Modeling of Melt Layer Splashing and Erosion Losses of PFC

Gennady V. Miloshevsky

Ahmed Hassanein

Center for Materials Under eXtreme Environment
School of Nuclear Engineering
Purdue University

Presented at PFC Meeting, ORNL, Tennessee, USA, August 10-12, 2011

PURDUE NUCLEAR ENGINEERING

PURDUE UNIVERSITY

Outline

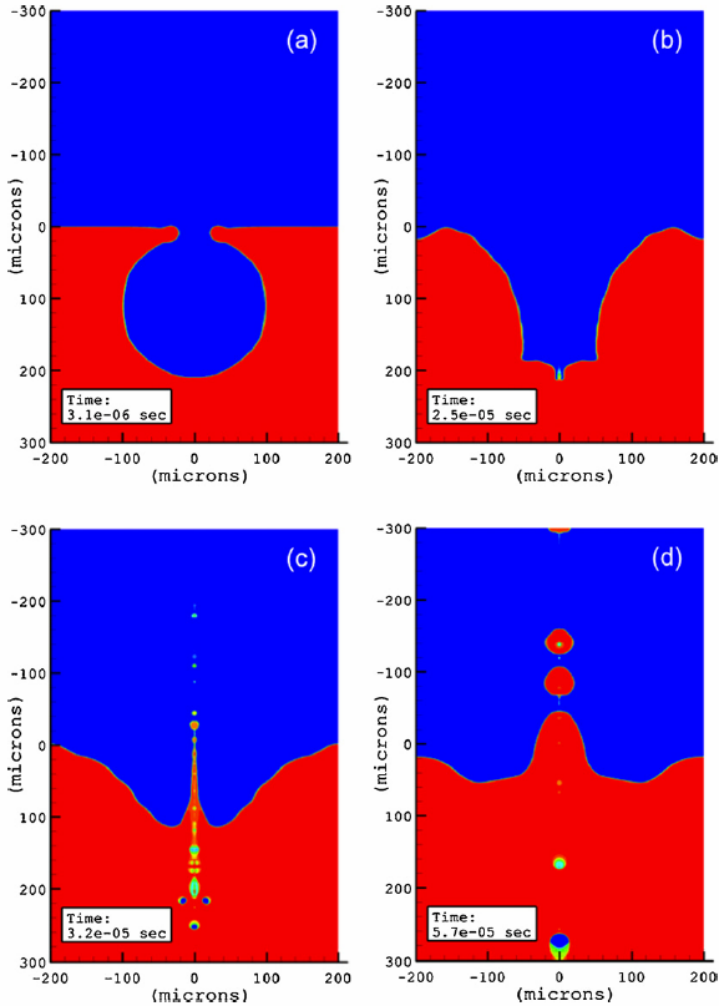
- Brief Overview of Previous Results
- Viscosity Effects on Kelvin-Helmholtz Instability
- Mass & Heat Effects on Kelvin-Helmholtz Instability
- OpenFOAM Modelling
- Summary

Outline

- **Brief Overview of Previous Results**
- Viscosity Effects on Kelvin-Helmholtz Instability
- Mass & Heat Effects on Kelvin-Helmholtz Instability
- OpenFOAM Modelling
- Summary

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

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.



- CFD simulations of bubble bursting and jet-droplet formation
- integration of amount of jet-droplets into a *moving boundary model* for estimating the erosion of melt layer due to boiling
- results provide insights toward the understanding of the bubble bursting mechanism and its quantitative contribution to the melt layer erosion

Inviscid Linear Stability Theory & Capillary Droplet Ejection Model as Its Limiting Case

Y. Shi, G. Miloshevsky & A. Hassanein. *Theoretical Studies of Macroscopic Erosion Mechanisms of Melt Layers Developed on Plasma Facing Components*. J. Nucl. Mater. 412 (**2011**) 123-128.

