Detail Modeling of Melt Layer Splashing and Erosion Losses of PFC

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Presented at PFC meeting, the Princeton Plasma Physics Laboratory, New Jersey, USA, June 20-22, 2012

Outline

- Brief Introduction
- Our Previous Work
- Viscous Linear Analysis with Heat & Mass Transfer
- CFD Modelling
- Summary

Melt Layer Erosion Mechanisms

- Macroscopic losses of melt layer during plasma disruptions is a *serious concern* because its thickness can be two orders of magnitude higher than vaporization thickness

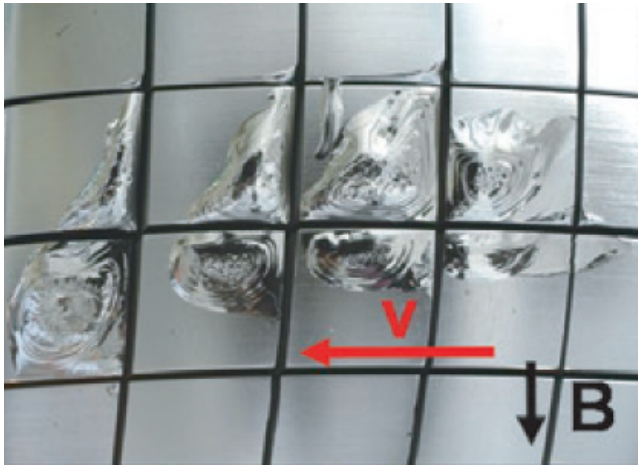
- Two main mechanisms of melt layer losses suggested:

  - Development and growth of ***hydrodynamic instabilities*** due to various forces on the melt surface resulting in liquid droplets that are carried away by the plasma wind
  - ***Boiling*** with vapor bubble bursting at the melt surface and formation of jet-droplets

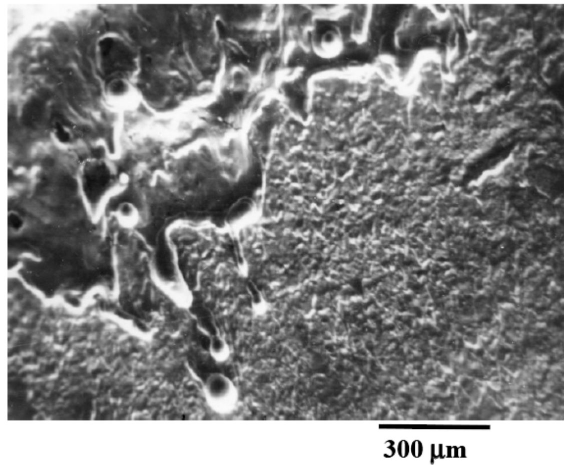
- Amount of lost melt is uncertain depending on disrupting plasma parameters, deposited energy flux, melt properties, design, etc.

Hassanein, Fusion Technology 15(2), (1989) 513
Hassanein et al., *Fusion Eng. Des.* 39 (1998) 201

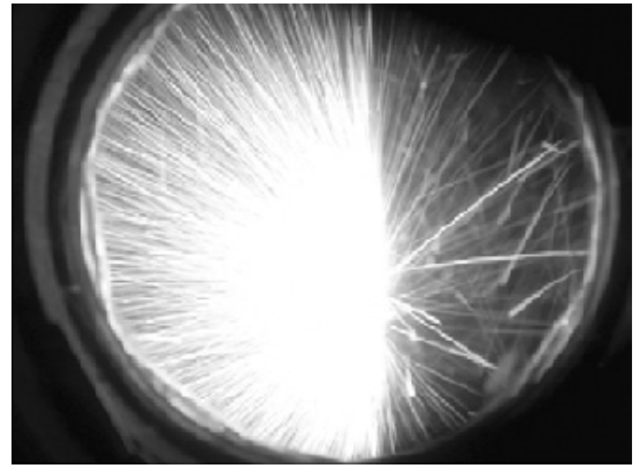
Examples of Macroscopic Melt Splashing



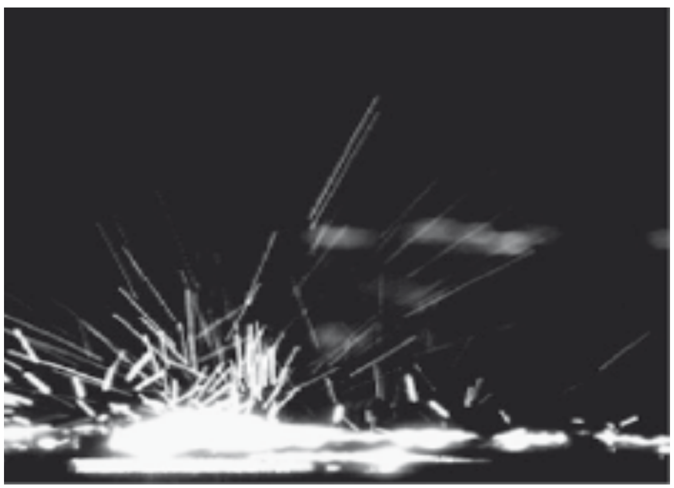
TEXTOR: Sergienko et al., Phys. Scr. T128 (2007) 81



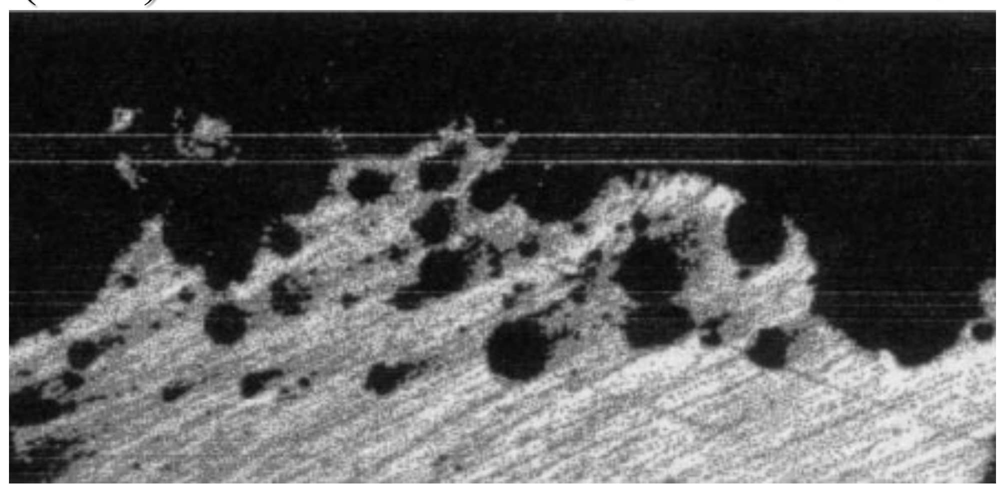
MK-200: Safronov et al., PAST 8 (2002) 27



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



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



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

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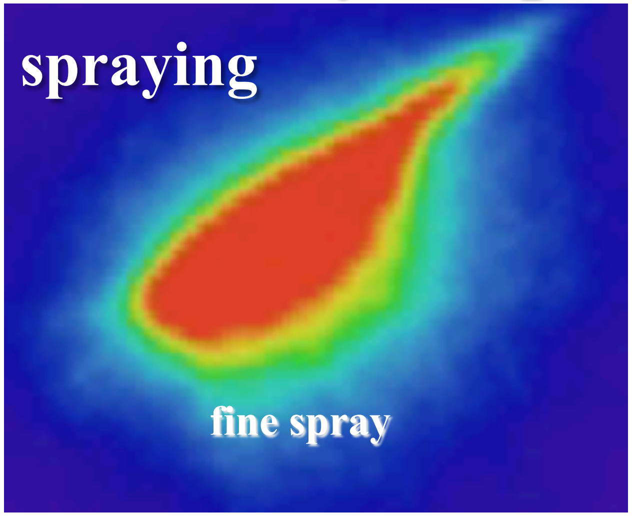
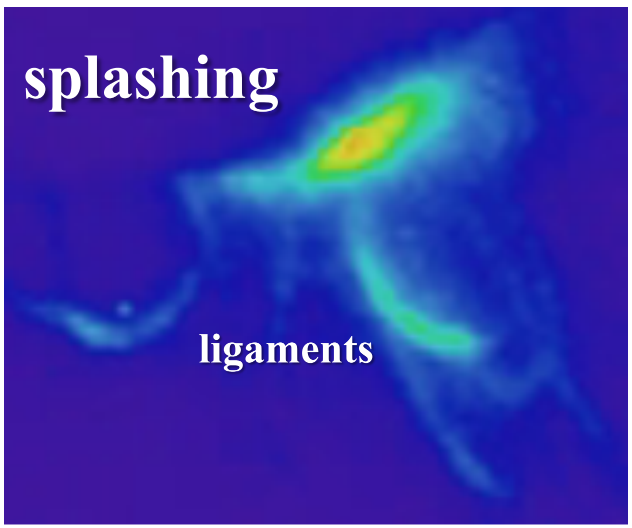
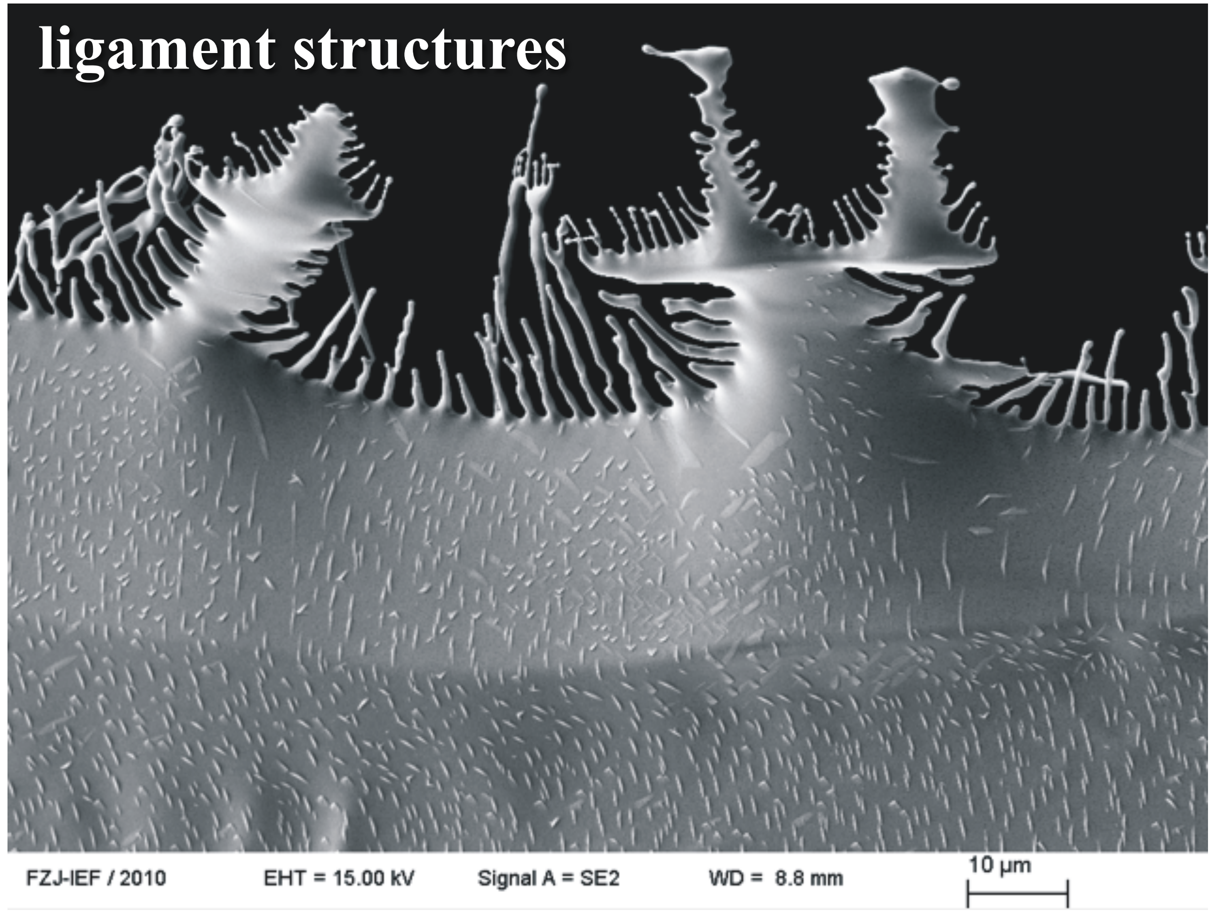
Melt Layer Spraying and Splashing in TEXTOR







Coenen et al., *J. Nucl. Mater.* 415 (2011) S78; Coenen et al., *Nucl. Fusion* 51 (2011) 083008; *Nucl. Fusion* 51 (2011) 113020.

