EUROfusion

Emitted current escaping from W, Dust production from melting & Dust adhesion

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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.

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SPD.1 (D006): Semi-empirical analytical description of emitted current escaping from W surfaces

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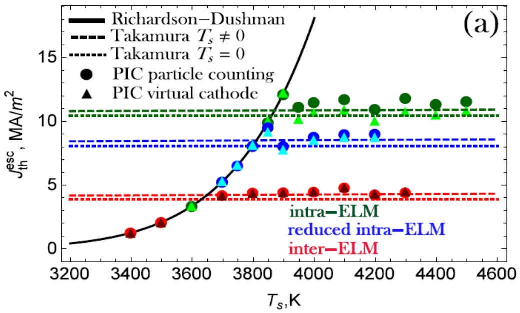
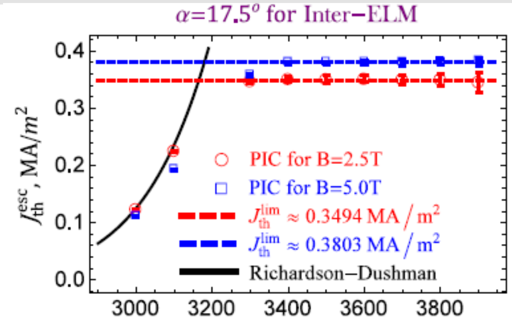
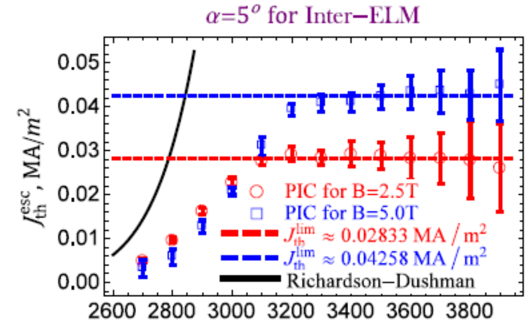
Space charge limited regime (general)

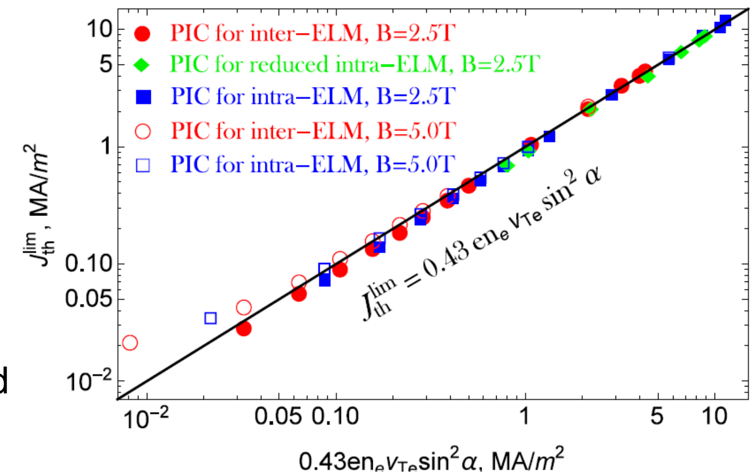






Komm, Ratynskaia, Tolias *et al*, PPCF **59** 094002 (2017);
Komm, Tolias, Ratynskaia *et al*, Phys. Scr. 014069 (2017);

The escaping current density follows the Richardson-Dushmann curve up to a surface temperature and then remains constant due to the formation of a virtual cathode. At very low inclination angles, prior to current limitation, the escaping current is lower than the Richardson Dushmann due to prompt re-deposition.



The escaping current density can be calculated as $J_{th} = \min\{J_{\rm th}^{\rm RD}, J_{\rm th}^{\rm lim}\}$ where $J_{\rm th}^{\rm lim} = 0.43 e n_e v_{Te} \sin^2\alpha$ is a semi-empirical expression that has been benchmarked against hundreds of PIC simulations for different plasma conditions, inclination angles and magnetic field strengths

Komm, Ratynskaia, Tolias and Podolnik, NF, **60** 054002 (2020)

- In DEMO and ITER sheaths, the situation can be much more complicated because thermionic emission is entangled with field emission and coexists with electron-induced electron emission as well as ion-induced electron emission.
- For modelling of W melt motion it is crucial that semi-empirical cost-effective descriptions are developed

Semi-empirical description

In the hot intra-ELM ITER plasmas, **at normal magnetic field inclination angles** relevant for exposed leading edges, a complicated **multi-emissive sheath** surrounds hot W PFCs, where:

(a) the transition to the space-charge limited regime occurs at unrealistically high surface temperatures so that the monotonic potential profile regime is the most relevant for W melt motion,

(b) the electron backscattering (EBS) and secondary electron emission (SEE) contributions to the escaping current density are very important prior to the virtual cathode formation,

(c) field assisted thermionic emission (TE) within the extended Schottky regime substitutes pure thermionic emission prior to the virtual cathode formation

[P. Tolias, M. Komm, S. Ratynskaia and A. Podolnik, NME **25**, 100818 (2020)].

Modelling of **W melt motion** requires the evaluation of the escaping current density at each time step and each grid point of the PFC free surface. **It is crucial that semi-empirical cost-effective descriptions are developed**.

- An electron emission model has been implemented in the SPICE2 2D3V code that describes SEE, EBS and field-assisted TE in the extended Schottky regime
  [P. Tolias, M. Komm, S. Ratynskaia and A. Podolnik, NME **25**, 100818 (2020)].
- More than 100 PIC simulations were carried out in order to guide the development of such a semi-empirical model and also benchmark it.

