Modelling of runaway electron - induced PFC damage

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Outline

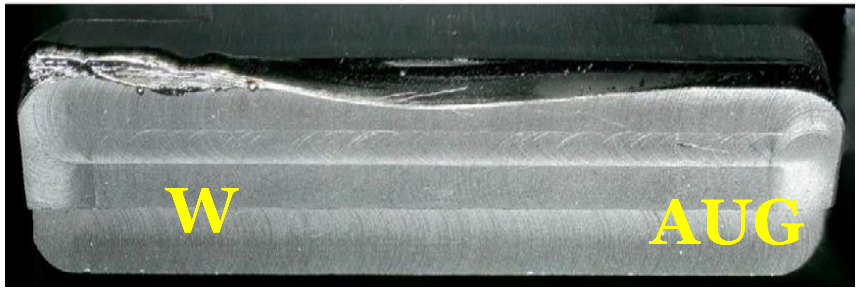
- ➢ Part I: Modelling of PFC damage due to <u>surface loading</u>
  - o Methodology and models
  - o Validation against controlled experiments

- ➢ Part II: Modelling of PFC damage due to <u>runaway electrons</u>
  - o Benchmarking activities
  - o Predictive modelling for ITER scenarios

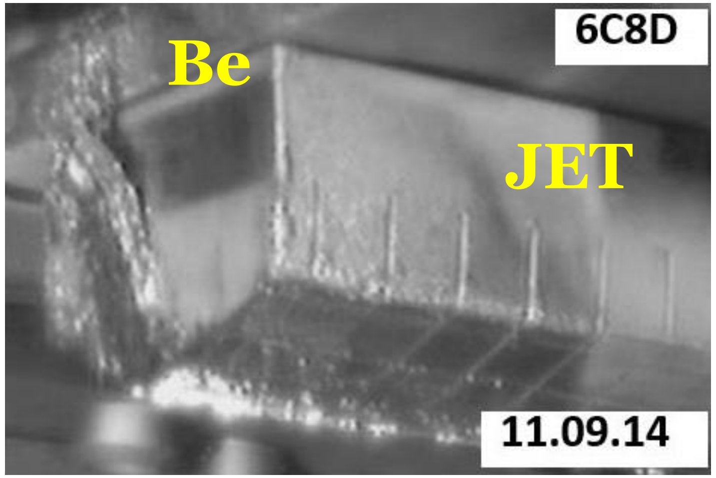
PFC damage: surface vs volumetric loading

Surface heat loads
ELMs, VDE, disruptions

Plasma particles with energies < few keV
→ Depth range ~ 10('s) nm (W)



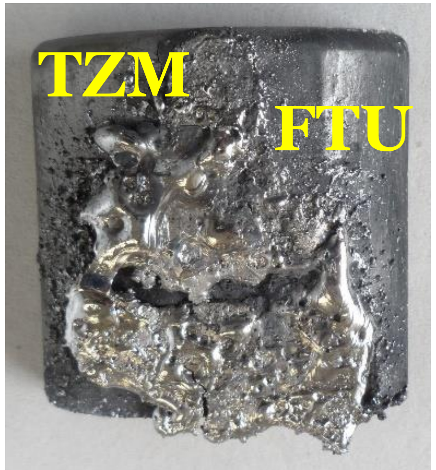
K. Krieger *et al* 2018 *NF* **58**

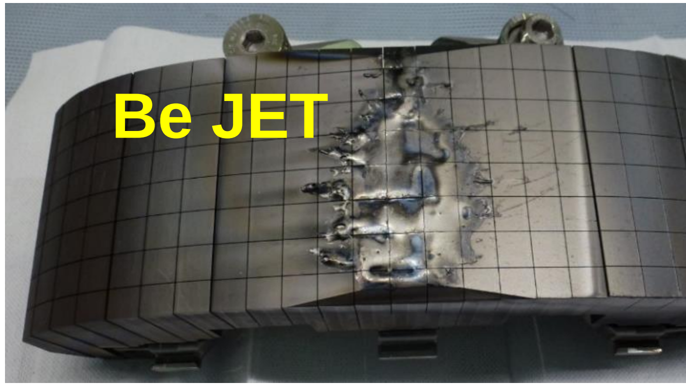


I. Jepu *et al* 2019 *NF* **59**

Volumetric heat loads
Disruptions

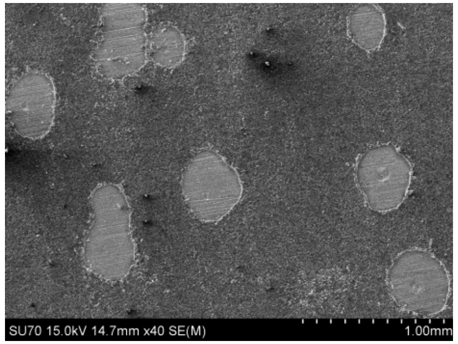
Runaway electrons with energies 1-50 MeV
→ Depth range 0.4-8mm (W)





G. F. Matthews et al., Phys. Scr. **T167** (2016)

M. De Angeli *et al 2023* NF **63**

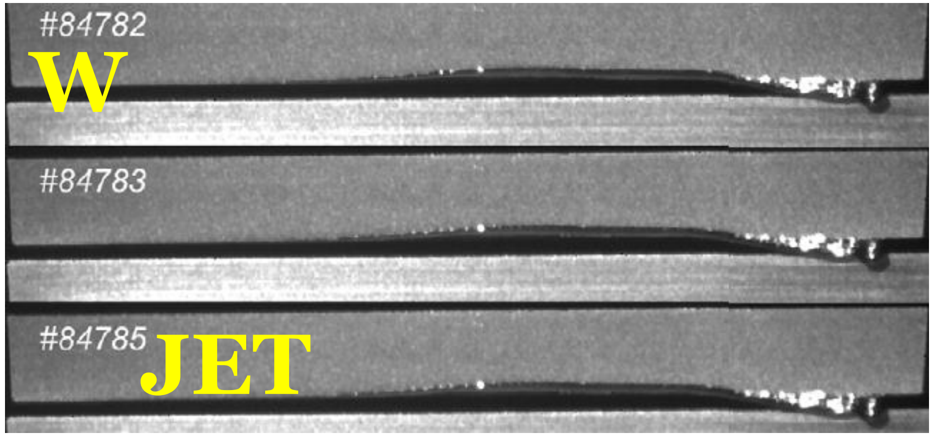


PFC damage under surface heat loads

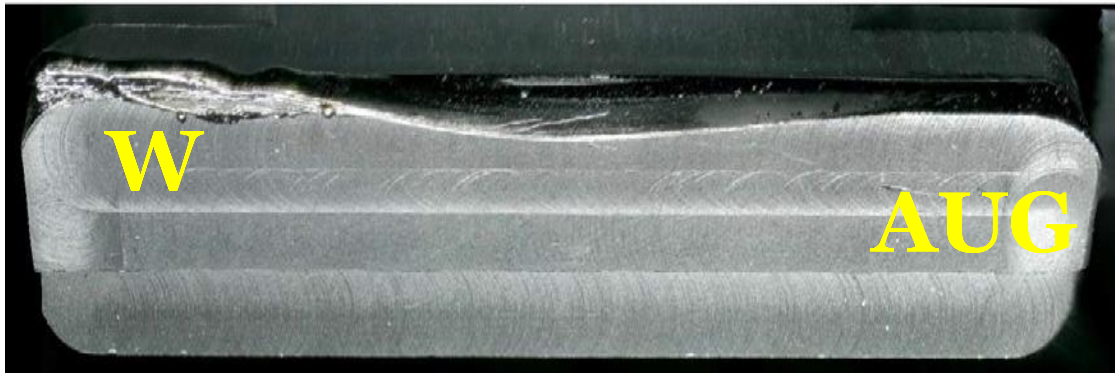
ELMs, VDEs, disruptions

General characteristics of melt events under surface loads

J. Coenen *et al* 2015 *NF* **55**



K. Krieger *et al* 2018 *NF* **58**



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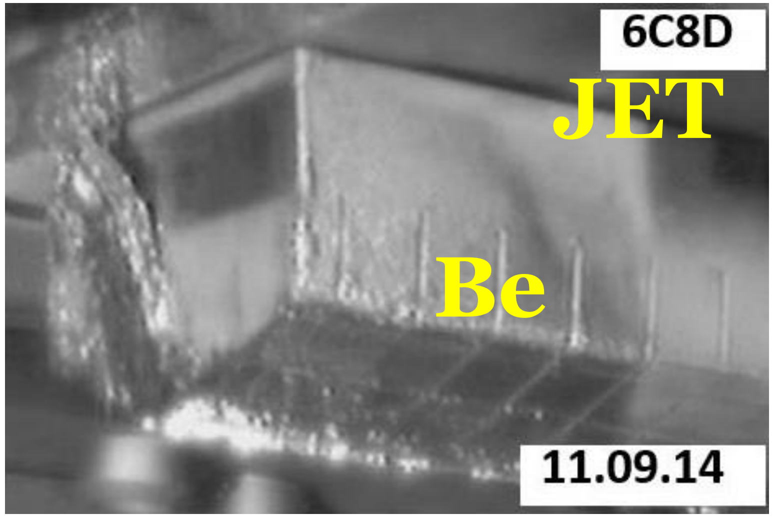


- Liquid pools surrounded by cold(er) solid surfaces.
- Large displacements
- Hot melt flows onto the colder adjacent surface → prompt re-solidification
- Splashing (from PFC edges)

Dynamics of liquid metals

Governed by the set of incompressible resistive thermoelectric magnetohydrodynamic (TEMHD) equations together with the convection-diffusion equation for the temperature   Shercliff J. A. 1979 *J. Fluid Mech.* **91** 231

$$\nabla \cdot \boldsymbol{v} = 0,$$

$$\rho_m \left[\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla) \boldsymbol{v} \right] = -\nabla p + \mu \nabla^2 \boldsymbol{v} + \boldsymbol{J} \times \boldsymbol{B},$$

$$\rho_m c_p \left[\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \nabla T \right] = \nabla \cdot (k \nabla T - S T \boldsymbol{J}) + \boldsymbol{J} \cdot \boldsymbol{E},$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t},$$

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J},$$

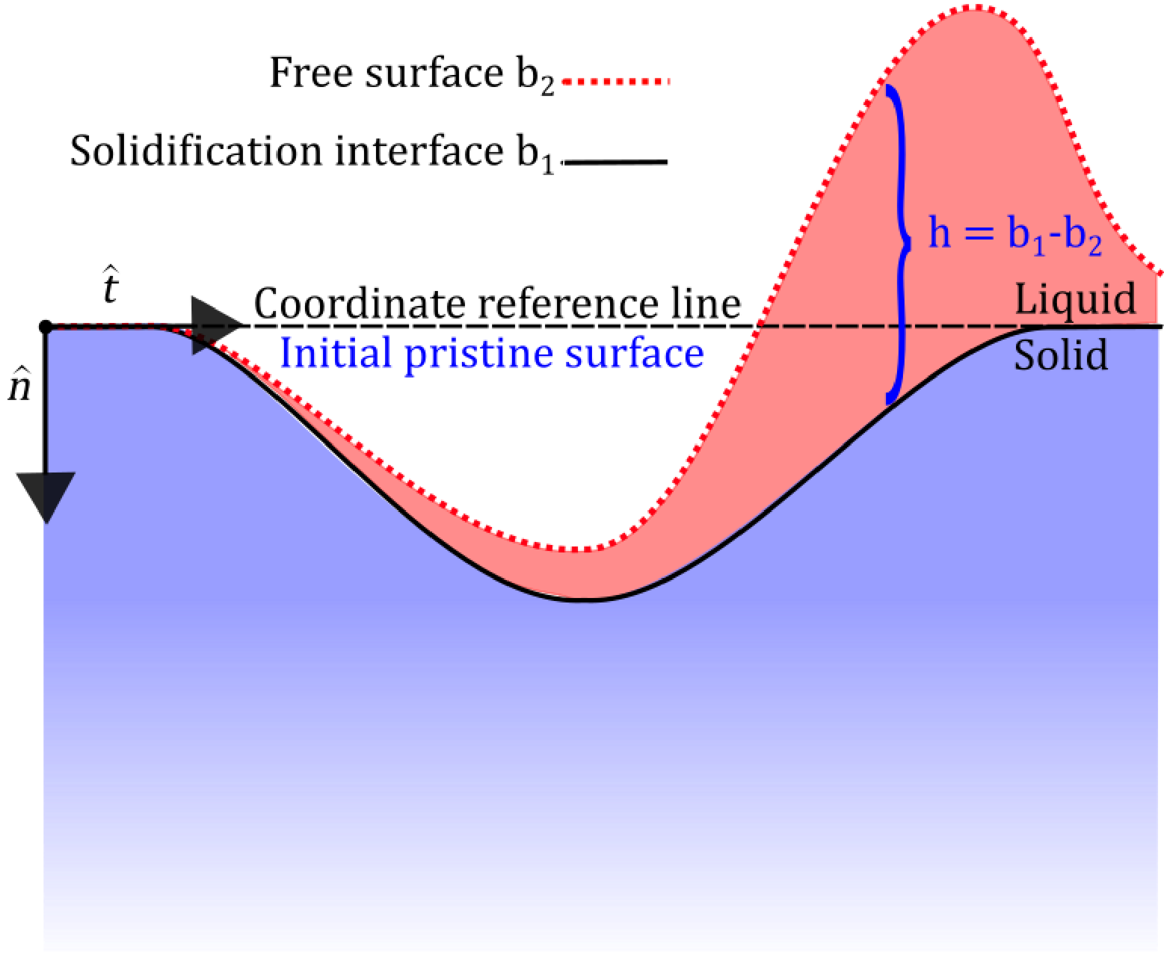
$$\boldsymbol{J} = \sigma_e (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} - S \nabla T),$$

(v, T) fluid velocity, temperature,
$(p, \boldsymbol{J})$ fluid pressure, current density,
$(\boldsymbol{B}, \boldsymbol{E})$ magnetic flux density, electric field strength,
(ρ_m, c_p) mass density, heat capacity
(k, S) thermal conductivity, thermoelectric power,
(μ) dynamic viscosity
(σ_e, μ_0) electrical conductivity, vacuum permeability

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



Multi-scale nature of the phenomena

- macroscopic motion along the PFC -- up to fraction of a meter
- the melt depth – 1-100'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 small domains to study stability and splashing

