EUROfusion

The successor to the MEMOS-U code:
physics model, capabilities and first DEMO transient runs

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Outline

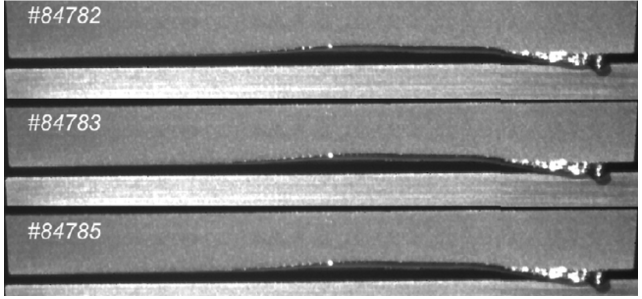
- MEMOS-U physics model and updates for reactor-relevant conditions
- MEMENTO code
- DEMO transients and melt-dust links in TSVV-7 tasks

M2.6	**Representative values of surface heat fluxes and halo current densities during DEMO VDEs and surface heat fluxes during DEMO loss of confinement events are obtained (external input). The respective data are processed for MEMOS-U simulations.**

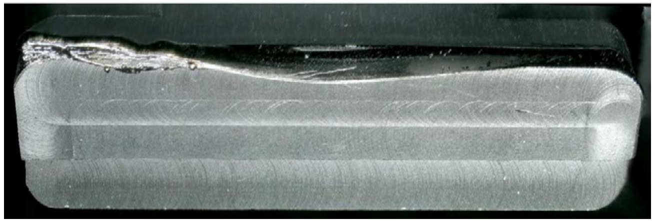
M3.3	**MEMOS-U simulations of PFC response under VDEs and loss of confinement are performed, macroscopic surface modifications and melt splashing are assessed.**

Melting of metallic PFC

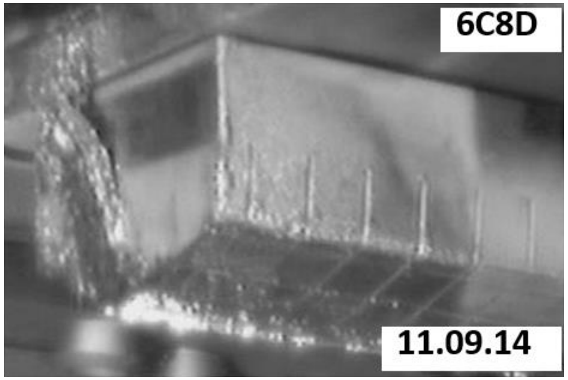
Coenen *et al* 2015 *Nucl. Fusion* **55**