Semi-empirical description

A **very accurate semi-empirical determination of the escaping current density** has been proposed
[P. Tolias, M. Komm, S. Ratynskaia and A. Podolnik, '*ITER relevant multi-emissive sheaths at normal magnetic field inclination*', EUROfusion pinboard entry No. 362, submitted to Nucl. Fusion]
which features

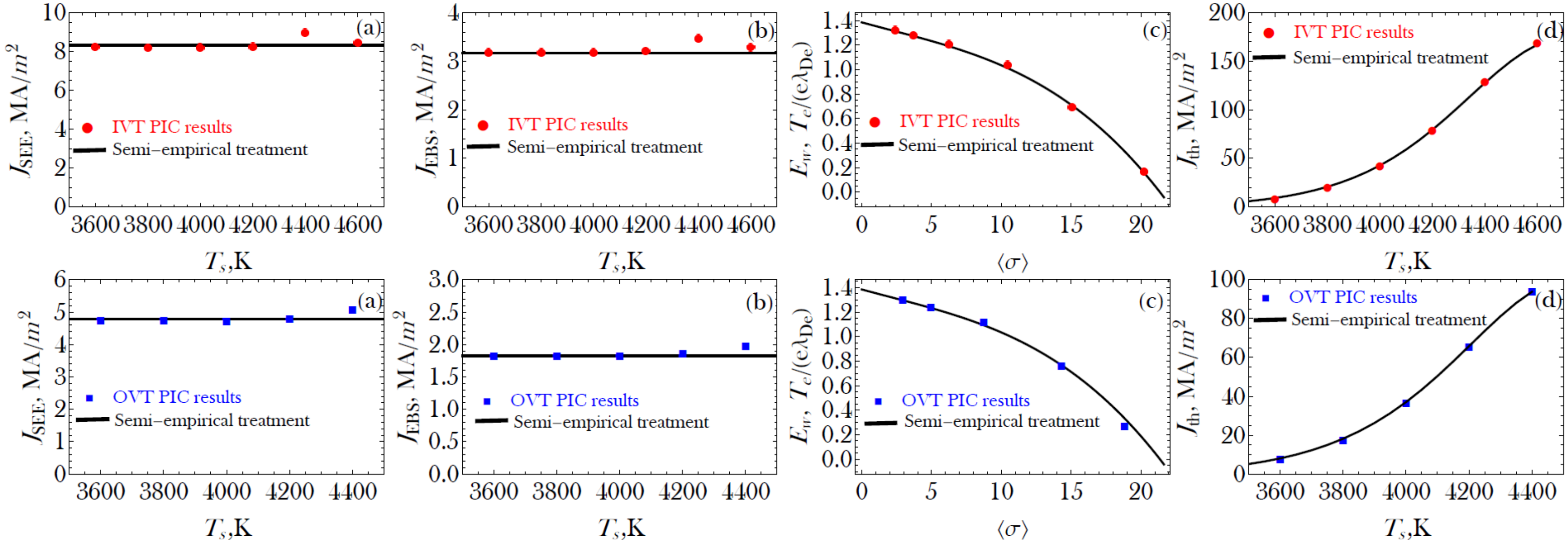
- A semi-empirical expression for the average SEE yields [started and completed in 2021]
- A semi-empirical expression for the average EBS yields [started and completed in 2021]
- An empirical expression for the normal wall electrostatic field [started in 2021, completed in 2022]
- A methodology for the solution of the non-linear problem for the Schottky effect [started and completed in 2022]

It has been demonstrated that the multi-emissive sheath treatment (relevant for ITER) leads to escaping current densities that are typically **3-5 times larger** than those resulting from the thermionic sheath treatment (relevant for present-day tokamaks).

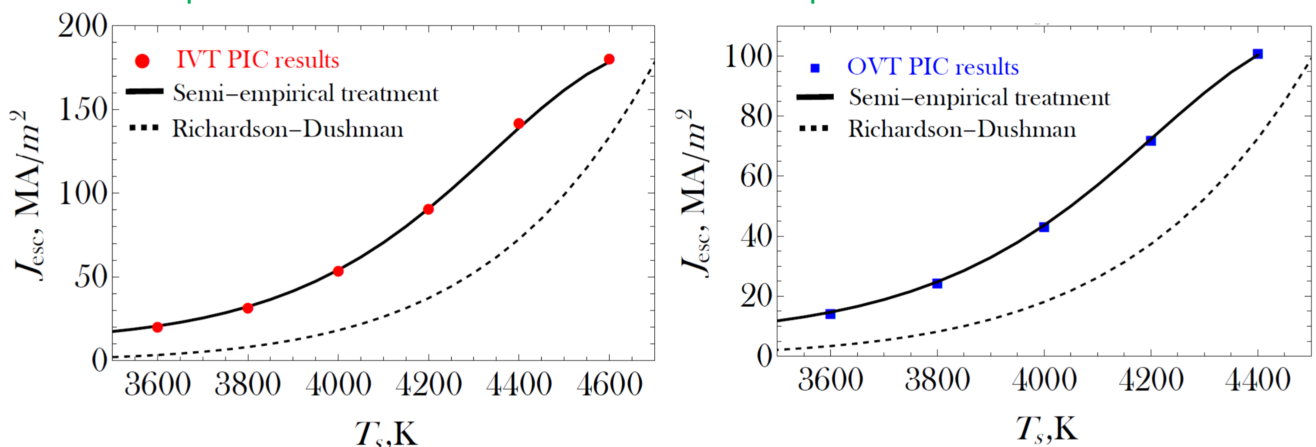
The Schottky effect is the main physical process behind this enhancement.
Note that there should be a corresponding increase in the **volumetric Lorentz force**. This highlights the importance of our studies.