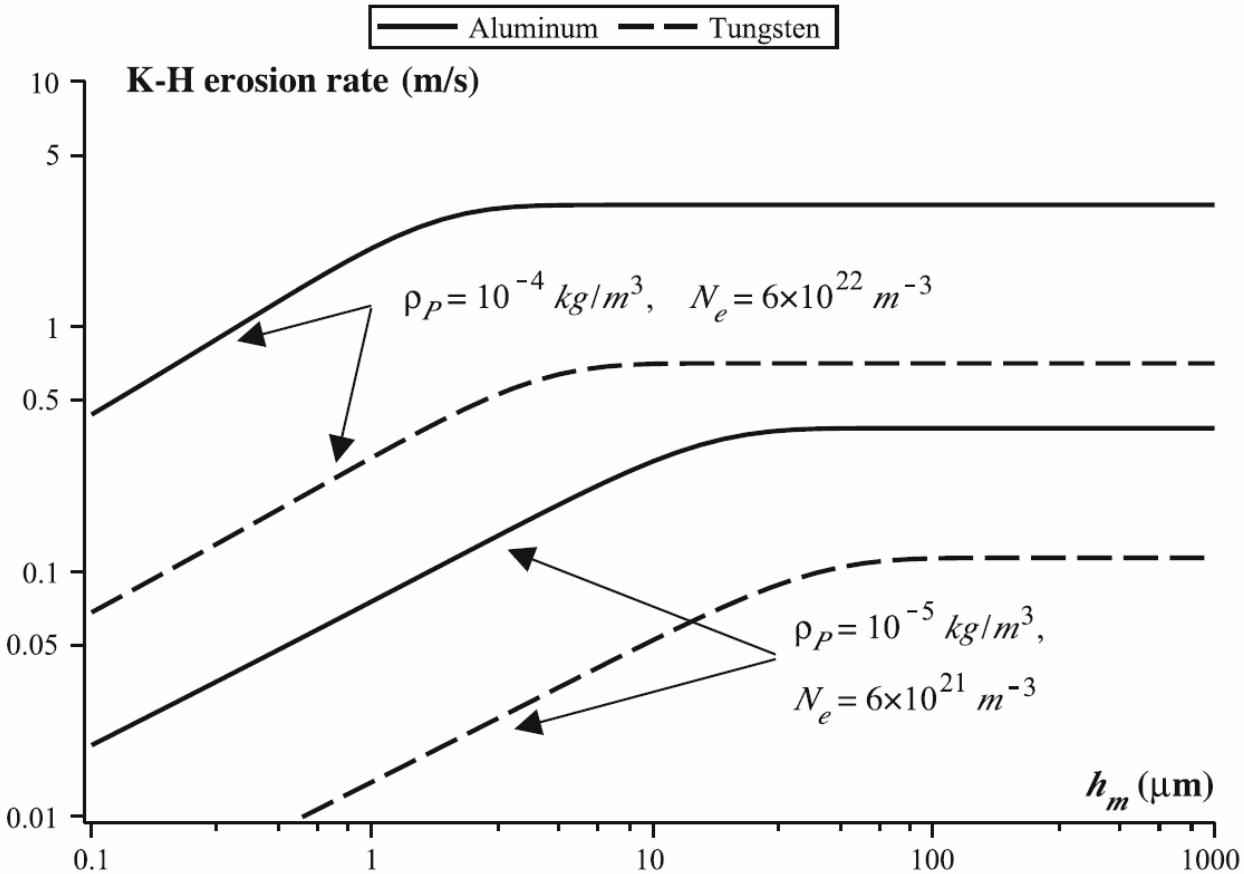
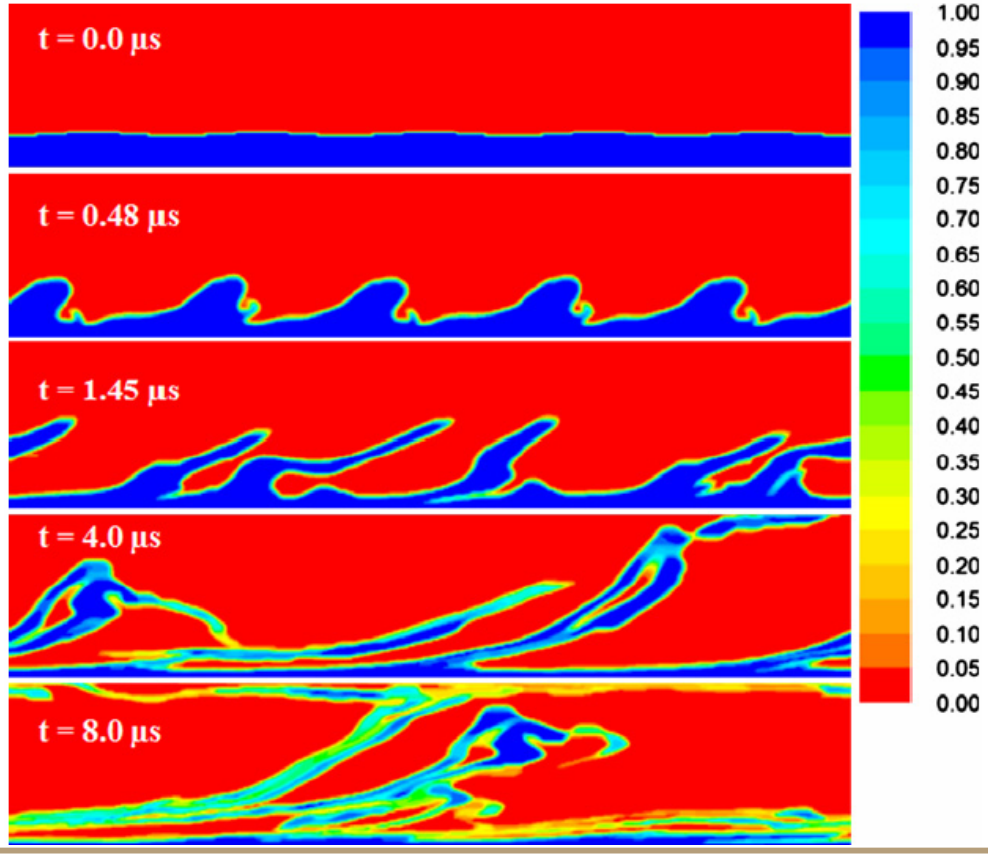


Fig. 7. K–H erosion rate versus melt layer thickness for aluminum and tungsten.

- stability criterion, cut-off wavelengths, most unstable waves, growth rates for tungsten and aluminum melt
- effects of melt layer thickness, plasma density & velocity, surface tension
- erosion rate estimates, material losses & PFC lifetimes using capillary droplet ejection model

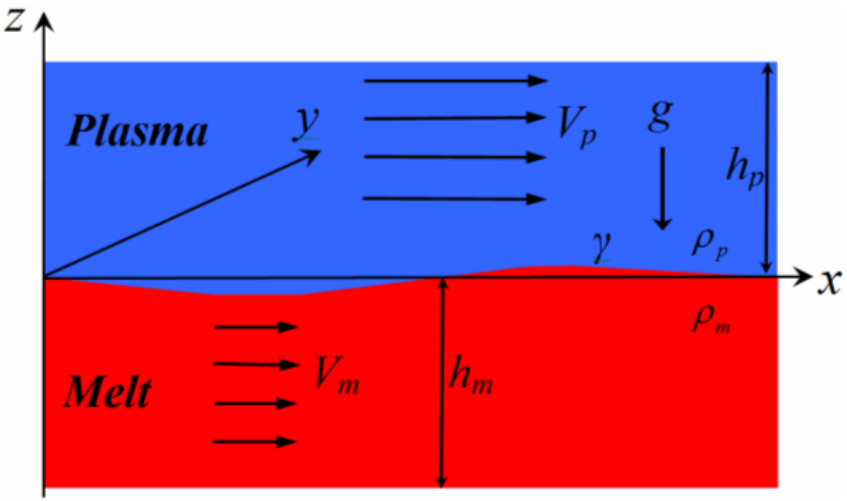
Splashing Mechanism of Inviscid Melt Layers due to Kelvin-Helmholtz Instability

- G. V. Miloshevsky & A. Hassanein. *Modeling of Kelvin-Helmholtz instability and splashing of melt layers from plasma facing components in tokamaks under plasma impact*. Nucl. Fusion 50 (**2010**) 115005.
- G. Miloshevsky & A. Hassanein. *Modeling of macroscopic melt layer splashing during plasma instabilities.* J. Nucl. Mater. (**2010**), doi:10.1016/j.jnucmat.2010.08.032



- splitting into ligaments, their elongation and development of long threads that can break into droplets
- the onset of K-H instability and most dangerous wavelength (~2 mm) predicted from the linear stability analysis are found in very good agreement with those observed in the inviscid CFD modeling

K-H Instability of Inviscid Plasma-Tungsten Melt



Critical Velocity & Growth Rate:

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

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

$V_p \sim 100\ km/s \quad \rho_p \sim 10^{-6}\ kg/m^3$

$V_m \sim 1\ m/s \quad \rho_m \sim 17600\ kg/m^3$

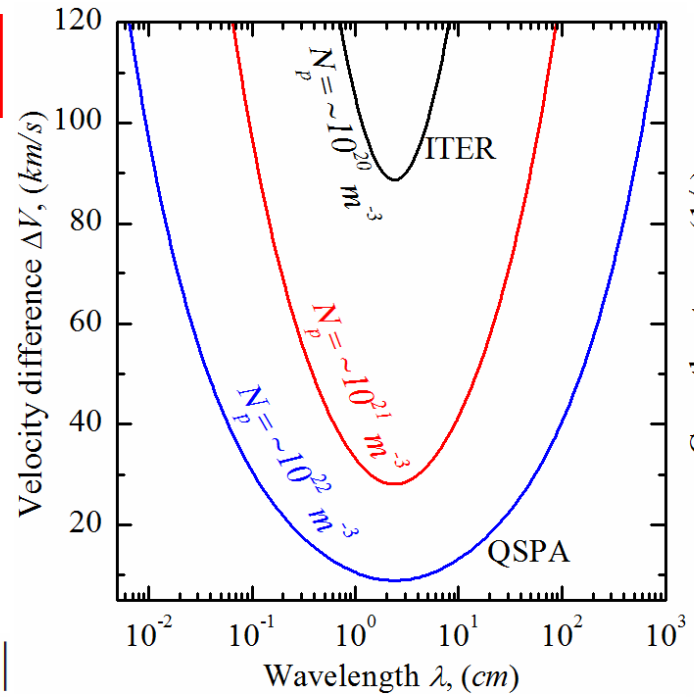
$h_p \sim \infty \quad r = \rho_p / \rho_m \sim 10^{-10}$

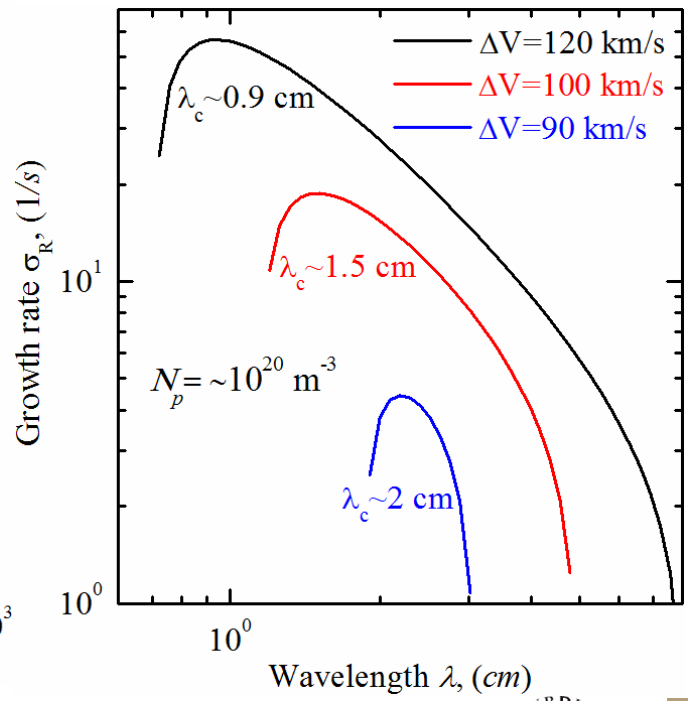
$h_m \sim 400\ \mu m \quad \gamma_H = \mu H^2 / 2\pi k$

$g \approx 9.81\ m/s^2 \quad \gamma \approx 2.5\ N/m$

$\rho'_m = \rho_m \coth(kh_m) \quad k = 2\pi/\lambda$

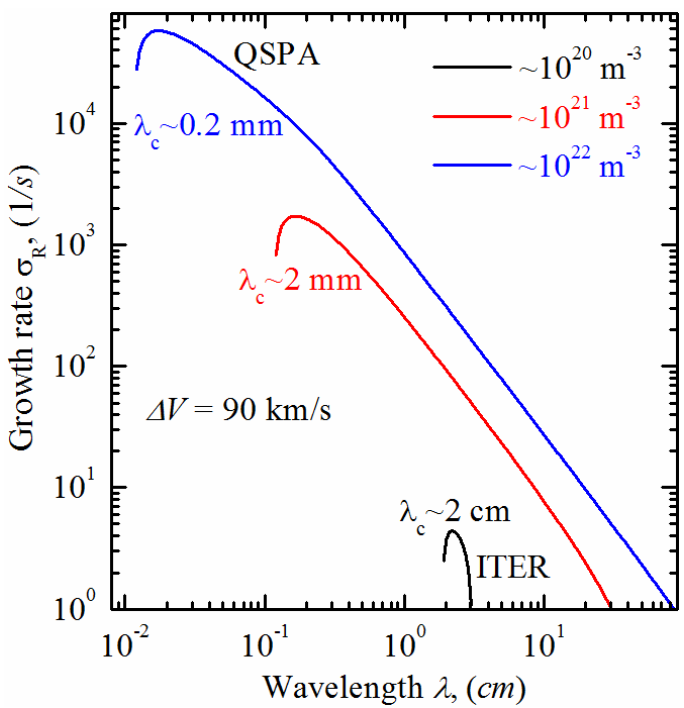
$\rho'_p = \rho_p \coth(kh_p) \quad \Delta V = |V_p - V_m|$