Seek simplifications if large-scale motion is of interest

How to incorporate plasma effects

- Commercial software allows treating plasma as a real fluid

However in fusion applications, this poses

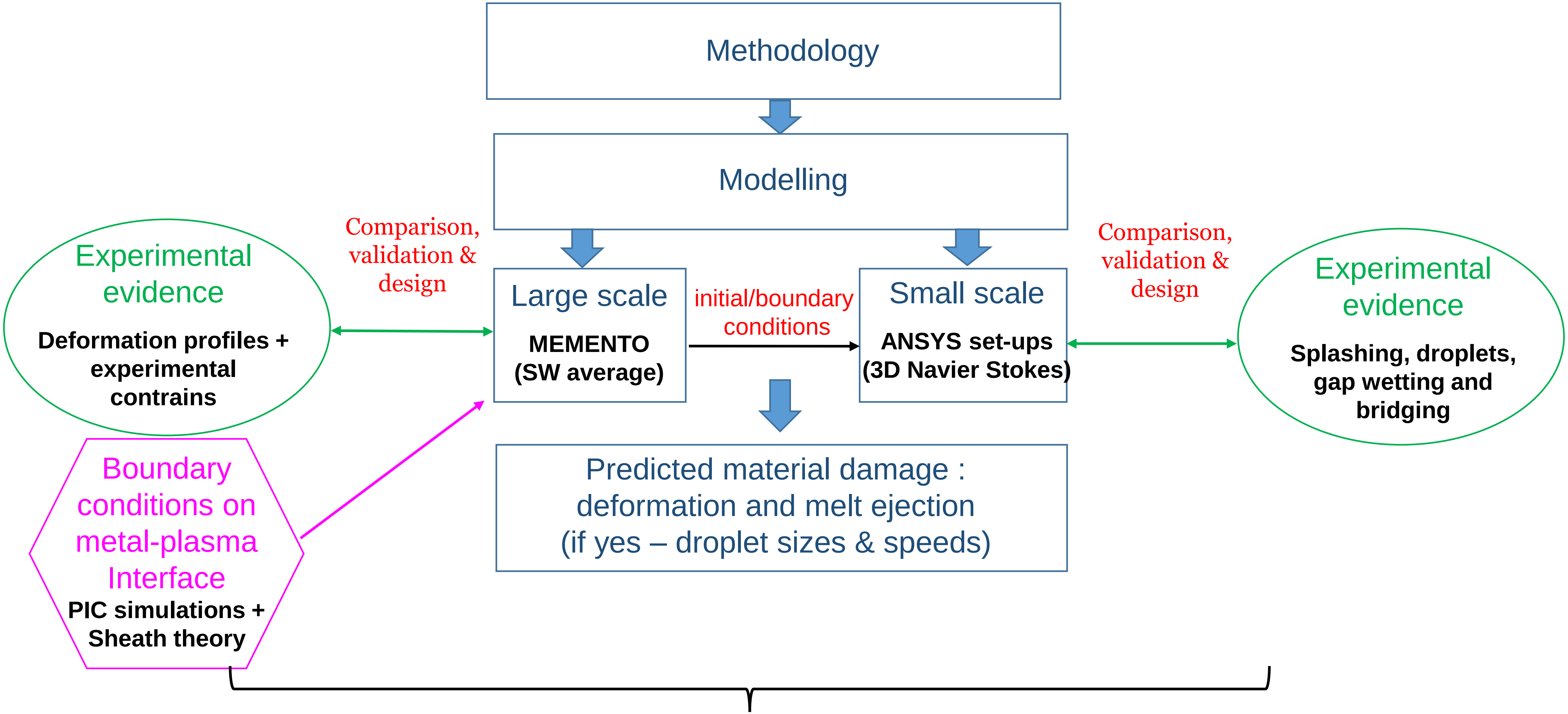
i. numerical problems due to the large disparity between the plasma and metallic densities (factor 10^{10})

ii. but also a conceptual issue: *near-surface dynamics of magnetized plasmas is driven by electromagnetic processes of kinetic origin*

- In PFC melting events, the retroaction of the melt on the plasma is of little practical interest
- Plasma modelling can be omitted as long as the proper (kin., dyn., therm.,EM) boundary conditions are *imposed on the free surface.*

- Enforcing *general* interface conditions that correspond to *realistic* situations and geometries remains a challenge that lies way beyond the customization capabilities of commercial software.

Towards predictive modeling of PFC damage (surface loads)



Validated framework for preditive studies of melt formation, dynamics & splashing

MEMENTO (**Me**tallic **M**elt **E**volution in **N**ext-step **TO**kamaks) physics model

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

$$\rho_m \left[\frac{\partial \boldsymbol{U}}{\partial t} + (\boldsymbol{U} \cdot \nabla_t)\boldsymbol{U}\right] = \langle \boldsymbol{J} \times \boldsymbol{B} \rangle - \frac{3\mu}{h^2}\boldsymbol{U} + \mu \nabla_t^2 \boldsymbol{U} + \frac{3}{2h}\left(\frac{\partial \sigma}{\partial \mathrm{T}} \nabla_t T_s + \boldsymbol{f}_d\right) - \nabla_t P + \sigma \nabla_t \nabla_t^2 b_2$$

Fluid (h, U)

Heat flux is an external input

$$c_p \rho_m \left[\frac{\partial T}{\partial t} + \boldsymbol{U} \cdot \nabla_t T\right] = \nabla \cdot (k \nabla T) + q_{vol}$$

$$-k\nabla T \,|_{S_e} = q_{\mathrm{inc}} - q_{\mathrm{cool}} \qquad -k\nabla T \,|_{S_{ne}} = -q_{cool}$$

Heat (T)

$$\nabla \cdot \left[\frac{1}{\rho_e}\nabla \psi\right] = \nabla \cdot \left[\frac{1}{\rho_e}\boldsymbol{U} \times \boldsymbol{B}\right] \qquad \boldsymbol{J} = -\frac{1}{\rho_e}[\nabla\psi + \boldsymbol{U} \times \boldsymbol{B}]$$

$$\left.\frac{\partial \psi}{\partial n}\right|_{b_2} = -\rho_e J_{th} + (\boldsymbol{U} \times \boldsymbol{B}) \cdot \widehat{\boldsymbol{n}_{b_2}} \qquad \left.\frac{\partial \psi}{\partial n}\right|_{S_{ne}} = 0 \qquad \psi|_{S_g} = 0$$

Current (J)

$(b_1, b_2, \dot{x}_{vap})$ Solid-liquid interface, liquid-plasma interface and its rate of change due to vaporization
$(h, \boldsymbol{U})$ Melt column height, depth-averaged velocity
$(P, \boldsymbol{B})$ Ambient pressure, magnetic flux density
$(\rho_m, \mu, \sigma, c_p, \rho_e)$ Mass density, dynamic viscosity, surface tension, heat capacity, electrical resistivity
(T, T_s) Bulk and surface temperature
$(\psi, \mathbf{J})$ Potential, current density

S. Ratynskaia et al (2020) NF **60**, E. Thorén et al (2021) PPCF **63**, S. Ratynskaia et al (2021) Phys. Scr. **96,** S. Ratynskaia et al (2022) NME **33**
Numerical implementation see K. Paschalidis et al, Fus. Eng. Des. 206, 114603 (2024)
Escaping thermionic emission scaling see M. Komm et al, *NF* **60** (2020)

Validation of MEMENTO physics model :

with the only heat flux variations allowed strictly within experimental uncertainties

First modelling of EUROfusion experiments with

two materials – W and Be
two loading scenarions – ELMs and disruptions (VDE CQ)
two different drives – thermionic vs halo currents
two geometries – leading edge vs shallow B-angle
two machines – JET and AUG

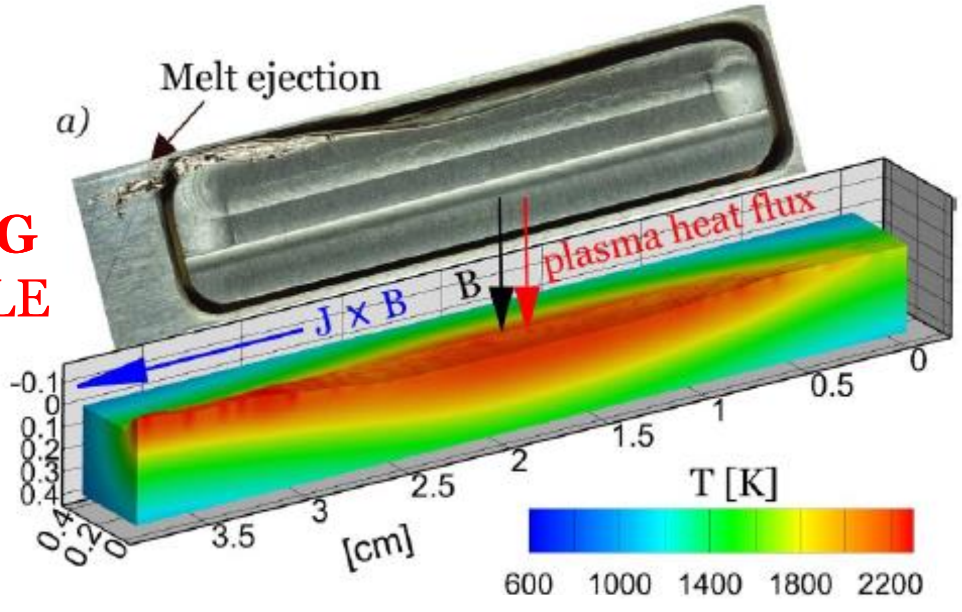
to develop a unified description

Principal experimental evidence to reproduce:

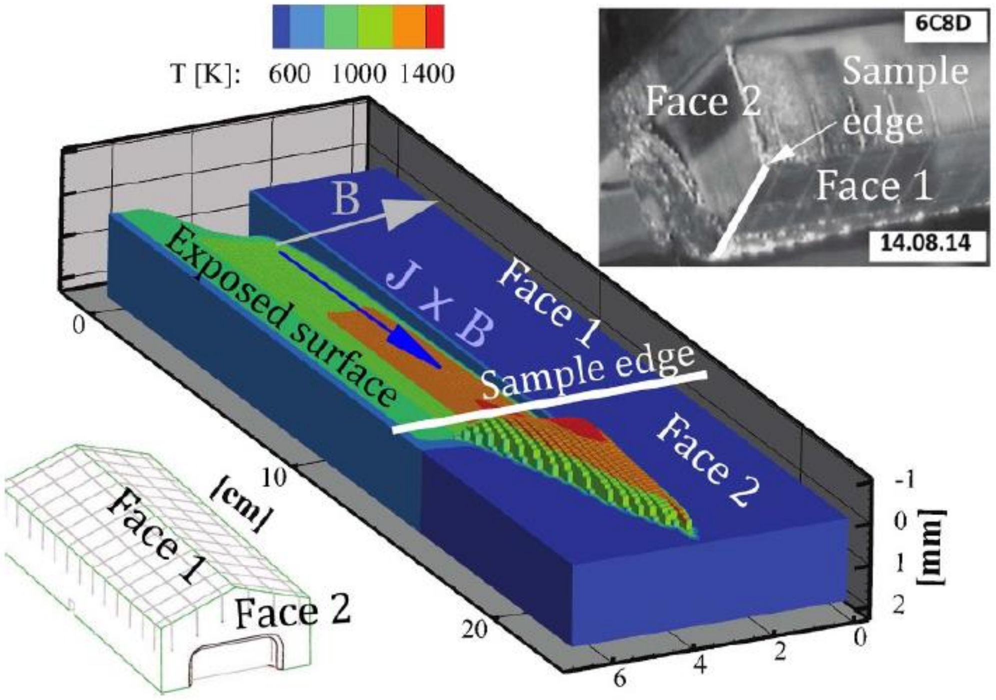
--final deformation profiles (extension and position of crater and hill)
--total melt volume displaced

Resolidification-controlled melt dynamics

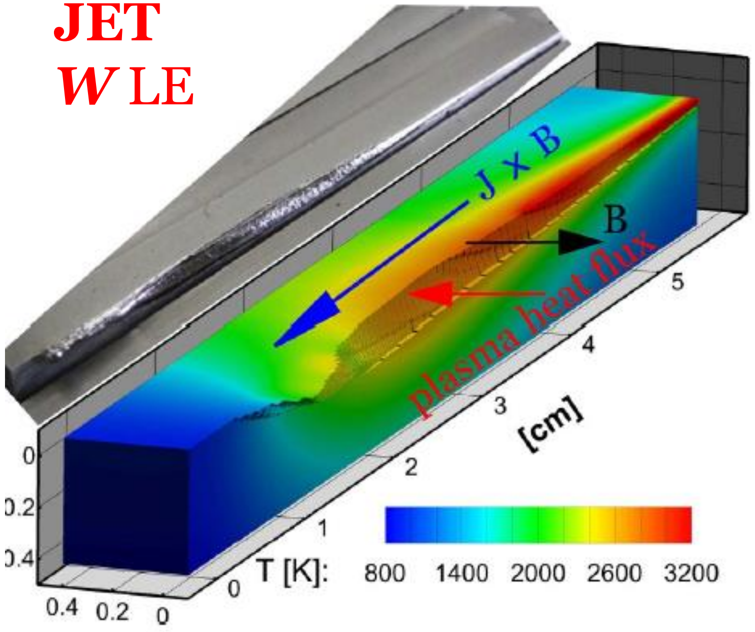
AUG
***W* LE**



JET
***Be* UDP**



JET
***W* LE**



A unified description was achieved

Importance of thermionic cooling, escaping TE limitation and replacement current bending + crucial role of re-solidification

Ratynskaia, Thoren, Tolias *et al* NF **60** (2020)

Novel experimental constrains fore more detailed validation

- ✓ Simultaneous exposure of ‘floating’ vs ‘grounded’ thermionic emitter exposures in AUG
  S. Ratynskaia et al Phys. Scr. **96** (2021)

- ✓ Simultaneous exposure of ‘poor’ vs ‘good’ thermionic emitter exposures in AUG
  (predictive modelling was carried out *prior* to the experiment) S. Ratynskaia et al (2022) NME **33**

- ✓ High resolution IR camera detection of the onset of melting and first detectable deformation (due to melt displacement) of LE in WEST S. Ratynskaia et al (2022) NME **33**

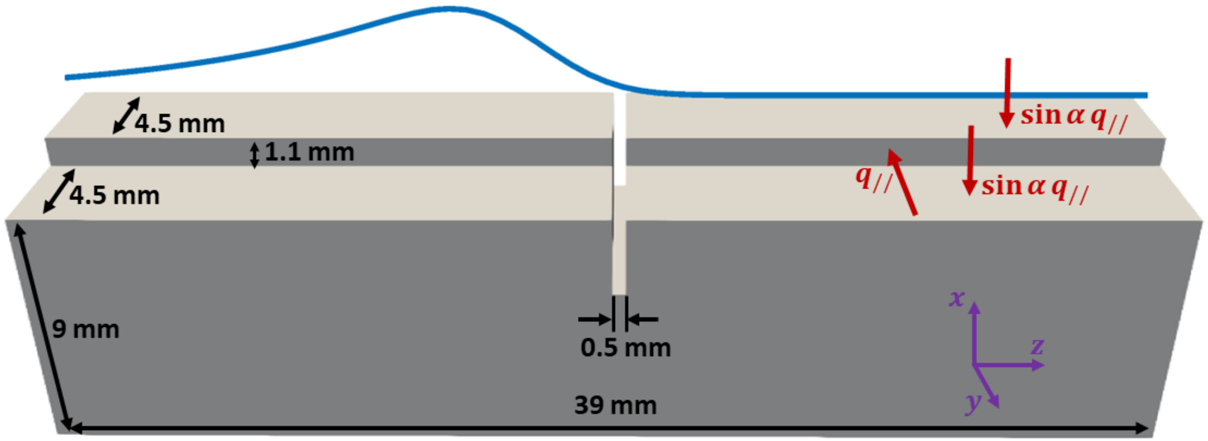
- ➢ Presence of gaps, including predictive modelling:

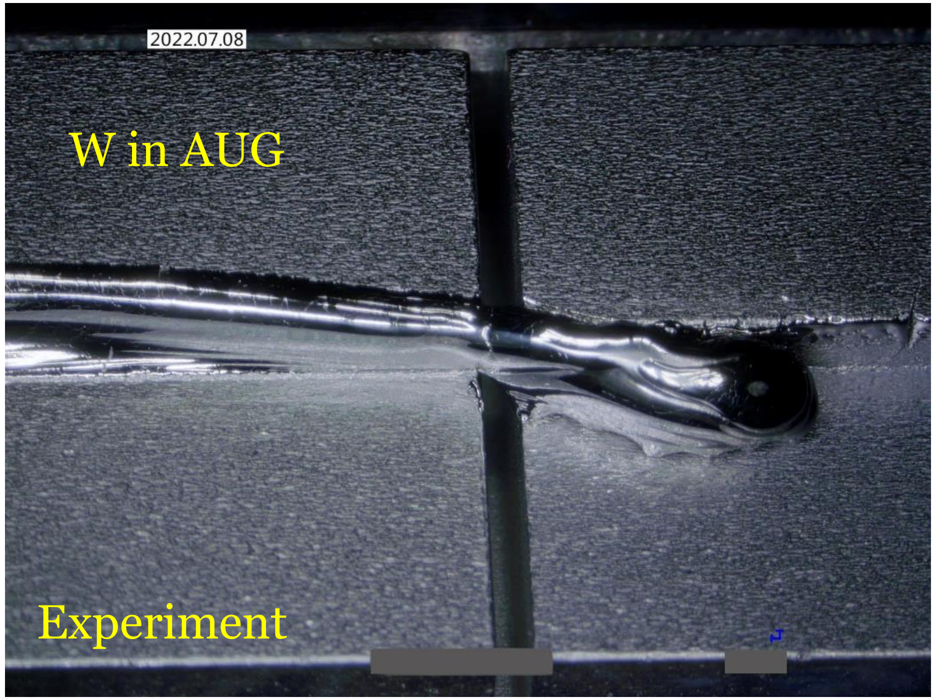
- ✓ AUG samples with gap and step, LE geometry (2022) S. Ratynskaia *et al* NF, **64** (2024)

