Modelling of macroscopic melt motion and melt splashing & dust/droplet transport, in-vessel survival and accumulation.

S. Ratynskaia, L. Vignitchouk, P. Tolias, E. Thoren (future NN)

Space and Plasma Physics
Royal Institute of Technology (KTH) Stockholm, Sweden

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Deliverables

❖ Year 1

MIGRAINe scoping dust transport simulations with ITER-like ramp-up and steady state plasma profiles are performed.

❖ Year 2

MIGRAINe dust transport simulations are performed using ITER-like profiles and preferable net deposition locations provided by preliminary ERO2.0 runs.

❖ Year 3

MEMOS-U simulations of PFC response under VDEs and loss of confinement are performed, macroscopic surface modifications and melt splashing are assessed.

MIGRAINe dust transport simulations are performed using DEMO steady state profiles and preferable net deposition locations provided by ERO2.0.

❖ Year 4

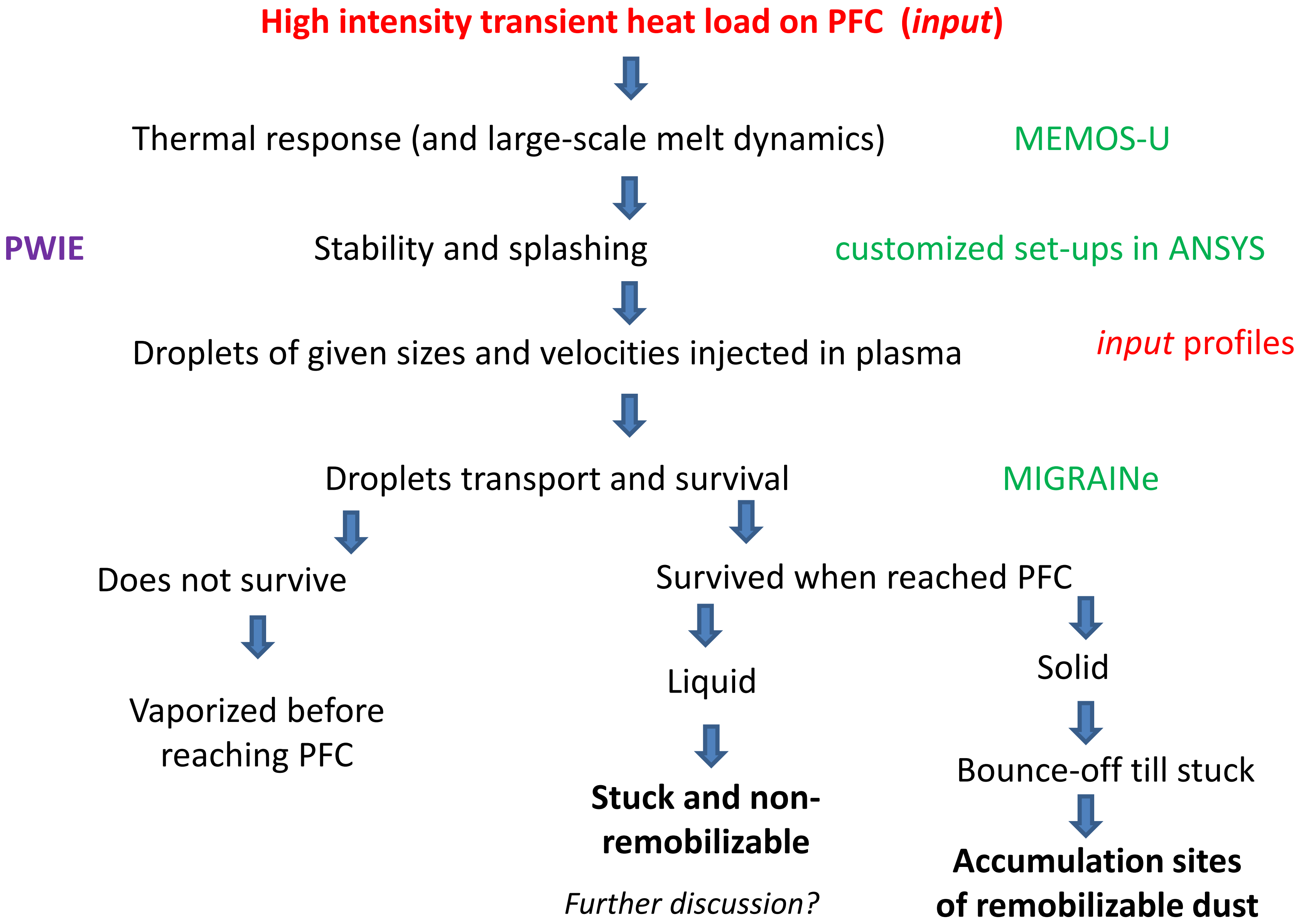
MIGRAINe transport simulations are performed for droplets in DEMO plasma transients.

