Physical Mechanisms of Melt Layer Splashing in Tokamaks

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Outline

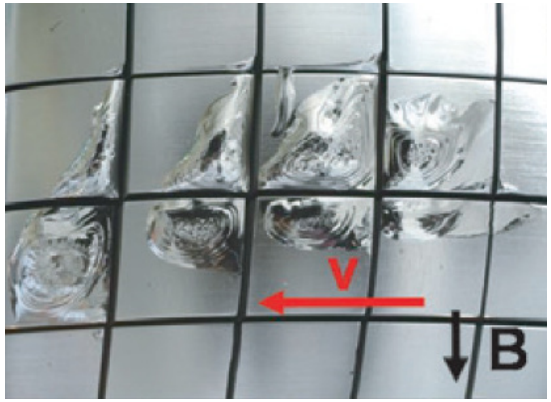
- Background & Previous Modelling
- Onset of Kelvin-Helmholtz Instability
- Modelling of Melt Instabilities & Splashing
- Summary

Our Recent Work & Collaboration

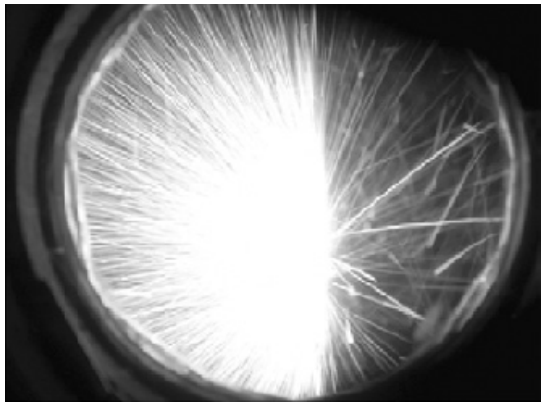
- G. Miloshevsky, A. Hassanein, ***Modeling of macroscopic melt layer splashing during plasma instabilities***. *J. Nucl. Mater.* 2010, (accepted, in press)
- G. Miloshevsky, A. Hassanein, ***Modeling of Kelvin-Helmholtz instability and splashing of melt layers from plasma facing components in tokamaks under plasma impact.*** *Nucl. Fusion* 2010, (in press)
- Y. Shi, G. Miloshevsky, A. Hassanein, ***Theoretical Studies of Macroscopic Erosion Mechanisms of Melt Layers Developed on Plasma Facing Components.*** *Phys. Fluids* 2010, (submitted)
- Y. Shi, G. Miloshevsky, A. Hassanein, ***Boiling Induced Macroscopic Erosion of Plasma Facing Components in Fusion Devices.*** *Fusion Eng. Des.* 2010 (submitted)