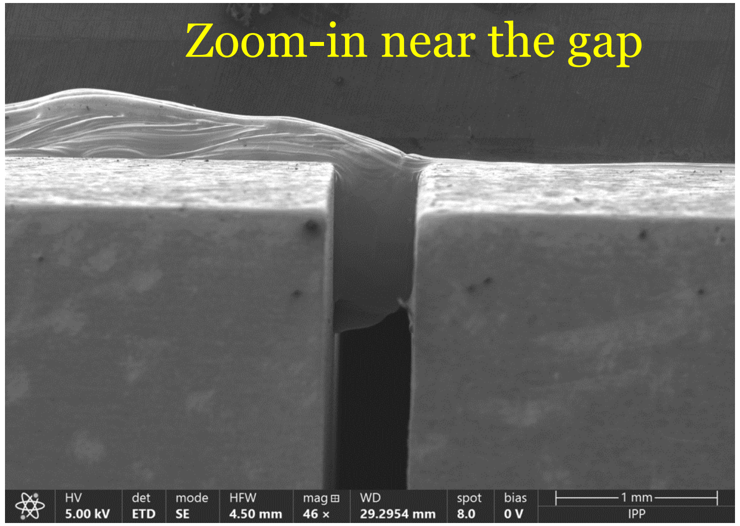
- ✓ WEST sample with gap, LE geometry (2024)
- o AUG sample with new gap sample (*shallow angle* geometry), planned fall 2024

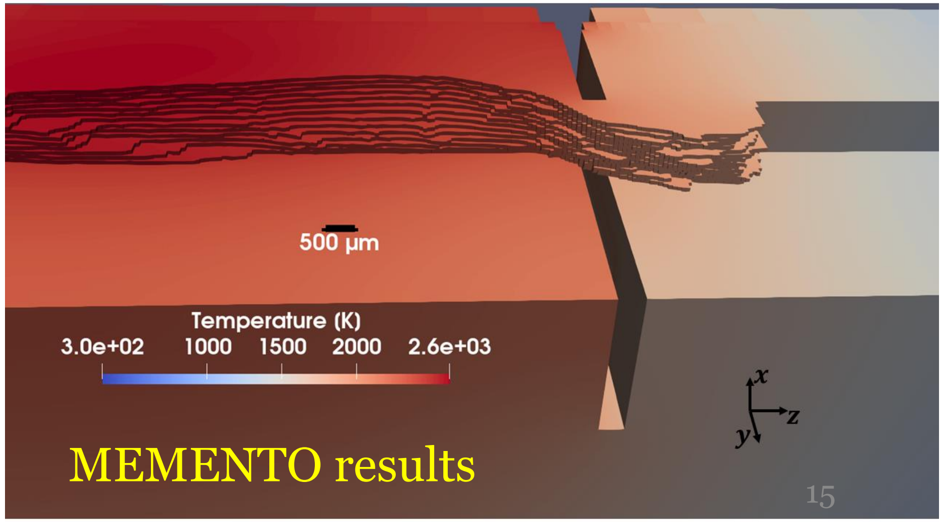
Melt edge wetting and bridging of gaps

S. Ratynskaia, K. Paschalidis, K. Krieger *et al* NF, **64** (2024)









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AUG
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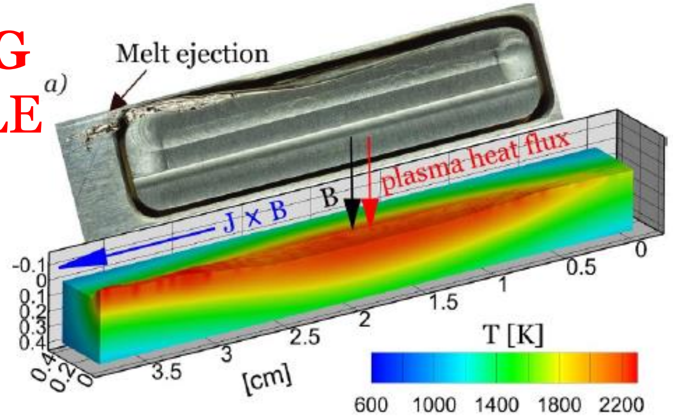
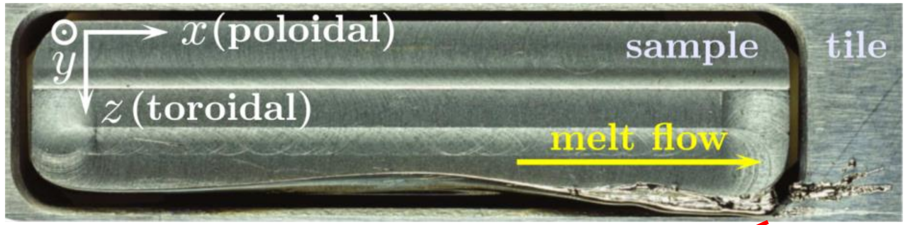
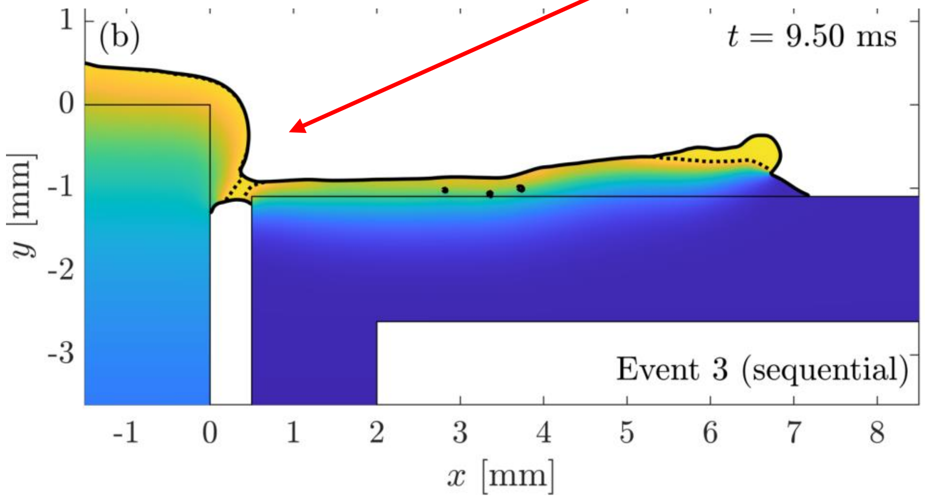
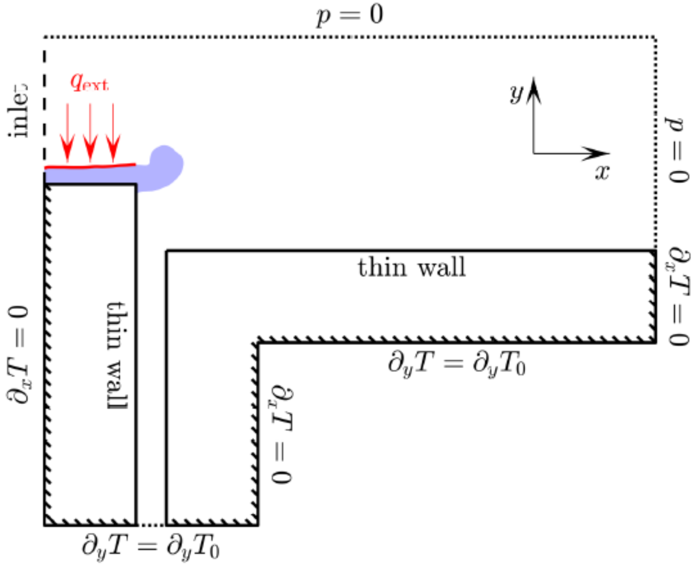






The dashed lines indicate the solidification fronts.



Two-step modelling approach:

MEMOS-U / MEMENTO to provide inlet conditions

→ more detailed Navier-Stokes simulations (ANSYS Fluent) restricted to the region surrounding the region of interest (here – the gap)

L. Vignitchouk and S. Ratynskaia, EUROfusion pinboard

Summary: PFC damage under surface heat loads

- ❖ Significant progress has been achieved on the development of methodology and modelling tools for simulations of the PFC response and melt dynamics under surface plasma heat loads.

- ❖ Large- and small-scale melt dynamics require different modelling approaches: in both plasma is a ghost (*not real*) fluid, whose effects are imposed through boundary conditions on the *free surface*

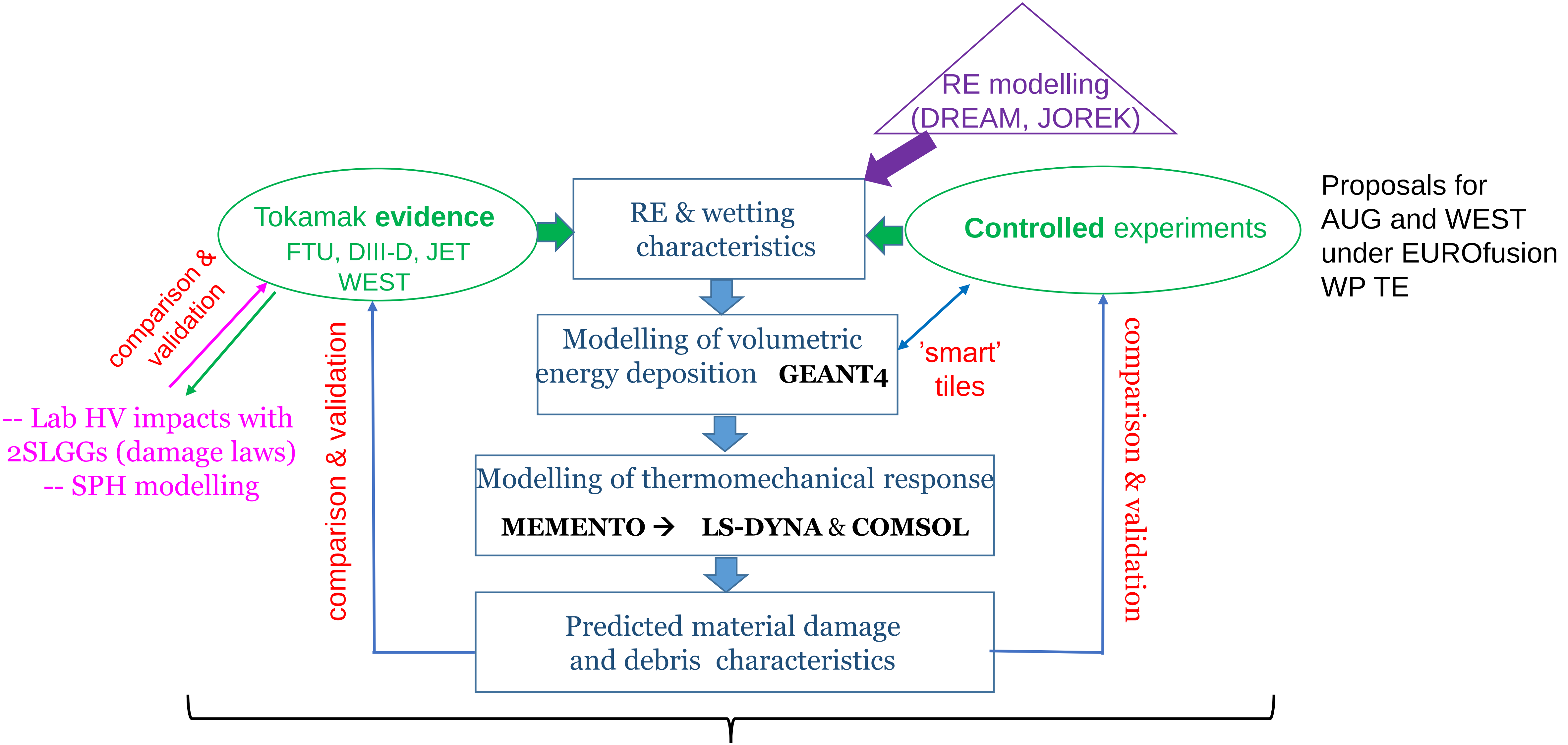
- ➢ **MEMENTO** describes macroscopic melt dynamics in large deformation - long displacement regimes and is based on a transparent physics model that is void of adjustable coefficients.
- ➢ **Specialized set-ups in ANSYS** allow for modelling of small scales- with input from MEMENTO to enforce the overall characteristics of the flow and PFC thermal response
- ➢ Emissive processes, central to the dynamics and thermal response, are modelled through **PIC** simulations and enforced through boundary conditions.

- ❖ Continuing extensive validation activity through dedicated EUROfusion experiments, designed to maximize experimental constraints (also including predictive modelling/design of new experiments)

Well on our way to high fidelity *cost-effective* modelling

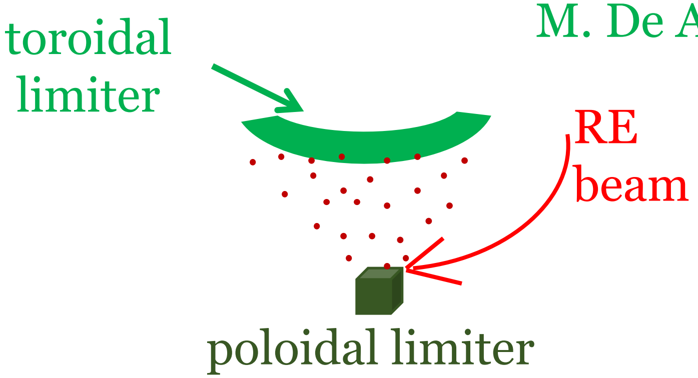
RE-induced damage

Towards predictive modeling of RE-induced damage



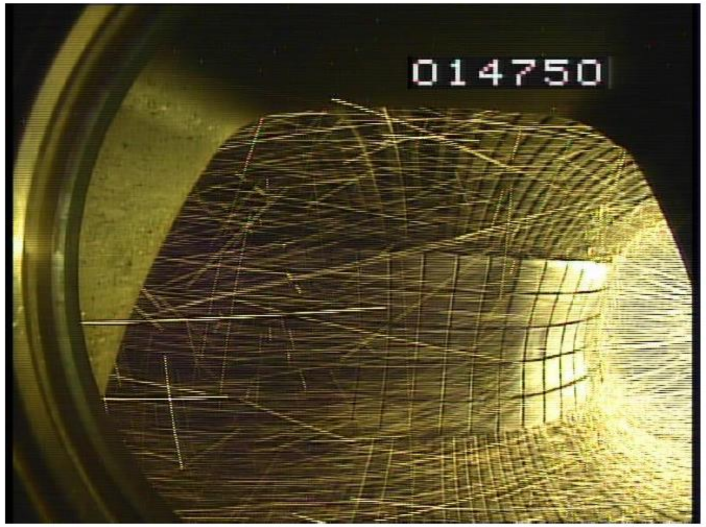
Validated framework for predictive studies of RE-induced PFC damage in fusion reactors