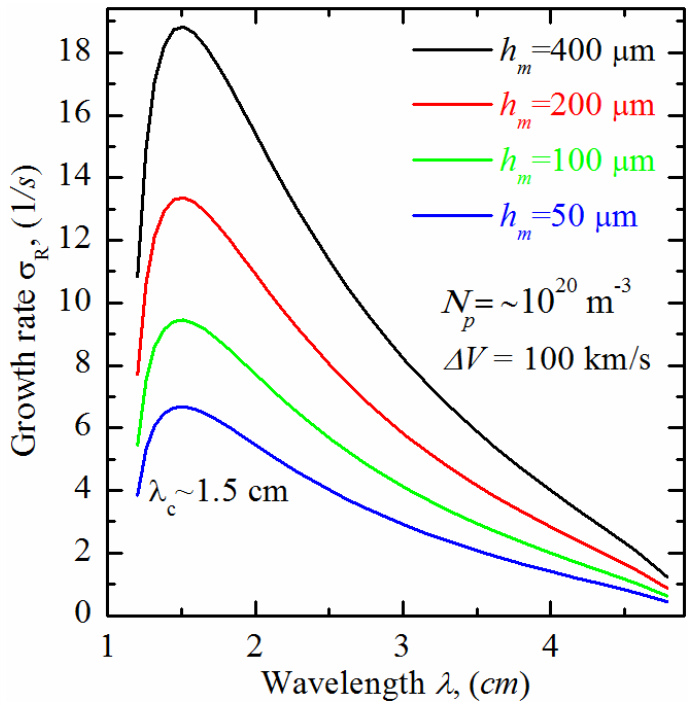


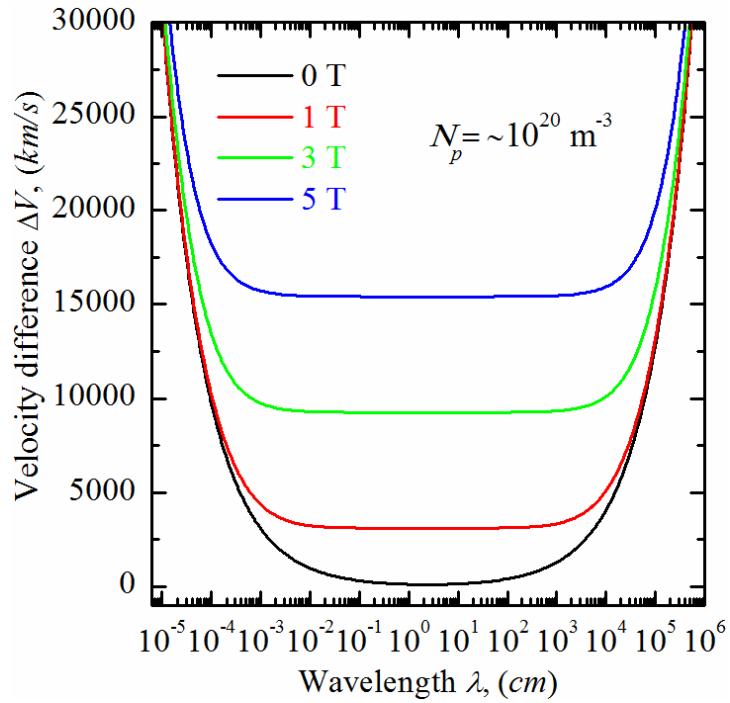


Miloshevsky & Hassanein, *Nucl. Fusion* 50 (2010) 115005; *J. Nucl. Mater.* (2010)