K. Krieger *et al* 2018 *Nucl. Fusion* **58** .



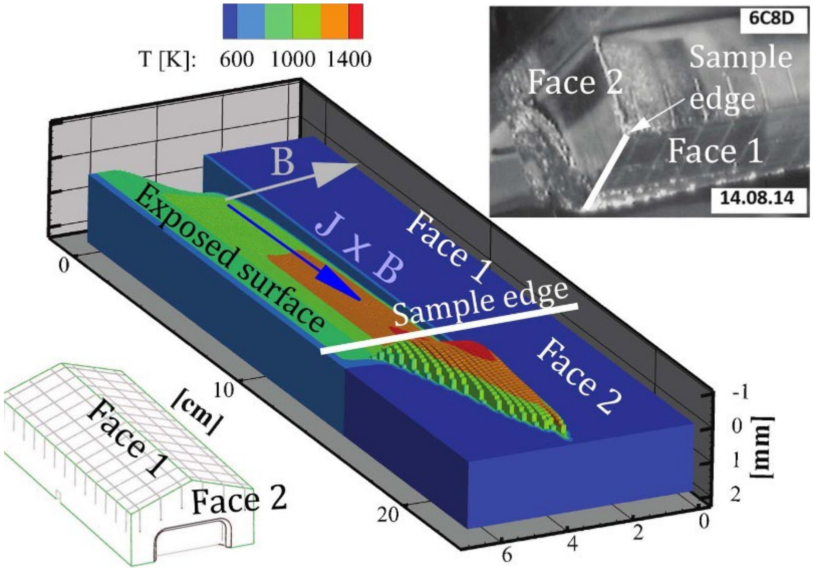
I. Jepu et al 2019 Nucl. Fusion **59**

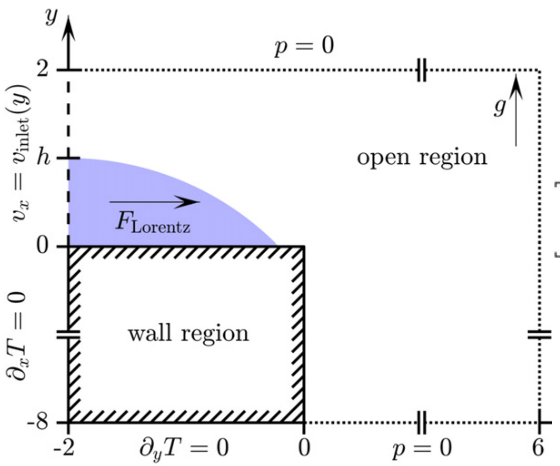


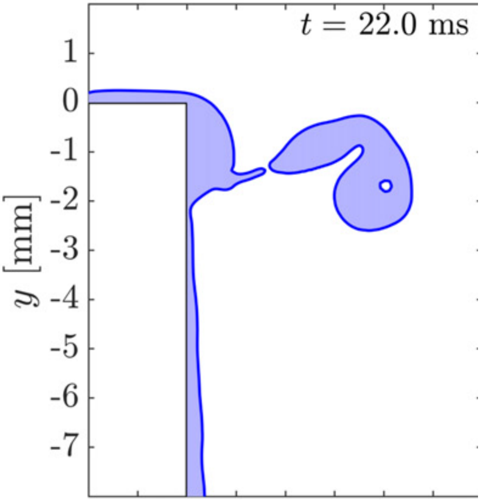
- ○ Melt extend (wetted area) → from ∽ cm to ∽ m
- ○ Melt thickness → from ∽ µm to ∽ mm
- ○ Splashing → need to resolve ∽ µm scale

- ➢ Highly deforming free surface (the metal-plasma interface)
- ➢ Plasma is a ‘ghost’ fluid
- ➢ Plasma effects imposed though free-surface boundary conditions
- ➢ The metal-plasma interface isn’t a computational boundary, volumetric sources must be used instead of surface boundary conditions

Our modelling approach







MEMOS-U (MEMENTO)

Large scale thermal response & melt dynamics

Navier-Stokes equations in the Shallow Water Approximation

Temperature profile
Melt depth
Melt speed

Specialized set-ups in ANSYS

‘Zoom-in’ in a region of interest
Imposing large-scale picture though boundary and initial conditions

Full Navier-Stokes equations

MEMENTO – successor of MEMOS-U

The **MEMENTO** code

MEtalic **M**elt **E**volution in **N**ext-step **TO**kamaks

It is a new numerical implementation of the physics model MEMOS-U (validated in multiple EUROfusion melt experiments)

Ratynskaia, Paschalidis, Tolias, *Experiments and modelling on ASDEX Upgrade and WEST in support of tool development for tokamak reactor armour melting assessments,* Nucl Mat Energy, 2022 to appear
Ratynskaia, Thoren, Tolias *et al,* Phys Scripta **96** (2021)
Thoren, Ratynskaia, Tolias *et al,* PPCF **63** (2021) 035021
Ratynskaia, Thoren, Tolias *et al,* Nucl Fusion **60** (2020)

The physics model is also being updated for reactor-relevant regimes

MEMOS-U model: updates for reactor relevant conditions

$$\frac{\partial h}{\partial t} + \nabla_{\mathrm{t}} \cdot (h\boldsymbol{U}) = \frac{\partial b_1}{\partial t} - \dot{x}_{\mathrm{vap}}\,, \tag{10}$$

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

+ surface tension $$+\,\mu\nabla_{\mathrm{t}}^2\boldsymbol{U} + \frac{3}{2h}\left(\frac{\partial\gamma}{\partial T}\nabla_{\mathrm{t}}T_{\mathrm{s}} + \boldsymbol{f}_{\mathrm{d}}\right), \tag{11}$$