Benchmarking of proposed description

Benchmarking of the semi-empirical description of the SEE current density, the EBS current density, the electrostatic field at the wall and the field-assisted thermionic current density against SPICE2 PIC simulations for IVT & OVT intra-ELM conditions.



Benchmarking of the semi-empirical description of the total escaping current density against SPICE2 PIC simulations for IVT & OVT intra-ELM conditions and comparison with the Richardson-Dushman expression.



Further plans for end 2022 -2023

- **The semi-empirical analytical description of the multi-emissive collisionless ITER sheath at normal inclination angles has been successfully completed.**

- **The semi-empirical analytical description of the multi-emissive collisionless ITER sheath at oblique inclination angles is the next objective [up to the end of 2023].**
  - The first sets of ITER intra-ELM PIC simulations at grazing inclination angles have been performed and will soon be analyzed.
  - A concrete *simulation plan* will be devised in order *to maximize the physics input that is necessary for the construction of a semi-empirical description.*

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SPD.2 (D005): Model development for dust production mechanisms from melting

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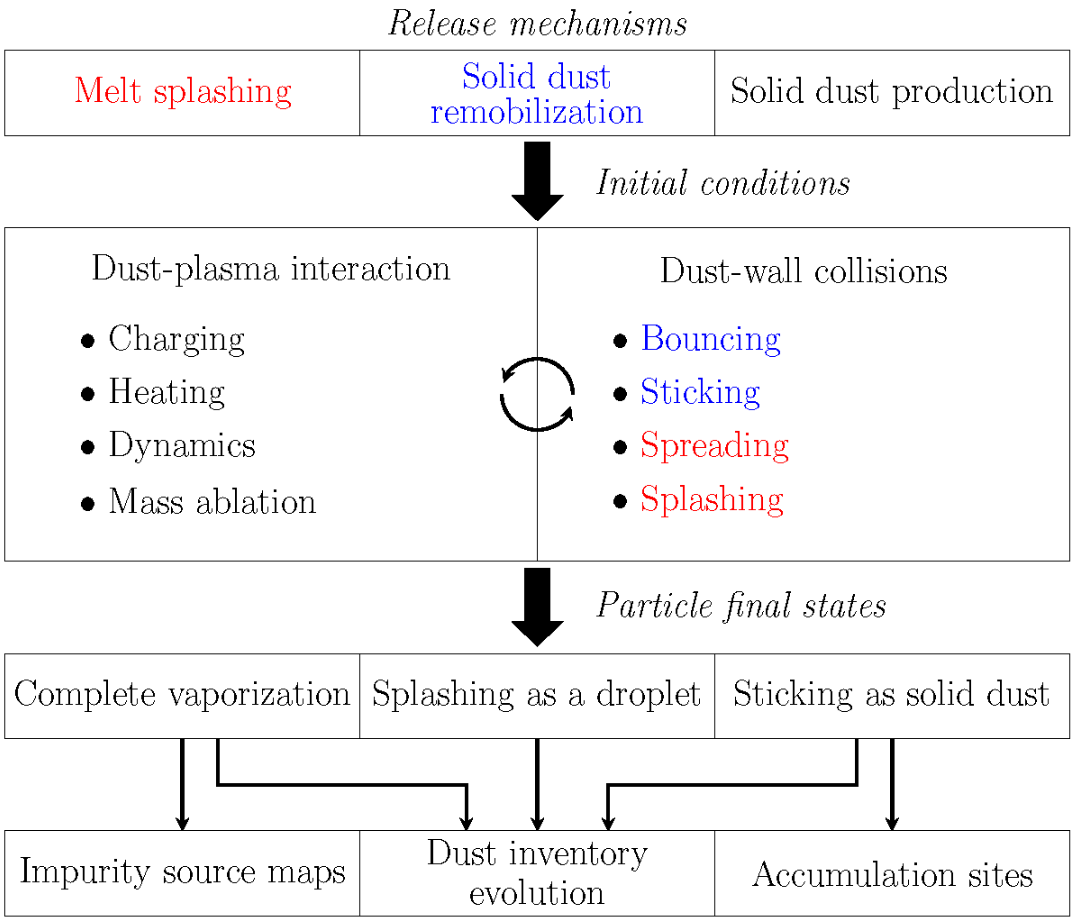
Dust production from melting

S. Ratynskaia, A. Bortolon, S. I. Krasheninnikov, “*Dust and powder in fusion plasmas: recent developments in theory, modeling, and experiments*”, Reviews of Modern Plasma Physics **6**, (2022) 20

S. Ratynskaia, L Vignitchouk, P Tolias, “*Modelling of dust generation, transport and remobilization in full-metal fusion reactors*”, Plasma Physics and Controlled Fusion **64** (2022) 044004



Dust production from melting: ”flow over edge”

Current quenches and ELMs

a) “Internal” destabilization by melt velocity gradients → Orr-Sommerfeld instability

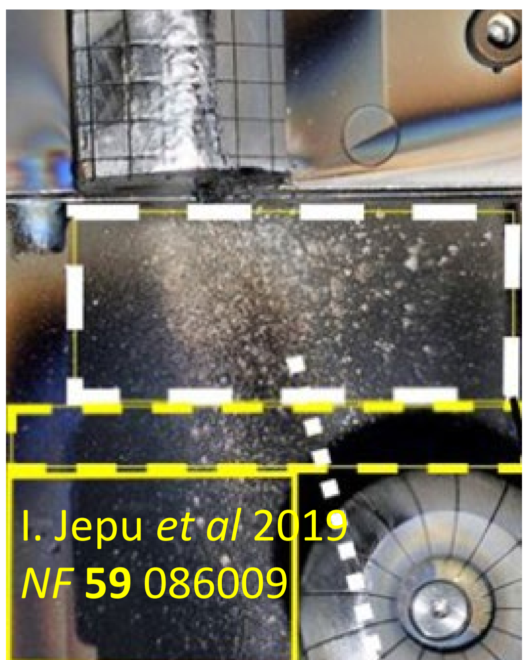
b) “External” destabilization by plasma flow (Kelvin-Helmholtz instability), plasma or vapor ∇p