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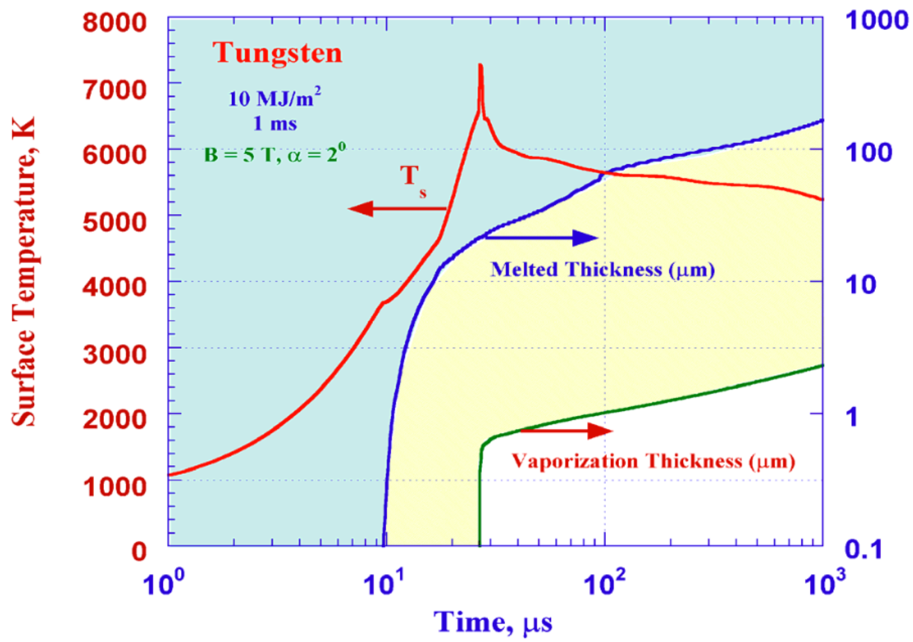
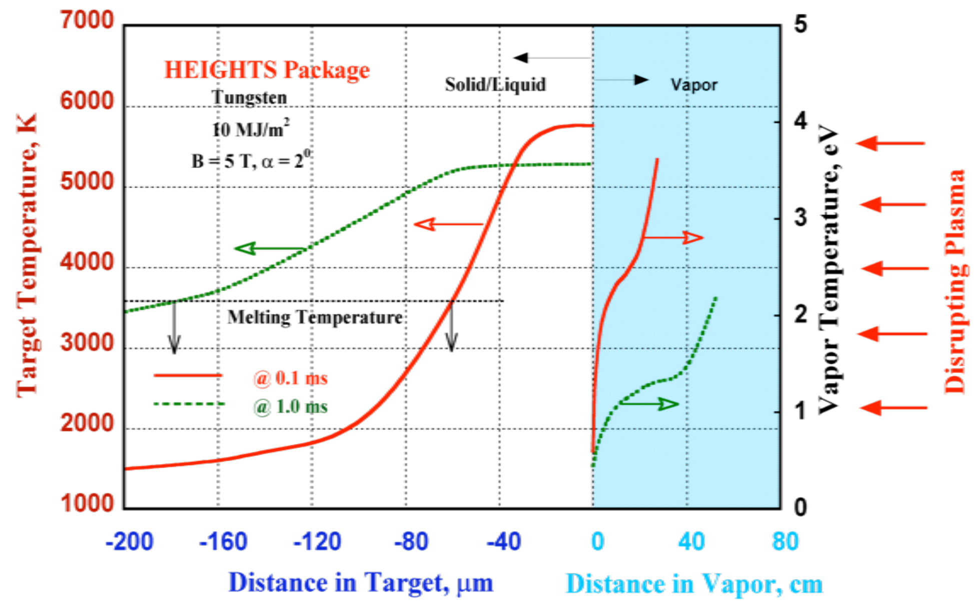
Erosion due to Vaporization & Melting

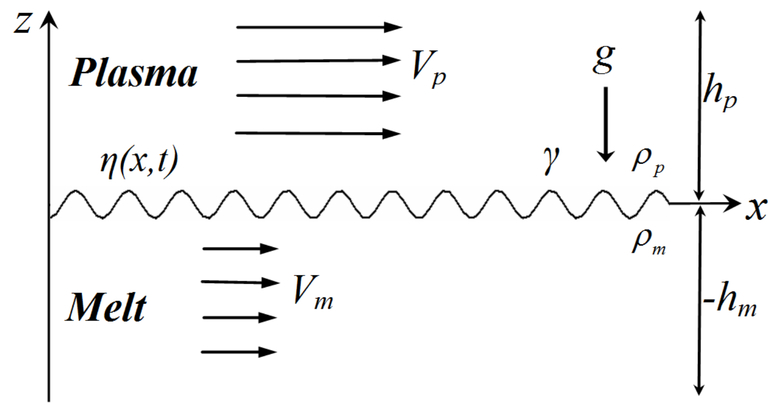




- ❑ Tungsten erosion due to vaporization ~ 1-2 μm
- ❑ Melt layer thickness ~200 μm at 1.0 ms
- ❑ Melt boiling can take place

Hassanein & Konkashbaev *J. Nucl. Mater.* 233 (1996) 713

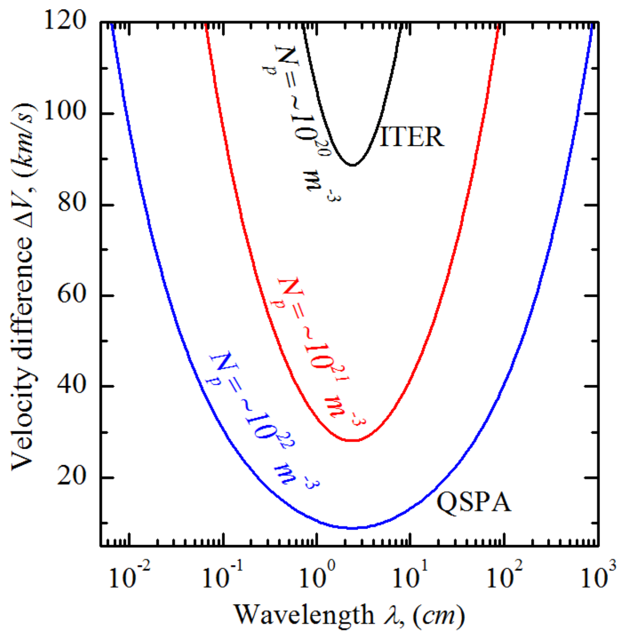
K-H Instability of Inviscid Plasma-Tungsten Melt

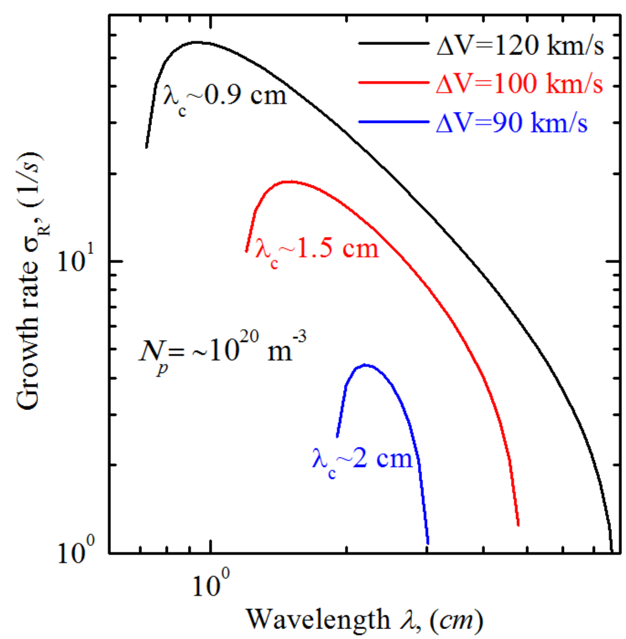


Critical Velocity & Growth Rate:

$$\Delta V > \sqrt{\frac{\rho'_m + \rho'_p}{\rho'_m \rho'_p}\left(\frac{g(\rho_m - \rho_p)}{k} + (\gamma + \gamma_H)k\right)}$$

$$\sigma_R = \pm\sqrt{\frac{k^2 \rho'_m \rho'_p}{(\rho'_m + \rho'_p)^2}\Delta V^2 - \left(kg\frac{\rho_m - \rho_p}{\rho'_m + \rho'_p} + \frac{k^3(\gamma + \gamma_H)}{\rho'_m + \rho'_p}\right)}$$





Miloshevsky & Hassanein, *Nucl. Fusion* 50 (2010) 115005; *J. Nucl. Mater.* 415 (2011) S74.

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Two-Fluid Computational Model

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

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

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

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

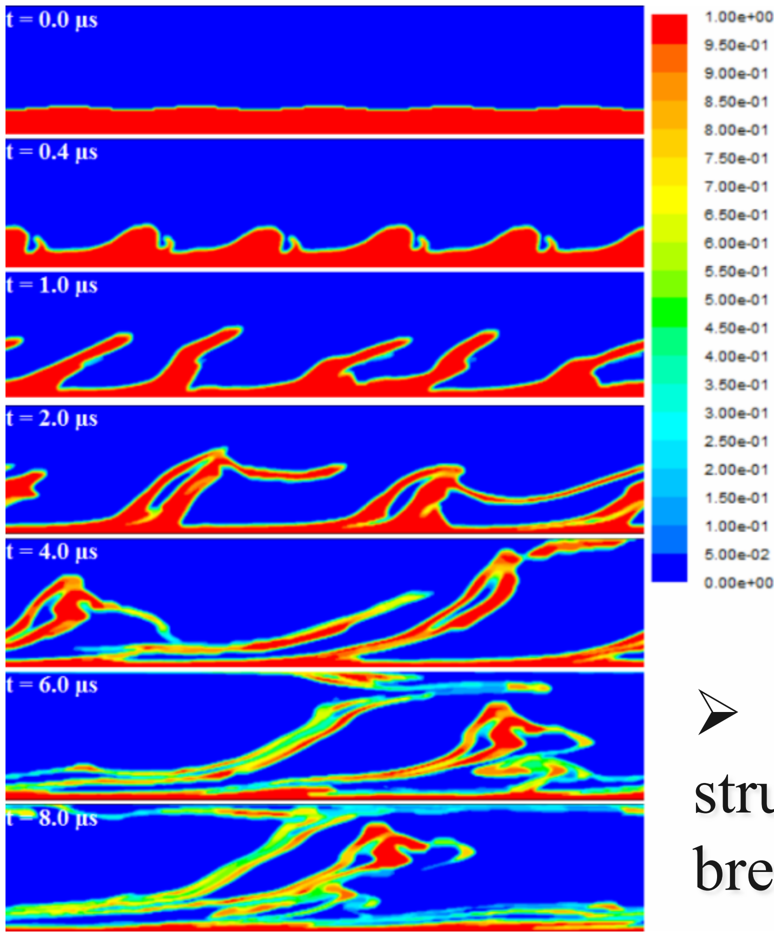
- **Incompressible and inviscid plasma & liquid metal flows**
- **Velocity and pressure fields for both melt and plasma; density is volume-fraction-average of fluid densities**

- Gravity and surface tension effects are included as source
- Modeling performed using FLUENT package

Miloshevsky & Hassanein, *Nucl. Fusion* 50 (2010) 115005; *J. Nucl. Mater.* 415 (2011) S74.