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

+ volum. source (for RE) $$-\,T\frac{\partial S}{\partial T}\boldsymbol{J}\cdot\nabla T\,, \tag{12}$$

$$\nabla\cdot(\sigma_{\mathrm{e}}\nabla\psi) = 0 \quad \text{with } \boldsymbol{J} = -\sigma_{\mathrm{e}}\nabla\psi\,, \tag{13}$$

+ $\boldsymbol{v}\times\boldsymbol{B}$ term

(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) electrical conductivity

Boundary conditions:

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

Updated thermionic emission

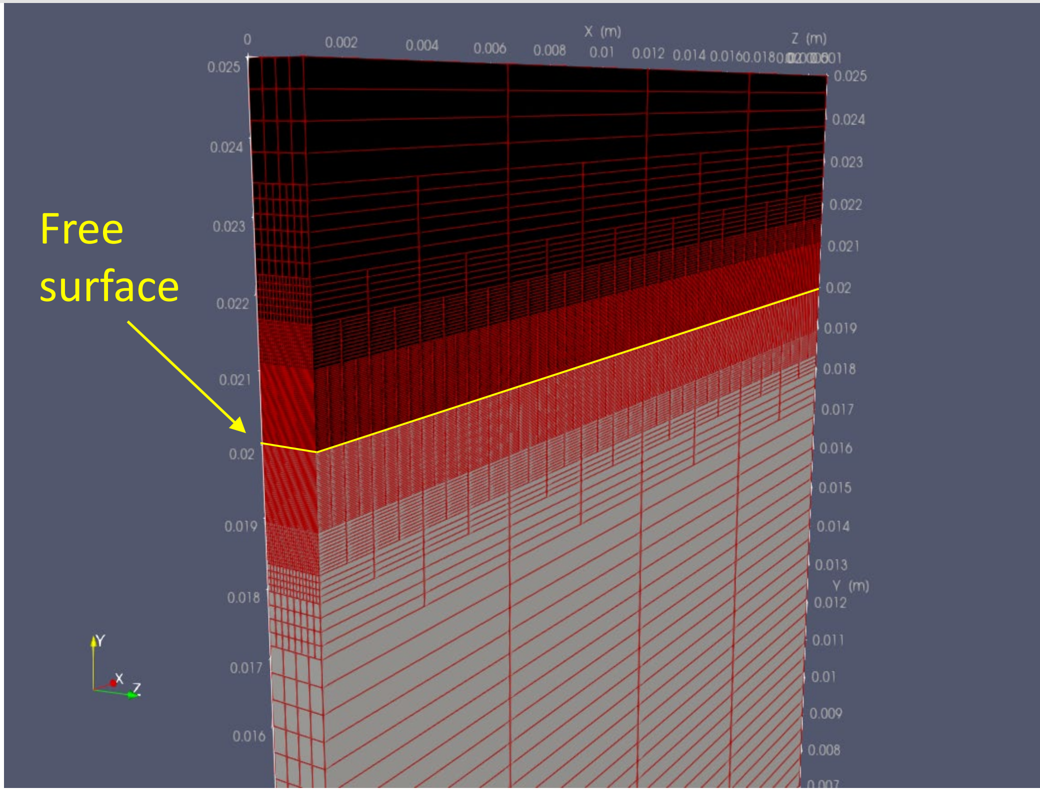
External input: $q_{inc}, J_{surf}, \boldsymbol{f}_d, \nabla \mathrm{P}_{plasma}$ + geometry and B field

MEMENTO mesh in AMReX open-source framework

The adaptive mesh refinement package AMReX is used in order to construct a non-uniform grid to:

1. Perform highly resolved calculations on the free surface
2. Save computational time by adopting a coarse grid for all the points far from the free surface
3. Subcycle in time to advance the lower levels with a larger time-step

MEMENTo utilizes AMReX's built-in parallelization capabilities



- Already implemented:
  Parallelization with OpenMP that allows to execute runs in shared memory devices

- Possibly with help of 2023 ACH help:
  Extension of parallelization capabilities to be able to utilize distributed memory devices by using the MPI standard.