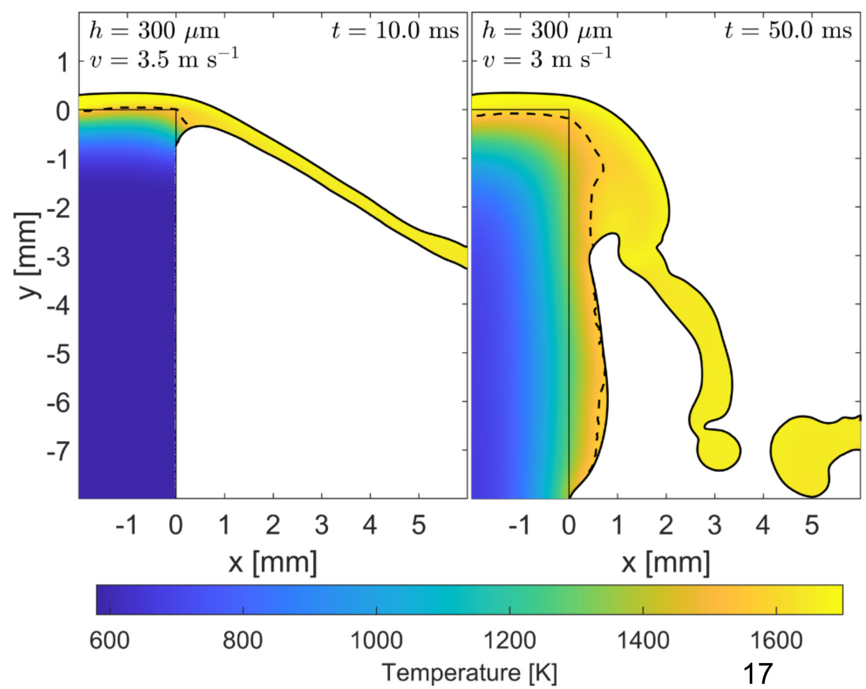
c) Geometrical obstacles (Rayleigh-Taylor analogy)

Present-day tokamaks:

Splashing observed when obstacles or the edge of a component are present

Vignitchouk et al NF **62** (2022) 036016

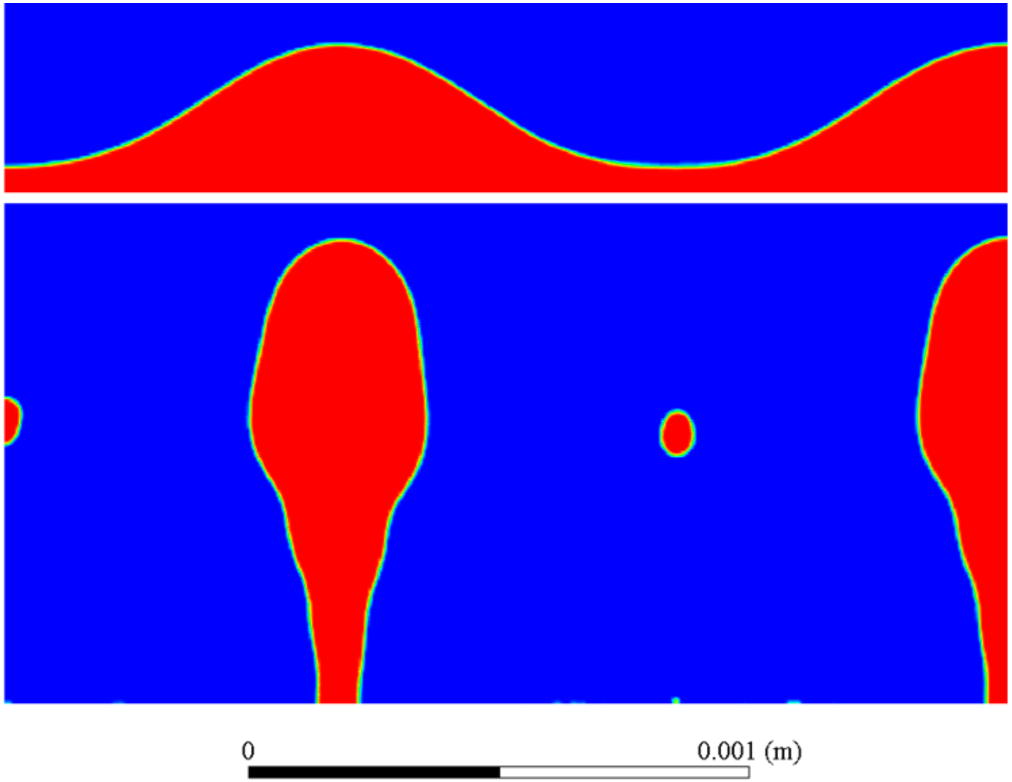




Dust production from melting: ”thermal quench”

Thermal quenches

$\boldsymbol{J}_{eddy}\times\boldsymbol{B}$ force normal to the pool surface – possibility for Rayleigh-Taylor instabilities