RE-induced PFC damage in FTU



M. De Angeli, P. Tolias, S. Ratynskaia *et al* *Nucl. Fusion* **63**, 014001 (2023)

Fast solid dust ejected from poloidal limiter, v>800 m/s



Primary damage: explosion of poloidal limiter

non monotonic profile → max temperature beneath the surface → internal stress buildup due to uneven thermal expansion & internal boiling → thermal shock, explosion and material detachment

Secondary damage: dust impacts on toroidal limiter

Craters reproduced with a two-stage light gas gun with impact speeds consistent with camera observations

Modelling of *brittle* materials with *no liquid phase*: C and BN

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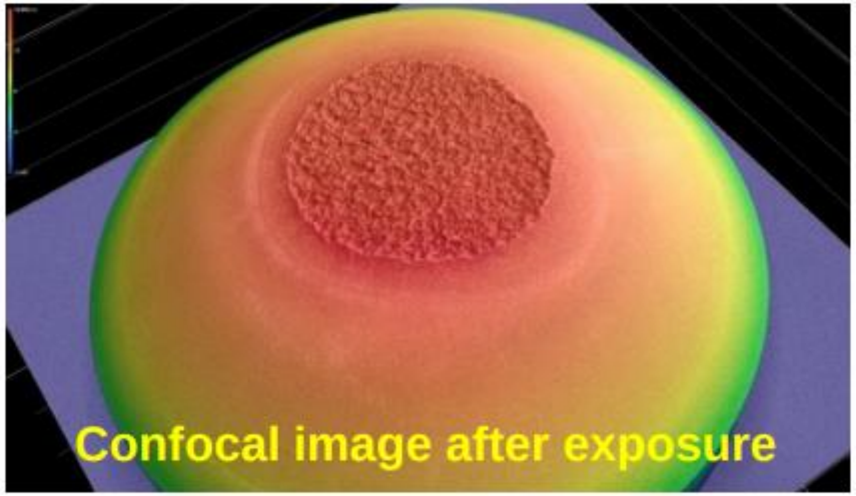
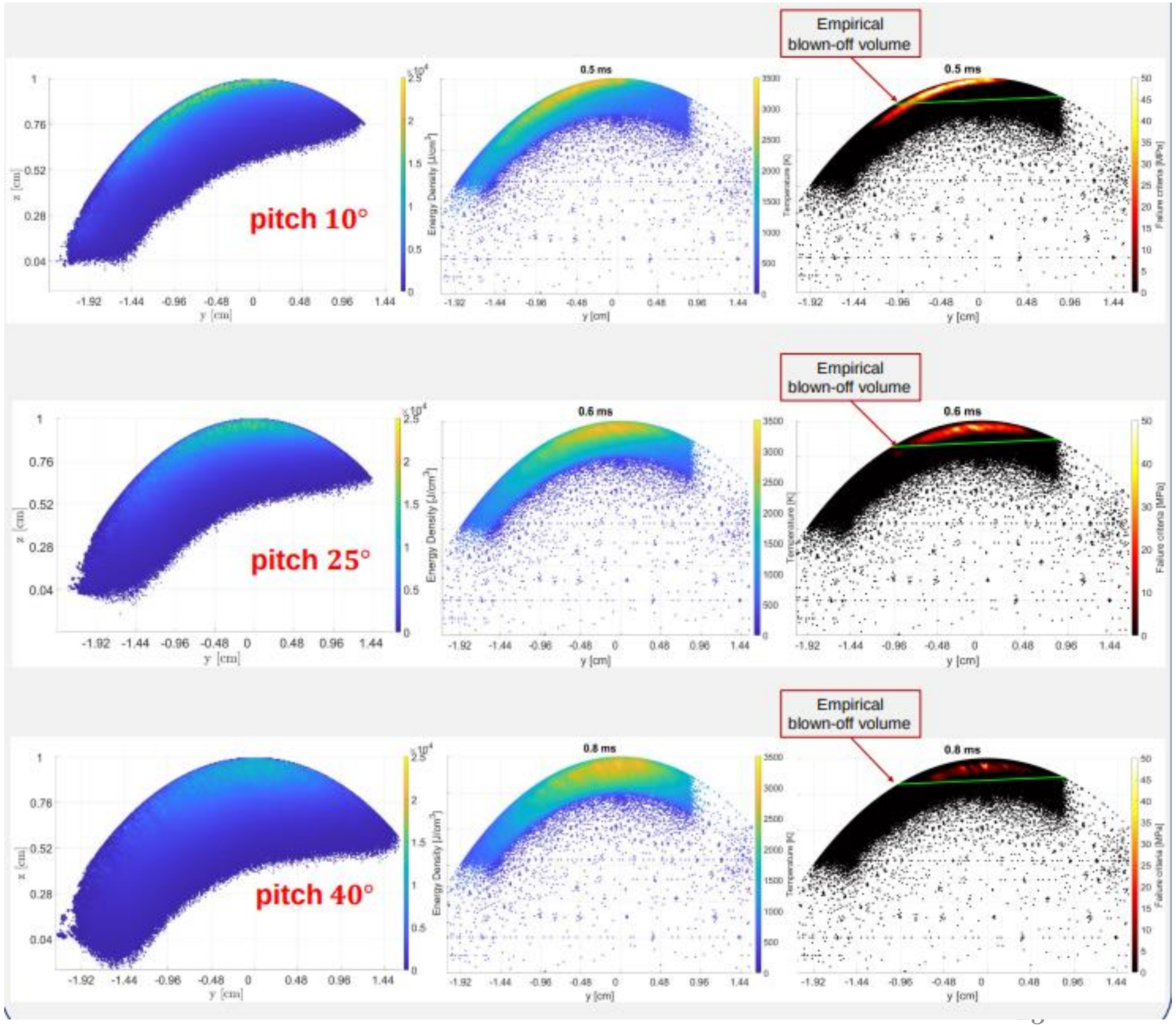
Thermo-mechanical response based on one-way coupled linear **thermoelasticity model** (KORC + Geant4 + COMSOL) → can predict position of brittle failure but not fragmentation → successful modelling of controlled DIII-D graphite experiment

"Simulation of graphite sample explosion due to RE impact: DIII-D experiment',
T. Rizzi, S. Ratynskaia, P. Tolias et al, *ITPA, divSOL*, Feb 2024 and 50th EPS July 2024
'Characterization of runaway electron wall damage in DIII-D"
E. Hollmann et al, Invited talk 50th EPS July 2024 and submitted to PPCF

Modelling of *brittle* materials with *no liquid phase*: C and BN





Simulation of graphite sample explosion due to RE impact: DIII-D experiment',
T. Rizzi et al, *poster* 50^{th} EPS July 2024

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Next step: Use of LS-DYNA (SPH module) instead of COMSOL Multiphysics
to also model fragmentation and debris ejection (to compare with camera observations)

'*Simpler*' modelling allowing faster progress towards predictions of actual damage and secondary products → the physics models are not of direct use for W *but*
this allows for validation of the INPUT on RE characteristics

Modelling of RE-induced W damage

State-of-the-art

Two-step modelling approach: volumetric energy deposition of impacting REs by a Monte Carlo transport code which provides the volumetric heat input for simulations of the W PFC response

W. Bartels, Fus. Eng. Des. 23, 323–328 (1994);
A. Cardella *et al.,* J. Nucl. Mater. 283-287, 1105 (2000);
G. Maddaluno *et al.,* J. Nucl. Mater. 313-316 651 (2003);
V. Sizyuk *et al.,* Nucl. Fusion 49 095003 (2009);
B. Bazylev *et al,* J. Nucl. Mater. 438 S237–S240 (2013)

- ➢ All modelling has thus far been limited to the W PFC thermal response.
- ➢ Thermomechanical response in the solid phase and the hydrodynamic motion in the liquid phase not considered yet.

- ❖ The development of more realistic physics models hindered by the absence of dedicated experiments
- ❖ Uncontrolled-damage observations cannot provide sufficiently detailed input concerning loading in terms of wetted area, RE impact characteristics and, crucially, energy absorbed.

Long-term goals

- To **realistically** model RE-induced W damage, we need to go beyond heat transfer and even beyond one-way coupled thermoelasticity

  - ✓ Use of LS-DYNA and COMSOL Multiphysics to include
    - visco-plasticity
    - compressive flows
    - internal phase transitions
    - shockwave propagation
    - large strains / deformations
    - material fragmentation

- **Currently** working with GEANT4 + MEMENTO   workflow

Monte Carlo simulations of energy deposition

Energy deposition simulations for fusion relevant scenarios:

- ❑ *Physics list /model choices and benchmarking*
- ❑ *Accuracy/computational cost trade-off: single vs multiple scattering*

- ❑ *Shallow impact angles*
- ❑ *Presence of magnetic field*

- ❑ *Realistic geometry and wetted area*

Particle-matter interactions of relevance to fusion scenarios

Involved EM processes		
Particle	**Process**	**Basics**
Electron e-	Scattering (e- on n)	single / mixed / multiple scattering
	Ionisation (e- on e-)	delta ray production + excited nucleus
	Bremsstrahlung (e- on n, e-)	photon production
Photon γ	Rayleigh scattering	elastic
	Compton scattering	inelastic + excited nucleus
	Photoelectric effect	delta ray production + excited nucleus
	Gamma conversion	positron production
Positron e+	Scattering (e+ on n)	single / mixed / multiple scattering
	Ionisation (e+ on e-)	delta ray production + excited nucleus
	Bremsstrahlung (e+ on n, e-)	photon production
	Annihilation (e+ on e-)	photon production
Excited atom n*	Radiative transition	photon production
	Auger transition	delta ray production

Monte Carlo simulations with Geant4

❖ GEANT4 benchmarking activities for energy deposition in W initiated

'*GEANT4 modelling of runaway electron transport into bulk tungsten*', T. Rizzi, P. Tolias, S. Ratynskaia, PSI 2024

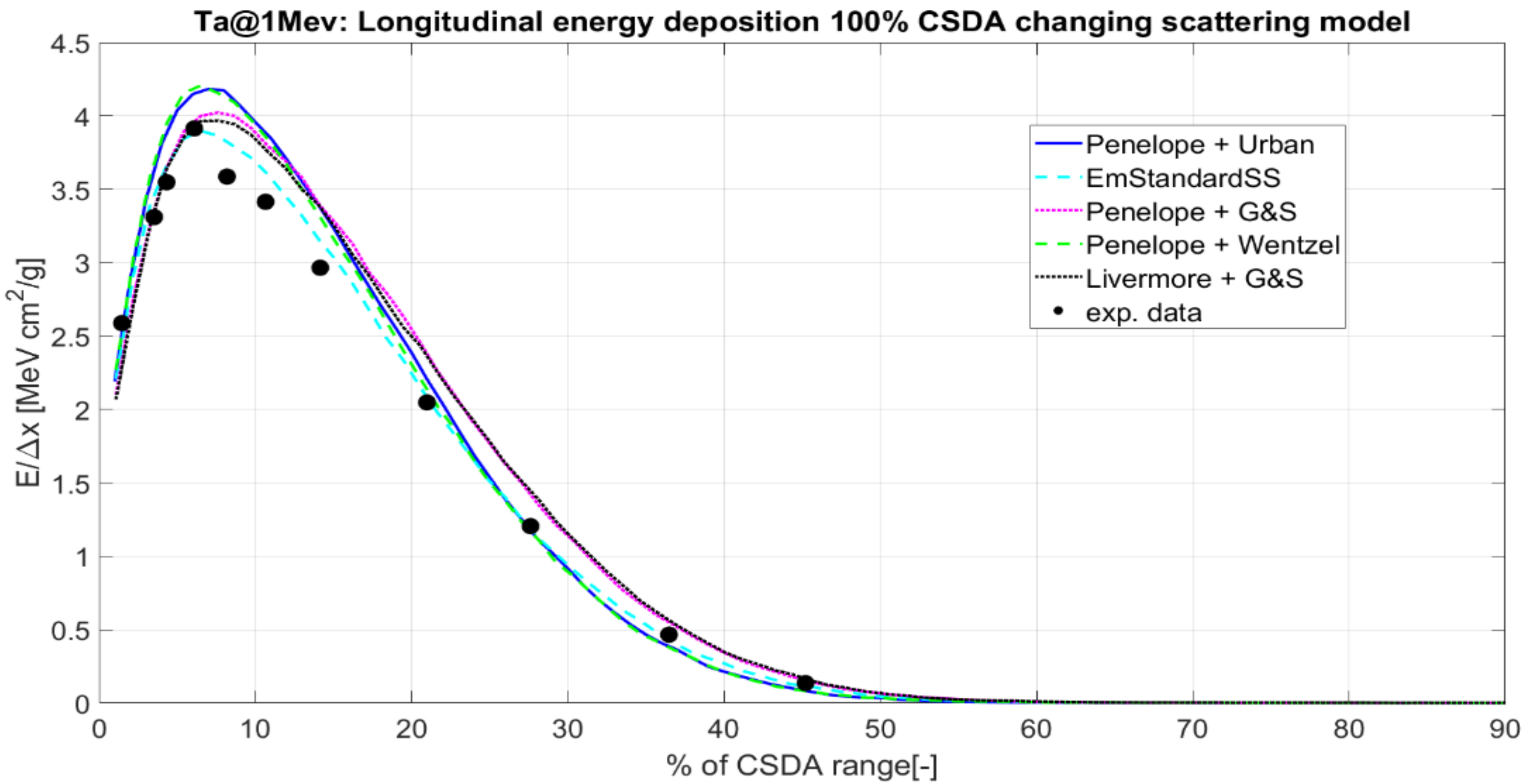
➢ Model benchmarking

- Electron **b**ack**s**cattering [**BS**] – comparison to experiments from bulk materials, including W
- Calorimetry – comparison to experiments in bulk materials, also high Z
- Electron transmission – comparison to experiments in thin foils, Gold (Z=79)

➢ Single vs multiple scattering

- Realistic scenarios (RE energy and angular distributions, B field, non-uniform loading, large wetted areas) are not computationally feasible with single scattering & sufficient statistics
- Multiple scattering is very fast to run but not accurate for lower energies
- Need for a mixed scheme with appropriate cut-off angle (angle separating small from large angle scattering)