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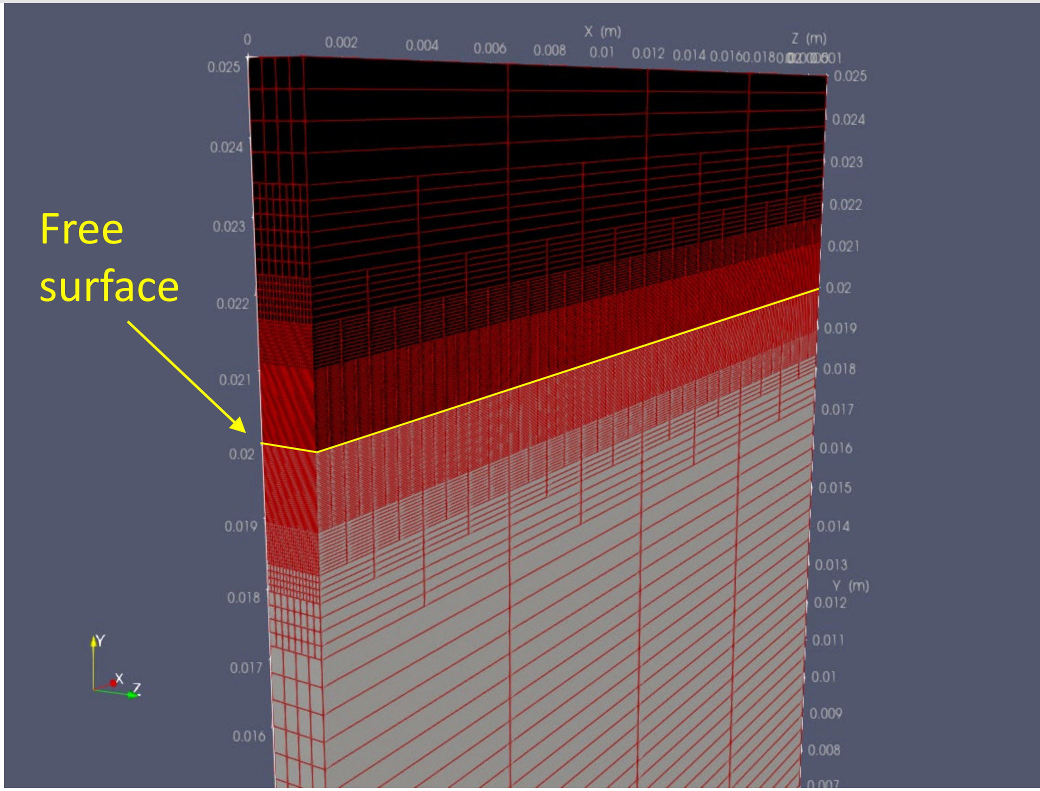
Free surface

- ‘physics-driven’ input file (to define surface processes such as e.g. thermionic emission)
- use by non-specialists
- flexibility for various scenarios including
  - ✓ complex PFC geometries
  - ✓ complex wetting geometries
  - ✓ active cooling