K-H Instability of Inviscid Plasma-Tungsten Melt

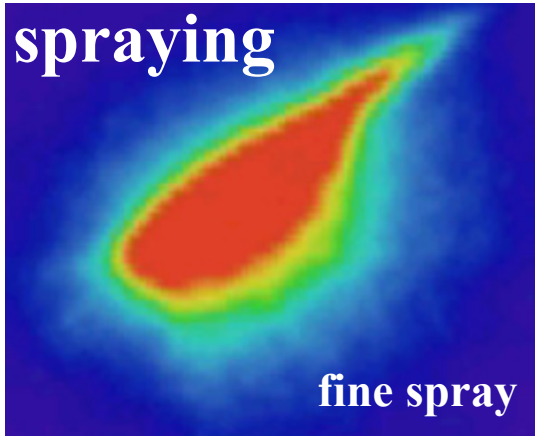


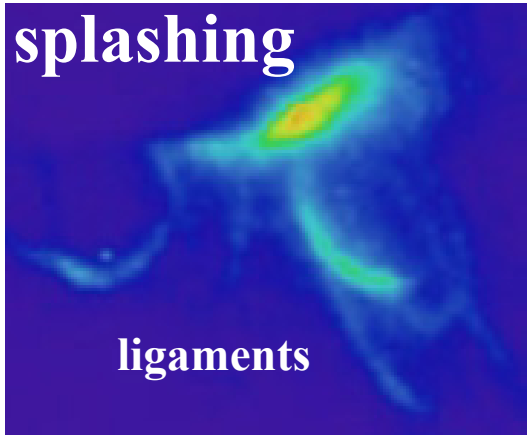


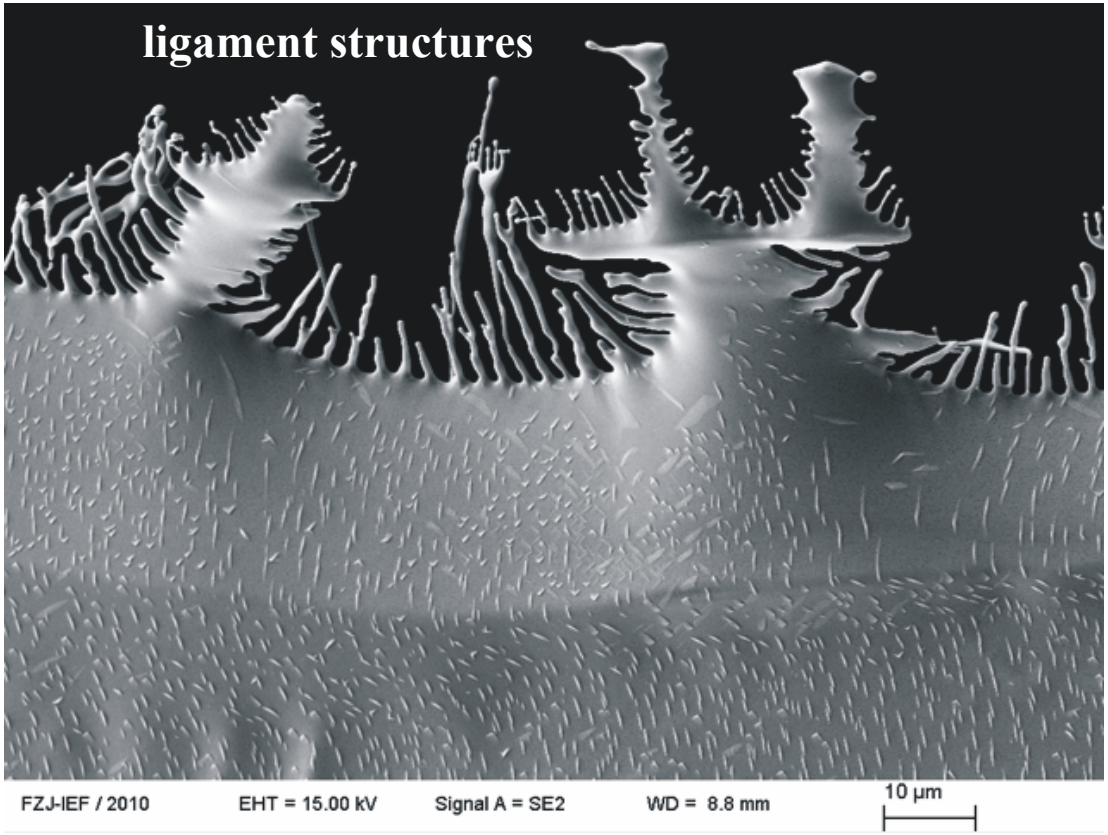


- with increase in plasma density: critical velocity and "dangerous" wavelength decreases, growth rate increases toward shorter waves
- thinner melt layers are more stable than thicker ones; critical velocity is not affected by the thickness of melt layer !
- magnetic field aligned along/against the plasma-melt flow completely suppresses the K-H instability; magnetic field perpendicular to the flow direction has no influence on the K-H instability

Melt Layer Spraying and Splashing in TEXTOR







J. W. Coenen et al *Analysis of tungsten melt-layer motion and splashing under tokamak conditions at TEXTOR.* Nucl. Fusion 51 (**2011**) 083008.

- spraying occurs continuously with ~4 µm droplets
- splashing events with droplets ~20-100 µm are rare
- finger-like structures on the surface with regular patterns
- **physics mechanisms of fine spray generation and splashing with long ligaments? What is the origin of regular fingers on the melt surface?**

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

Outline

- Brief Overview of Previous Results
- **Viscosity Effects on Kelvin-Helmholtz Instability**
- Mass & Heat Effects on Kelvin-Helmholtz Instability
- OpenFOAM Modelling
- Summary

K-H Instability of Viscous Potential Plasma-Melt Flow

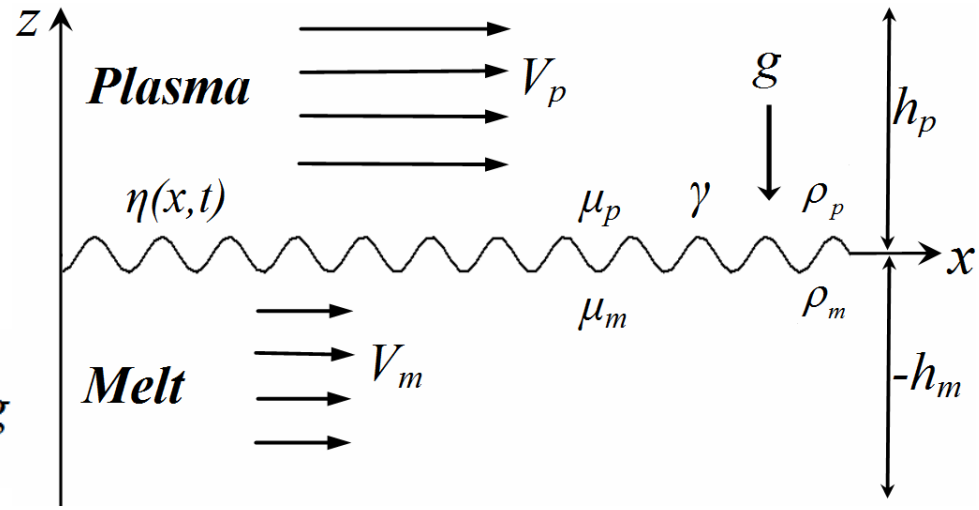
Linearized Navier-Stokes Equations:

$$\mu_\alpha \nabla(\nabla^2 \varphi_\alpha) \equiv 0$$

Momentum:

$$\rho_\alpha\left(\frac{\partial u_\alpha}{\partial t}+V_\alpha\frac{\partial u_\alpha}{\partial x}\right)=-\frac{\partial p_\alpha}{\partial x}+\mu_\alpha\left(\frac{\partial^2 u_\alpha}{\partial x^2}+\frac{\partial^2 u_\alpha}{\partial z^2}\right)$$

$$\rho_\alpha\left(\frac{\partial v_\alpha}{\partial t}+V_\alpha\frac{\partial v_\alpha}{\partial z}\right)=-\frac{\partial p_\alpha}{\partial z}+\mu_\alpha\left(\frac{\partial^2 v_\alpha}{\partial x^2}+\frac{\partial^2 v_\alpha}{\partial z^2}\right)-\rho_\alpha g$$



Continuity and Potential Flow:

$$\frac{\partial u_\alpha}{\partial x}+\frac{\partial v_\alpha}{\partial z}=0 \quad \text{with } u_\alpha=\frac{\partial \varphi_\alpha}{\partial x} \text{ and } v_\alpha=\frac{\partial \varphi_\alpha}{\partial z}$$

$$\Longrightarrow \frac{\partial^2 \varphi_\alpha}{\partial x^2}+\frac{\partial^2 \varphi_\alpha}{\partial z^2}=0 \qquad \alpha=(p,m)$$

Perturbation normal modes:

$$\eta = A_0 \exp(\sigma t + ikx) + c.c.$$

$$\varphi_\alpha = A_\alpha \cosh[k(z-h_\alpha)]\exp(\sigma t + ikx) + c.c.$$

Boundary conditions at interface:

$$\frac{\partial \eta}{\partial t}+V_\alpha\frac{\partial \eta}{\partial x}=v_\alpha$$ - kinematic condition

$$\left\| -p_\alpha + 2\mu_\alpha\frac{\partial v_\alpha}{\partial z} + \rho_\alpha g \eta \right\| = -\gamma\frac{\partial^2 \eta}{\partial x^2}$$

- dynamic condition

Boundary conditions at h_α : $v_\alpha = 0$

Viscous Potential Flow Analysis: *no-slip conditions at walls and interface are not satisfied → viscous shear stress is neglected*

