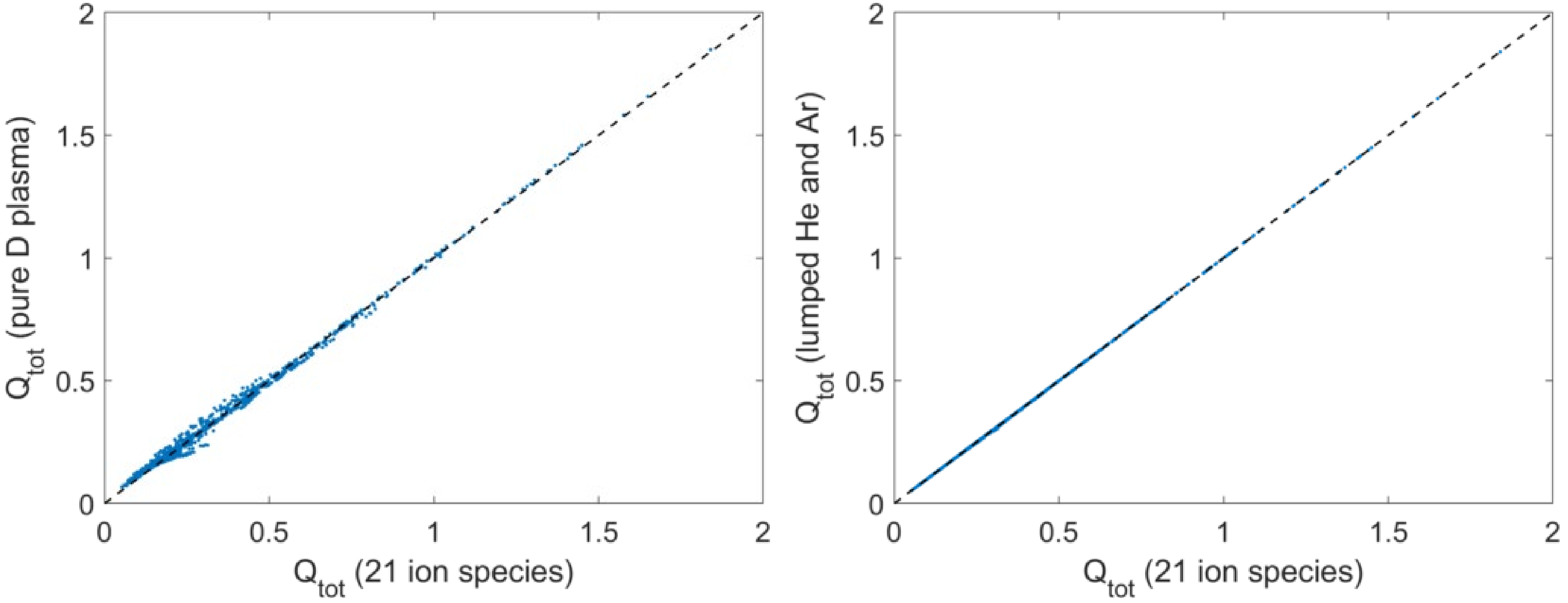
$$0 \leq |I_\mathrm{em}/I_\mathrm{e}| \leq 0.95$$

- Lumping scheme for ion charge states

$$\bar{n}_s = \frac{\left(\sum_i n_i Z_i\right)^2}{\sum_i n_i Z_i^2} \qquad \bar{Z}_s = Z_s^\mathrm{eff} = \frac{\sum_i n_i Z_i^2}{\sum_i n_i Z_i} \qquad \bar{U}_s = \frac{1}{\bar{n}_s}\sum_i n_i U_i$$

Pre-implementation testing

Heat flux errors introduced by ion lumping remain below 1% in almost all cases



Summary and outlook

- W inventory evolution studies carried out for ITER-like start-up plasmas
  - Focus on 12 remobilization scenarios
  - Detailed MIGRAINe output saved so more initial statistical distributions (within the same parameter range) can be explored without need for new simulations
  - Threshold-like dependence on dust mobilization speed
  - Analytical fit formulae can be exploited for future studies

- DEMO profiles tested and ready to be implemented in MIGRAINe
  - Impurity species lumping leads to negligible errors
  - MIGRAINe modification to allow multiple impurity species is in progress