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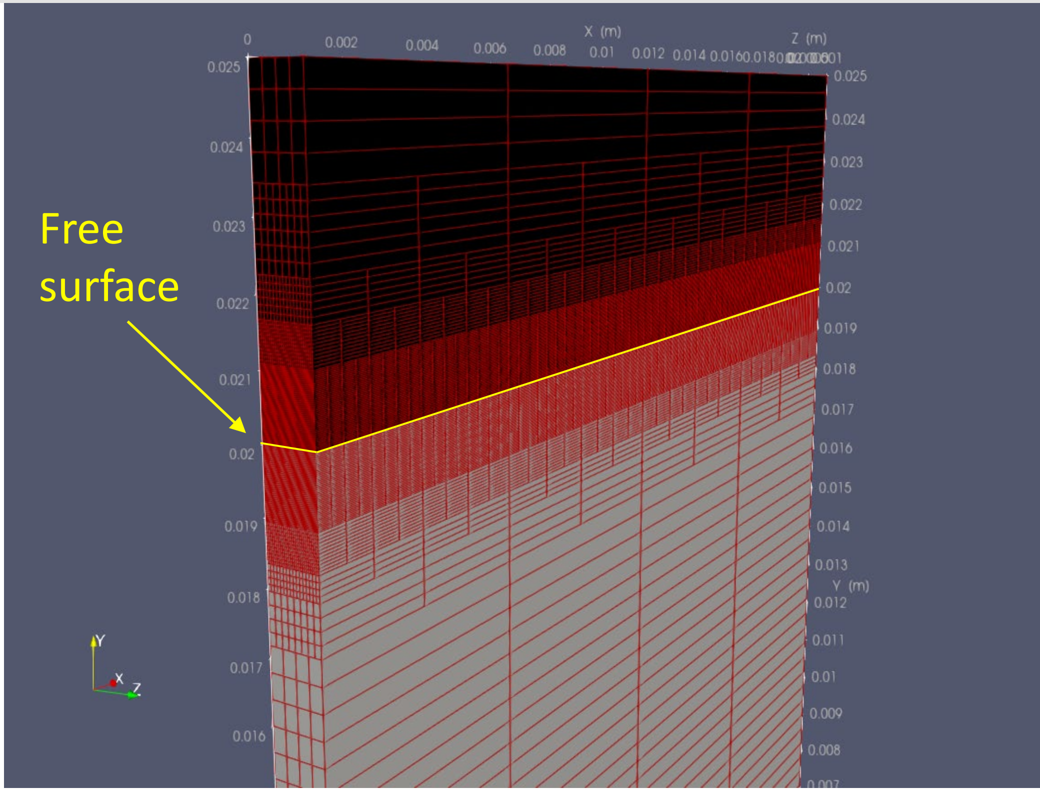


- ➢ There is a functioning MEMENTO version, adequate to carry out current tasks
- ➢ In parallel, there is a development work to enhance code’s flexibility, optimize performance and aim for new physics regimes which might also need updated work flow (e.g. melting under RE – also includes MC input, e.g. from GEANT4)

Model validation vs EUROfusion melt experiments

Exposure geometries: (AUG, JET, WEST)

- Flat
- Leading edge
- Sloped
- Complex with step/gap/bridge

Cooling

- Passive (JET, AUG)
- Active (WEST)

Type of heat load:

- ELMs (JET, AUG)
- CQ (JET)
- steady-state (WEST)

Materials:

- Be (JET)
- W (JET, AUG, WEST)
- Ir and Nb (AUG)

Electrical connection

- Grounded (JET, AUG, WEST)
- Floating (AUG)

New experimental constrains:

- simultaneous exposure of two samples

(different geometry or different materials)

- detection of onset of melting (very high resolution IR)
- backside TC
- timing of material ejection

TSVV 7 task ’melt-dust’ links

DEMO transient heat flux → Melt production MEMENTO → Splashing ANSYS set-ups + tested DR → Solid dust MIGRAINe

IF splashing: dust dynamics code MIGRAINe runs (droplet to solid dust conversation and dust inventory evolution predictions)

MIGRAINe needs as input: results of ANSYS set-ups (droplet size & speeds) and transient plasma profiles

More pronounced surface modifications and/or splashing require driving current (JxB is typically dominant force)

1. Thermionic emission – always present at elevated T_{surf}, but killed by $sin^2\alpha$ in the limiting regime → PCFs facing B at larger/normal angles?
2. Halo current – CQ phase of disruption → are heat loads sufficient to produce melt ? Answer: NO, tbc
   is there a PFC **edge** melt can reach during its life time ?
3. Eddy currents – TQ phase of disruption →
   melt characteristics from MEMENTO known + estimates of eddy currents → ANSYS set-up (2023-2024)