High Z model benchmarking: calorimetry



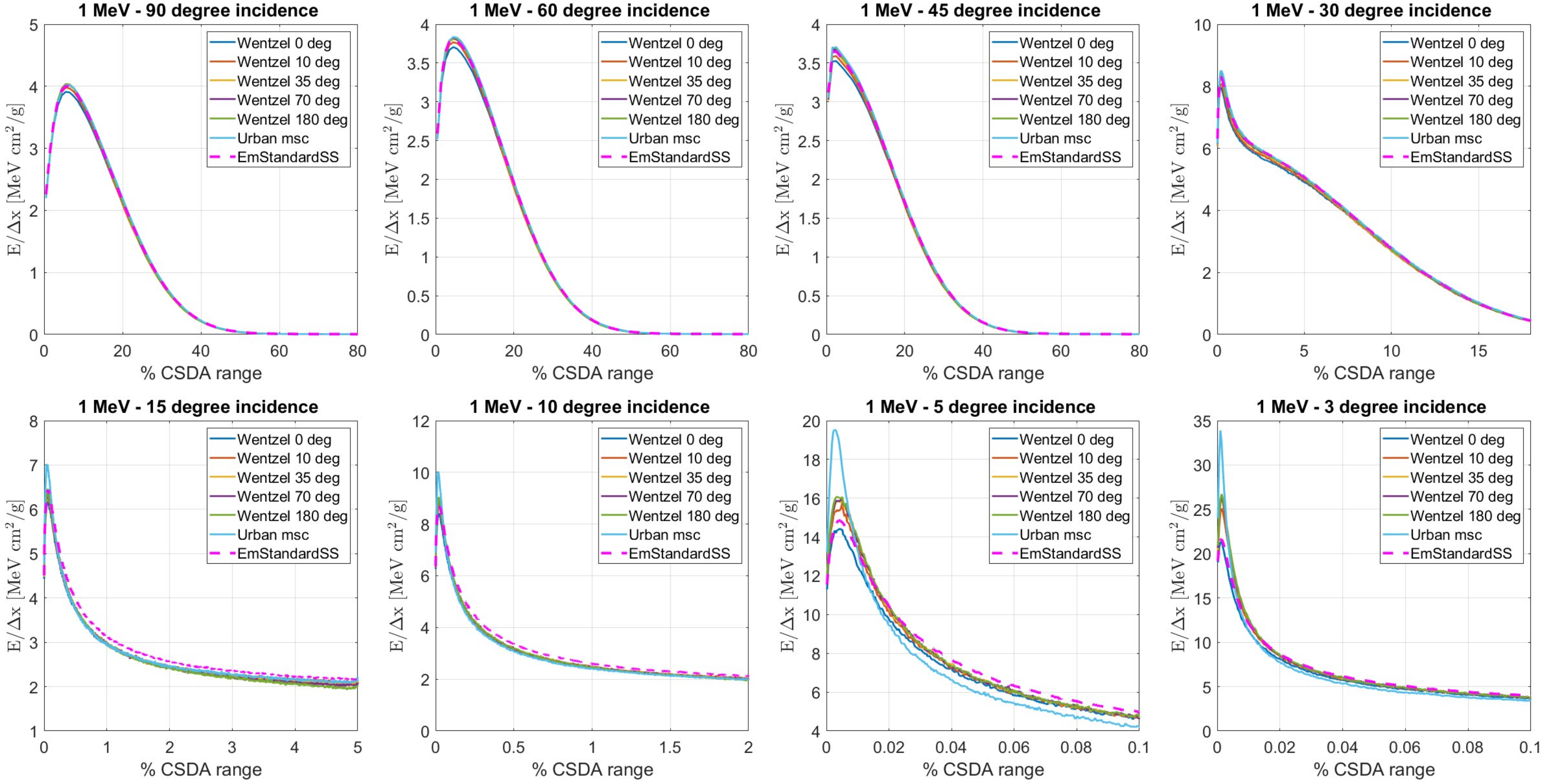
An example for Ta (Z=73)

GEANT4 physics model benchmarking against experimental data for energy deposition by 1 MeV electrons normally impacting bulk Tantalum.
[G. J. Lockwood et al., IEEE Trans. Nucl. Sci., 6, 326-330 (12 1973)]

- The experimental energy deposition profile can be reproduced over the entire CSDA range only by the model which employs single scattering (light dashed blue line)
- Other models available in the GEANT4 physics lists are 'missing out' either on the vicinity of the maximum of the experimental energy deposition or at the tail of the profile

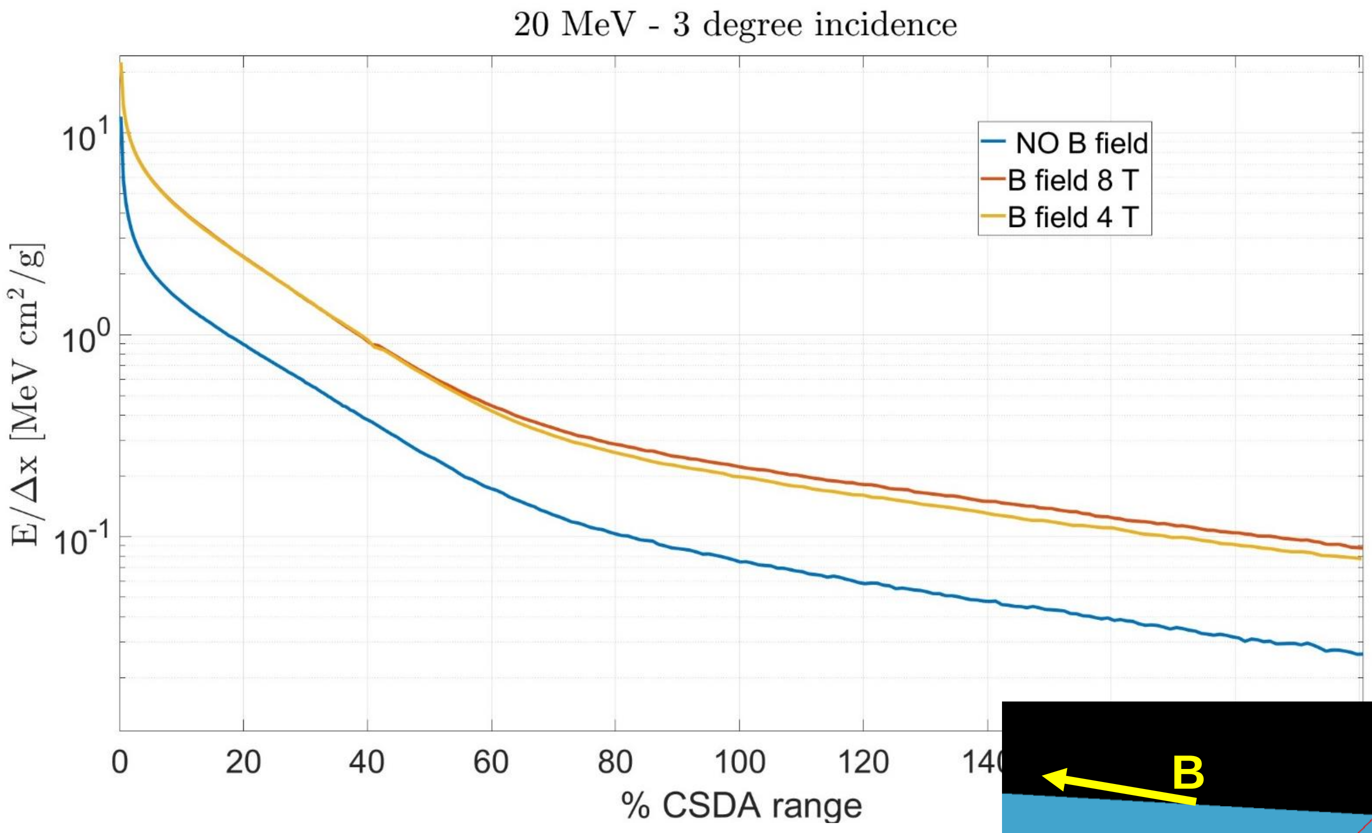
Energy deposition from normal to grazing angles

1 MeV, no B field (CSDA range 0.4 mm)



0.1% CSDA = 0.4 um

B field + grazing angle (single point e-gun)



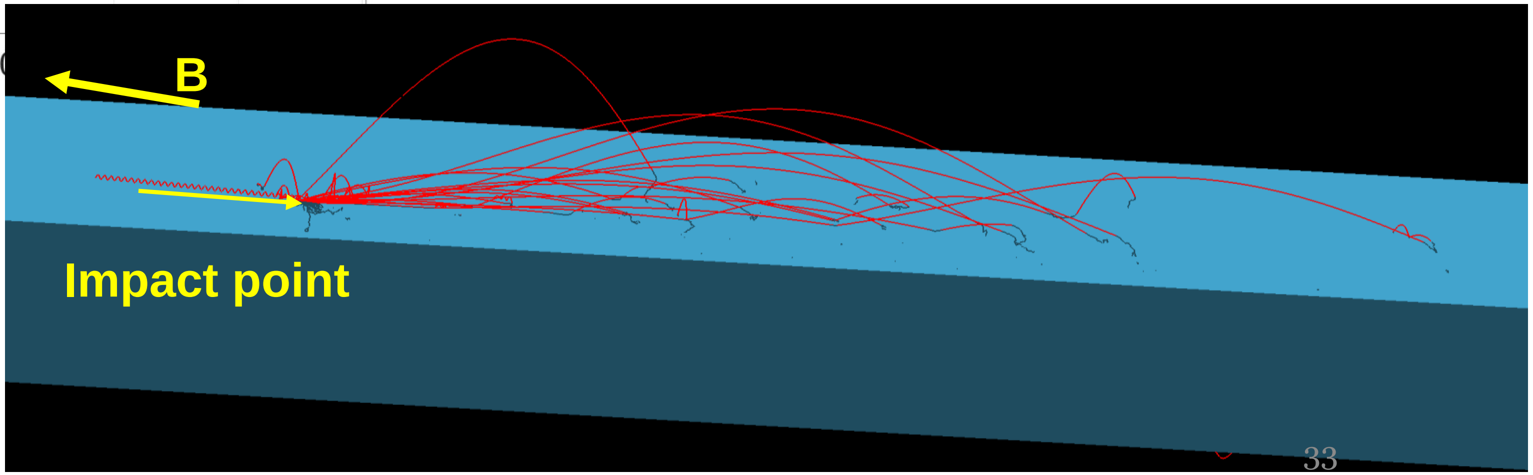
Impacting : 10^6 electrons at 20 MeV at 3°

Energy deposited:

0T : 6.3 10^6 MeV

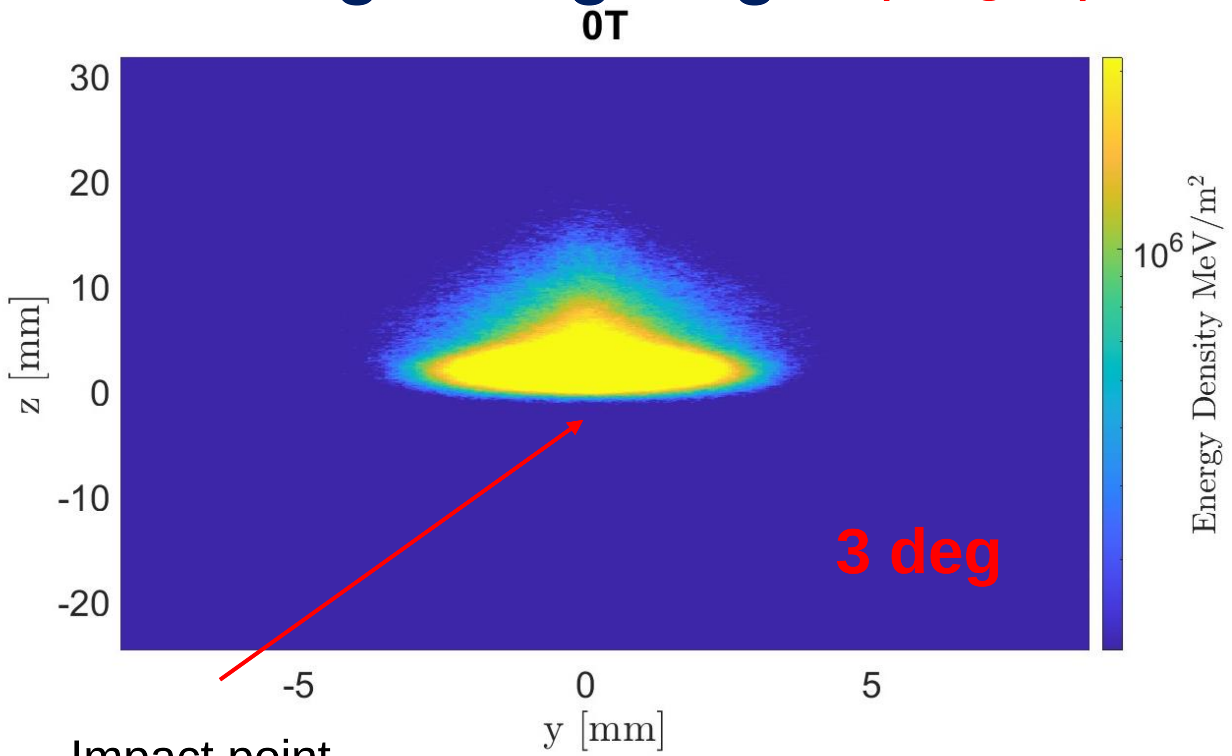
4T : 16.4 10^6 MeV

8T : 16.7 10^6 MeV

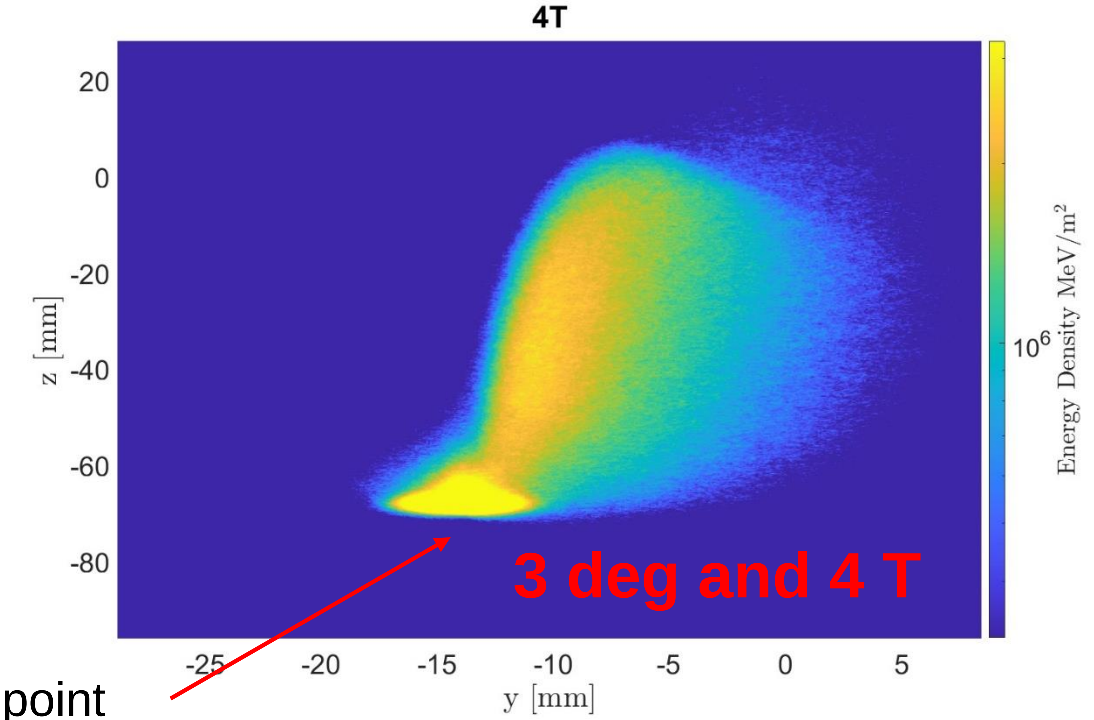


- ➢ For E > 1 MeV at normal incidence the BS yield is insignificant
- ➢ BUT grazing angles change the EBS yield to ~50%

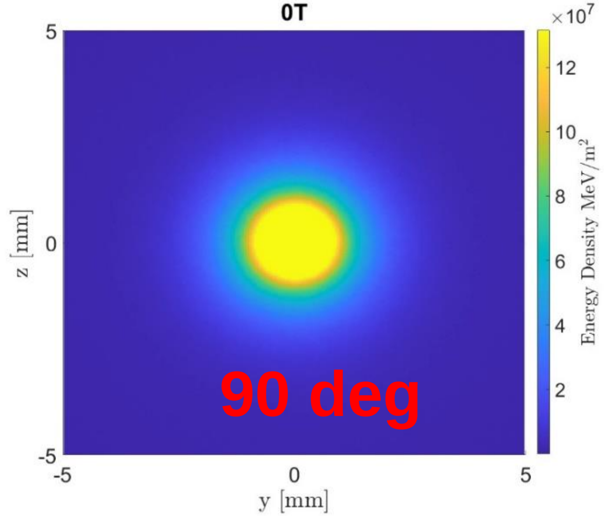
B field + grazing angle (single point e-gun)