Computational Modeling of Plasma-Melt Flow

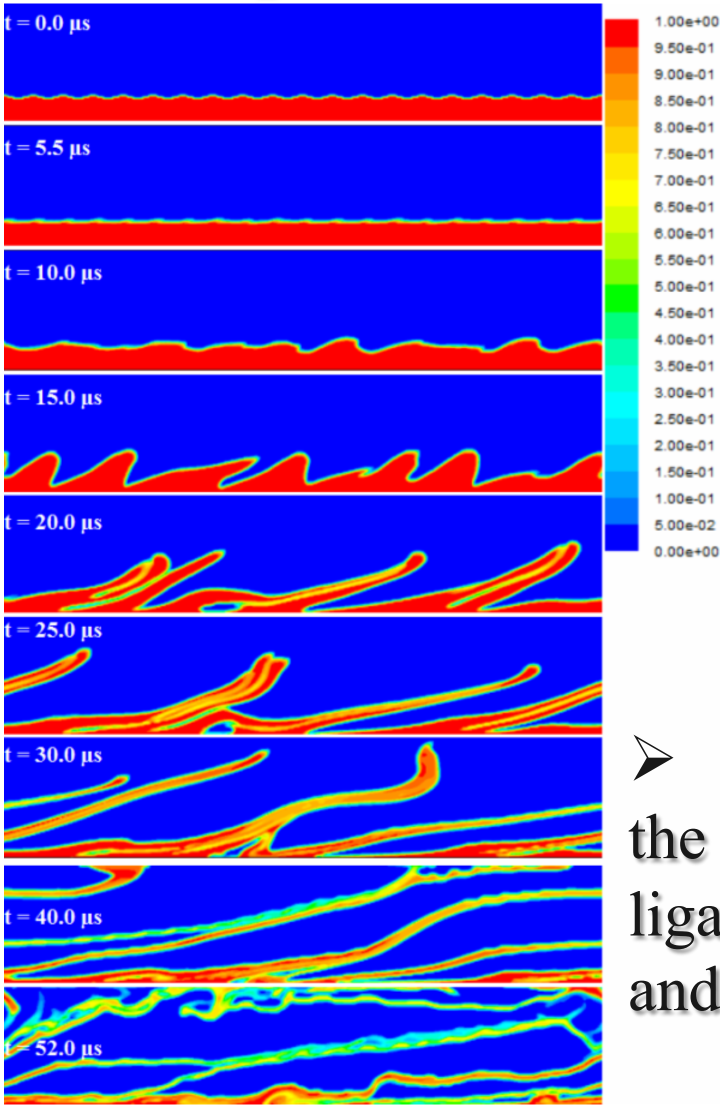
Plasma-liquid interface perturbed with most unstable wavelength predicted by the linear stability analysis, ~2 mm



- ➢ at ~0.4 µs, small liquid tungsten plumes ~2 mm at the wave crests
- ➢ at ~1 µs, elongated liquid tungsten ligaments penetrating into the plasma
- ➢ at ~2-4 µs, lengthening, thinning, and collisions of melt ligaments with capture of small pockets of the plasma
- ➢ at > 6 µs, highly irregular topological structures of liquid tungsten patterns with breaks and holes

Miloshevsky & Hassanein, *Nucl. Fusion* 50 (2010) 115005; *J. Nucl. Mater.* 415 (2011) S74.

Computational Modeling of Plasma-Melt Flow

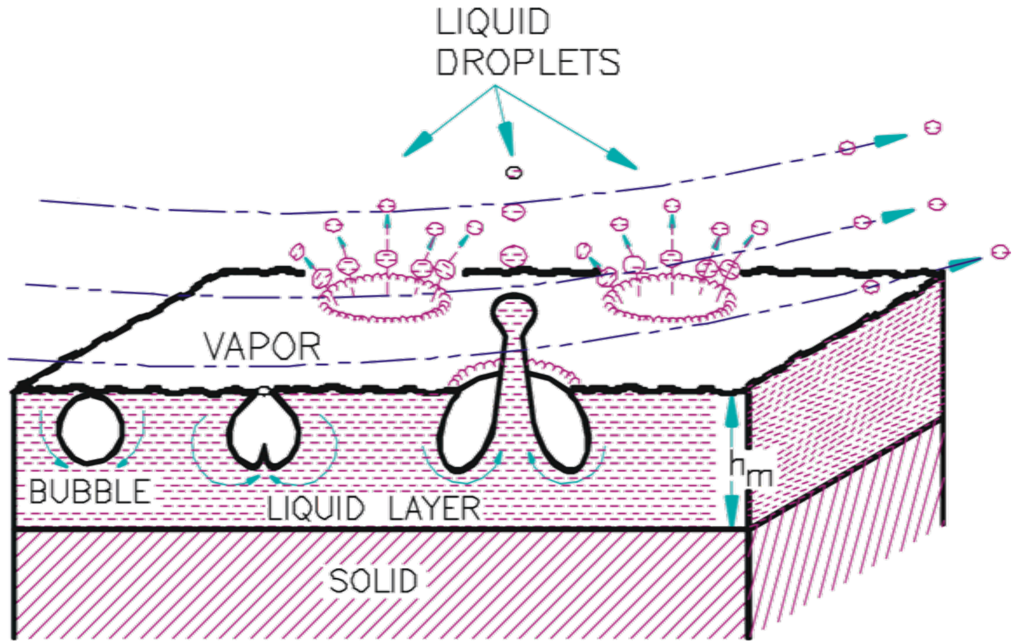


Plasma-liquid tungsten interface perturbed with shorter wavelength, ~0.5 mm

- 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

Miloshevsky & Hassanein, *Nucl. Fusion* 50 (2010) 115005; *J. Nucl. Mater.* 415 (2011) S74.

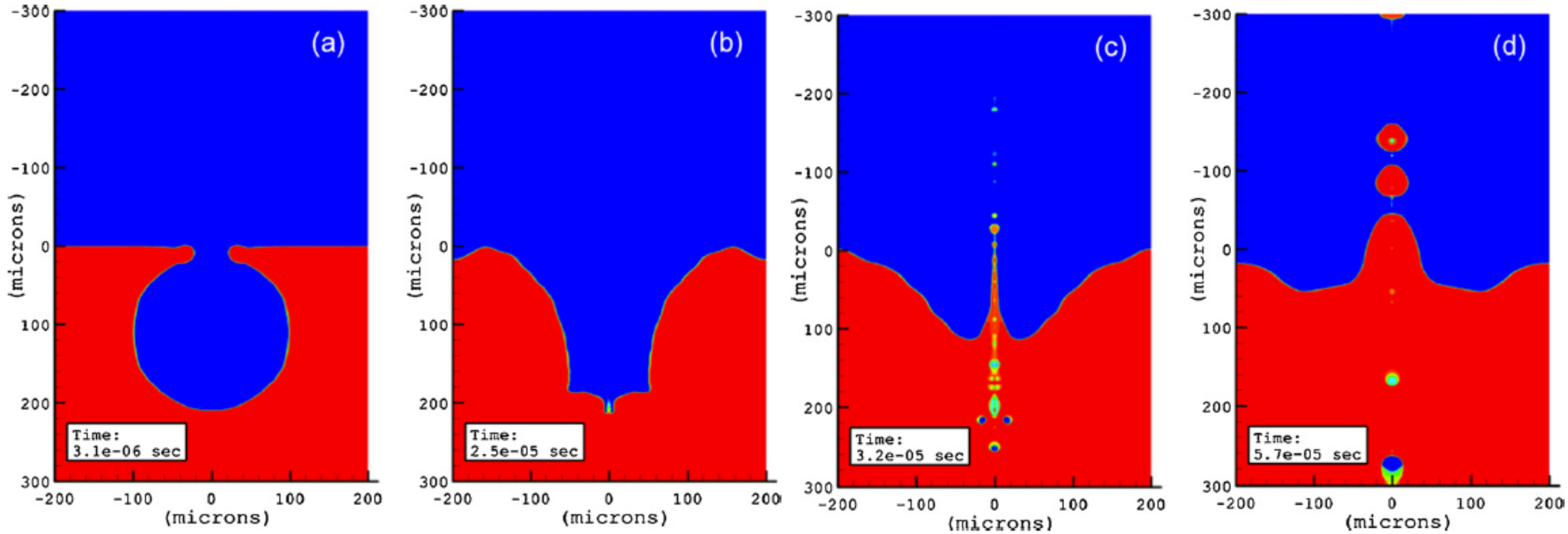
Bubble Growth, Vaporization, and Melt Loss due to Incident Plasma Wind



- Another mechanisms of melt-layer loss is volume bubble boiling due to overheating of melt layer
- Bubbles can grow, reach liquid surface, and then burst. Bursting bubble forms a jet. The jet is then disintegrates into droplets
- The melt erosion has a form of a splashing wave. The liquid droplets are then carried away by the incident plasma stream

Hassanein et al. *J. Nucl. Mater.* 241 (1997) 288

CFD Simulations of Erosion due to Boiling and Bubble Bursting with Ejection of Jet-Droplets



- ❑ CFD showed formation of jets and breakage into droplets
- ❑ Amount of jet-droplets was integrated into moving boundary model
- ❑ Final erosion from boiling depends on many parameters and uncertain

Y. Shi, G. V. Miloshevsky & A. Hassanein. *Boiling induced macroscopic erosion of plasma facing components in fusion devices*. Fusion Eng. Des. 86 (2011) 155-162.

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Instability of Viscous Potential Plasma-Melt Flow

Critical Velocity & Growth Rate:

Viscous Potential Flow:

$$\Delta V > \sqrt{\frac{(\mu'_m + \mu'_p)^2}{\rho'_m \mu'^2_p + \rho'_p \mu'^2_m}\left(\frac{g(\rho_m - \rho_p)}{k} + (\gamma + \gamma_H)k\right)}$$

$$\sigma_R = \pm\sqrt{\frac{k^2(\rho'_m \mu'^2_p + \rho'_p \mu'^2_m)}{(\mu'_m + \mu'_p)^2(\rho'_m + \rho'_p)}\Delta V^2 - \left(kg\frac{\rho_m - \rho_p}{\rho'_m + \rho'_p} + \frac{k^3(\gamma + \gamma_H)}{\rho'_m + \rho'_p}\right)}$$

if $\dfrac{\mu'_p}{\mu'_m} = \dfrac{\rho'_p}{\rho'_m}$ ⇒ $\mu_p \to 0$

$$r = \rho_p / \rho_m \sim 10^{-10}$$

$$n = \mu_p / \mu_m \sim 10^{-3}$$

$$r << n$$

low viscosity case

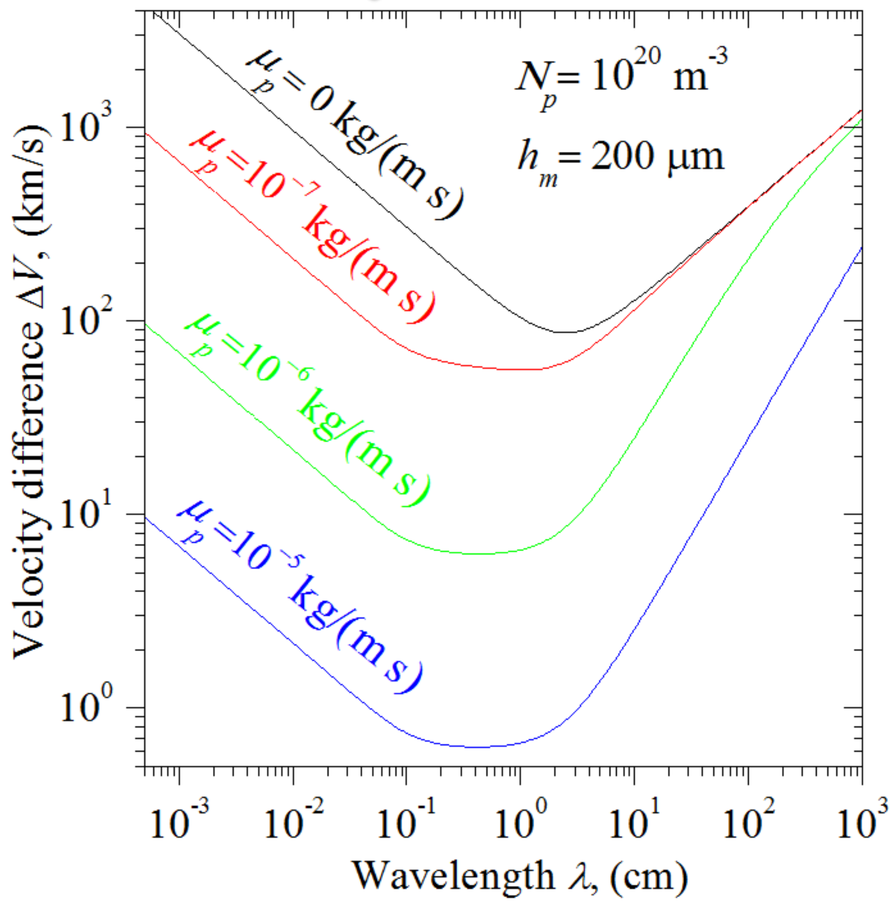
Inviscid Potential Flow:

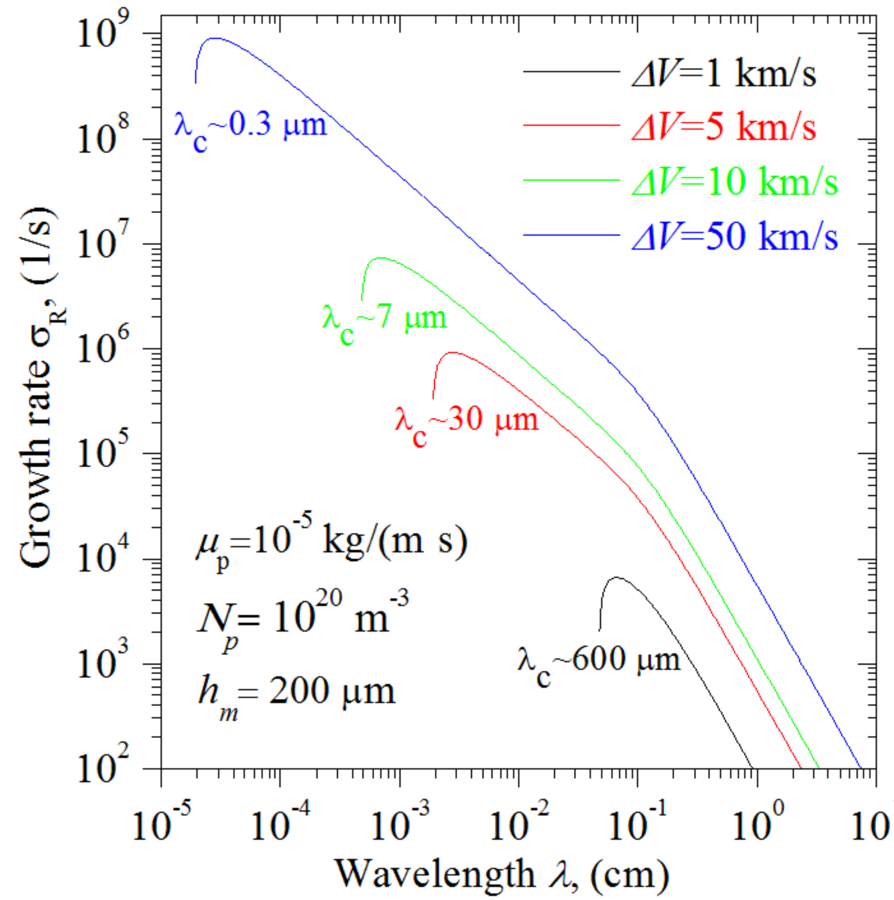
$$\Delta V > \sqrt{\frac{\rho'_m + \rho'_p}{\rho'_m \rho'_p}\left(\frac{g(\rho_m - \rho_p)}{k} + (\gamma + \gamma_H)k\right)}$$

$$\sigma_R = \pm\sqrt{\frac{k^2 \rho'_m \rho'_p}{(\rho'_m + \rho'_p)^2}\Delta V^2 - \left(kg\frac{\rho_m - \rho_p}{\rho'_m + \rho'_p} + \frac{k^3(\gamma + \gamma_H)}{\rho'_m + \rho'_p}\right)}$$

Funada & Joseph, *J. Fluid Mech.* 445 (2001) 263-283

Instability of Viscous Potential Plasma-Melt Flow

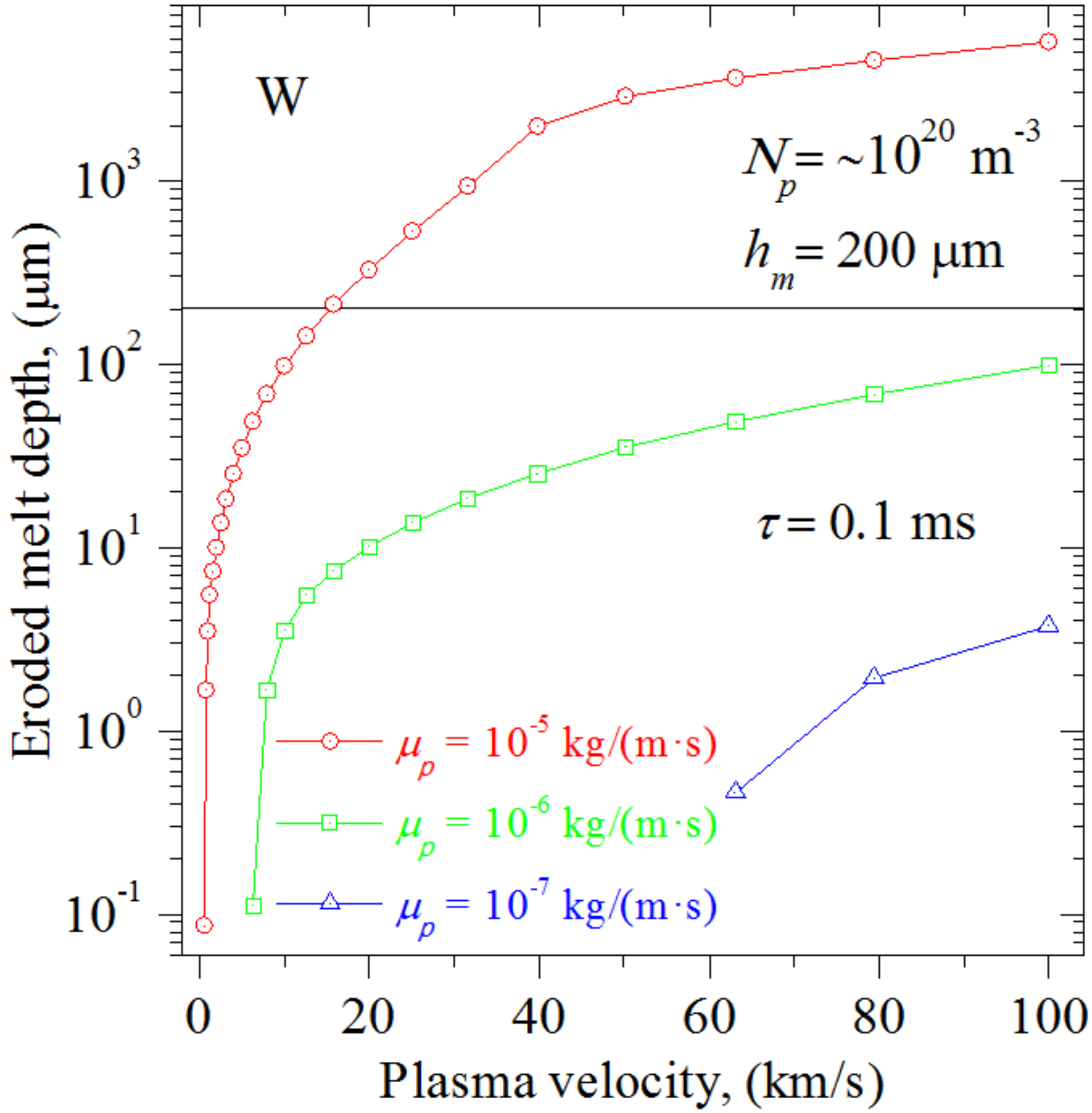




melt destabilization due to plasma viscosity effects with a slight shift in critical wavelength toward shorter waves

significant increase in growth rate of short waves (dangerous wavelengths) with increase in plasma velocity

Melt Erosion from Capillary Droplet Ejection Model



Instability of Viscous Potential Plasma-Melt Flow

Effects of Mass & Heat Transfer Across the Interface

$$\Delta V > \sqrt{\frac{2(\delta(\coth(kh_m)+\coth(kh_p))+2k^2(\mu'_m+\mu'_p))^2 \times \left(\frac{kg(\rho_m-\rho_p)+k^3(\gamma+\gamma_H)}{2k^2}+\delta\left(\frac{\mu'_m}{\rho_m}+\frac{\mu'_p}{\rho_p}\right)\right)}{\delta^2(\rho'_p\coth^2(kh_m)+\rho'_m\coth^2(kh_p))+4k^4(\rho'_m\mu'^2_p+\rho'_p\mu'^2_m)+4\delta k^2(\rho'_p\mu'_m\coth(kh_m)+\rho'_m\mu'_p\coth(kh_p))}}$$

$$\delta = \frac{F}{L}\left(\frac{1}{h_m}+\frac{1}{h_p}\right)$$

For tungsten melt:

$L \sim 4620\ kJ/kg$ - latent heat of vaporization

$F = -\frac{K_m(T_m - T_i)}{h_m}$ - equilibrium heat flux

with $K_m \sim 70\ W/(m\cdot K)$ at $T_i \sim 5933\ K$

$T_m = 3683 \div 300\ K$

$\delta \sim 2.1\cdot 10^5 \div 5.3\cdot 10^5$

$kg/(m^3\cdot s)$

Hsieh, *Phys. Fluids* 21 (1978) 745

Asthana & Agrawal, *Physica A* 382 (2007) 389-404

Instability of Viscous Potential Plasma-Melt Flow

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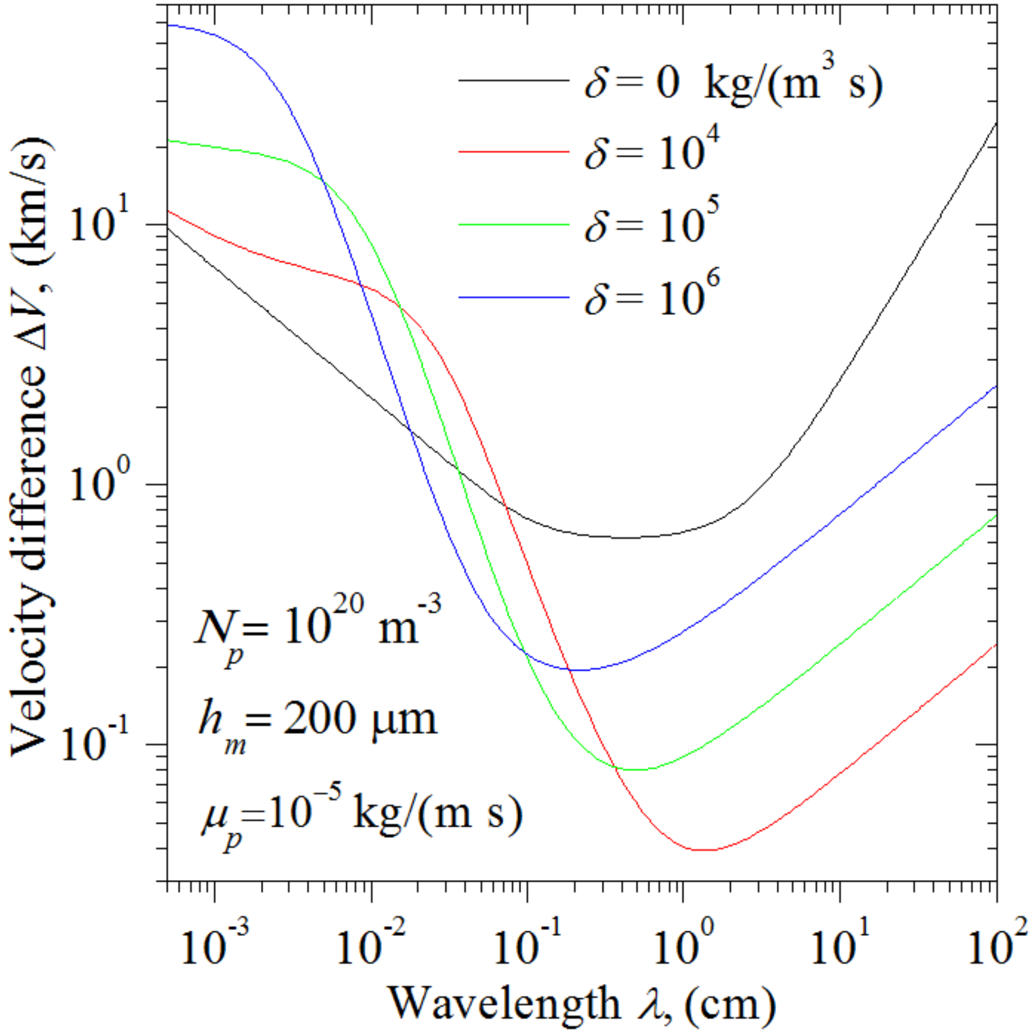

stabilization of short waves & destabilization of long waves

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Modelling: OpenFOAM

- Open Field Operation and Manipulation (OpenFOAM) is Open Source CFD Toolbox with extensive multi-physics capabilities
- Numerous pre-configured finite volume solvers, utilities, and libraries that are written in C++ and under active development with capabilities of commercial CFD software
- 2D or 3D structured/unstructured mesh and parallel running
- Possibility for users to extend and implement new physics models: existing solvers can be used as templates for further development
- Representation of partial differential equations through natural language of *equation mimicking*:

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \bullet \phi \mathbf{U} - \nabla \bullet \mu \nabla \mathbf{U} = -\nabla p \quad \Longrightarrow$$

```
solve
(
    fvm::ddt(rho, U)
  + fvm::div(phi, U)
  - fvm::laplacian(mu, U)
    ==
  - fvc::grad(p)
);
```

http://www.openfoam.com/

Modelling: OpenFOAM

Volume of Fluid (VOF) Model available in OpenFOAM:

two immiscible & isothermal fluids

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \nabla \cdot (\mu (\nabla \vec{u} + (\nabla \vec{u})^T)) + \sigma \kappa \nabla \alpha_m + \rho \vec{g}$$ - momentum

$$\frac{\partial \alpha_m}{\partial t} + \nabla \cdot (\alpha_m \vec{u}) + \nabla \cdot (\alpha_m (1 - \alpha_m) \vec{u}_c) = 0$$ - volume fraction

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$ - continuity

$$\rho = \alpha_m \rho_m + \alpha_p \rho_p \qquad \mu = \alpha_m \mu_m + \alpha_p \mu_p \qquad \alpha_p = 1 - \alpha_m$$

$$\rho_j = \rho_{0j} + \psi_j (p - p_{0j}), \; j = m, p$$

http://www.openfoam.com/

Modelling: OpenFOAM

Implementation of Heat & Mass Transfer Models in VOF Model:

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \nabla \cdot (\mu (\nabla \vec{u} + (\nabla \vec{u})^T)) + \sigma \kappa \nabla \alpha_m + \rho \vec{g}$$ - momentum

$$\frac{\partial \alpha_m}{\partial t} + \nabla \cdot (\alpha_m \vec{u}) + \nabla \cdot (\alpha_m (1-\alpha_m)\vec{u}_c) = \frac{\dot{m}}{\rho}$$ - volume fraction

$$\frac{\partial \rho c_p T}{\partial t} + \nabla \cdot (\rho c_p \vec{u} T) = \nabla \cdot (K \nabla T) + \dot{h}$$ - heat conduction

$$c_p = \alpha_m c_{pm} + \alpha_p c_{pp}$$

$$K = \alpha_m K_m + \alpha_p K_p$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = \dot{m}$$ - continuity

$$\rho = \alpha_m \rho_m + \alpha_p \rho_p \qquad \mu = \alpha_m \mu_m + \alpha_p \mu_p$$

$$\rho_j = \rho_{0j} + \psi_j (p - p_{0j}) - \zeta_j (T - T_{0j}), \; j = m, p \qquad \alpha_p = 1 - \alpha_m$$

Hardt evaporation model: $\dot{m} = (T_i - T_s) N \alpha_m \nabla \alpha_m / (R_{mp} L)$ with

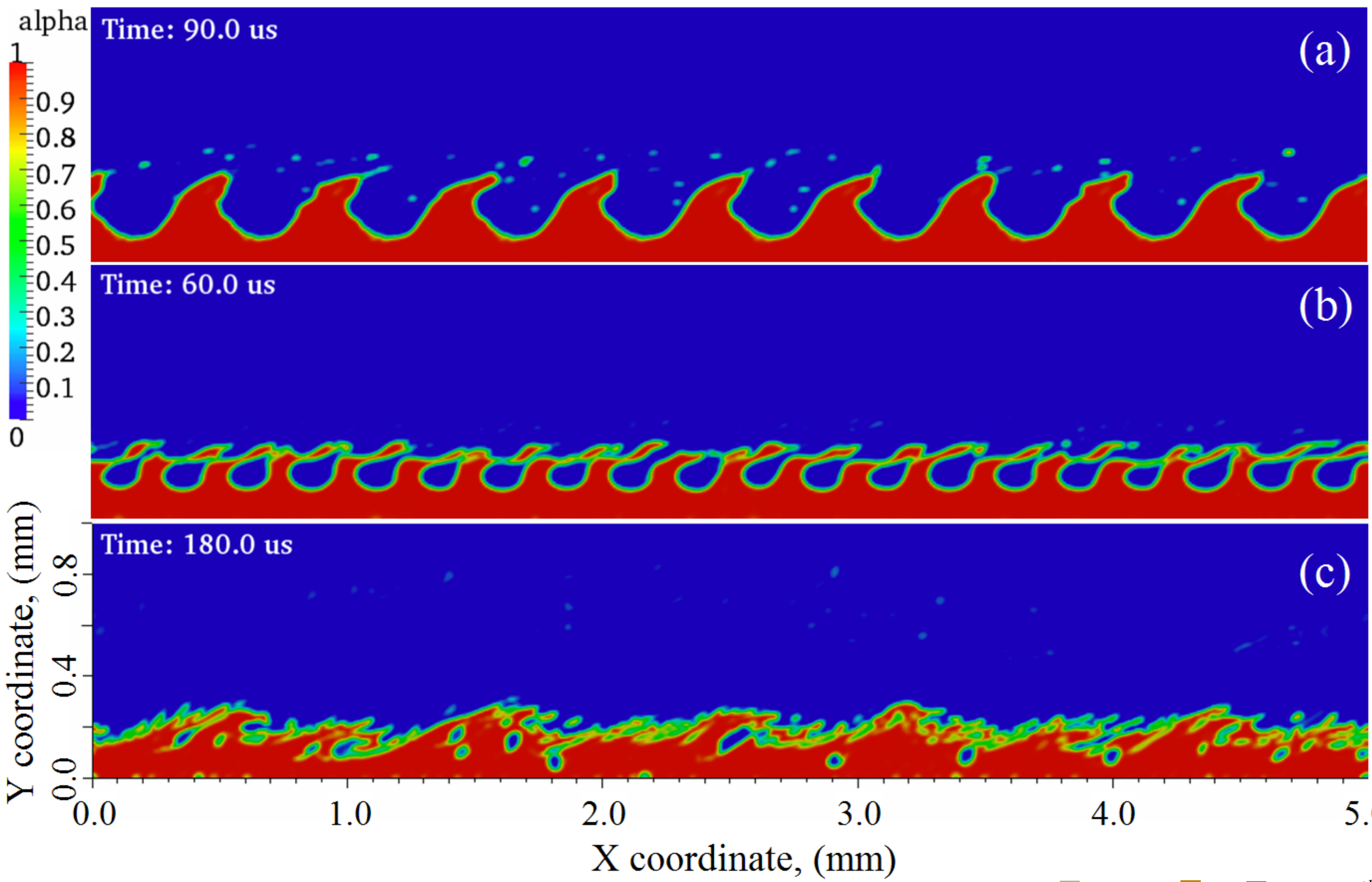
$$R_{mp} = (2-\chi) T_s^{3/2} \sqrt{2\pi R_p} / (2\chi L^2 \rho_p)$$ and $$\dot{h} = L\dot{m}$$

Hardt & Wondra, *J. Comput. Phys.* 227 (2008) 5871

Modelling: OpenFOAM

Effects of Viscous & Thermal Stresses

Plasma-liquid interface perturbed with 10, 20 & 40 wavelengths (wavelength: 500 μm, 250 μm & 125 μm):



$V_p = 10\, km/s$

$\mu_p = 10^{-5}$ kg/(m s)

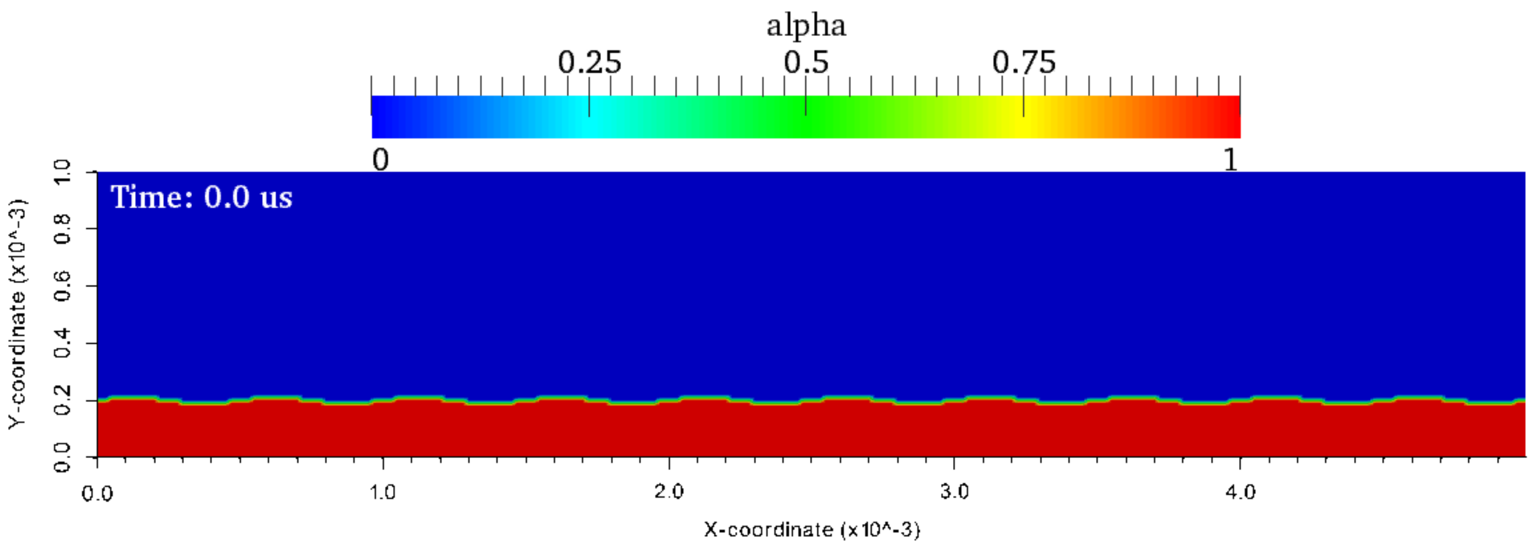
$N_p = 10^{20}$ m^{-3}

$h_m = 200$ μm

$T_m = 3695\, K$

OpenFOAM modeling of plasma-melt flow

Movie of plasma-liquid interface perturbed with 10 wavelengths (wavelength: 500 µm):