❖ Year 5

Post-processing of final MIGRAINe simulations for DEMO plasma transients is finalized

D5	**Stability of melt layers during transients. Droplet sizes and speeds in case of splashing.**
D6	A catalog of representative cases for dust (re-)mobilization conditions.
D7	Dust survival rates, inventory evolution and accumulation maps of re-solidified droplets.

Transient scenarios



High intensity transient heat load on PFC (*input*)

Thermal response (and large-scale melt dynamics) MEMOS-U

PWIE Stability and splashing customized set-ups in ANSYS

Droplets of given sizes and velocities injected in plasma *input* profiles

Droplets transport and survival MIGRAINe

Does not survive

Vaporized before reaching PFC

Survived when reached PFC

Liquid

Stuck and non-remobilizable

Further discussion?

Solid

Bounce-off till stuck

Accumulation sites of remobilizable dust

Ramp up/Steady state

Solid dust is lifted-up from **mobilization sites** by contact with the plasma

Accumulation sites

From previous slide: location and sizes are known

Creation sites

Postulated mechanisms (cracking? delamination?) will dictate location and sizes

For given material/sizes speeds to be postulated/scaned based on empirical evidence and contact mechanics scalings (previous work under WP PFC)

Plasma profile input

Dust transport and survival

MIGRAINe

Iteration to produce dust inventory evolution

Dust modelling in MIGRAINe

Generic equations for the time evolution of the dust position, mass, enthalpy/temperature and (floating) electric potential

$$M_\mathrm{d}\frac{\mathrm{d}^2\vec{r}_\mathrm{d}}{\mathrm{d}t^2} = \vec{F}_\mathrm{tot} \qquad \frac{\mathrm{d}M_\mathrm{d}}{\mathrm{d}t} = \Gamma_\mathrm{tot} \qquad \frac{\mathrm{d}H_\mathrm{d}}{\mathrm{d}t} = Q_\mathrm{tot} \qquad I_\mathrm{tot}(\varphi_\mathrm{d}) = 0$$

All physical processes of interest are embedded in the source terms. In particular, the total current and heating power include numerous contributions: electron and ion collection, thermionic and induced electron emission, ion neutralization and backscattering, thermal radiation, vaporization

$$I_\mathrm{tot} = I_\mathrm{e} + \sum_j I_{\mathrm{i},j} + I_\mathrm{EIEE} + I_\mathrm{IIEE} + I_\mathrm{TE}$$