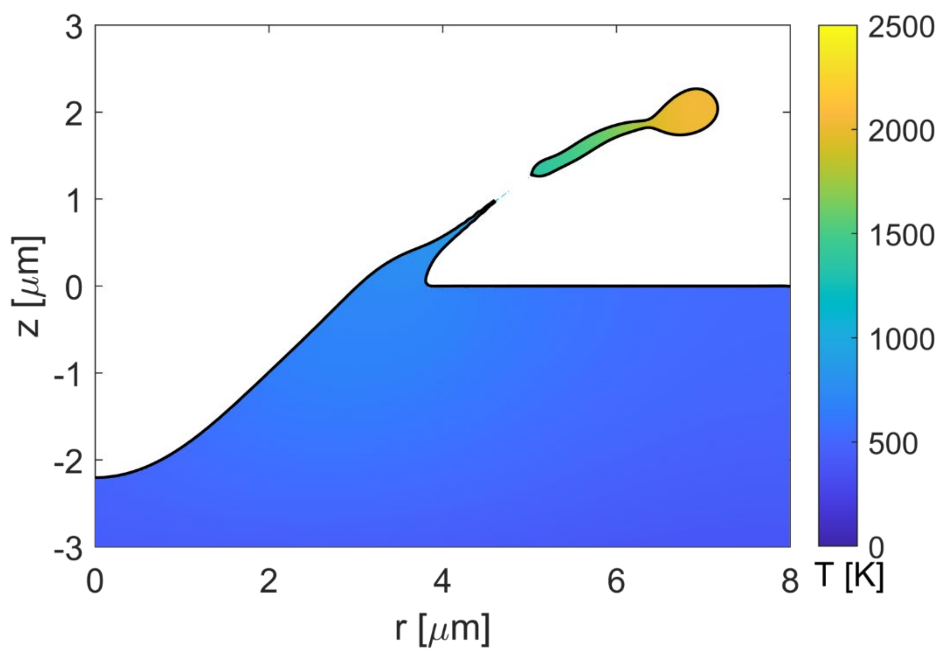


Melt pool of thickness 160 µm subjected to a uniform ‘upward’ body force F =37 MN/m^3 during 5 ms.

Dust production from melting: arcing

Pressure driven flows

Cathode spots:
axisymmetric plasma heat fluxes and pressure gradients lead to local surface melting followed by crater formation as the melt is pushed outwards within a few tens of ns

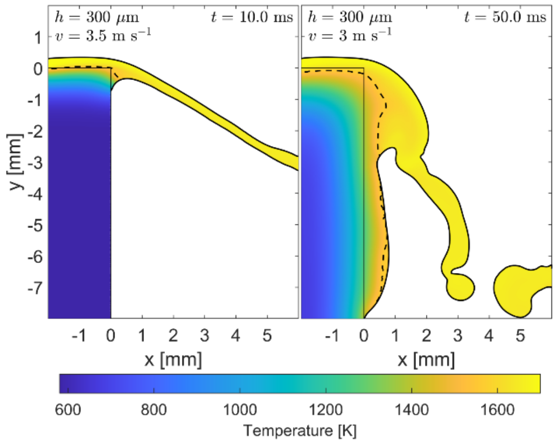


Dust production from melting: RE-induced

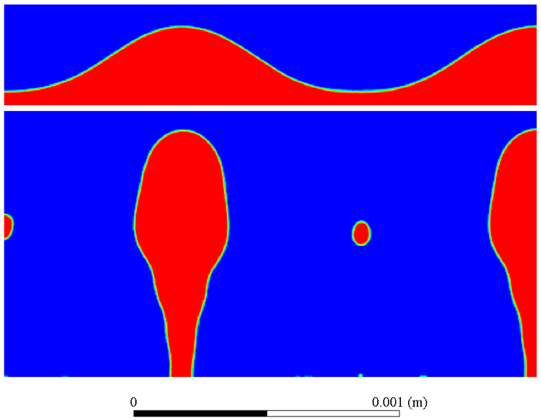
PFC – RE interaction is not part of this task

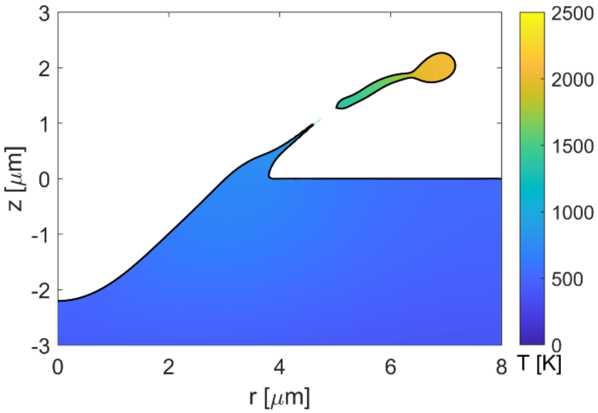
(a brief discussion can be found in the reviews cited on 1st slide)

Modelling of splashing events



Time scale ∽ 100 ms
Scale of mm, resolution ∽ μm





Time scale ∽ few ns,
Scale of μm, resolution ∽ 10's nm

Vaporization	Not very crucial	Effect stability	Driving melt (secondary plasma)

Commercial software (e.g. ANSYS, COMSOL)

- Limited by the customization capabilities in terms of free-surface conditions
- Licenses issues, cost of 3D runs

Development of *in-house* code

- Manpower costly

Volume-of-fluid (VOF) framework

- Metal-plasma interface tracked via metal volume fraction α
- Single computational fluid with averaged properties, e.g.

$$\rho = \alpha\rho_{metal} + (1-\alpha)\rho_{plasma}$$

- "Plasma" is a ghost fluid, not meant to be physically relevant
- Incompressible Navier-Stokes system with heat conduction-convection and mass, momentum and energy sources