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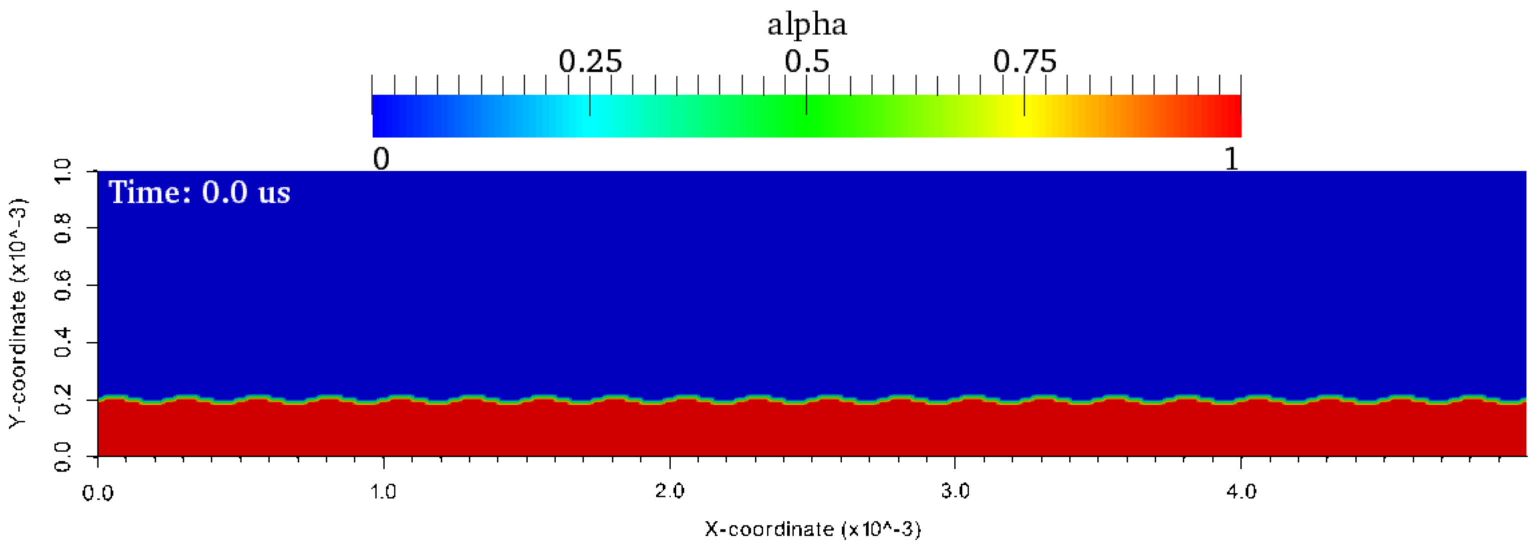
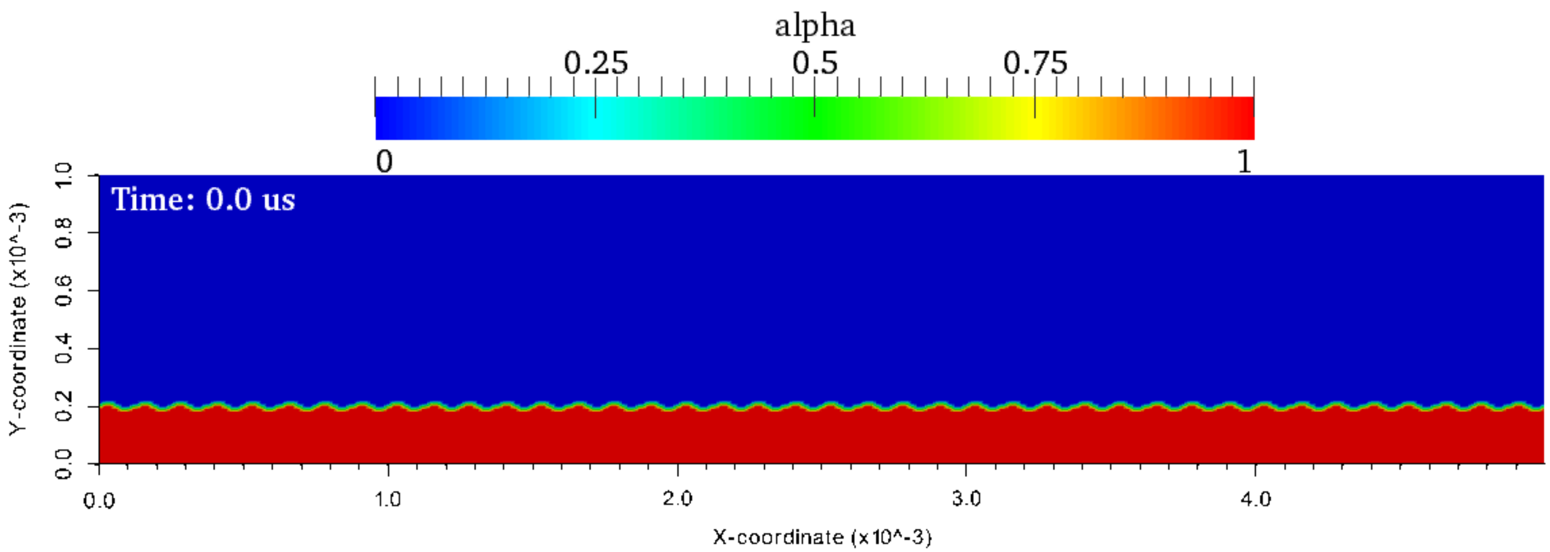
OpenFOAM modeling of plasma-melt flow

Movie of plasma-liquid interface perturbed with 20 wavelengths (wavelength: 250 μm):



OpenFOAM modeling of plasma-melt flow

Movie of plasma-liquid interface perturbed with 40 wavelengths (wavelength: 125 µm):



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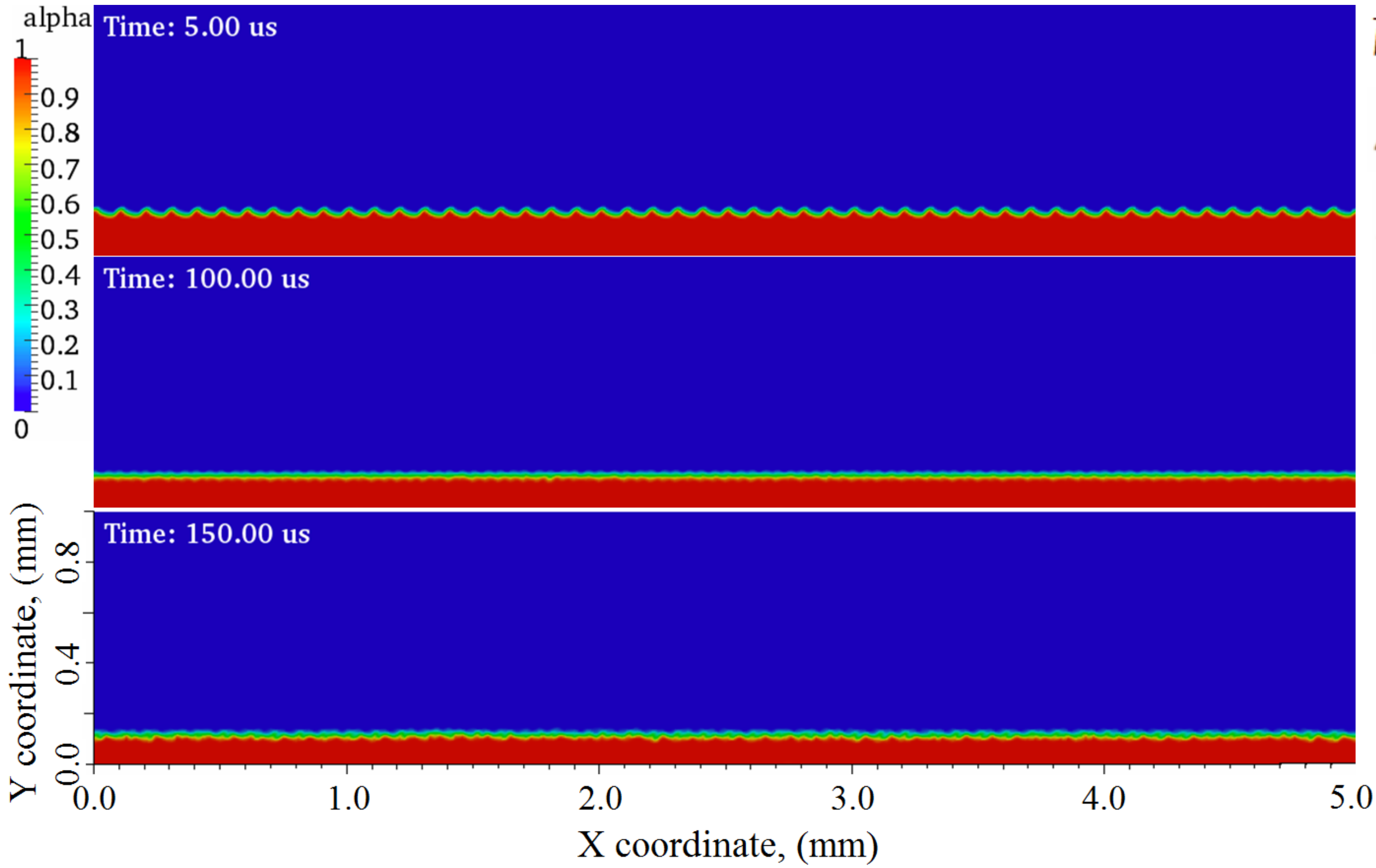
Modelling: OpenFOAM

Stabilizing Effect of Mass & Heat Transfer Across the Interface

Plasma-liquid interface perturbed with 50 wavelengths (100 µm):



$V_p = 10\, km/s$

$\mu_p = 10^{-5}$ kg/(m s)

$N_p = 10^{20}$ m^{-3}

$h_m = 200$ µm

$T_m = 5936\, K$

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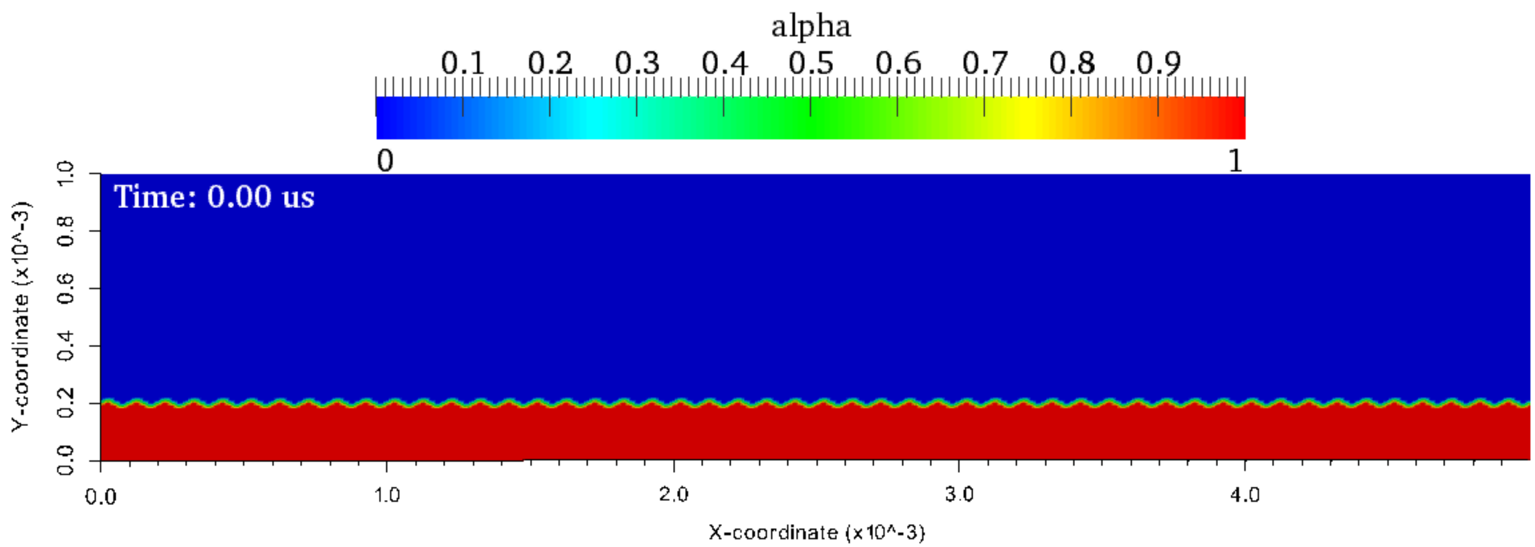
OpenFOAM modeling of plasma-melt flow

Movie of plasma-liquid interface perturbed with 50 wavelengths (wavelength: 100 µm):