- J.W. Coenen, V. Philipps, the TEXTOR-Team, Forschungszentrum Jülich, Germany

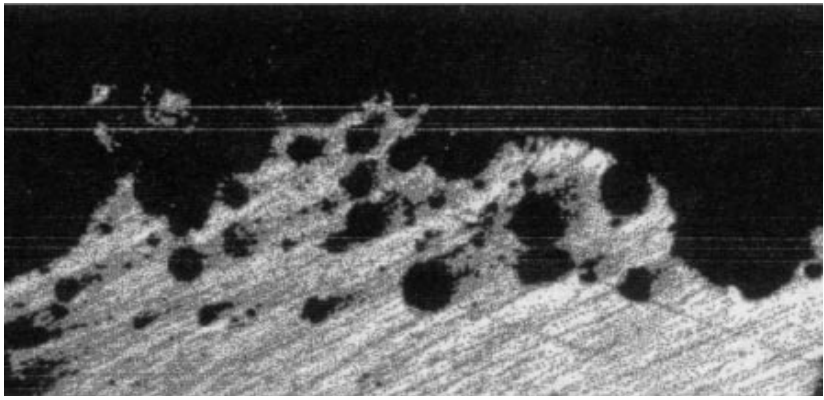
Samples of macroscopic melt splashing



TEXTOR: Sergienko et al., Phys. Scr. T128 (2007) 81

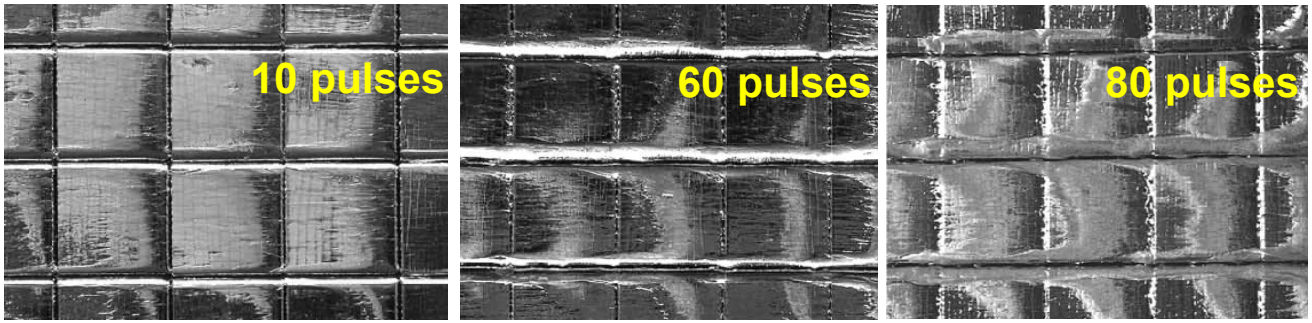


QSPA-T: Bazylev et al., Fusion Eng. Des. 84 (2009) 441



VIKA: Litunovsky et al., Fusion Eng. Des. 49-50 (2000) 249

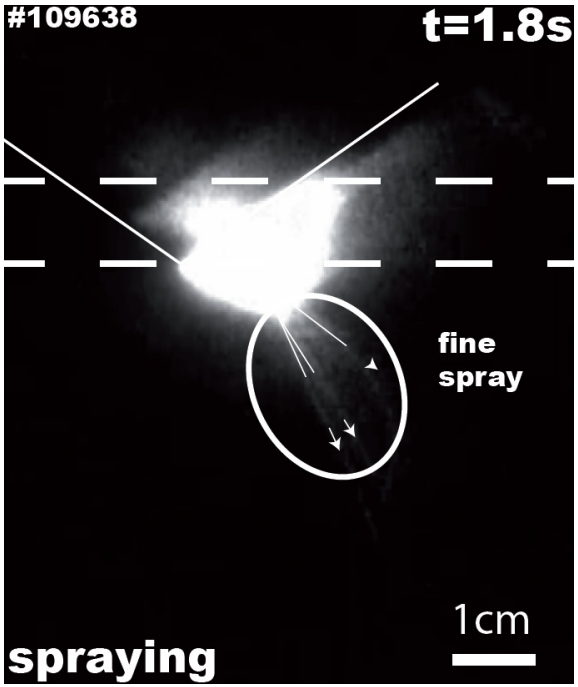
QSPA Kh-50: Garkusha et al., J. Nucl. Mater. 390-391 (2009) 814