Inputs					Outputs: max HF (MW/m²) *(Italic)*: with radiation, **Bold: GW/m²**				
Scenario	Case	P_{SOL} (MW) +(*P_{RAD}*)	λ_q (mm)	Deposition time	OML	UL	OLL	IML	FW
SOF	Diverted	69 +*(300 core + 130 SOL)*	50	Steady state	0.53 *(0.65)*	0.82 *(1.10)*	0.09 *(0.33)*	0 *(0.19)*	0.40 *(0.59)*
EOF	Diverted	69 +*(300 core + 130 SOL)*	50	Steady state	0.54 *(0.74)*	1.25 *(1.42)*	0.1 *(0.36)*	0.9 *(1.11)*	0.48 *(0.67)*
Min disr	Diverted	69	50	15-50ms	<0.01	0.13	0.01	3.06	0.69
ELM	Diverted	69	50	15-50ms	1.40	0.56	0	0	1.48
Ramp-Up	Limited	3.5	6	17.5-35s	2.37	0	0	0	0.29
Ramp-Down	Limited	5	6	25-50s	<0.01	<0.01	<0.01	0.02	0.01
		5	50	25-50s	<0.01	<0.01	<0.01	1.39	0.60
U-VDE	First touch	69	1	20-35ms	<0.01	114(2)	<0.01	0	0
		69	5	20-35ms	<0.01	15.6	<0.01	0	0.02
	TQ	$325 \cdot 10^3$	7	1-4ms	<0.01	**63**(3)	0	<0.01	138(8)
	Current Quench	10	10	74-200ms	<0.01	2.52	0	<0.01	0.01
		10	30	74-200ms	<0.01	1.53	0	<0.01	0.11
D-VDE	First touch	10 (*69)	10 (*1)	15-35ms	<0.01 (*0.01)	0 (*0)	<0.01 (*24.8)	<0.01 (*<0.01)	<0.01 (*<0.01)
		10 (*69)	30 (*5)	15-35ms	<0.01 (*0.01)	0 (*0)	<0.01 (*7.83)	<0.01 (*<0.01)	0.08 (*0.01)
	TQ	$325 \cdot 10^3$	7	1-4ms	0.77 (*182)(1)	0 (*0)	**4.4** (***306**(4))	0.84 (*11.3)	8.11 (*292(9))
	Current quench	10	10	74-200ms	<0.01	<0.01	<0.01	<0.01	<0.01
		10	30	74-200ms	<0.01	<0.01	<0.01	<0.01	<0.01
H-L transition	Limited (inboard)	30	2	1-5s	<0.01	<0.01	<0.01	64(5)	1.06
		30	4	1-5s	<0.01	<0.01	<0.01	44.5(6)	5.48
Major Disruption (MD)	TQ	$325 \cdot 10^3$	7	1-4ms	0.61	1.46	0.84	**1.44**(7)	333(10)
	CQ	10	10	74-200ms	<0.01	<0.01	<0.01	0.01	<0.01
		10	30	74-200ms	<0.01	<0.01	<0.01	0.21	0.05
Mitig.disr.	TQ	*$P_{RAD.}$: 2.2 GW*		1ms	**2**(11)	**1.8**(11)	**1.8**	**1.5**	**2**(11)

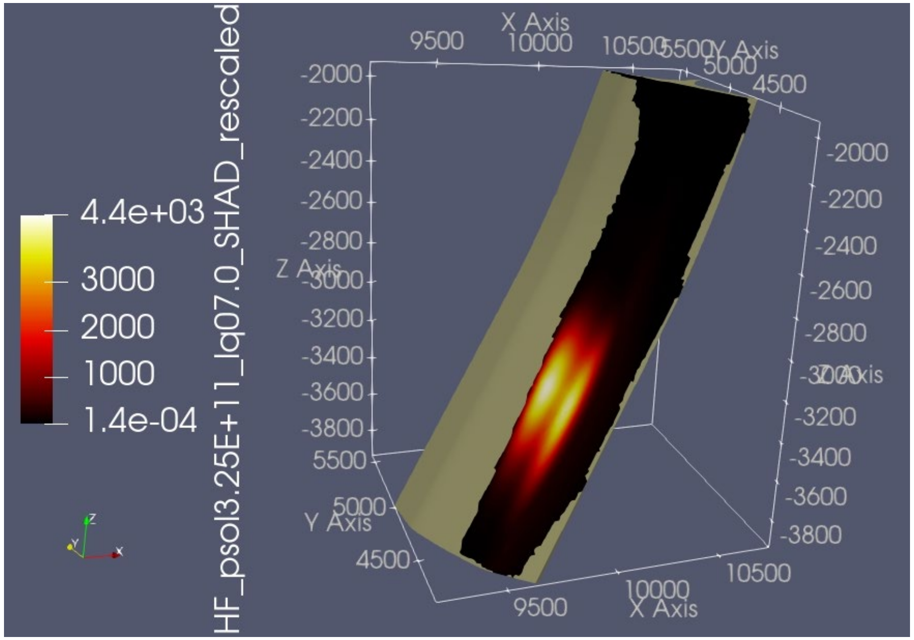
F. Maviglia et al.
Fusion Engineering and Design
178 (2022) 113125