Summary

- ***Plasma instabilities have serious effects on PFCs and should be significantly minimized or totally mitigated***

- ***Melt layer erosion can substantially reduce lifetime and contaminate the plasma***

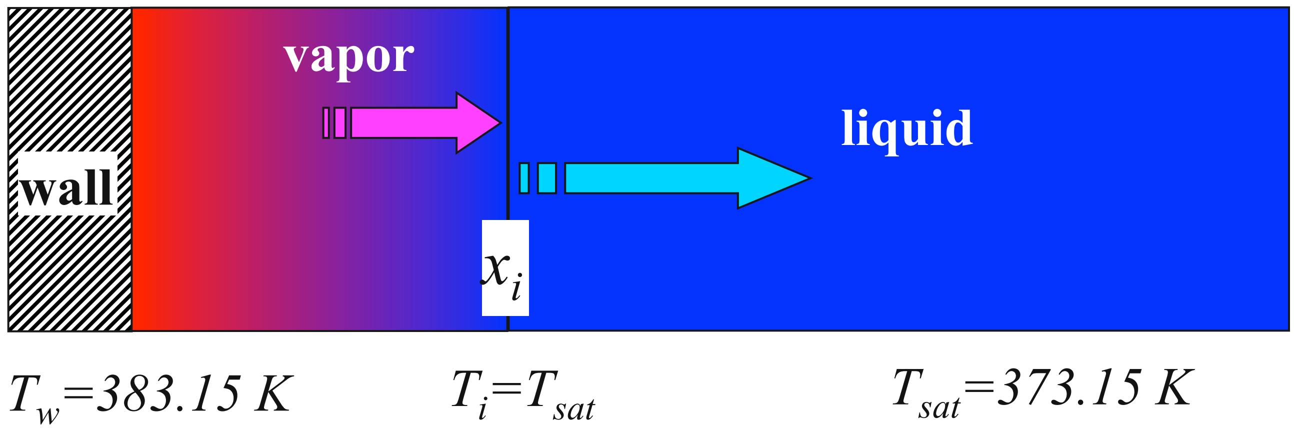
- **Viscous forces have strong destabilizing effects on melt layer: reduced critical velocity & wavelength of fasters growing waves**

- **Phase change with intense vaporization stabilizes short-length waves suppressing the growth of viscous instability**

- ***When Vaporization is insignificant* → growth of *short-length waves*, their transformation into ligaments, fine melt droplets from ligament tips, droplet collisions and drag by plasma flow**

Reserved Slides

Stefan Test Problem



Analytical solution:

$$x_i(t) = 2\beta\sqrt{k_v t}$$

$$T(x,t) = T_w + \frac{T_{sat} - T_w}{erf(\beta)} erf\left(\frac{x}{2\sqrt{k_v t}}\right)$$

$$k_v = \frac{\lambda_v}{\rho_v c_{pv}} \text{ and } \beta \exp(\beta^2) = \frac{c_{pv}(T_w - T_{sat})}{\sqrt{\pi} h_e}$$

Model parameters:

$$\lambda_v = 10^{-2} \div 10^{-1}\ W/(m\ K) \quad \lambda_l = 1 W/(m\ K)$$

$$c_{pv} = 10^3\ J/(kg\ K) \quad c_{pl} = 10^3\ J/(kg\ K)$$

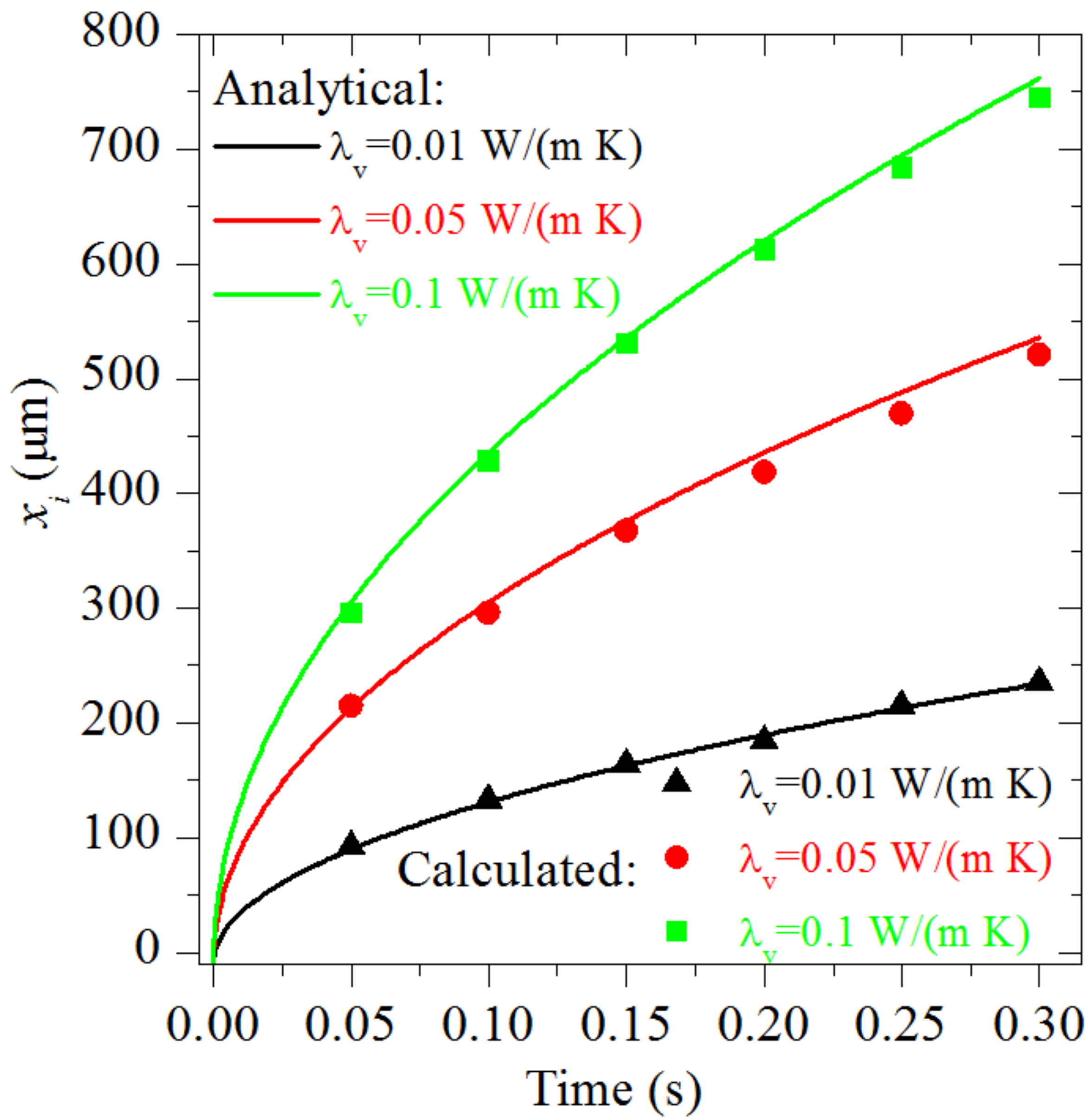
$$h_e = 10^6\ J/kg \quad \sigma = 10\ mN/m$$

$$\mu_v = 10^{-5}\ Pa\ s \quad \mu_l = 10^{-2}\ Pa\ s$$

$$\rho_v = 1\ kg/m^3 \quad \rho_l = 1\ kg/m^3$$

Hardt & Wondra, *J. Comput. Phys.* 227 (2008) 5871

Stefan Test Problem



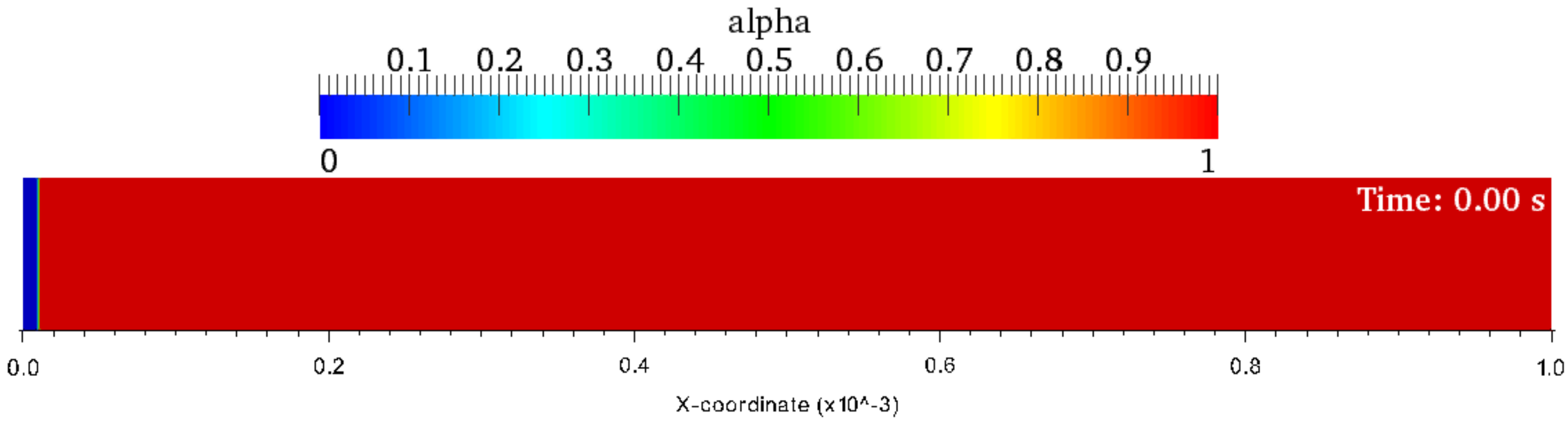
Vapor-liquid interface position x_i as a function of time for different values of λ_v:

solid lines –> analytical results

symbols –> CFD calculation data

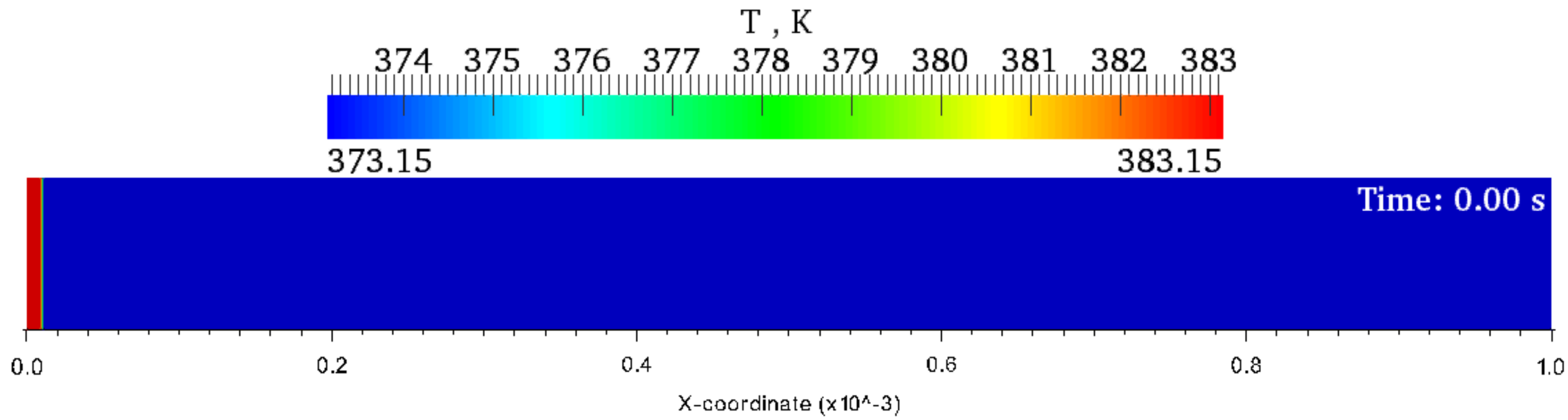
Stefan Test Problem

Movie of volume fractions of vapor & liquid: λ_v =0.1 W/(m K)