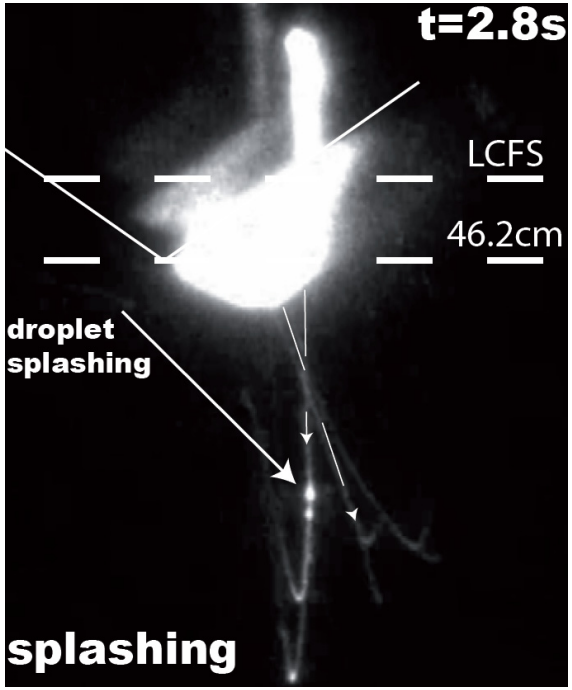


QSPA and MK-200UG: Federici et al., J. Nucl. Mater. 337-339 (2005) 684

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

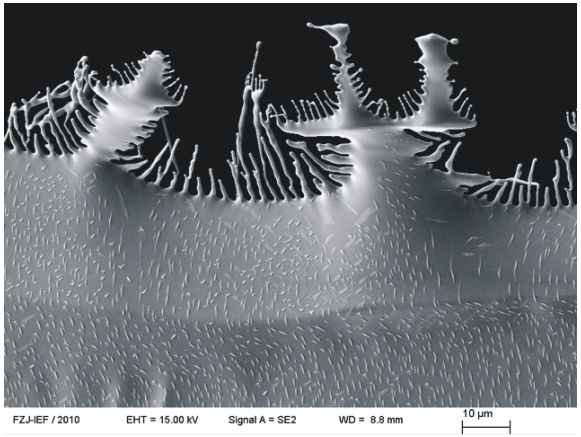
Melt Layer Motion and Splashing in TEXTOR

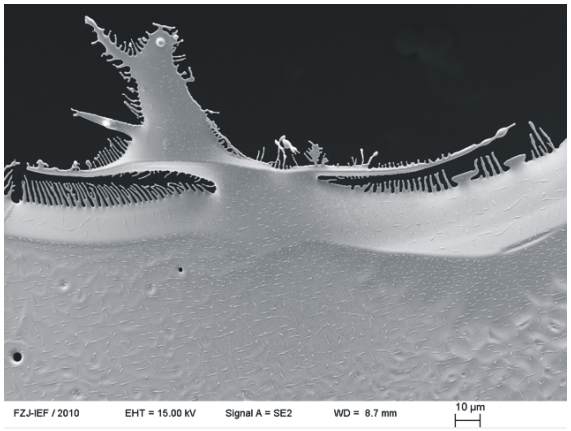




- tungsten melt layer spraying and splashing: fine spray of small droplets & melt splashes with large droplets

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

Coenen et al., *PSI-2010, O-1*; *J. Nucl. Mater.* (2011) in press.

Melt Layer Motion and Splashing in TEXTOR

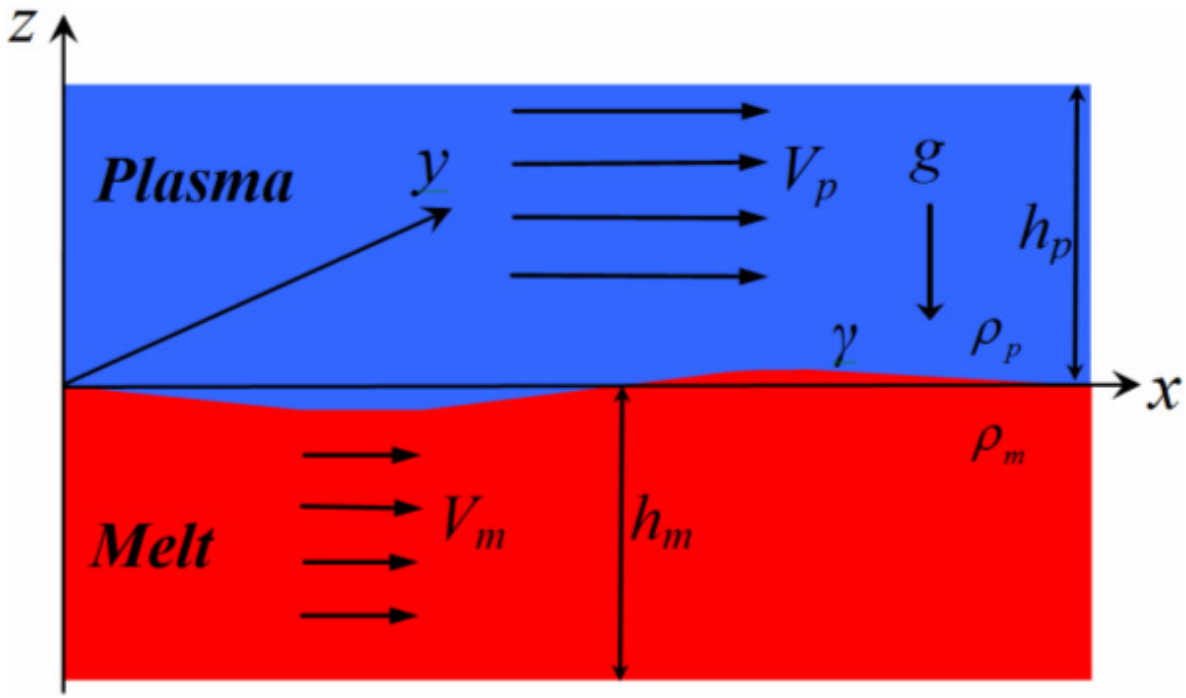
Roof shaped limiter moved close to the Last Close Flux Surface