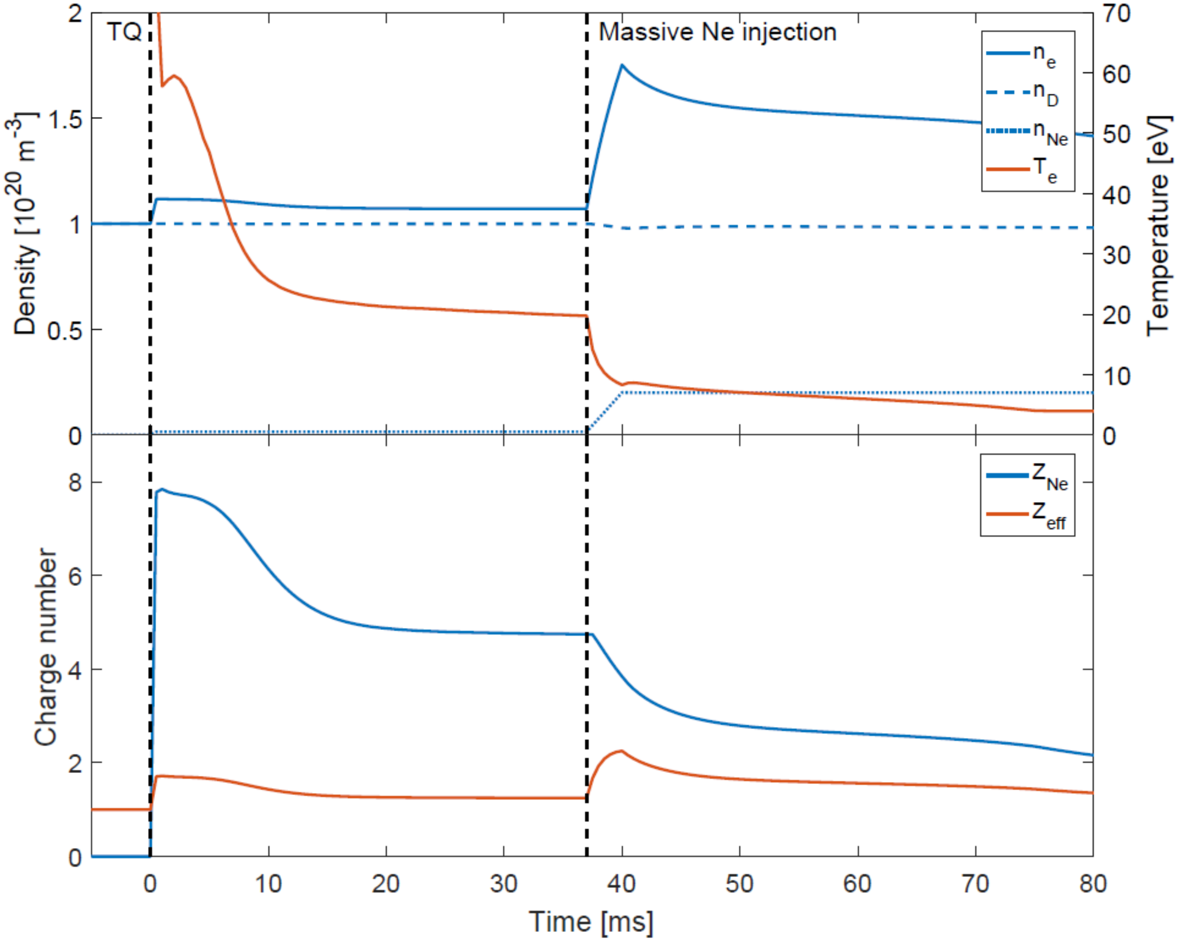
$$Q_\mathrm{tot} = Q_\mathrm{e} + \sum_j \left(Q_{\mathrm{i},j} + Q_{\mathrm{i},j}^\mathrm{bs} + Q_{\mathrm{i},j}^\mathrm{neut}\right) + Q_\mathrm{EIEE} + Q_\mathrm{IIEE} + Q_\mathrm{TE} + Q_\mathrm{rad} + Q_\mathrm{vap}$$

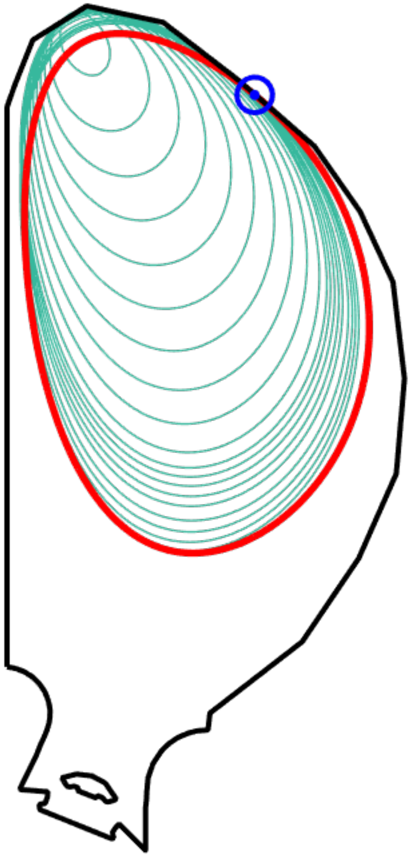
The functional form taken by each of these contributions can vary depending on the length scale ordering between the dust size and the plasma species' Debye lengths, Larmor radii and collisional mean free paths.