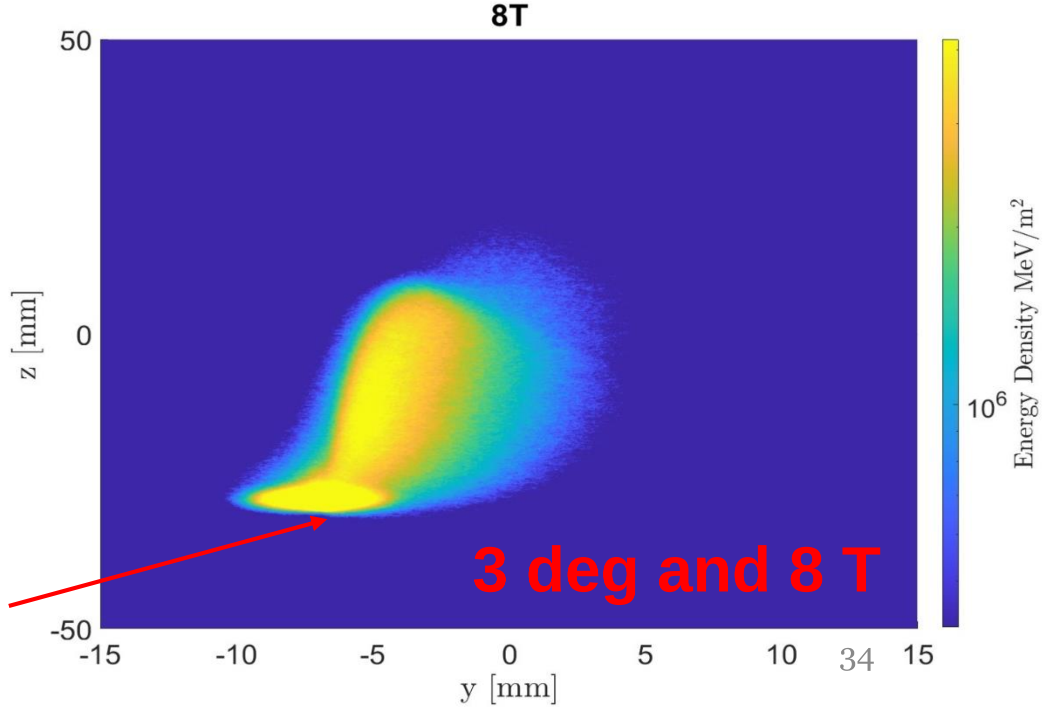
Impact point



Impact point



Depth-integrated energy density maps

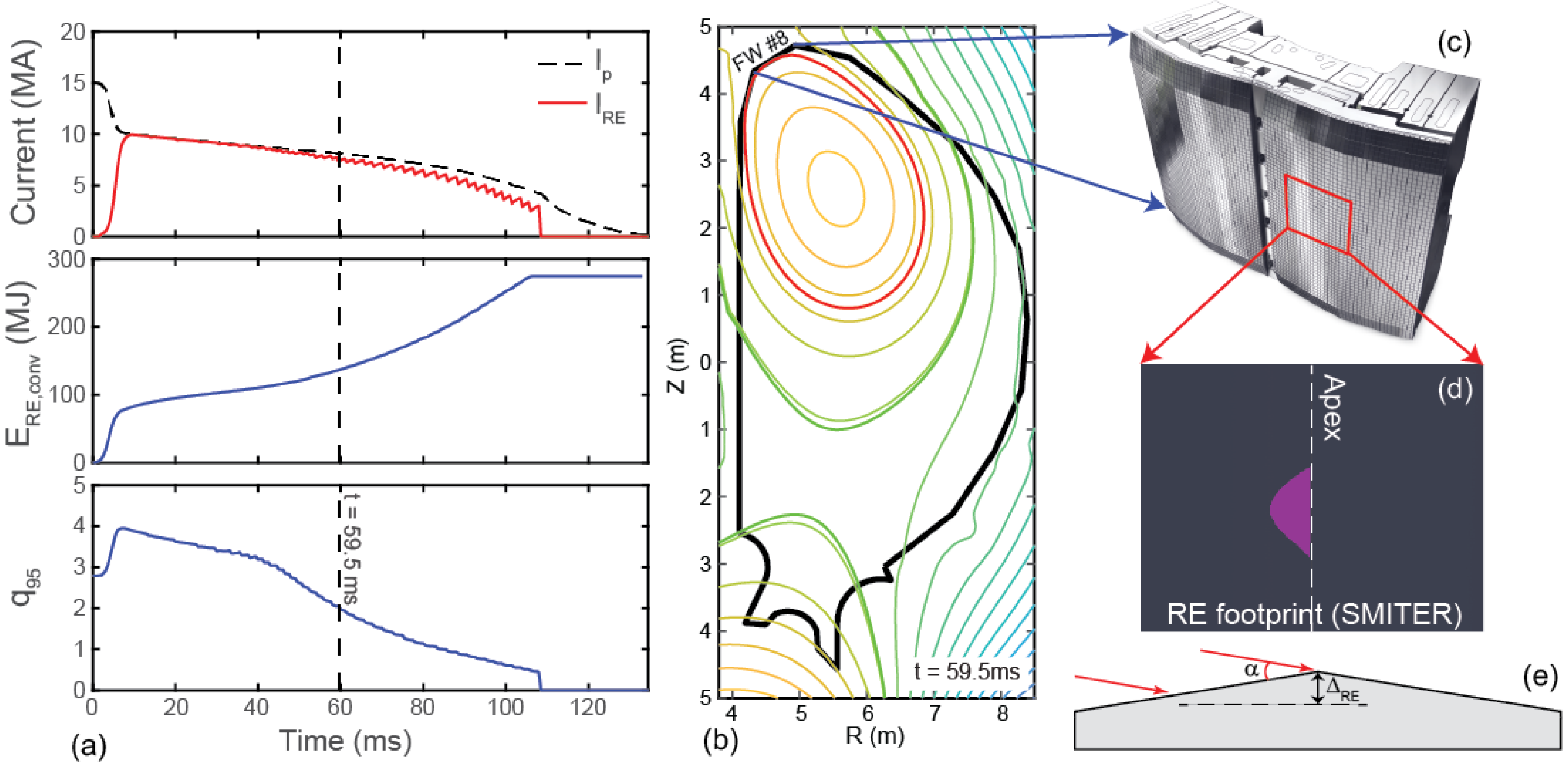


Impact point

Thermal response of ITER W tiles to REs

1. Simplified input
2. JOREK input

1. Simplified input : W runs



R.A. Pitts et al, *Plasma-wall interaction impact of the ITER re-baseline,* PSI 2024, submitted to NME

NB: single "tiles" (16 x 16 mm^2) referred hereafter are illustrative and taken from the original water cooled Be wall

a) DINA DS simulation including RE conversion during an upward going CQ at 15 MA, 5.3 T showing the runaway current and magnetic energy conversion with q95 = 2 reached at t = 59.5 ms;

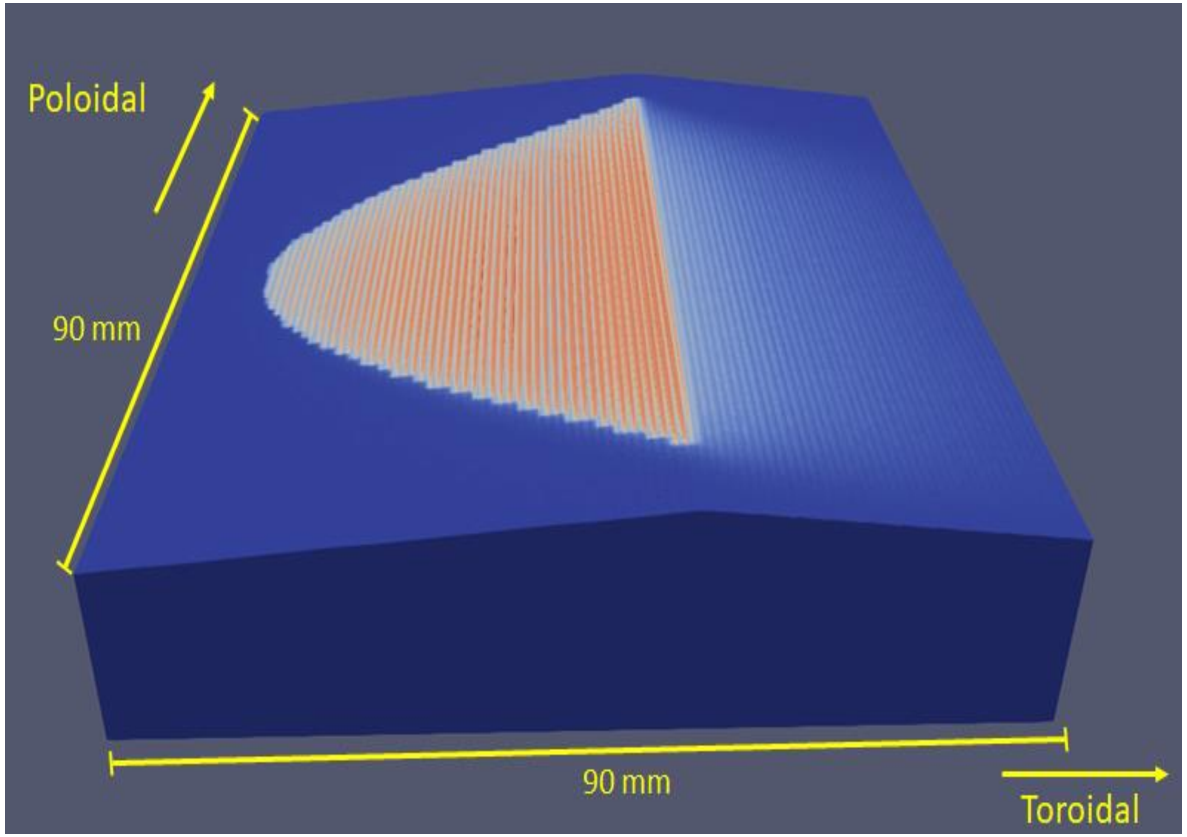
b) magnetic equilibrium at q95 = 2 assumed as the instant at which the RE beam is destabilized with impact on FW panel #8;

c) Blanket Module CAD model illustrating the double winged apex structure of the FW panel;

d) SMITER field line tracing calculation of the RE beam wetted area for DRE = 4 mm;

a) schematic representation of the FW panel apex modelled as a simple rooftop with given fixed RE beam impact angle.

Problem postulation



Total energy loss % of energy loaded	neutrons	photons	EBS	PBS
24.7 %	0.0042%	11.81%	12.5%	0.05%

- Exponential RE energy distribution, mean 15 MeV, cut 1-50 MeV
- B field 7 T, at 5° w.r.t. the surface
- Zero pitch
- Uniformly distributed impacts

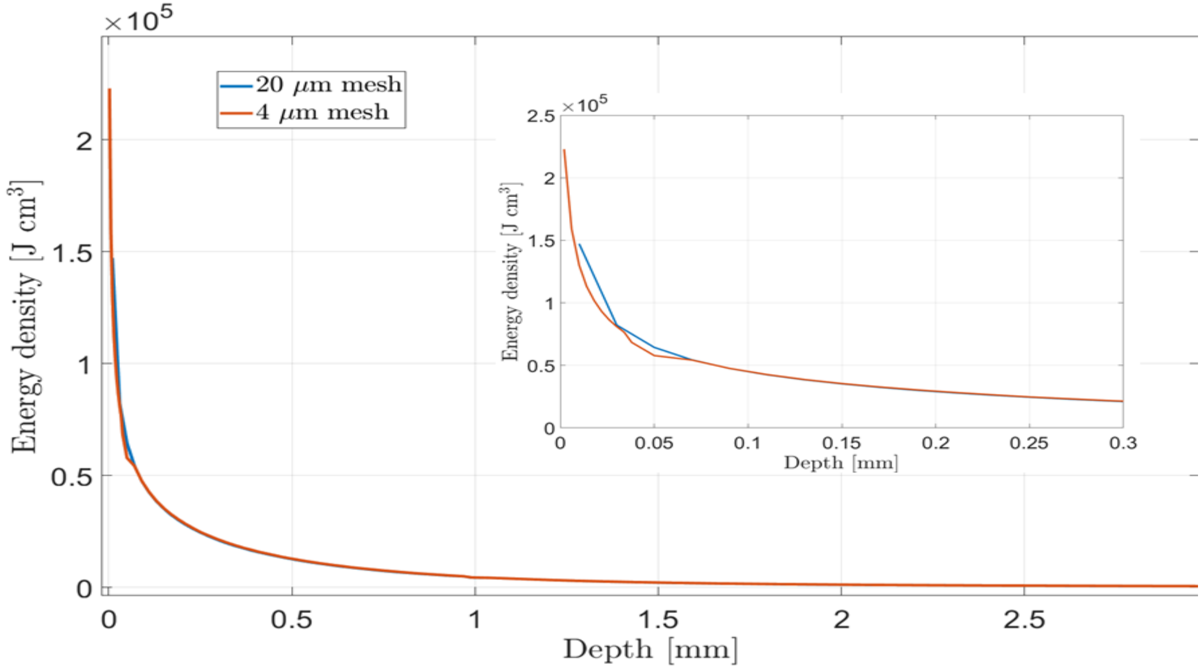
- 3D geometry is respected and a 90x90 mm^2 domain is simulated, encompassing about 20 *single tiles* .

- 8 mm thick W tiles + few 12 mm runs

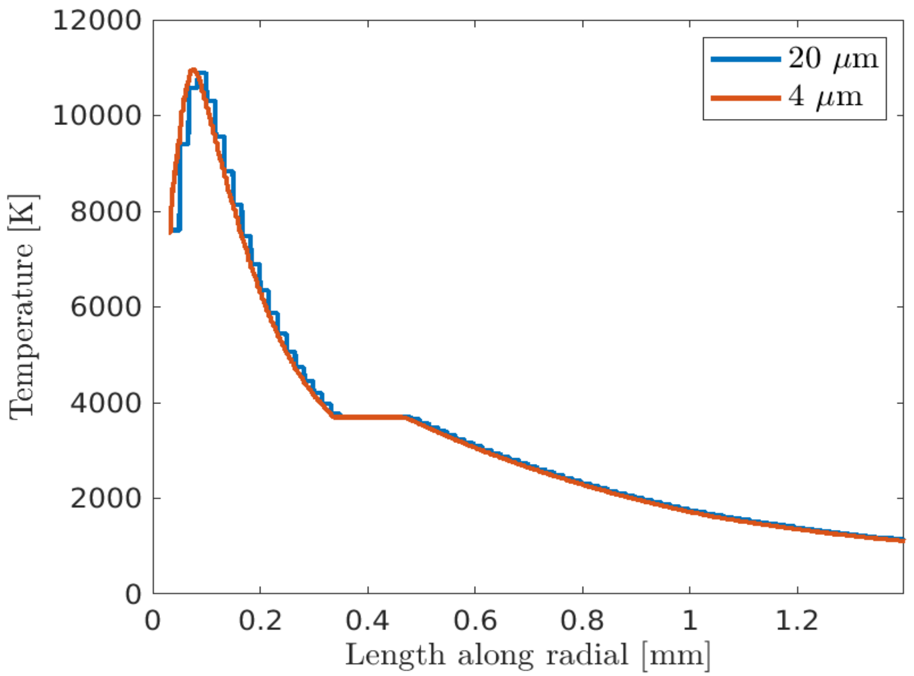
All loads are referred to as *‘X kJ over Y ms’*, where X refers to the energy deposited per apex and Y to the loading duration.