Movie of disruption

Coenen et al., *PSI-2010, O-1*; *J. Nucl. Mater.* (2011) in press.

Plasma-Melt Kelvin-Helmholtz Instability

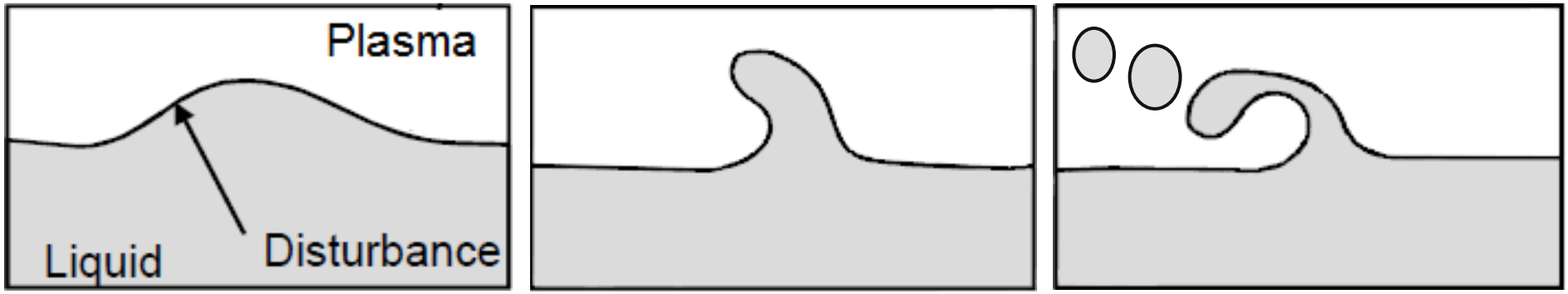
➢ plasma & liquid tungsten → two immiscible, inviscid and incompressible fluids with the interface subjected to velocity shear



➢ 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)

Bazylev et al., *Fusion Eng. Des.* 84 (2009) 441; Bazylev et al., *Phys. Scr.* T128 (2007) 229; Bazylev & Landman, *Problems Atomic Sci. Technol.* 13 (2007) 35

Phenomenological Capillary Droplet Model

Maximum increment coefficient and fastest growing wavelength:

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

the radius of droplets assumed as $\sim \lambda_\theta / 4$

<u>For ITER conditions:</u> weak ELMs <2.5 MJ/m^2 during <0.3 ms

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

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

Our estimate: $\lambda_\theta \sim 14 - 1.4$ cm >> $h_m \Rightarrow$ model is not valid!

<u>For QSPA-T conditions:</u> heat loads <1.6 MJ/m^2 during <0.3 ms

$$V_p \approx 10^4 - 10^5\ m/s,\ N_p < 10^{22}\ m^{-3} \Rightarrow \rho_p < 1.7 \cdot 10^{-5}\ kg/m^3$$

It is stated: droplets with $\lambda_\theta / 4 \sim 10\ \mu m$ and $\tau \sim 1/\Gamma_\theta < 0.1\ ms$

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

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:

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

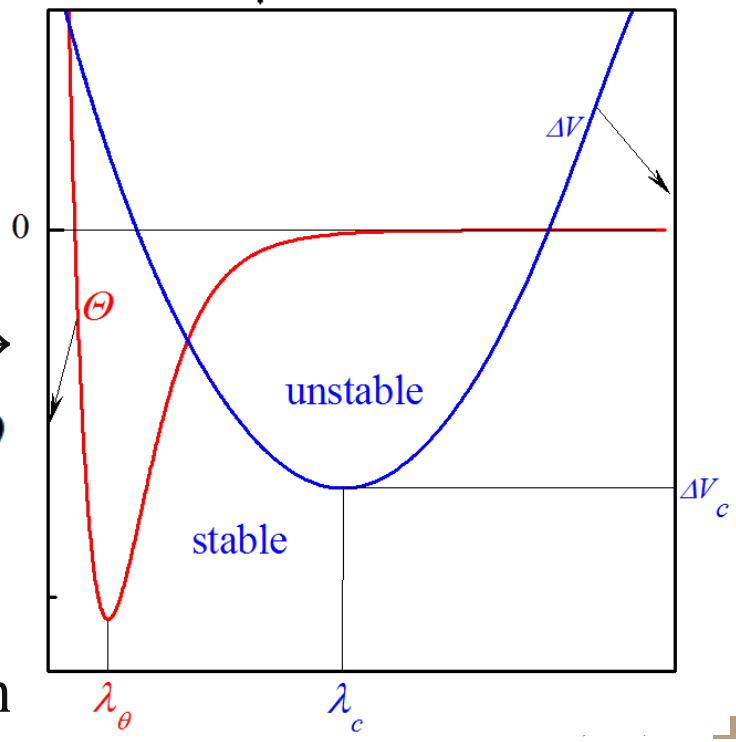
with $\rho'_m = \rho_m \coth(\kappa h_m)$, $\rho'_p = \rho_p \coth(\kappa h_p)$ and $\kappa = \sqrt{k_x^2 + k_y^2} = 2\pi/\lambda$

Critical velocity:

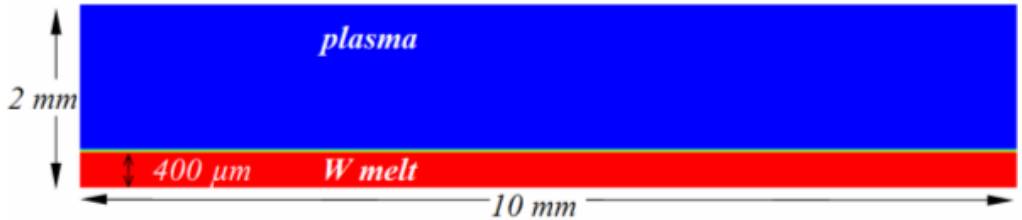
$$\Delta V = |V_m - V_p| > \sqrt{\frac{\rho'_m + \rho'_p}{\rho'_m \rho'_p}\left(\frac{g(\rho_m - \rho_p)}{\kappa} + \gamma\kappa\right)}$$

Most unstable wavelength: $\lambda_\theta = 2\pi/\kappa_\theta \rightarrow$ corresponds to the minimum of function Θ 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 ΔV