Be dust production from transient melt events during ITER disruptions

- External input: disrupting plasma profiles and droplet injection points
- Assumptions: range and distribution of droplet sizes and speeds from theoretical estimates

[Vignitchouk, Ratynskaia, Tolias, Pitts et al, NF **58** (2018) 076008]

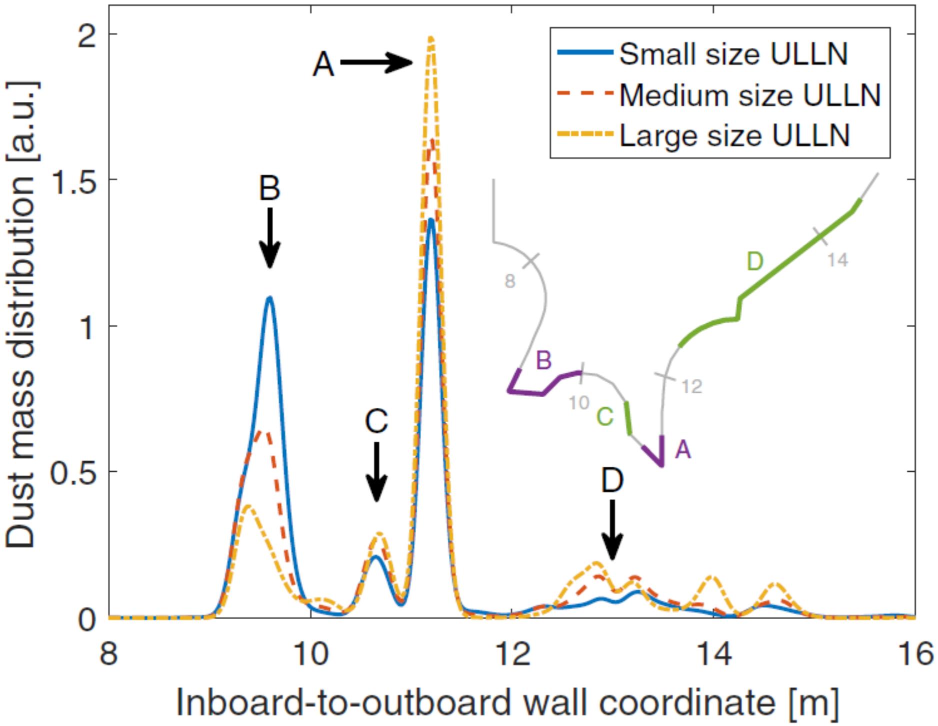


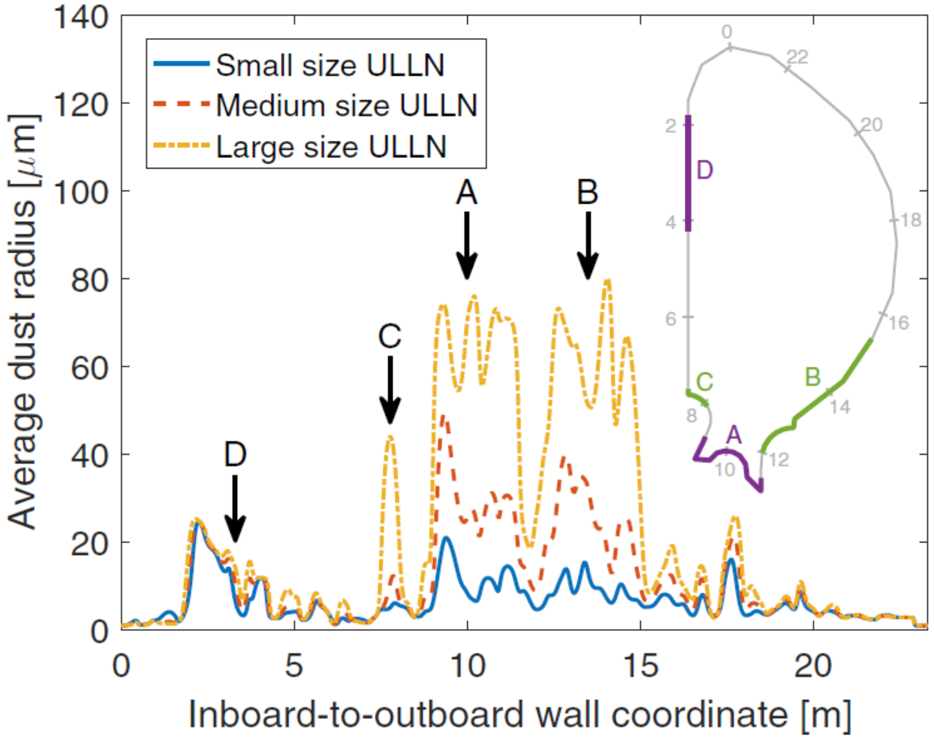


Be dust production from transient melt events during ITER disruptions

Output: droplet-to-dust conversion rates, identification of dust accumulation sites, size distribution of accumulated dust