The combination of X and Y provides *the power density*

Energy deposition: grazing angle

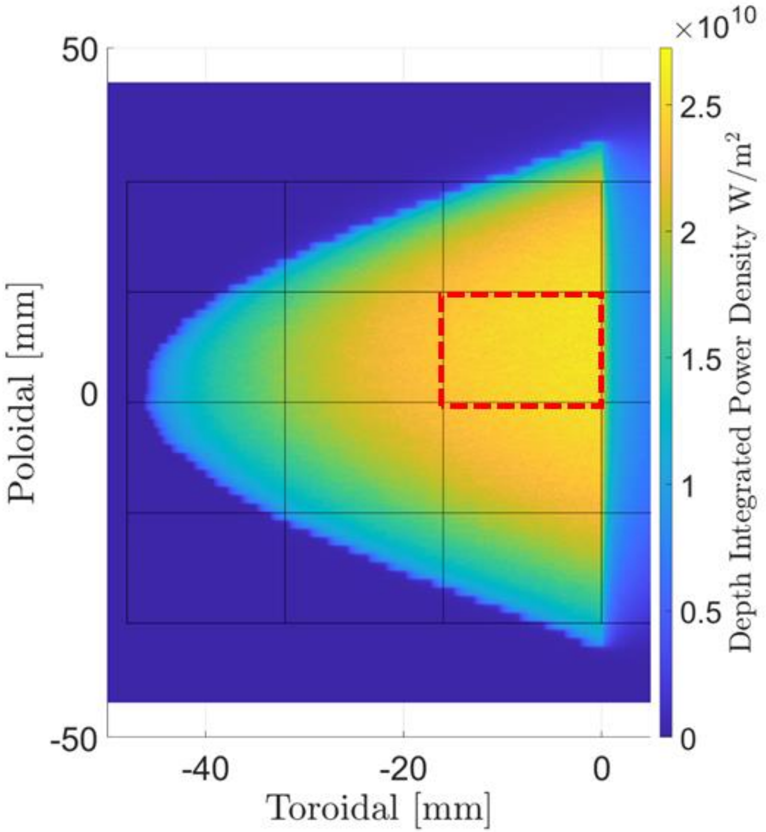


In-depth energy density profiles for the most loaded tile under ‘50 kJ over 1 ms’. Results for resolution of 4 μm and 20 μm. Insert is a zoom-in of the first 300 μm.

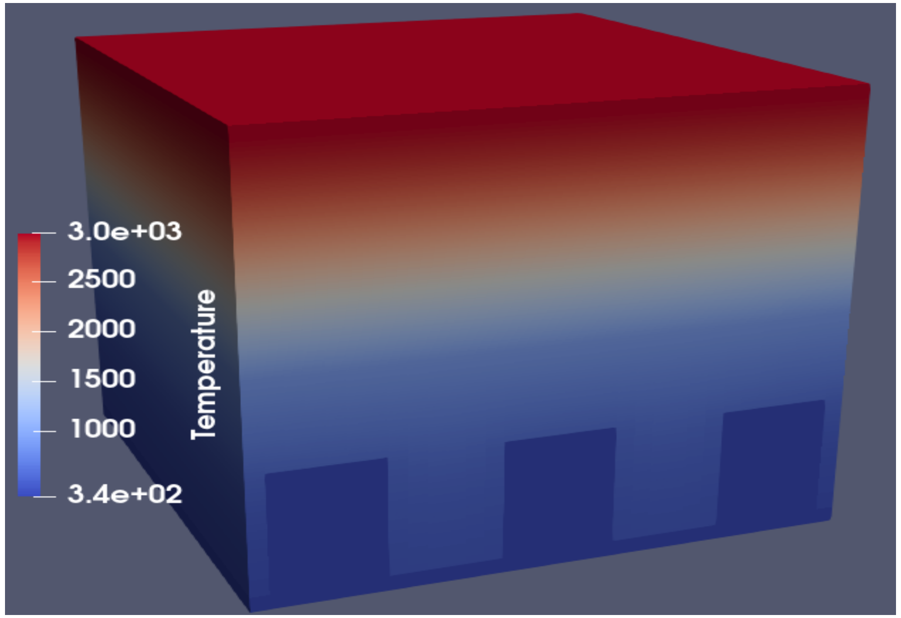


In-depth temperature profiles obtained with the energy deposition of resolution of 4 μm and 20 μm for ‘150 kJ over 1 ms’ loads. The results shown are at 0.27 ms (due to extreme T reached). The profiles are shifted from the free surface (at 0 mm) due to erosion.

Energy deposition: magnetic field



Single-point source wetting of the most loaded MB
(high statistics)

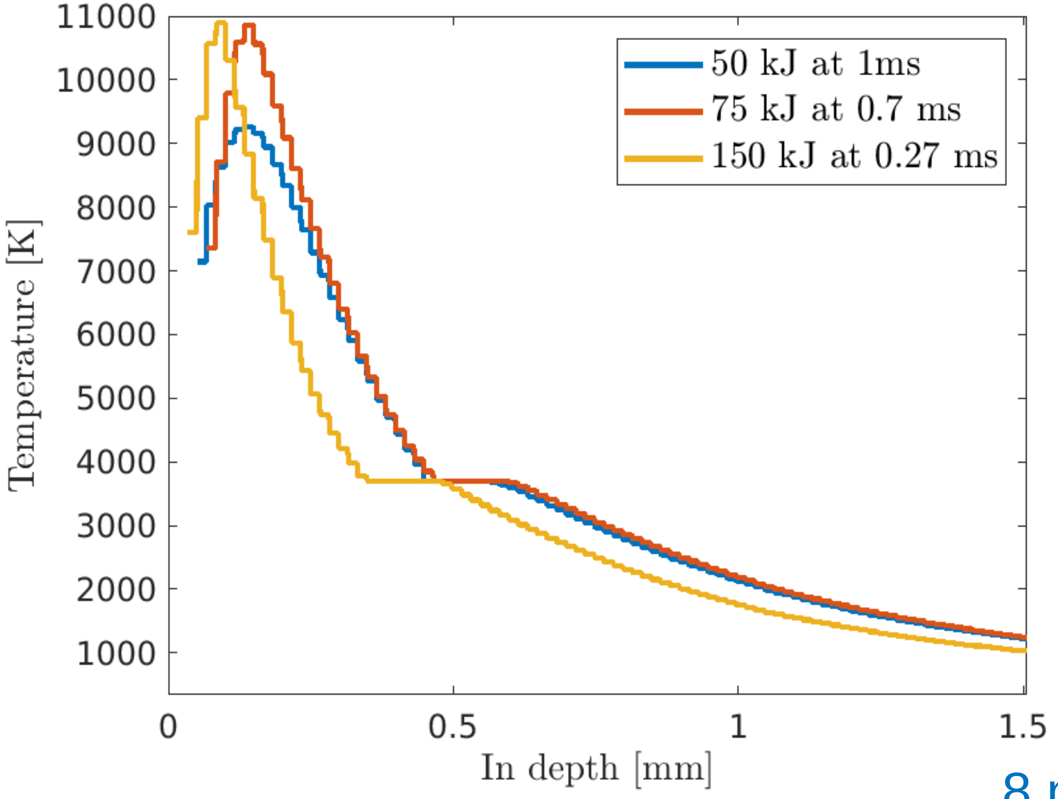


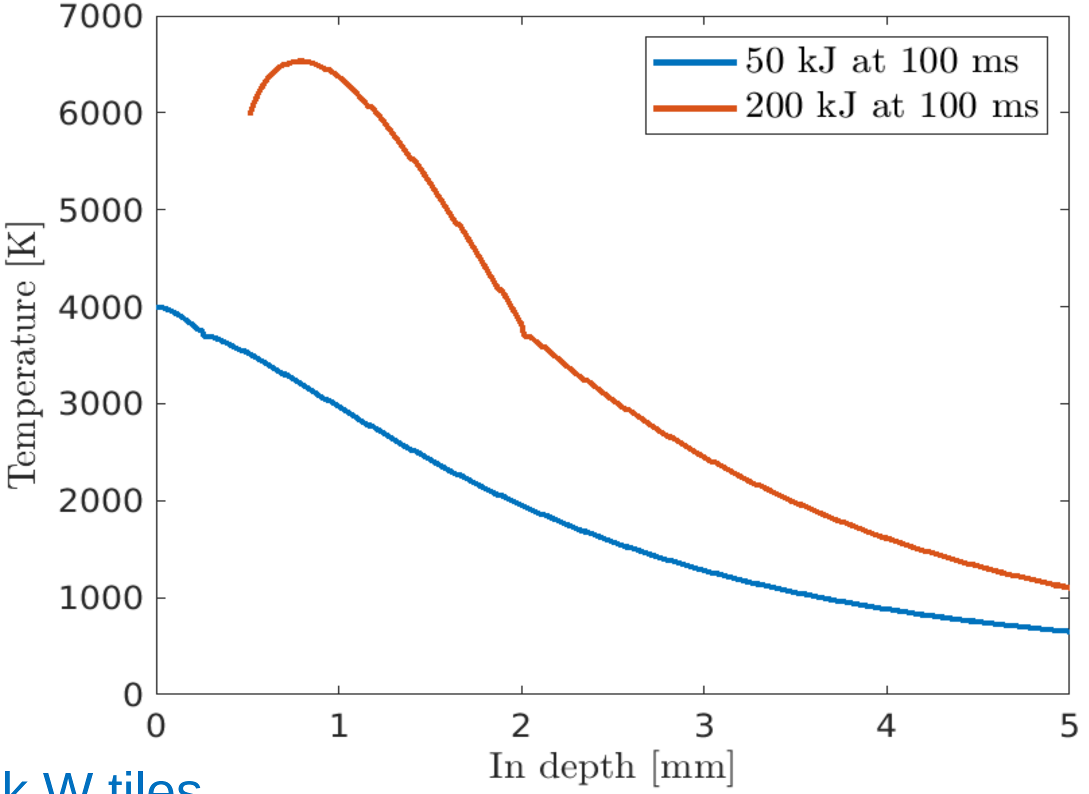
Depth-integrated power density for the "50 kJ over 1 ms" loading scenario. The apex corresponds to the 0 mm position toroidally. Thin black lines indicate the tiles, the most loaded tile is marked by the dashed red line.

Scaling: for "50 kJ" it is 6.7 kJ on the most loaded MB

- A 3D temperature response of a single tile on the MEMENTO simulation domain.
- Note colors correspond to the temperature bar and do not indicate material layers.
- The hypervapotron position and shape can be appreciated.

Results: surface damage (short time scale)

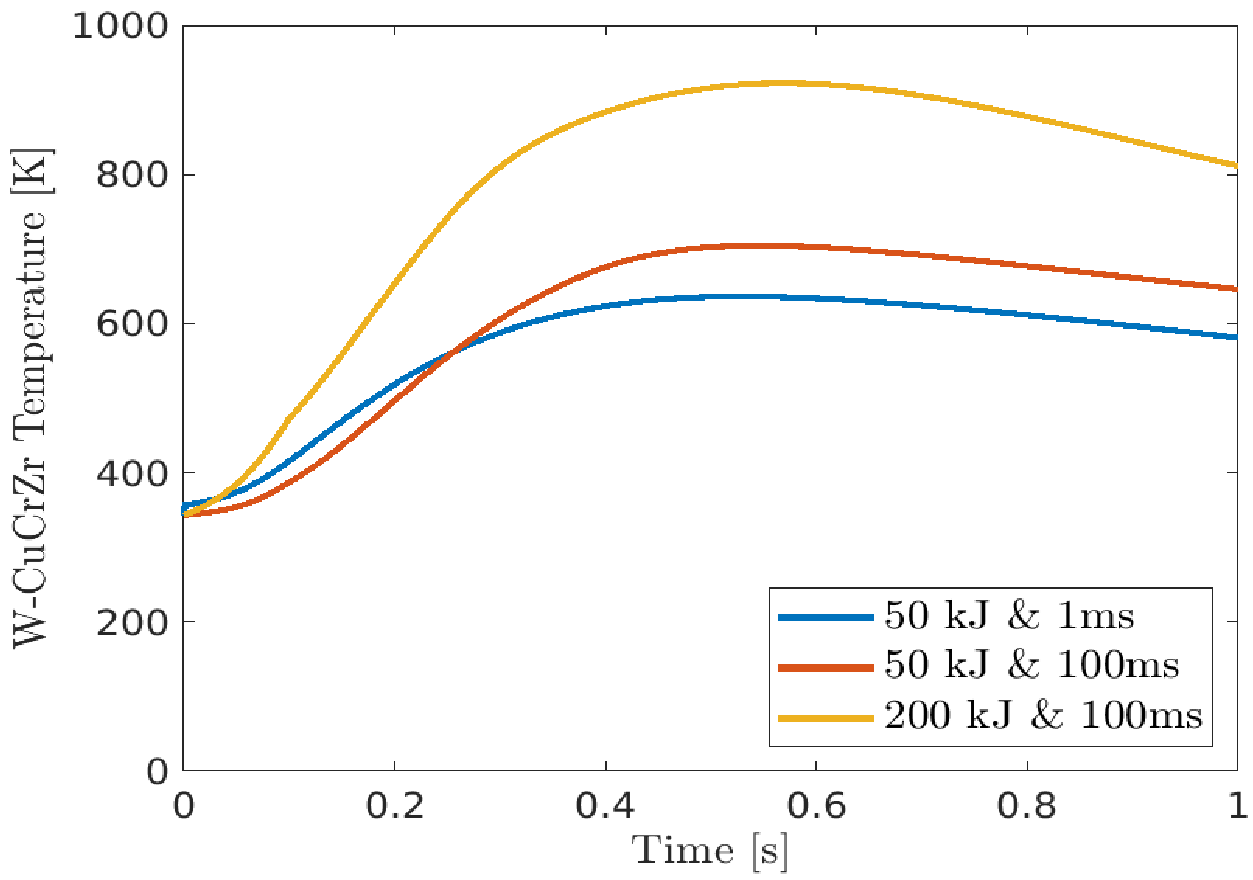




8 mm thick W tiles

non monotonic profile → max temperature beneath the surface → internal stress buildup due to uneven thermal expansion & internal boiling → thermal shock, explosion and material detachment

Results: coolant damage (long time scale)



Vaporization losses at 1 ms reduce T

Temperature evolution at the W-CuCrZr interface for three loading scenarios.

8 mm thick W tiles

Summary tables

1 ms loading

* crashed runs due to extreme T

	8 mm			8 mm *without energy map shifting*	12 mm	12 mm *without active cooling*
deposited	50 kJ	75 kJ*	150 kJ*	50 kJ	50 kJ	50 kJ
$T_{surface}^{max}$	7146 K	7361K	7600 K		7105 K	7068 K
h_{melt}	0.46 mm at 1.8 ms	0.396 mm	0.313 mm	Not significant effect overall	0.48 mm at 2 ms	0.47 mm at 2 ms
h_{vap}	93 μm	67 μm	31 μm		87 μm	84 μm
$T_{W-CuCrZr}^{max}$	636 K at 0.52 s	N/A	N/A		524 K at 0.95 s	930 K at >1 s

100 ms loading

	8 mm		8 mm *without energy map shifting*	12 mm	12 mm *without active cooling*
deposited	50 kJ	200 kJ	200 kJ	50 kJ	50 kJ
T_s^{max}	3995 K	5972 K	5654 K	4014 K	3957 K
h_{melt}	0.25 mm at 100 ms	1.5 mm at 114 ms	1.6 mm at 105 ms	0.27 mm at 100 ms	0.23 mm at 100 ms
h_{vap}	0 μm	540 μm	264 μm	0 μm	0 μm
$T_{W-CuCrZr}^{max}$	704 K at 0.54 s	922 K at 0.57 s	902 K at 0.58 s	576 K at 1 s	1144 K at 2 s

- ➢ Surface damage is independent of the tile thickness (due to grazing angles + short loading times)
- ➢ Increased thickness reduces coolant interface temperature
- ➢ Vaporization losses reduce coolant interface temperature (explosions effect is similar)

→ different interpolations to go from GEANT4 energy density to MEMENTO grid which varies between the runs to accommodate different size and/or cooling pipe → small deviations in case which must be similar otherwise

2. JOREK input

Run ID	Pitch	Energy	MHD case
1	0.99	Mono-dist (26MeV)	Unmitigated
2	0.99	Mono-dist (26MeV)	Mitigated
3	0.99-1	Avalanching-dist	Unmitigated
4	exp(-10*pitch)	Avalanching-dist	Unmitigated

H. Bergstrom *et al*, PPCF **66** 095001

Critical assessment of the results

- The contact of the tiles through the CuCrZr layer is neglected (minor effect)

- Unavoidable uncertainties in the W thermo-physical properties at the *extreme temperature range* above the normal boiling point, as commented above, lead to not-easily-quantifiable inaccuracies, but do not undermine the overall conclusions with respect to the predicted damage.