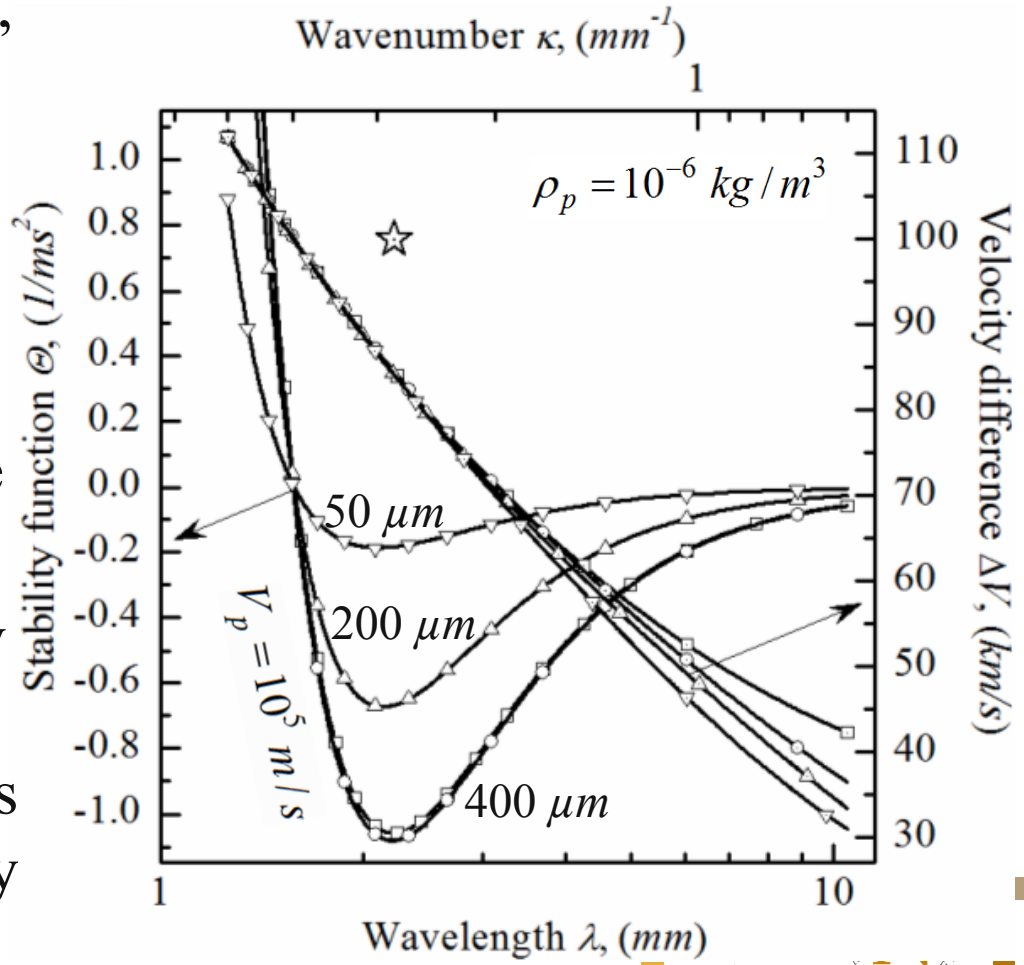


Classical Stability Analysis



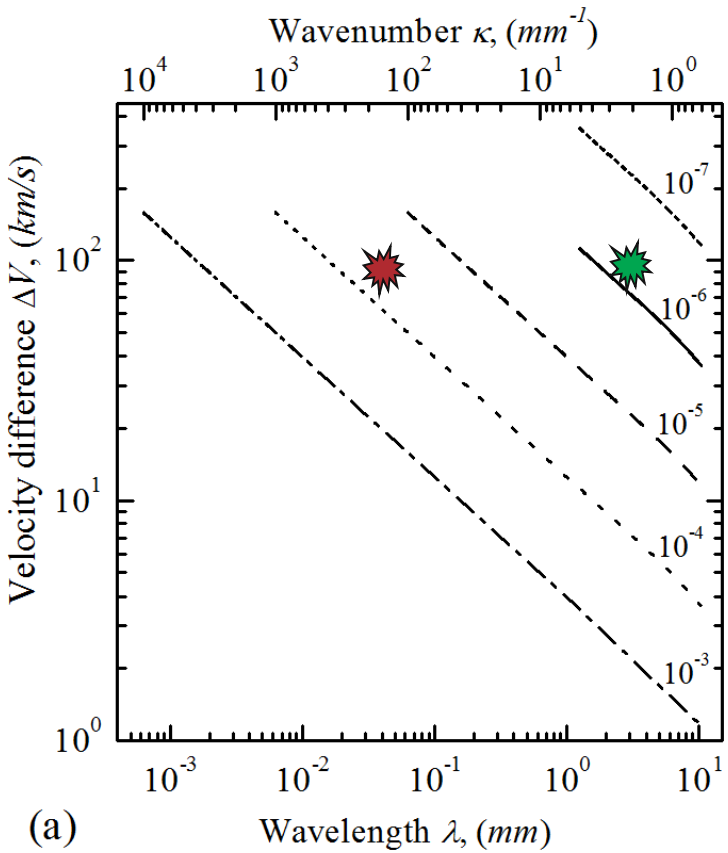
Stability function and relative velocity curves for different melt-plasma thicknesses