Stefan Test Problem

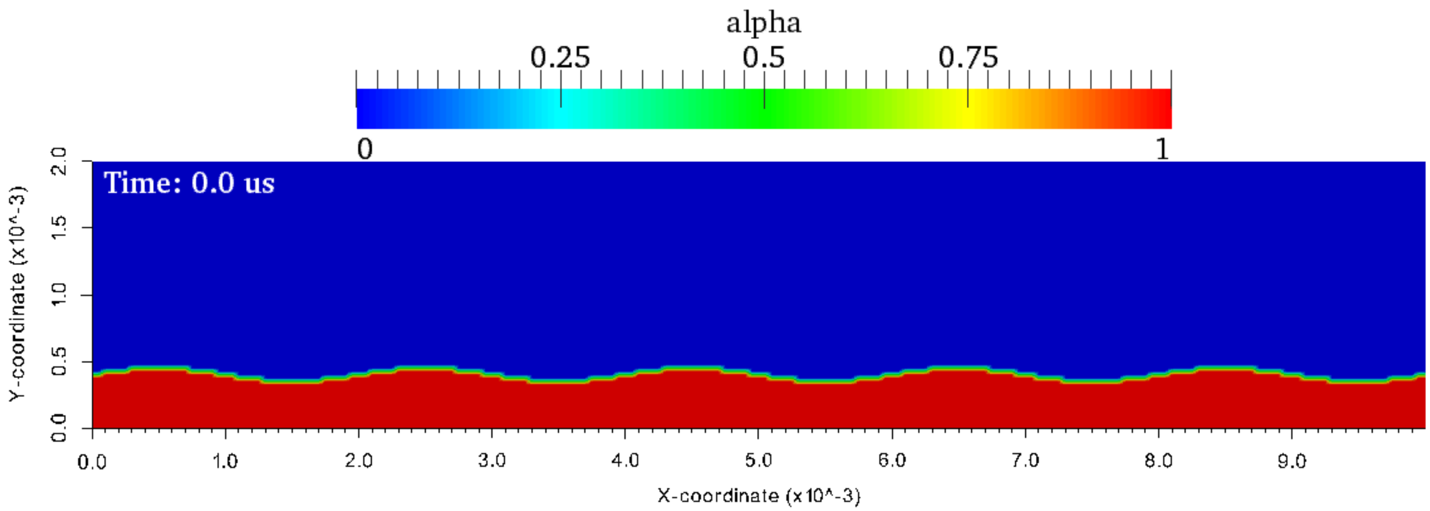
Movie of evolution of temperature of vapor & liquid: λ_v =0.1 W/(m K)



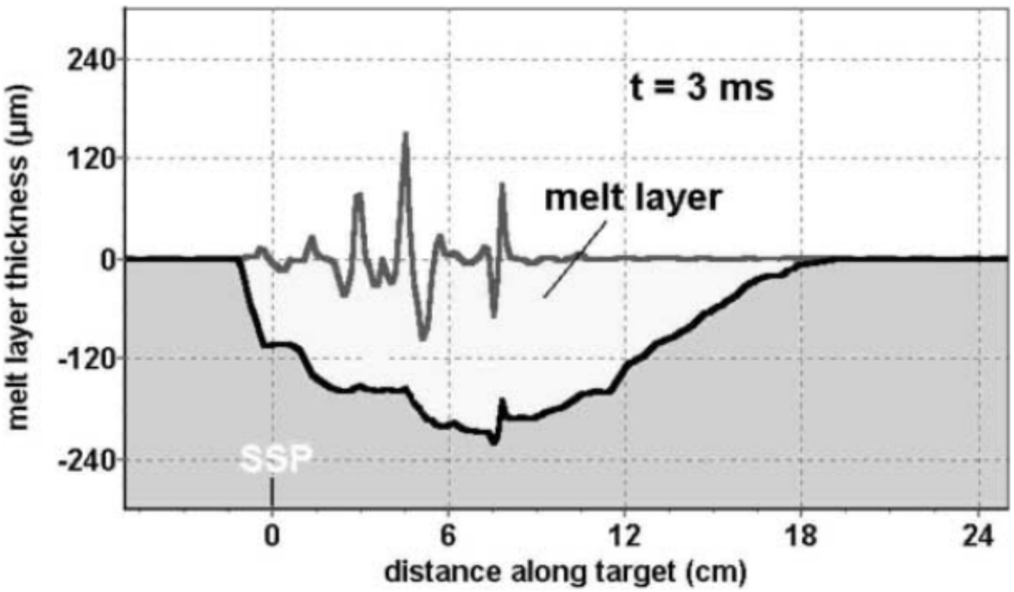
OpenFOAM modeling of plasma-melt flow

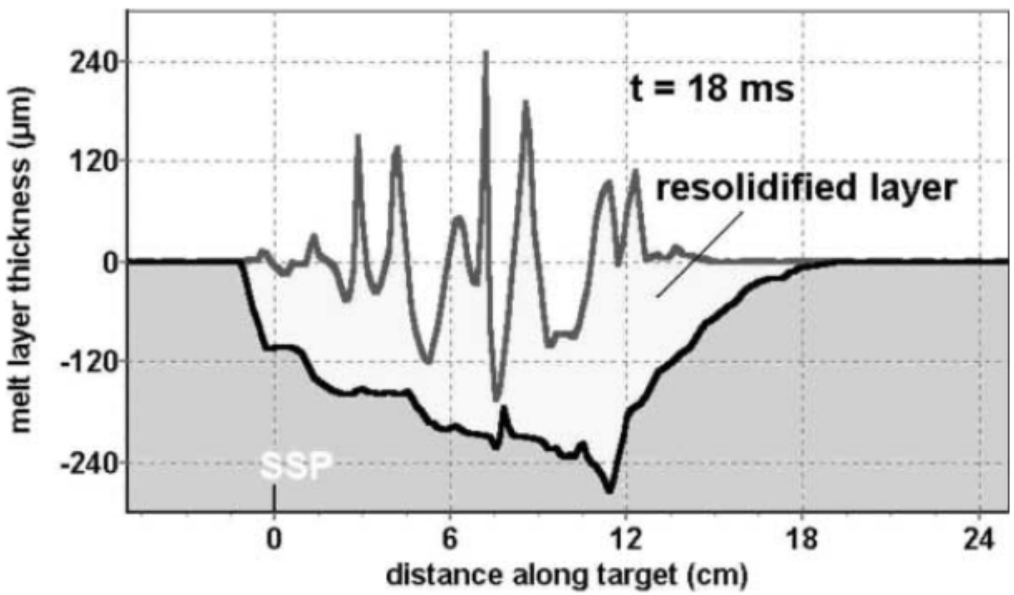
Plasma impact with velocity 100 km/s in two times larger domain

Movie of plasma-liquid interface perturbed with 5 wavelengths:



Wavy Structure of Melt Layer from FOREV-2





- weak melt motion with wavy surface

- wavelength of surface waves ~60 μm

Würz et al. *Fus. Eng. Design* 56 (2001) 397

Phenomenological Capillary Droplet Model

Main assumptions:

- extension of linear stability analysis to an essentially non-linear regime
- approximation of a deep melt: dangerous wavelength $\lambda_\theta << h_m$
- fine droplets at wave's peaks are dragged away by the plasma wind

Maximum increment coefficient and dangerous wavelength:

$\Gamma_\theta = 2\left(\rho_p \Delta V^2\right)^{3/2} \Big/ \left(3\gamma\sqrt{3\rho_m}\right)$ and $\lambda_\theta = 3\pi\gamma \Big/ \left(\rho_p \Delta V^2\right)$ with the radius of droplets assumed as $\sim \lambda_\theta / 4$

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

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

$\lambda_\theta \sim 40\ \mu m$; K-H instability time $\tau \sim 1.8\ \mu s$

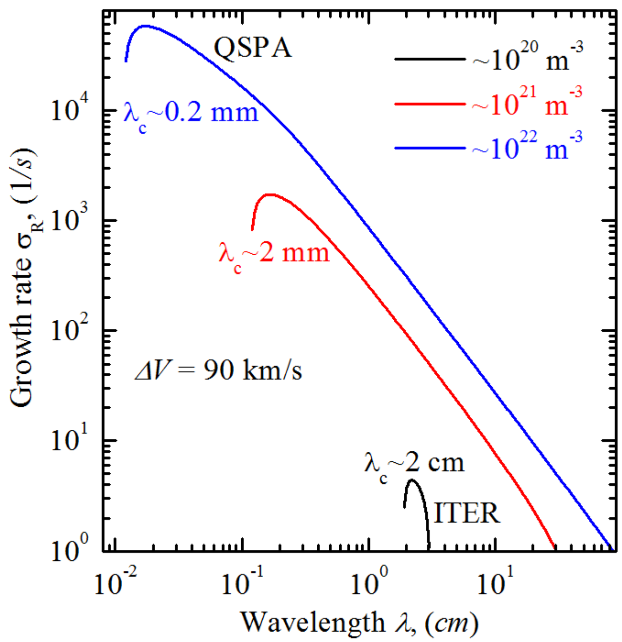
<u>For ITER conditions:</u> weak ELMs <2.5 MJ/m^2 during <0.3 ms

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

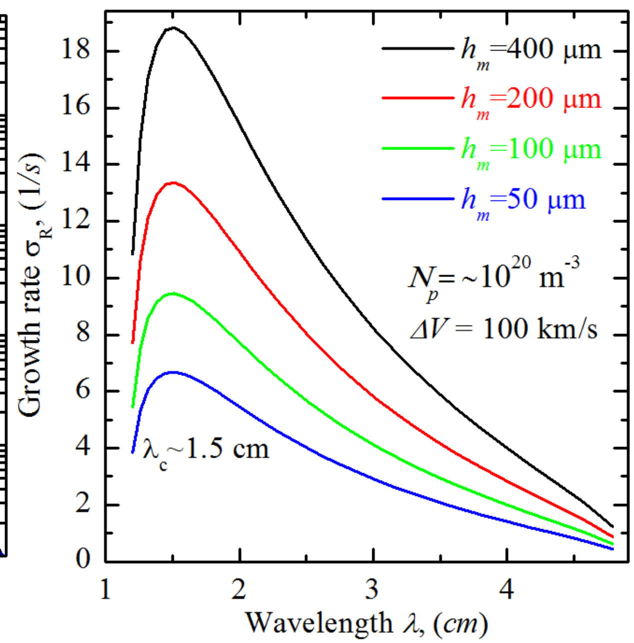
$\lambda_\theta \sim 14 - 1.4$ cm >> $h_m \Rightarrow$ ***model is not valid!***

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

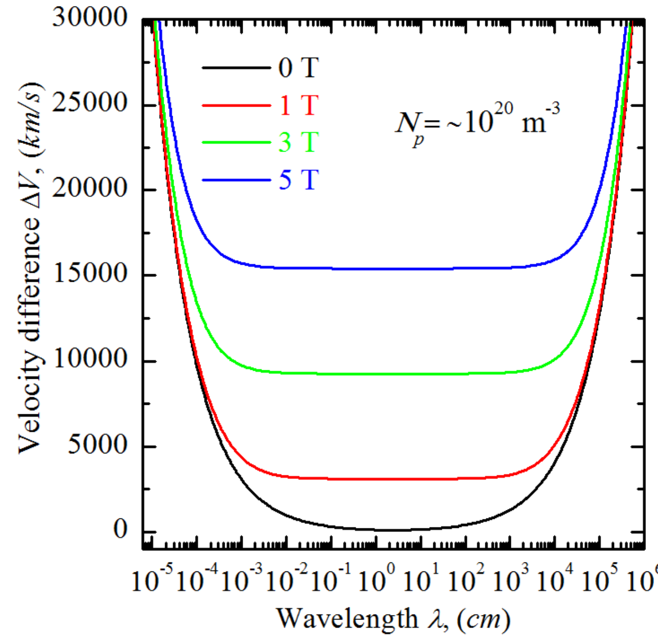
K-H Instability of Inviscid Plasma-Tungsten Melt



denser plasma shifts dangerous wavelength toward shorter waves, growth rate increases



thinner melt layers are more stable than thicker ones



H aligned with the melt flow suppresses instability

H perpendicular to the flow has no influence

G. Miloshevsky & A. Hassanein, *Nucl. Fusion* 50 (2010) 115005; *J. Nucl. Mater.* 415 (2011) S74.

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