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

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \boldsymbol{v}) = S$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla p + \nabla \cdot \left(\mu(\nabla v + \nabla v^{\top})\right) + \boldsymbol{F}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \varepsilon \boldsymbol{v}) = \nabla \cdot (k \nabla T) + Q$$

$$\varepsilon(T) = \int_{T_0}^{T} c_p(T')\, dT' + \mathbb{H}(T - T_{melt})\Delta H_{melt}$$

Interface conditions in VOF simulations

The metal-plasma interface isn't a computational boundary, volumetric sources must be used instead of surface boundary conditions

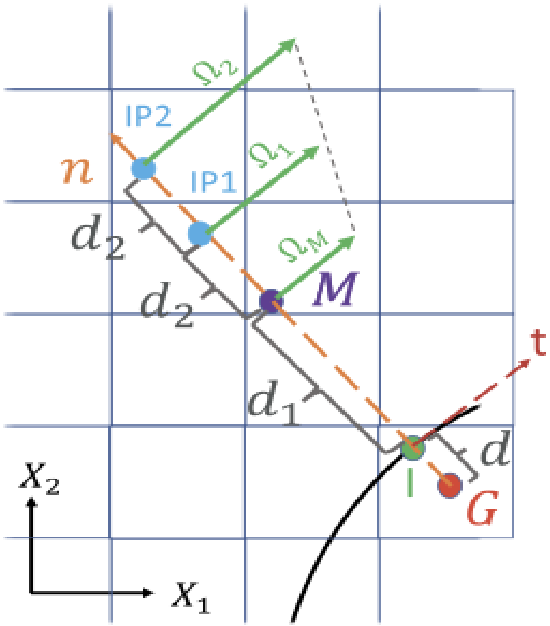
- Most field values inside the interface volume have no direct physical meaning; only their gradients do, to ensure that the solutions are correct in the metal domain
- Gradients through the interface volume are large → interface field values are **very** badly defined

Vaporization processes are particularly challenging since

- they depend **exponentially** on the surface temperature, which itself is an ill-defined quantity
- they appear in the continuity and momentum equations, hence they directly affect free-surface dynamics and the solution for $\alpha(\boldsymbol{r}, t)$

In-house code

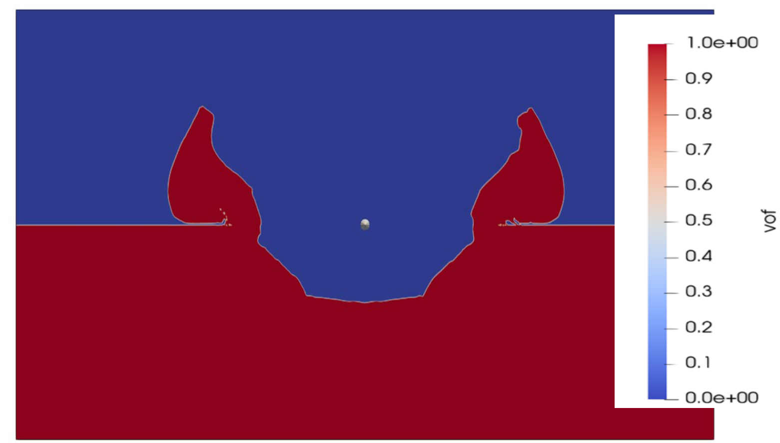
- Development of *in-house* parallel and scalable code (up to 32000 processors) aiming to solve the coupled multi-phase Navier-Stokes and heat conduction-convection equations
- Use of the PLIC-VOF method (piecewise linear interface-capturing volume of fluid) together with free-surface boundary conditions imposed at the discrete level on the



Shahmardi, A., Rosti, M. E., Tammisola, O., & Brandt, L. (2021). A fully Eulerian hybrid immersed boundary-phase field model for contact line dynamics on complex geometries. *Journal of Computational Physics*, 110468.

- The two phases are decoupled at a discrete level
- The material properties of the plasma, often difficult to predict, do not affect the fluid dynamics of the liquid metal.

RESULTS: the multi-phase fluid dynamics solver has been tested on arcing-relevant scenarios



Simulated metal volume fraction after exposure of a pre-existing pool of liquid copper to arc-like conditions (external pressure profile with peak value 200 MPa, characteristic decay length 1 μm and duration 30 ns). The snapshot is taken at t=90 ns, the radius of the crater is ~ 3 μm.

In-house code status

- Methodology choice based on the specificity of fusion relevant melting scenarios

- The multi-phase fluid dynamics solver has been successfully tested on arcing-relevant scenarios