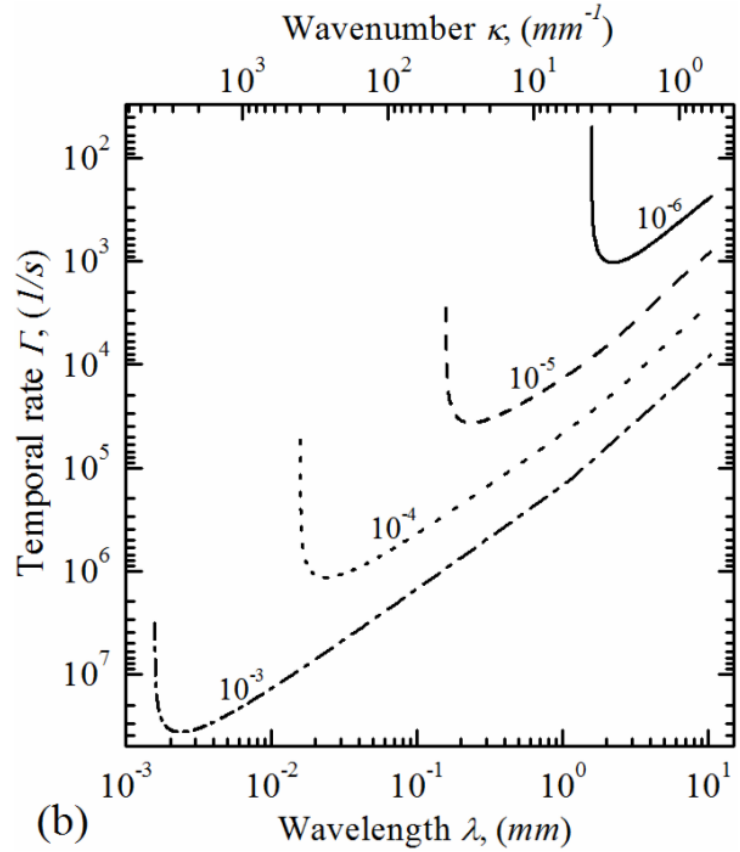
- most unstable "dangerous" wavelength ~2.2 mm
- no effect of gravity on Θ
- for h_m=400 μm, plasma with h_p=1600 μm is infinitely thick
- melt layer more stable with the decrease of melt thickness
- relative velocity curves nearly coincide in the unstable region
- plasma streaming with 10^5 m/s (marked by star) will amplify fastest growing waves



Classical Stability Analysis

Density effects of the impacting plasma on a melt layer





- for fixed wavelength, ΔV decreases as plasma density increases
- for ΔV=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 $\alpha_p + \alpha_m = 1$

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

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

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

- 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

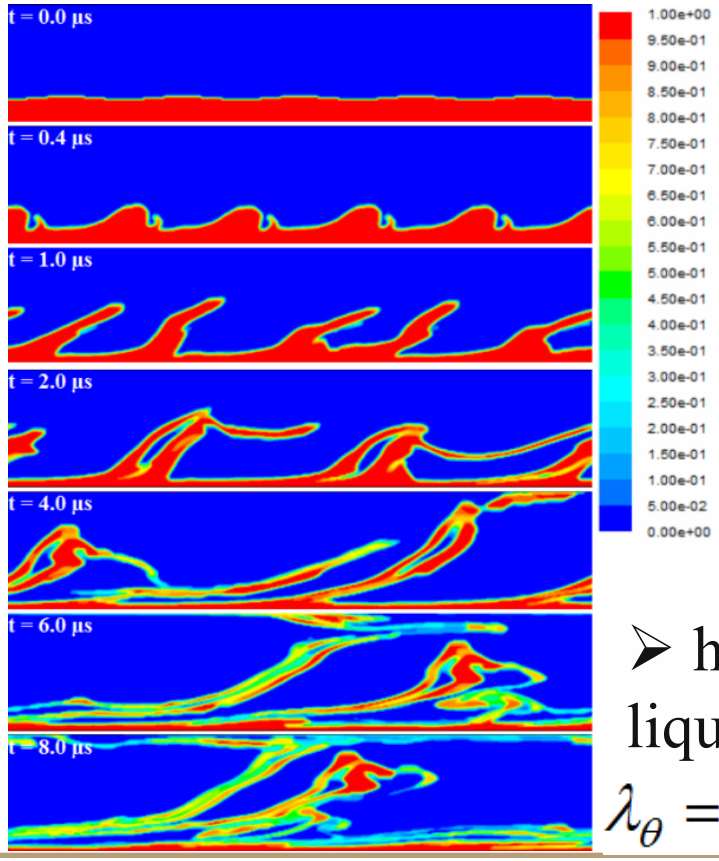
Computational modeling of plasma-melt flow