<u>Given the lack of a complete picture of the thermo-*mechanical* response, only general comments can be made</u>

- Surface modifications (vaporization, explosion, melt motion) → the incident REs might not hit the deformed surface anymore and/or impact the surface at different angles thus changing the energy deposition.

- Non-monotonic temperature profiles → possibility for explosive detachment of material

- Melt evolution: even in absence of a drive, the surface tension will force melt to drip over the corners and into the gaps → cannot exclude that the hot melt might reach the CuCrZr layer or arrive in its proximity, bridge or bridge/fill in gaps

Summary : PFC damage under volumetric heat loads

- Big investment in scattering implementation schemes but will pay off in modelling of experiments and ITER-relevant scenarios, in particular for realistic, large & complex geometry PFCs

- ITER-relevant scenarios are challenging due to the grazing angle RE-impacts and B field
  - Ultra-shallow energy deposition and regimes of extreme temperatures and intense vaporization
  - Challenges for both GEANT4 and MEMENTO – high resolution, rapid loss of cells, non-uniform loading due to presence of B field, demanding 'large panel' runs to identify the most loaded MB

- Surface damage is basically independent of the tile thickness (due to grazing angles + short loading times)
- The increased thickness reduces coolant interface temperature and can give more margin to survive more events
- Vaporization (similarly - explosions) initially reduce coolant interface temperature but benefit is lost when the erosion depths are extreme (proximity to coolant)

- Higher energy of REs and **steeper impact angles** relax energy density profiles : benefit of reduced surface damage but energy is deposited closer to the coolant

Outlook

Short term

Continue benchmarking/validation activity

- ❖ Thermal response of ITER W panels with simplified input – remaining parameter scans
- ❖ Thermal response of ITER W panels with JOREK input

Short-mid term

- ❖ Controlled W experiments – design through predictive modelling and eventual validation

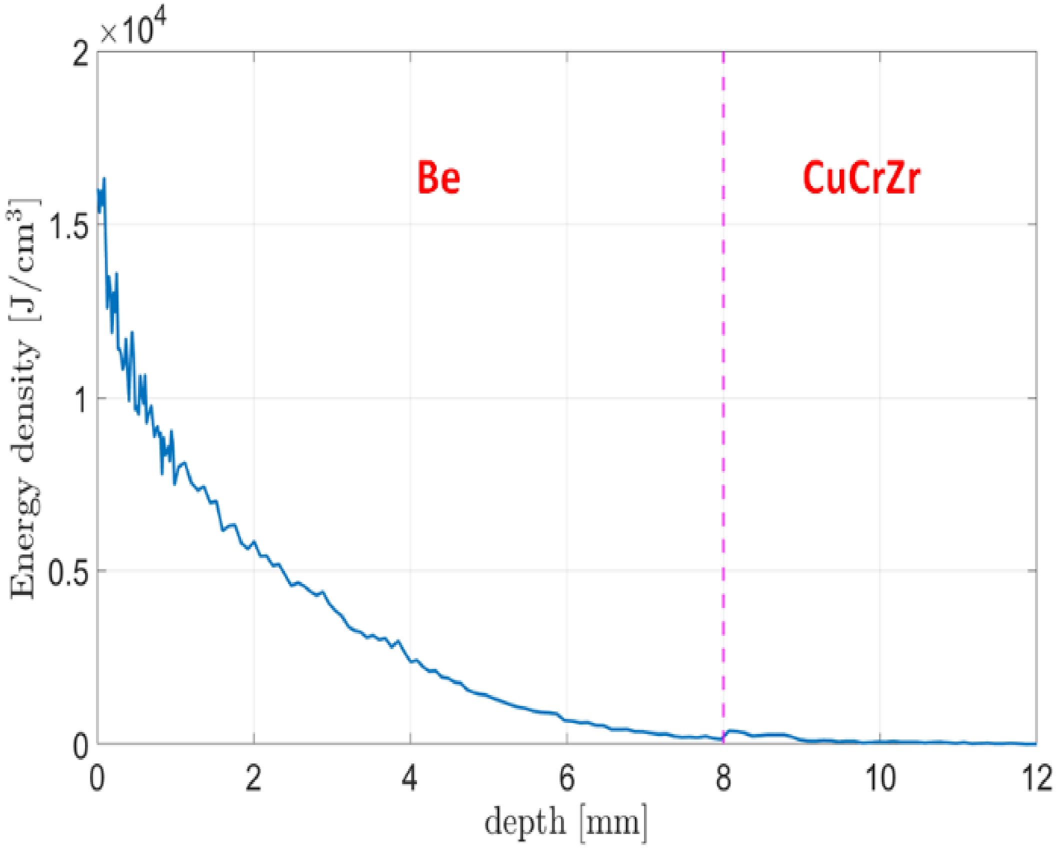
Long term

- ❖ Going beyond heat transfer (development of physics models for thermo-mechanical response)
- ❖ Improve thermophysical properties at extreme temperatures beyond 6000K

EXTRA SLIDES

1. Simplified input : Be runs

Energy deposition : B field



Energy density depth profile for the most loaded Be tile in the “50 kJ over 1 ms” loading scenario.

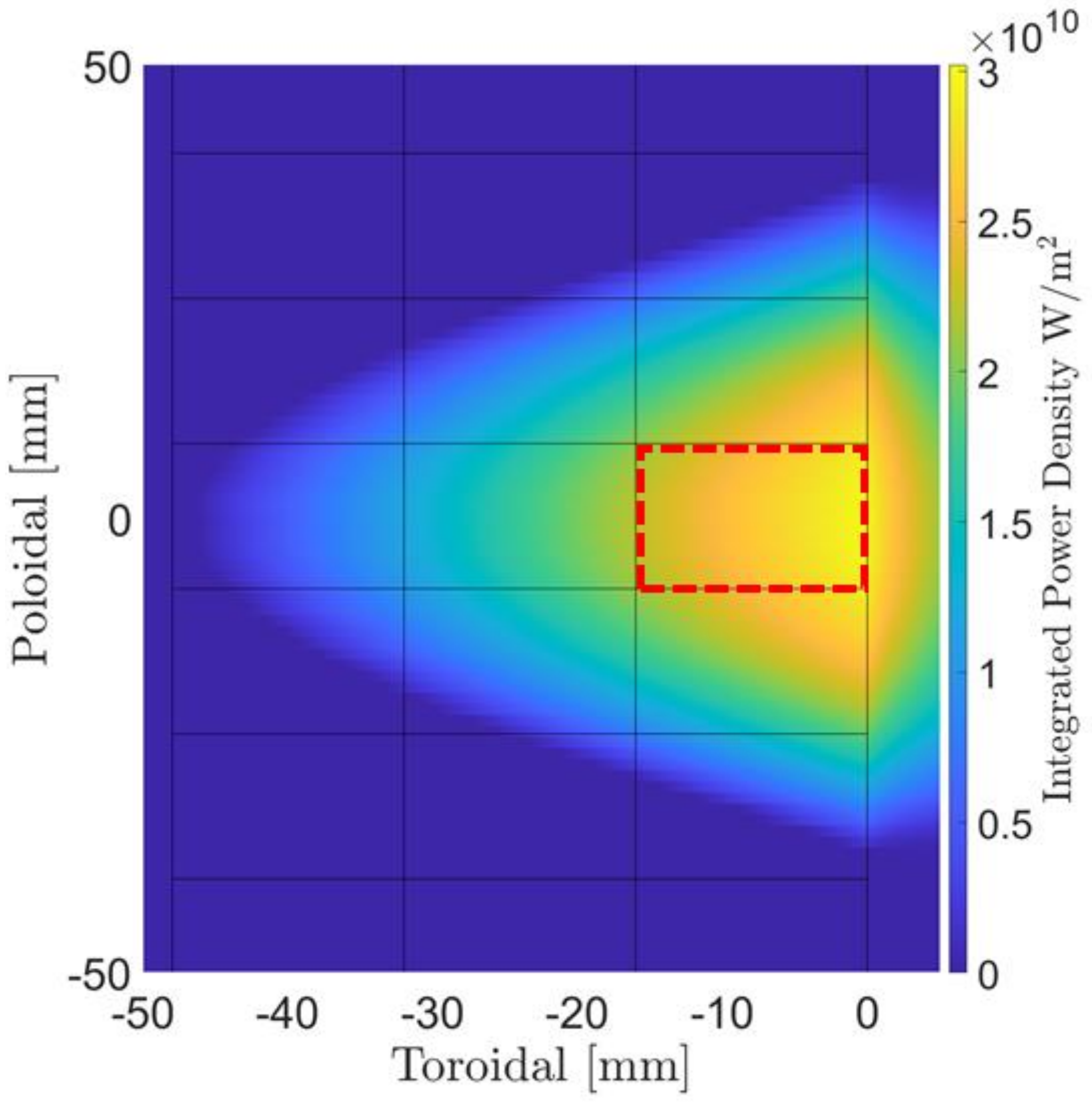
Depth range for 1-10 MeV electrons
in W is about one -few mm
in Be within 0.3-3.5cm

In Be large fraction of the REs leaving the surface due to *gyromotion inside the tile*

For the same incident RE beam, the Be apex will receive appreciably less energy (1.6 times less).

In order facilitate a meaningful comparison with the W results, we deal with the energy deposited (absorbed) per apex and not with the incident energy (i.e. the energy of the RE beam).

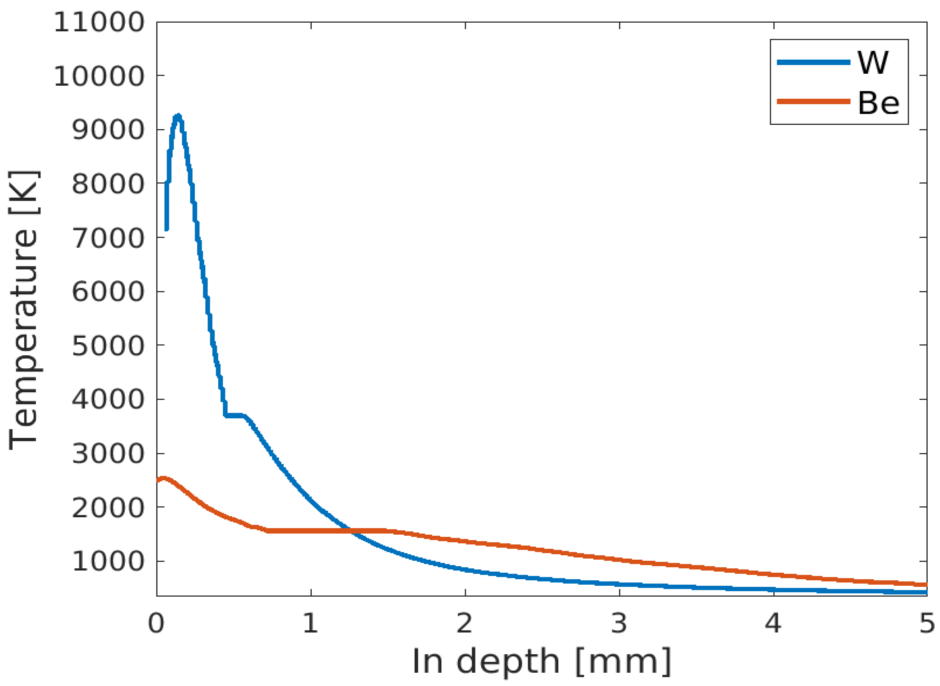
Energy deposition: B field effect



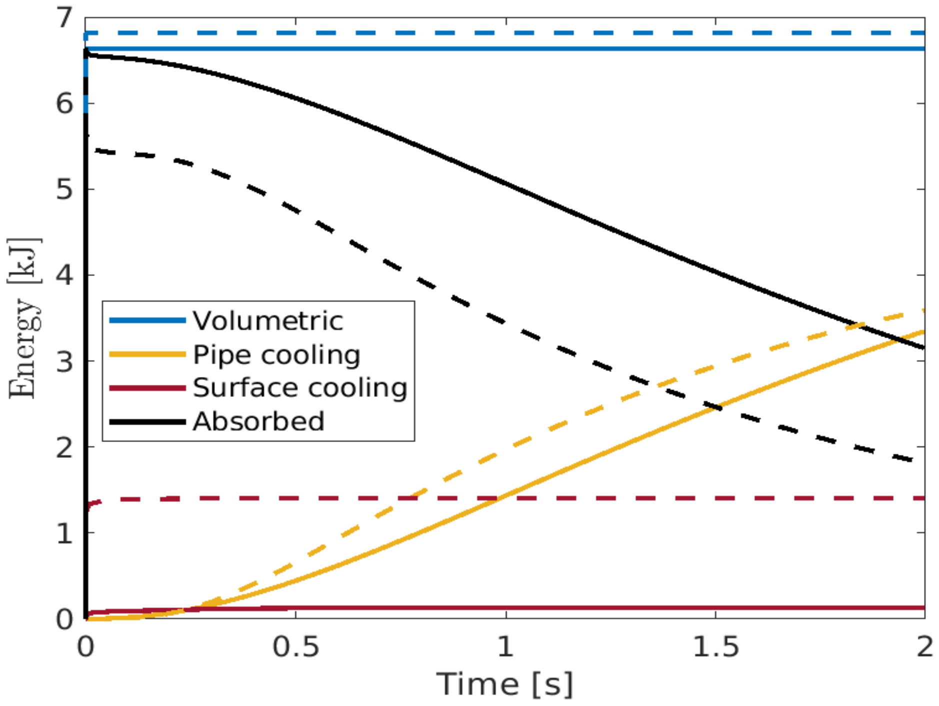
Depth-integrated power density for the “50 kJ over 1 ms” loading scenario.
The apex corresponds to the 0 mm position toroidally.
Thin black lines indicate the tiles, the most loaded tile is marked by the dashed red line.

Results

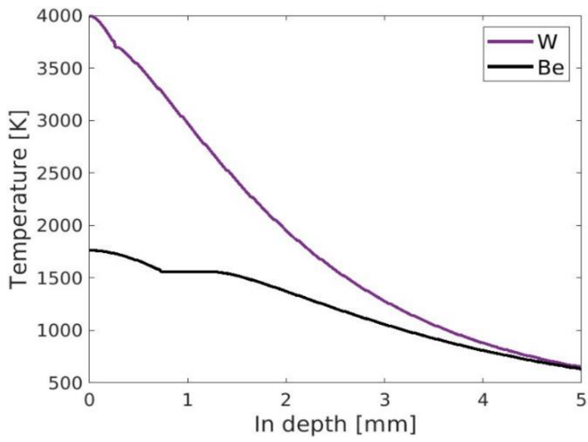
~2 times lower thermal diffusivity of Be compared to W



Temperature depth profiles for the “50 kJ over 1 ms” scenario at the end of loading on the W and Be most loaded tile. The W profile is shifted from the free surface (at 0 mm) due to erosion.



Energy balance for the most loaded tile under ’50 kJ over 1 ms’ scenario. Color code is identified in the figure label and for the same color dashed lines are for W and solid are for Be.



“50 kJ over 100 ms”