- Numerical implementation of heat solver is not completed yet

Attempts at designing highly customizable set-ups in ANSYS Fluent

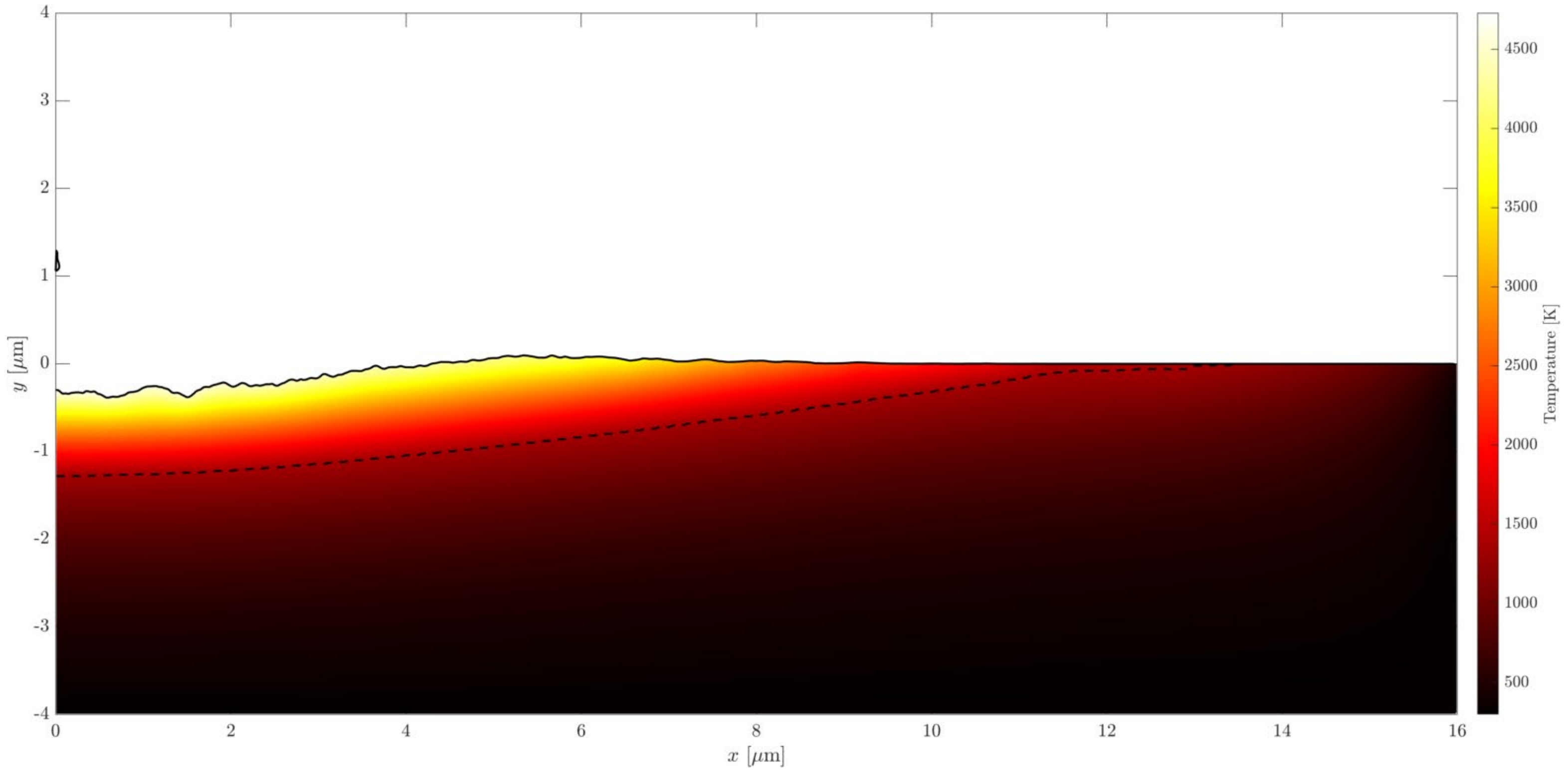
4 possibilties envisaged for vaporization sources

(tests shown here for heat and momentum only, i.e. no mass loss)

- Direct approach: use local temperature (numerically unstable)
- Interface-seeking approach: fetch T_{surf} from the nearest metal cell (costly)
- Auxiliary field approach: estimate T_{surf} from local data in the interface volume (currently under test)
- Conservative source approach: mimic the form of a conservative source term (future work)

Direct approach results (Cu arc cathode)

- The strong temperature gradients through the interface magnify the errors in the volumetric source terms
- Numerically unstable free-surface deformations develop at the mesh cell scale, ultimately crashing the simulations



Auxiliary field results (Cu arc cathode)

- Auxiliary temperature defined by $\rho_{metal}\varepsilon_{metal}(T_{aux}) = \alpha\rho\varepsilon$
- Numerical instabilities well suppressed (some oscillations still arise, but they might be physical)

Outlook for end 2022 - 2023

- In-house code: Resume heat solver implementation and testing if time/manpower permits

- Continue designing ANSYS Fluent set-ups with better customizability to include a wider variety of plasma-surface interactions processes

- Exploring in full detail unstable scenarios of thermal quenches (highly relevant to ITER)

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SPD.3 (D006): Dust adhesion and self-charging

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Adhesive force measurements

- Systematic measurements of the W-on-W adhesive force have been performed with the electrostatic detachment method. They managed to elucidate the physical mechanism behind adhesion which is dominated by long range multipole-multipole interactions and not by short range metallic bonding.

- These measurements also quantified the effect of various tokamak non-idealities:
- **(a)** dust deposition speed, **(b)** tokamak impurities, **(c)** surface roughness, **(d)** atmospheric impurities, **(e)** heat exposure [Tolias *et al.* NME **12** 593 (2017); NME **15** 55 (2018); NME **18** 18 (2019); NME **24** 100765 (2020)].

- The latest measurements focused on the effect of high temperature pre-history on W-on-W adhesion. It was revealed that it leads to enhancements **even by an order of magnitude** due to diffusion bonding effects. This level of enhancement could only be roughly estimated due to technical limitations in the electrostatic detachment device.

- **Perform accurate measurements of the W-on-W adhesion enhancement owing to prolonged thermal treatments with an upgraded detachment device that can reliably measure six times stronger adhesive forces.**

- The new HV supply that will expand the technical capabilities of the electrostatic detachment device was delivered a month ago (it has ordered a year ago!). The supply has been tested and the detachment device is now being updated to withstand the higher voltage differences.