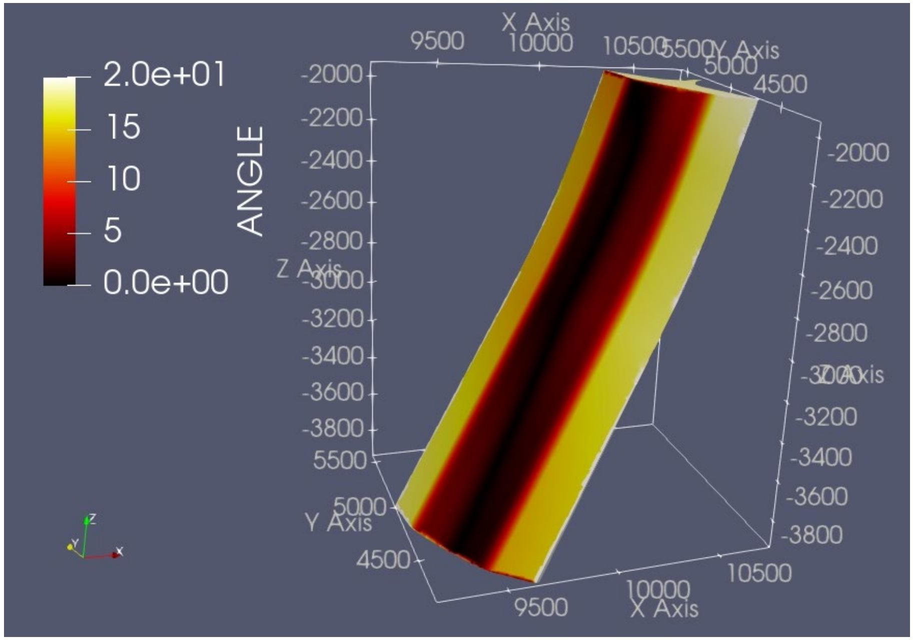
Integrated design strategy for EU-DEMO first wall protection from plasma transients

DEMO Lower limiter melting

Melting under D-VDE TQ

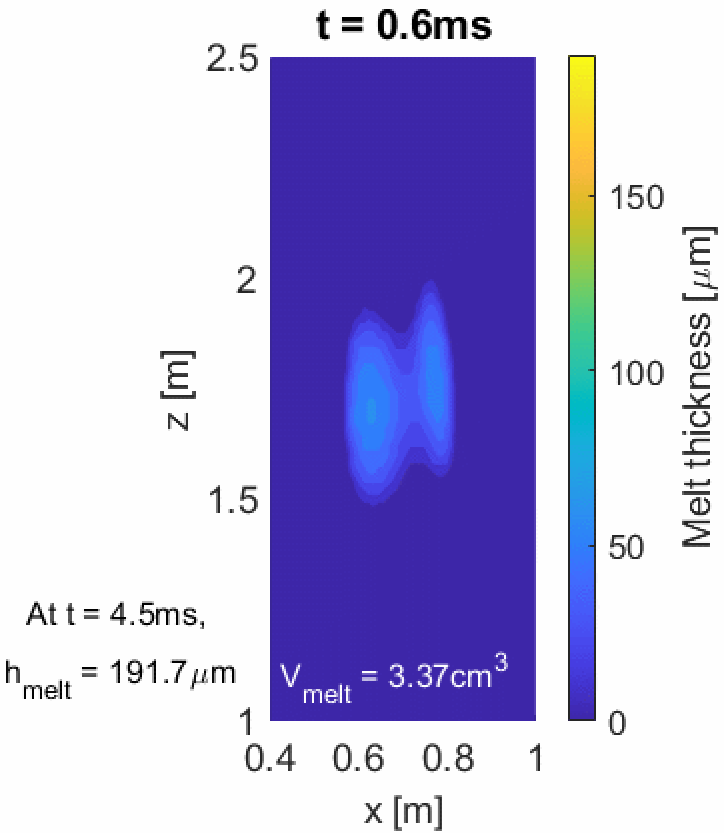
- Surface normal heat $q \sim 4\ \mathrm{GW/m^2}$for 4 ms
- B inclination angle 2.5-5°
- Plasma density
  ’low’ $n_e = 2 \times 10^{18} \mathrm{m}^{-3}$
  ’high’ $n_e = 2 \times 10^{19} \mathrm{m}^{-3}$