	MD			VDE		
	Small	Medium	Large	Small	Medium	Large
Modal droplet radius (μm)	30	75	120	30	75	120
Vaporized mass (%)	40.2	26.7	18.3	88.5	67.9	50.1
Liquid mass (%)	56.5	71.3	80.7	10.9	31.0	49.2
Dust mass (%)	3.3	2.0	1.0	0.6	1.1	0.7
3 μm dust fraction (%)	26.1	11.9	0.5	48.6	23.3	3.1
2nd modal dust radius (μm)	17	65	105			85





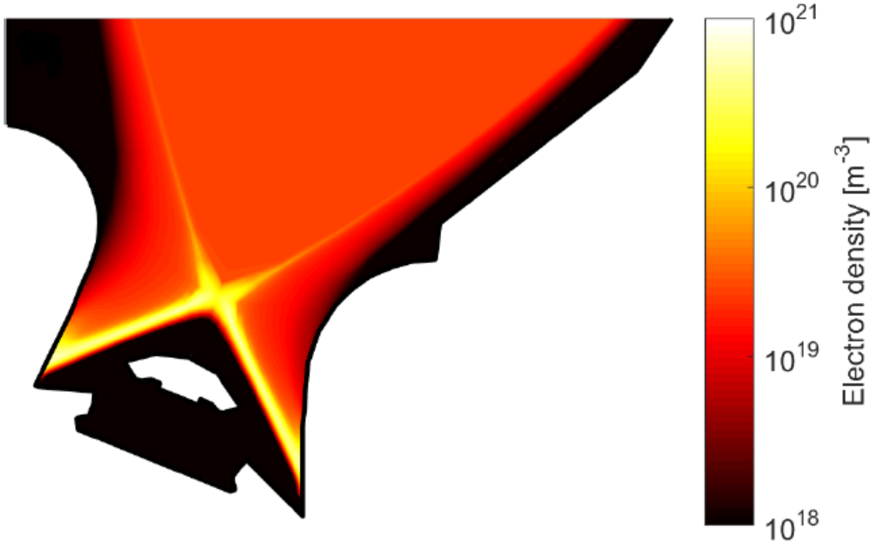
Dust in ramp-up plasmas

Main questions

- How does a given dust inventory evolve during normal discharges?
- Can the impurities released by dust vaporization affect the discharge start-up?

