Physical Mechanisms of Melt Layer Splashing in Tokamaks

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Outline

- Background & Previous Modelling
- Onset of Kelvin-Helmholtz Instability
- Modelling of Melt Instabilities & Splashing
- Summary
Our Recent Work & Collaboration


- J.W. Coenen, V. Philipps, the TEXTOR-Team, Forschungszentrum Jülich, Germany
Samples of macroscopic melt splashing

- Melt losses are due to plasma impact and/or various Lorentz forces
- Hydrodynamic instabilities of melt layers are important mechanism for their macroscopic losses
Melt Layer Motion and Splashing in TEXTOR

- tungsten melt layer spraying and splashing: fine spray of small droplets & melt splashes with large droplets

Lorentz force dominates and drives melt motion & splashing in TEXTOR

- ligament-like structure at the front of tungsten melt layer as well as on the molten surface from SEM

Melt Layer Motion and Splashing in TEXTOR

Roof shaped limiter moved close to the Last Close Flux Surface

Plasma-Melt Kelvin-Helmholtz Instability

- plasma & liquid tungsten → two immiscible, inviscid and incompressible fluids with the interface subjected to velocity shear

- two stages: 1) linear stage → wave speed, most unstable and critical wavelengths, critical velocity difference, growth rate; 2) non-linear stage → growth of waves, formation of liquid metal plumes, ligaments and droplets dragged by the plasma flow
Phenomenological Capillary Droplet Model

Kelvin-Helmholtz instability mechanism:

Caveat: linear stability analysis is extended to an essentially non-linear regime to predict droplet formation and melt layer losses

Main assumptions:

- most unstable wavelength is always significantly smaller compared to the melt thickness (an approximation of the deep melt)
- fine droplets are formed at the peaks of these short waves dragged away by the plasma flow ("plasma wind" effect)

Phenomenological Capillary Droplet Model

Maximum increment coefficient and fastest growing wavelength:

\[ \Gamma_\theta = 2\left(\rho_p \Delta V^2\right)^{3/2} / \left(3\gamma \sqrt{3\rho_m}\right) \quad \text{and} \quad \lambda_\theta = 3\pi\gamma / \left(\rho_p \Delta V^2\right) \]

with the radius of droplets assumed as \( \sim \lambda_\theta / 4 \)

For ITER conditions: weak ELMs <2.5 MJ/m² during <0.3 ms

\[ V_p \sim 10^5 \text{ m/s, } N_p \approx 10^{19} - 10^{20} \text{ m}^{-3} \implies \rho_p \approx 1.7 \cdot (10^{-8} - 10^{-7}) \text{ kg/m}^3 \]

It is stated: no growth of K-H waves and melt splashing

Our estimate: \( \lambda_\theta \sim 14 - 1.4 \text{ cm} \gg h_m \implies \text{model is not valid!} \)

For QSPA-T conditions: heat loads <1.6 MJ/m² during <0.3 ms

\[ V_p \approx 10^4 - 10^5 \text{ m/s, } N_p < 10^{22} \text{ m}^{-3} \implies \rho_p < 1.7 \cdot 10^{-5} \text{ kg/m}^3 \]

It is stated: droplets with \( \lambda_\theta / 4 \sim 10 \mu m \) and \( \tau \sim 1 / \Gamma_\theta < 0.1 \text{ ms} \)

Our estimate: \( V_p \sim 10^5 \text{ m/s, } N_p \sim 3.5 \cdot 10^{22} \text{ m}^{-3} \implies \rho_p \sim 6 \cdot 10^{-5} \text{ kg/m}^3 \)

required for \( \lambda_\theta \sim 40 \mu m \); the time of K-H instability \( \tau \sim 1.8 \mu s \)
Classical Stability Analysis

Dispersion relation:

$$\omega = -k_x \left( \frac{\rho'_m V_m + \rho'_p V_p}{\rho'_m + \rho'_p} \right) \pm \sqrt{\left( \kappa g \frac{\rho_m - \rho_p}{\rho'_m + \rho'_p} + \frac{\kappa^3 \gamma}{\rho'_m + \rho'_p} \right) - \frac{k^2 x \rho'_m \rho'_p}{(\rho'_m + \rho'_p)^2} (V_m - V_p)^2}$$

with $\rho'_m = \rho_m \coth(\kappa h_m)$, $\rho'_p = \rho_p \coth(\kappa h_p)$ and $\kappa = \sqrt{k_x^2 + k_y^2} = 2\pi/\lambda$