MEMOS-U results: Spatial maps in time

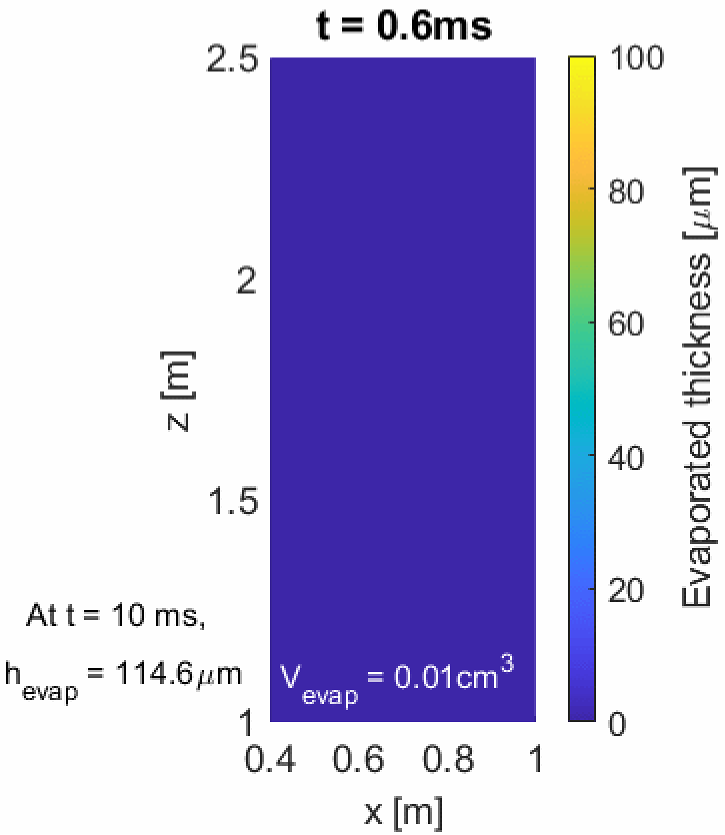
Melt thickness



At t = 4.5ms,

h_{melt} = 191.7μm

Evaporated thickness



At t = 10 ms,

h_{evap} = 114.6μm

DEMO Upper limiter melting

Melting under U-VDE TQ

- Surface normal heat $q \sim 60\ \mathrm{GW/m^2}$ for 4 ms (vapor shielding – drastic effect on evaporation losses, moderate effect on predicted melt depth)
- B inclination angle $2.5\text{-}20^{\circ}$

- Current uderstanding of the scenario (awating answer by Francesco and Sven)

1). We load TQ HF fluxes for the duration of 4 ms.
2). After TQ HF is terminated, the melt will live some ms (contribution of CQ HF is negligible)
3). Under *assumption that wetted and halo areas overlap-* we will start driving the pool from 4 ms and on with JxB, where J assumes a given halo current density value
4). Run simulation till the pool totally resolidifies (well before the end of CQ lasting ~100 ms)

Outcome: how effective is displacement during CQ? Is there chance to reach a PFC edge?

In 2023-2024: for TQ phase and with given eddy current – check stability with ANSYS simulations