Input and assumptions

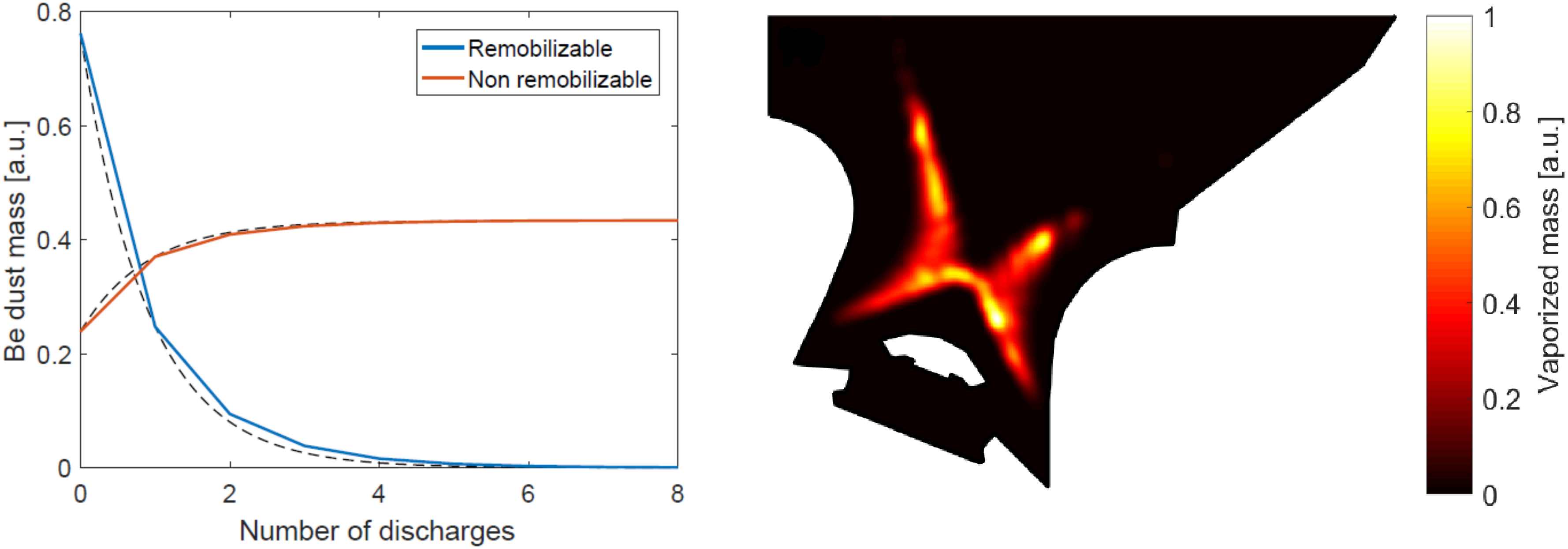
- External input: plasma profiles (here low-power ITER steady-state profiles meant to emulate ramp-up plasmas)
- Assumptions: dust mobilization sites (accumulation sites identified from MIGRAINe disruption simulations and/or regions with strong impurity deposition or PWI), size and speed distributions



Dust in ramp-up plasmas

- Assuming that dust mobilization sites remain consistent over discharges (supported by results on Be mobilization), MIGRAINe dust transport output from a single discharge can be iterated “externally” (without the need to re-run MIGRAINe) to deduce long-term dust inventory evolution
- Tracking the vaporization of moving particles in MIGRAINe can also produce statistical 2D maps of the atomic impurity source during ramp-up, which can then serve as input for, e.g., impurity transport codes

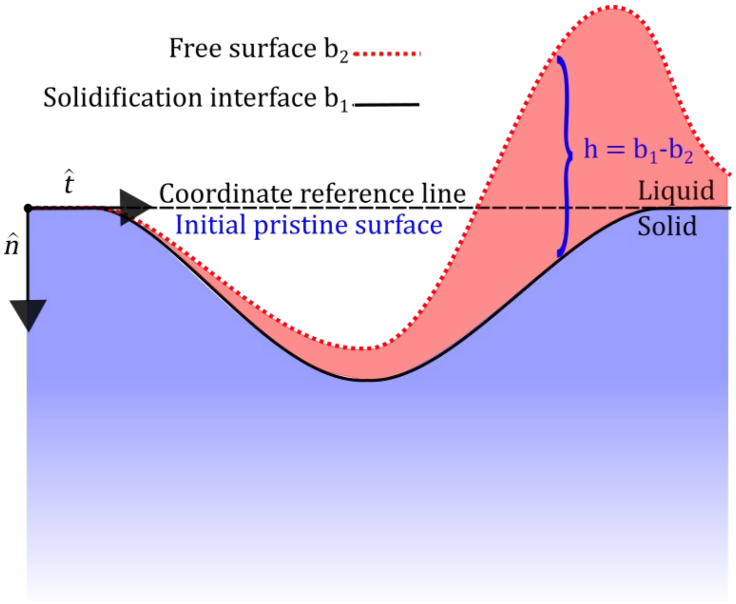
Examples of preliminary results for Be in ITER