Plasma - liquid tungsten flow parameters used in the modeling:

$$V_p = 10^5\ m/s \quad h_p = 1600\ \mu m \quad \rho_p = 10^{-6}\ kg/m^3 \quad g = 9.81\ m/s^2$$

$$V_m = 1\ m/s \quad h_m = 400\ \mu m \quad \rho_m = 17600\ kg/m^3 \quad \gamma = 2.5\ N/m$$

Behavior of plasma-liquid interface perturbed with five wavelengths:

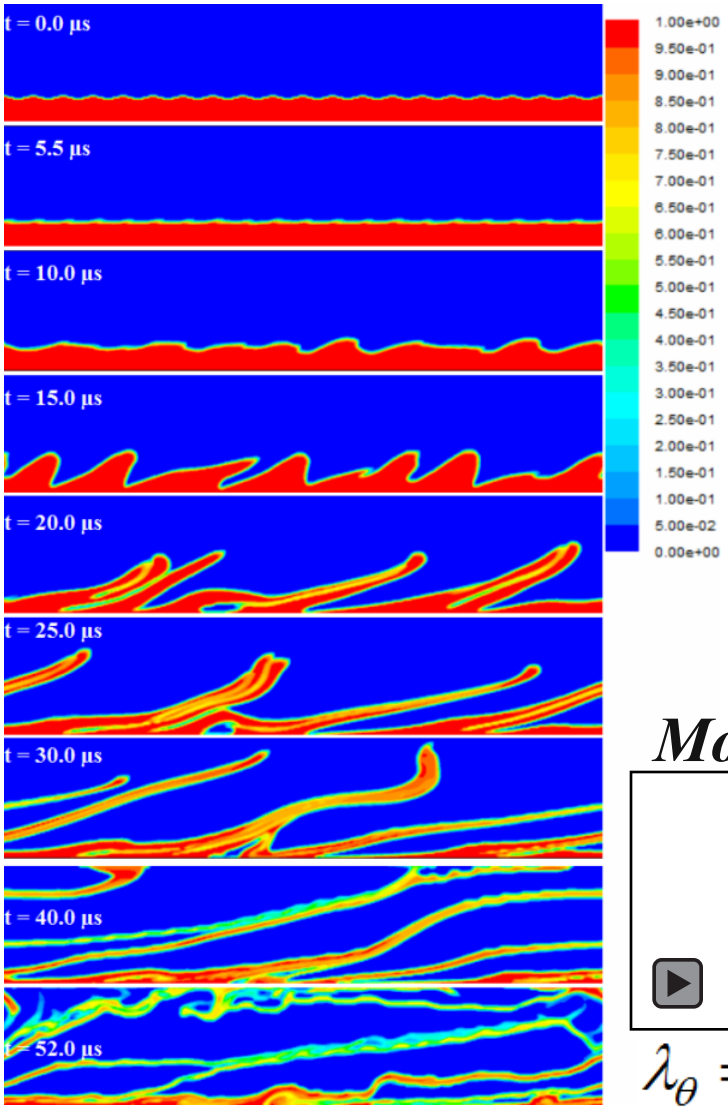


- initially small liquid tungsten plumes at the wave crests develop ~2 mm
- elongated liquid tungsten protrusions (ligaments) penetrating into the plasma
- lengthening, thinning and collisions of melt ligaments with capture of small pockets of the plasma
- highly irregular topological structures of liquid tungsten patterns with breaks and holes

$$\lambda_\theta = 2\ mm$$

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:

$\lambda_\theta = 0.5\ mm$

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