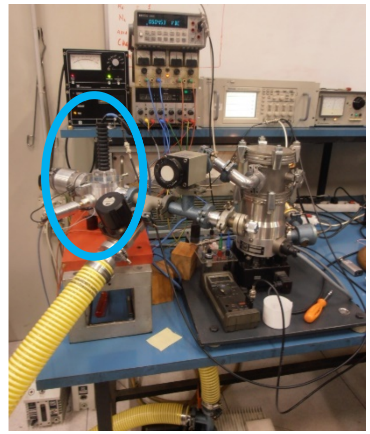
Adhesion forces device upgrade

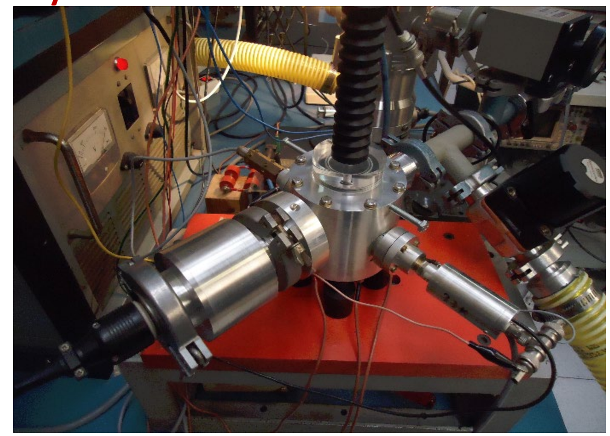
- ➢ Acquired a new HV power supply, mod. XP GLASSMAN MK60P1.2:
  - V=0-60kV, I=0-1.2mA;
  - Voltage & current regulation;
  - Protected against arching and cc;
  - Remote control.

- ➢ The device and vacuum chamber layout have been revised to withstand HV field (see images on the right):
  - New insulated HV connection to the chamber;
  - Inserted current limiting resistor to prevent power supply damage in case of arching;
  - Inserted new HV breakers;
  - Revised the vacuum chamber layout (not showed in figures).

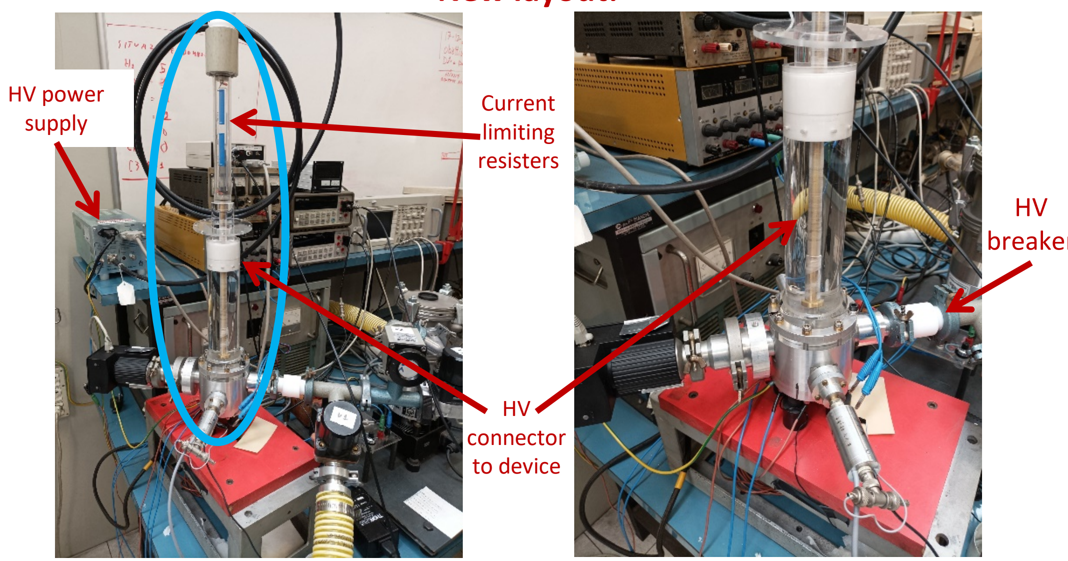
- ➢ Device tested up to 60kV.

Previous layout:





New layout:



Adhesive force calculations

- Theoretical calculations of the adhesive force between fusion-relevant materials have been performed with the non-retarded Lifshitz theory of van der Waals forces [P. Tolias, FED **133** 110 (2018); Surf. Sci. **700** 121652 (2020)].

- Counterintuitively, adhesive forces caused by van der Waals interactions have a range of few microns in contrast to adhesive forces caused by metallic bonding whose range is less than a nanometer.

- This range is comparable to the typical sheath thickness of the cold dense plasma of the divertor. Thus, adhesive forces need to be calculated not only at contact but also at different separations.

- **Perform ultra-accurate fully retarded Lifshitz theory calculations of the adhesive force for fusion relevant dust-wall combinations from the Hamaker limit at contact up to the Casimir asymptotic limit at long separations.**

- Fully retarded Lifshitz theory calculations have been performed for fusion relevant dust-wall combinations from the Hamaker non-retarded limit up to the Casimir asymptotic limit within the proximity force approximation or Derjaguin approximation.

- A novel compact semi-empirical expression has been proposed for the separation-dependence of the Hamaker coefficient that has been demonstrated to be very accurate for any metal-metal combination embedded in vacuum or water [P. Tolias, Surf. Sci. **723** 122123 (2022)].

- Fully retarded Lifshitz theory calculations will be performed for fusion relevant dust-wall combinations from the Hamaker non-retarded limit up to the Casimir asymptotic limit without invoking the proximity force approximation. These are computationally heavy calculations that are expected to be finished by the end of 2022.

Outlook for end 2022 - 2023

- Calculations that are expected to be finished by the end of 2022
- The first accurate W-on-W adhesion measurements will be carried out within 2022.
- The analysis of the new experimental results will take place in 2023.