PFC melting: Multiphase flow with envolving interfaces

Free-surface MHD flows with phase transitions

- fluid dynamics
- heat diffusion
- melting and re-solidification
- current distribution into the PFC bulk



The *multi-scale* nature of the phenomena

- macroscopic motion along the PFC -- up to fraction of a meter
- the melt depth -- 100’s of μm
- nonlinear free -surface instabilities on much smaller scales

Brute-force computations of the fully self-consistent model on the relevant scales are computationally prohibitive

‘ Zoom-in ’ on ~mm to ~cm domains to study stability and splashing

Seek simplifications if large-scale motion is of interest

MEMOS-U model

$$\frac{\partial h}{\partial t} + \nabla_{\mathrm{t}} \cdot (h\boldsymbol{U}) = \frac{\partial b_1}{\partial t} - \dot{x}_{\mathrm{vap}}\,,$$

$$\rho_{\mathrm{m}}\left[\frac{\partial \boldsymbol{U}}{\partial t} + (\boldsymbol{U}\cdot\nabla_{\mathrm{t}})\,\boldsymbol{U}\right] = \langle(\boldsymbol{J}\times\boldsymbol{B})_{\mathrm{t}}\rangle - \nabla_{\mathrm{t}} P - 3\frac{\mu}{h^2}\boldsymbol{U} + \mu\nabla_{\mathrm{t}}^2\boldsymbol{U} + \frac{3}{2h}\left(\frac{\partial\gamma}{\partial T}\nabla_{\mathrm{t}} T_{\mathrm{s}} + \boldsymbol{f}_{\mathrm{d}}\right)\,,$$

$$\rho_{\mathrm{m}} c_{\mathrm{p}}\left[\frac{\partial T}{\partial t} + \boldsymbol{U}\cdot\nabla_{\mathrm{t}} T\right] = \nabla\cdot(k\nabla T) + \rho_{\mathrm{e}}|\boldsymbol{J}|^2 - T\frac{\partial S}{\partial T}\boldsymbol{J}\cdot\nabla T\,,$$

$$\nabla\cdot(\sigma_{\mathrm{e}}\nabla\psi) = 0 \quad \text{with } \boldsymbol{J} = -\sigma_{\mathrm{e}}\nabla\psi\,,$$

(U) depth-averaged fluid velocity,
(h, P) melt column height, ambient pressure
$(\boldsymbol{J}, \boldsymbol{B})$ current density, magnetic flux density,
$(b_1, \dot{x}_{vap})$ solidification interface, rate of change of interface position due to vaporization,
(T, T_s) bulk and surface temperature
(ρ_m, c_p) mass density, heat capacity
(k, S) thermal conductivity, thermoelectric power,
(μ, γ) dynamic viscosity, surface tension
(σ_e, μ_0) electrical conductivity, vacuum permeability

Liquid-solid phase transition: heat integration method
(the enthalpy budget is kept by an extra set of algorithms)

Boundary conditions:

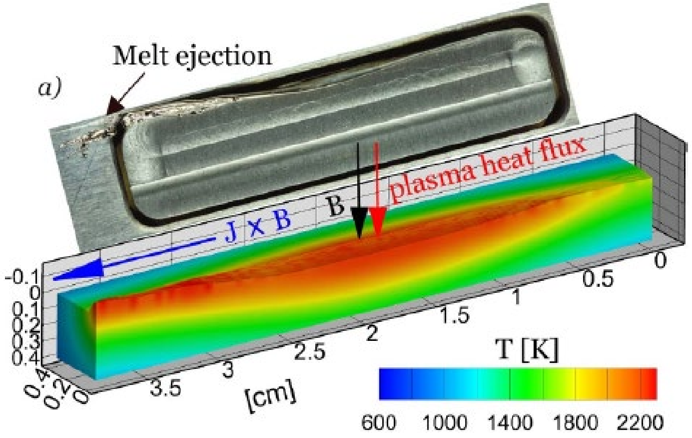
$(k\nabla T - ST\boldsymbol{J})\cdot\hat{\boldsymbol{n}} = q_{\mathrm{inc}} - q_{\mathrm{cool}}\,,$ q_{inc} is the incident heat flux and and q_{cool} is the surface cooling fluxes

$\sigma_{\mathrm{e}}\frac{\partial\psi}{\partial n} = J_{\mathrm{surf}}\,,$ J_{surf} is the current density on the surface

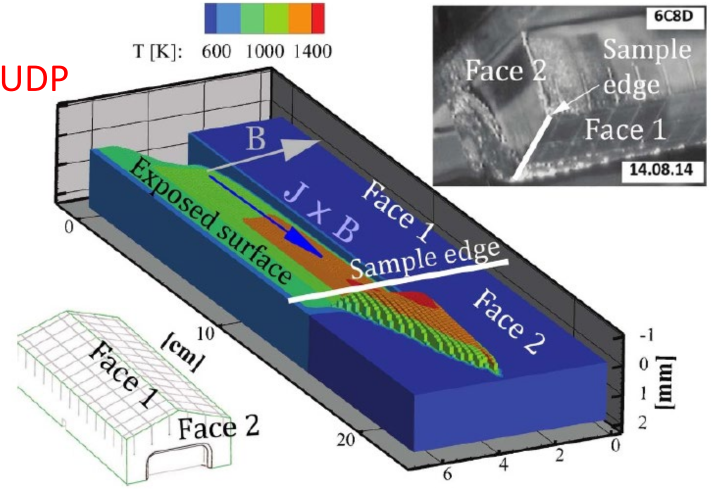
External input: $q_{inc}, J_{surf}, \boldsymbol{f}_d, \nabla \mathrm{P}_{plasma}$ + geometry and B field

Validation against JET and AUG experiments

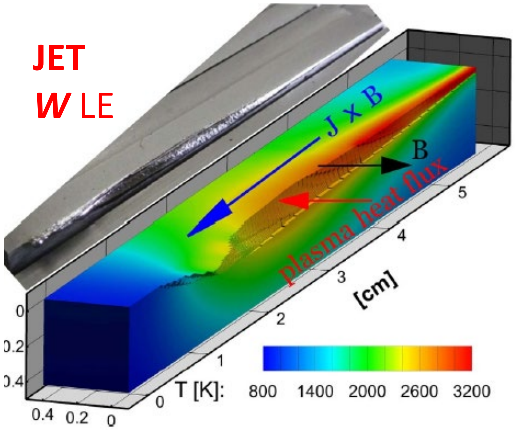
AUG
***W* LE**



JET
***Be* UDP**



JET
***W* LE**



- A unified description of ELM-induced W divertor melting & disruption-induced Be first wall melting
- A quantitative agreement with observations with the only heat flux variations allowed strictly within experimental uncertainties

Ratynskaia, Thoren, Tolias *et al* Nucl. Fusion **60** (2020) 104001

Current work with MEMOS-U

- Inclusion of active cooling
- Modelling of the sustained melting experiments in WEST with ITER-like W water-cooled PFCs
- Modelling of the Ir & Nb ELM-induced melting experiments in AUG
- Initial conditions for models simulating melt splashing

WP PWIE

- Importance of TE: Sensitivity to W_f and limiting escaped TE current scaling for reactor conditions

MOVING THE MODEL TO AMReX

- Adaptive meshing (AMReX open source framework for adaptive mesh refinement)
  Zhang et al., (2019) Journal of Open Source Software, 4(37), 1370