Critical velocity:

$$\Delta V = |V_m - V_p| > \sqrt{\frac{\rho'_m + \rho'_p}{\rho'_m \rho'_p} \left( g \frac{\rho_m - \rho_p}{\kappa} + \gamma \kappa \right)}$$

Most unstable wavelength: $\lambda_\theta = 2\pi/\kappa_\theta \rightarrow$ corresponds to the minimum of function $\Theta$ under square root in the dispersion relation

Critical wavelength: $\lambda_c = 2\pi/\kappa_c \rightarrow$ corresponds to the minimum of function under square root of the critical velocity $\Delta V$
Classical Stability Analysis

- most unstable “dangerous” wavelength $\sim 2.2$ mm
- no effect of gravity on $\Theta$
- for $h_m = 400 \, \mu m$, plasma with $h_p = 1600 \, \mu m$ is infinitely thick
- melt layer more stable with the decrease of melt thickness
- relative velocity curves nearly coincide in the unstable region
- plasma streaming with $10^5 \, m/s$ (marked by star) will amplify fastest growing waves
Classical Stability Analysis

Density effects of the impacting plasma on a melt layer

- for fixed wavelength, $\Delta V$ decreases as plasma density increases
- for $\Delta V = 100$ km/s, as density increases by an order of magnitude, fastest growing wavelength decreases by an order of magnitude
Computational model

- VOF method → plasma & melt are pure, immiscible fluids with volume fractions $\alpha_p + \alpha_m = 1$

- $\frac{\partial \alpha_p}{\partial t} + \nabla \cdot (\alpha_p \mathbf{V}) = 0$

- $\rho \frac{\partial \mathbf{V}}{\partial t} = -\nabla p + \mathbf{F}_\sigma + \rho \mathbf{g}$

- $\rho = \alpha_p \rho_p + \alpha_m \rho_m$

- incompressible plasma & liquid metal flows

- single-field velocity and pressure are used for both melt and plasma; density is volume-fraction-average of fluid densities

- plasma - liquid metal flow is isothermal

- gravity and surface tension effects are included as source terms

- numerical methods: iterative pressure-based solver with PISO; MUSCL scheme; PRESTO and HRIC schemes

- computational modeling performed using commercial FLUENT program package
Computational modeling of plasma-melt flow

Plasma - liquid tungsten flow parameters used in the modeling:

\[ V_p = 10^5 \text{ m/s} \quad h_p = 1600 \text{ \(\mu\)m} \quad \rho_p = 10^{-6} \text{ kg/m}^3 \quad g = 9.81 \text{ m/s}^2 \]
\[ V_m = 1 \text{ m/s} \quad h_m = 400 \text{ \(\mu\)m} \quad \rho_m = 17600 \text{ kg/m}^3 \quad \gamma = 2.5 \text{ N/m} \]

Behavior of plasma-liquid interface perturbed with five wavelengths:

- Initially small liquid tungsten plumes at the wave crests develop \(\sim 2 \text{ mm} \)
- Elongated liquid tungsten protrusions (ligaments) penetrating into the plasma
- Lengthening, thinning and collisions of melt ligaments with capture of small pockets of the plasma
- Highly irregular topological structures of liquid tungsten patterns with breaks and holes

\( \lambda_0 = 2 \text{ mm} \)
Computational modeling of plasma-melt flow

Behavior of plasma-liquid interface perturbed with twenty wavelengths:

- smoothing of original short wavelength disturbances by the surface tension force
- growing of new waves with most dangerous wavelengths in agreement with predictions from the linear stability analysis
- development of ligaments penetrating into the plasma, splitting the bulk of a melt layer, ligament collisions and coalescence, thinning and breaking into droplets

Movie:

$$\lambda_\theta = 0.5 \text{ mm}$$
Summary

- Breakdown of a melt layer is observed with splitting the interface into ligaments, their elongation by plasma flow and development of long, thin threads that eventually can break into liquid droplets.

- Linear stability analysis provides firm grounds for predicting the onset of K-H instability and most dangerous wavelengths, and predictions are in good agreement with computational modeling.

- For predicted plasma-melt conditions, it is found analytically and numerically that short and long waves are damped, but intermediate unstable waves (~2 mm) develop and grow disrupting the melt layer.

- Tungsten melt layer motion and splashing in the form of continuous ligaments with droplets is observed in recent TEXTOR experiments complementing our numerical results that this phenomenon does exist.