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

K-H Instability of Viscous Potential Plasma-Melt Flow

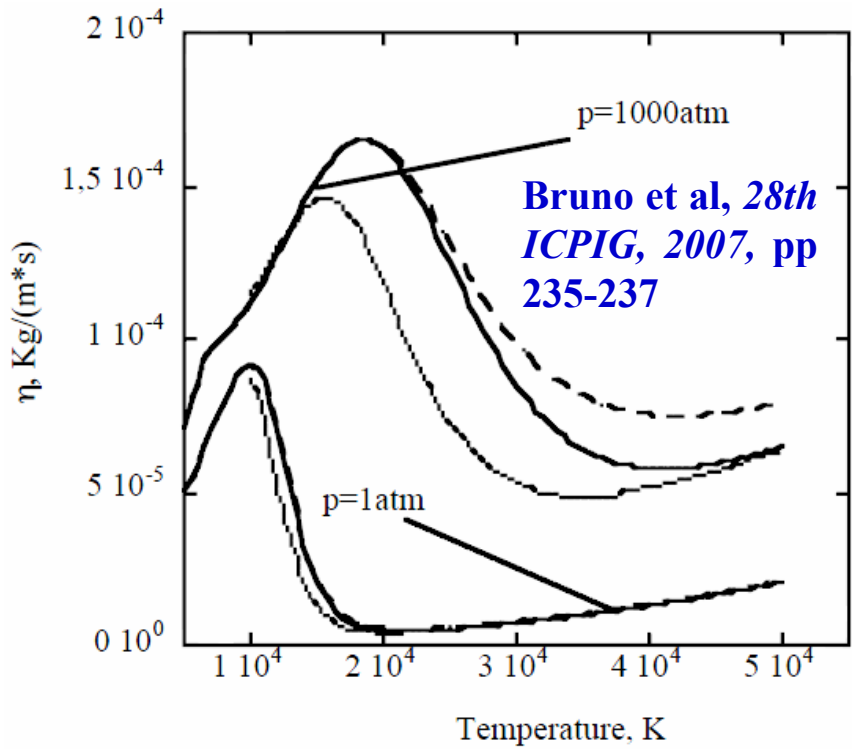
Critical Velocity & Growth Rate:

$$\Delta V > \sqrt{\frac{(\mu'_m + \mu'_p)^2}{\rho'_m \mu'^2_p + \rho'_p \mu'^2_m}\left(\frac{g(\rho_m - \rho_p)}{k} + (\gamma + \gamma_H)k\right)} \quad \text{with} \quad \begin{aligned} \mu'_m &= \mu_m \coth(kh_m) \\ \mu'_p &= \mu_p \coth(kh_p) \end{aligned}$$

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

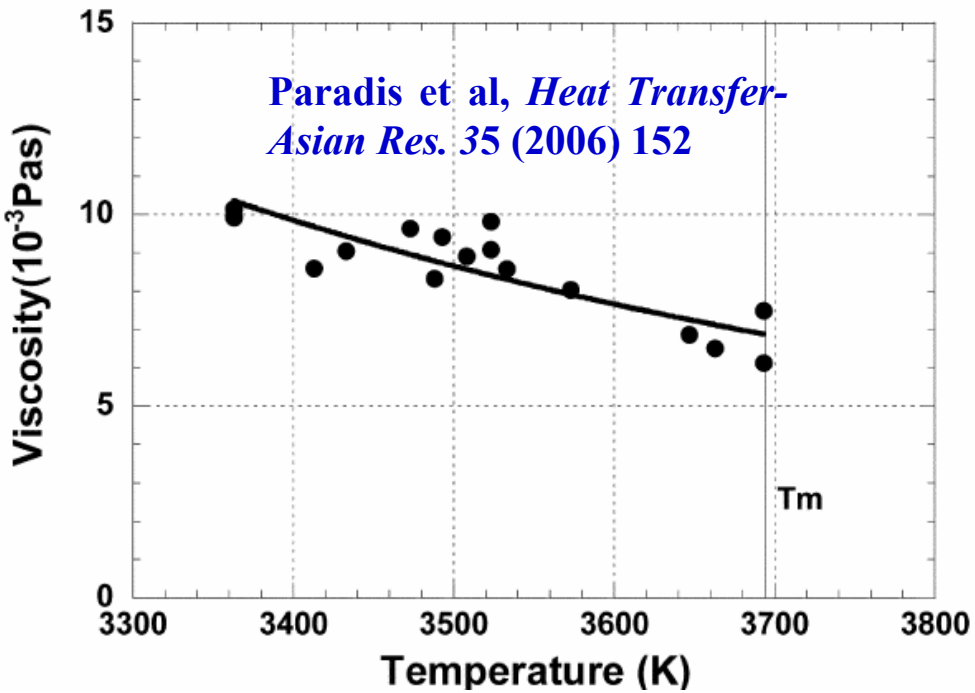
$$\mu_m \sim 7 \cdot 10^{-3} \ kg/(m \cdot s)$$

$$\boxed{\mu_p \sim 10^{-5} \ kg/(m \cdot s)}$$



Bruno et al, *28th ICPIG, 2007,* pp 235-237

Viscosity of hydrogen plasma



Paradis et al, *Heat Transfer-Asian Res.* 35 (2006) 152

Viscosity of molten tungsten

K-H Instability of Viscous Potential Plasma-Melt Flow

Critical Velocity & Growth Rate:

$$\nu_m = \mu_m / \rho_m \sim 4 \cdot 10^{-7} \ m^2/s$$

$$\nu_p = \mu_p / \rho_p \sim 10 \ m^2/s$$

$$m = \nu_p / \nu_m \sim 2.5 \cdot 10^7$$

Viscous Potential Flow:

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

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

$$\mathrm{Re}_p = \frac{L\Delta V}{\nu_p} \le 100$$

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

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

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

$$r << n$$

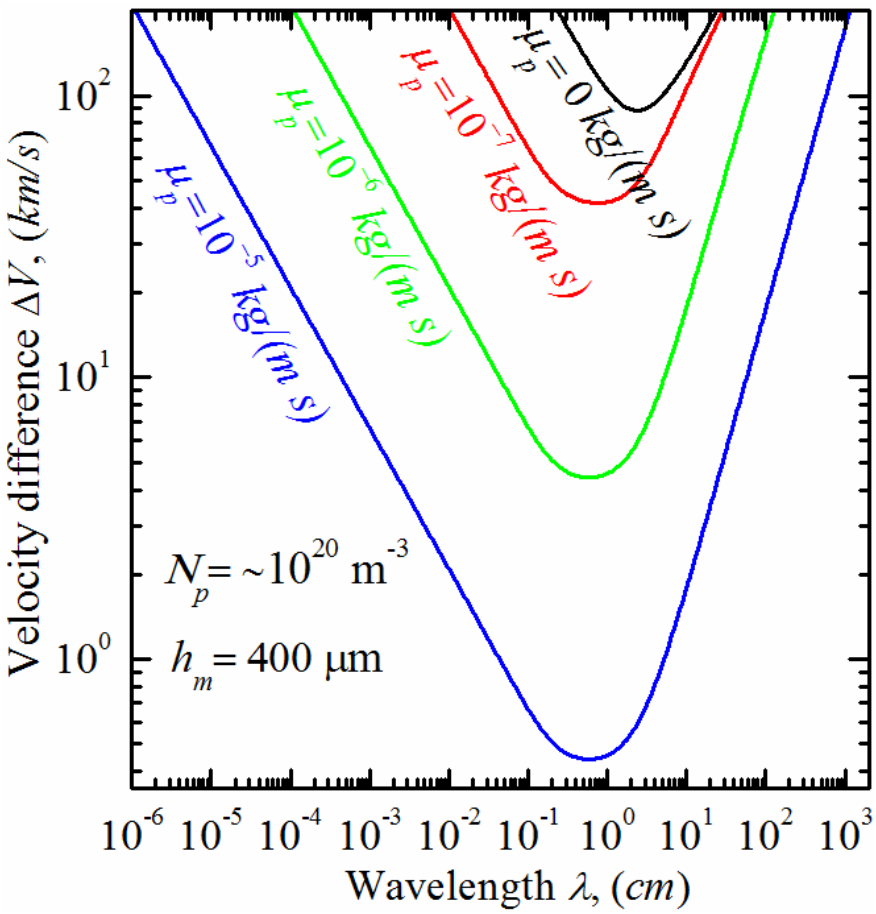
low viscosity case

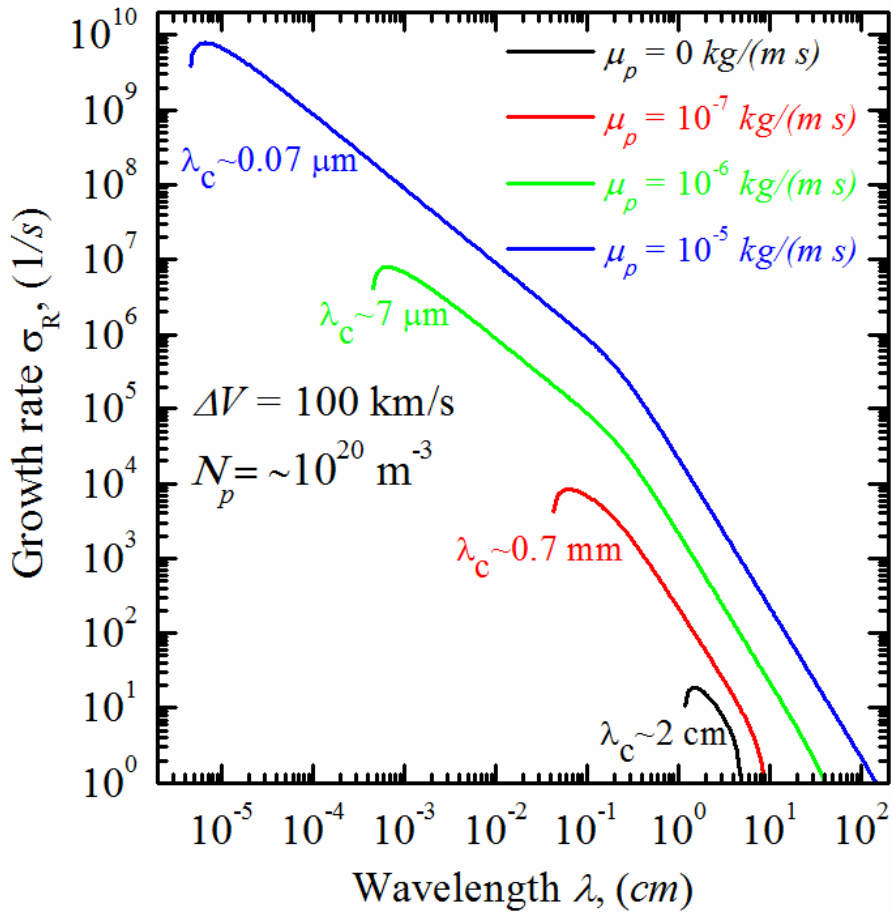
Inviscid Potential Flow:

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

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

K-H Instability of Viscous Potential Plasma-Melt Flow

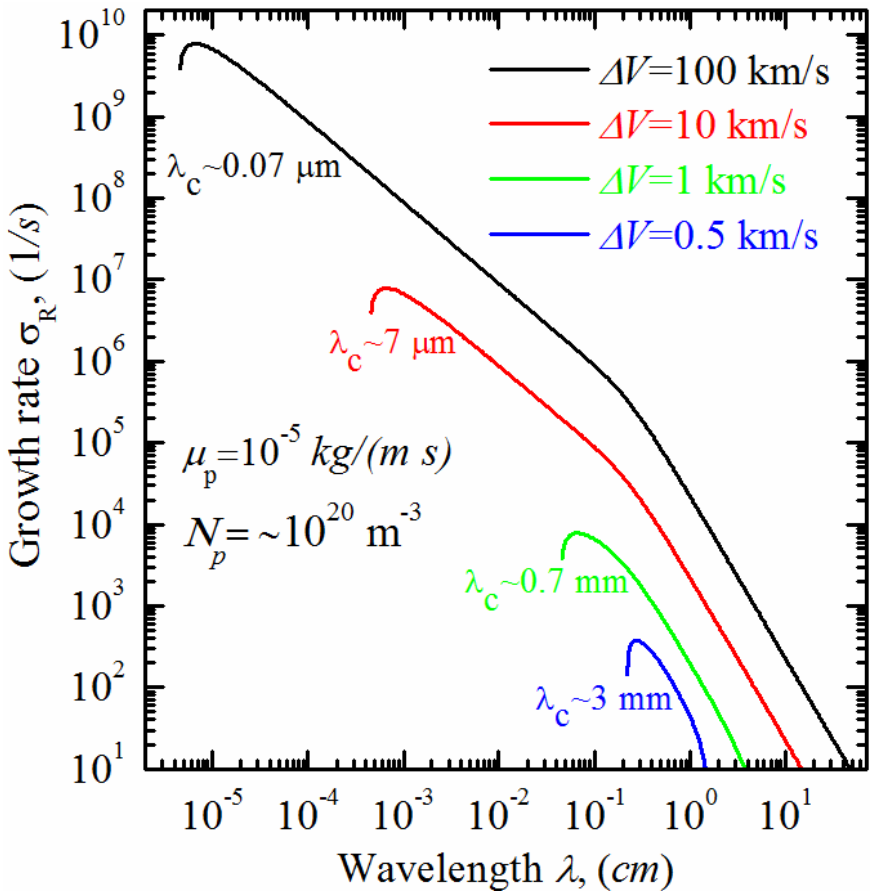


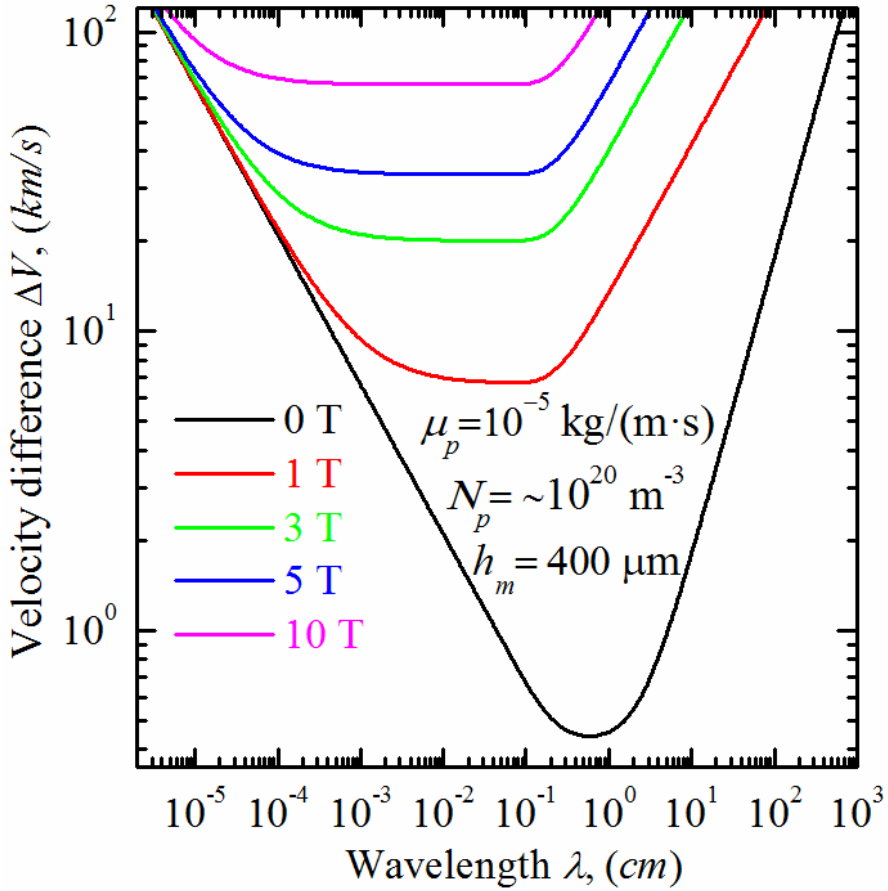


melt destabilization due to plasma viscosity effects with a slight shift in critical wavelength toward shorter waves

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

K-H Instability of Viscous Potential Plasma-Melt Flow

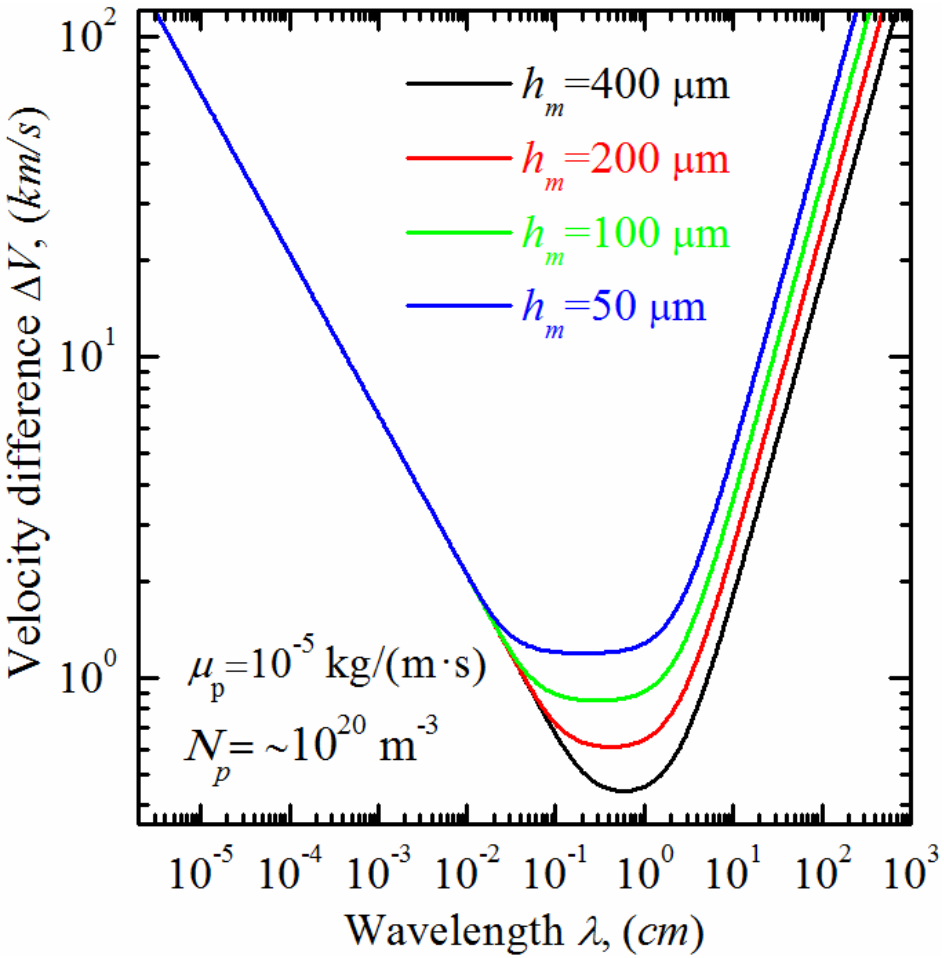


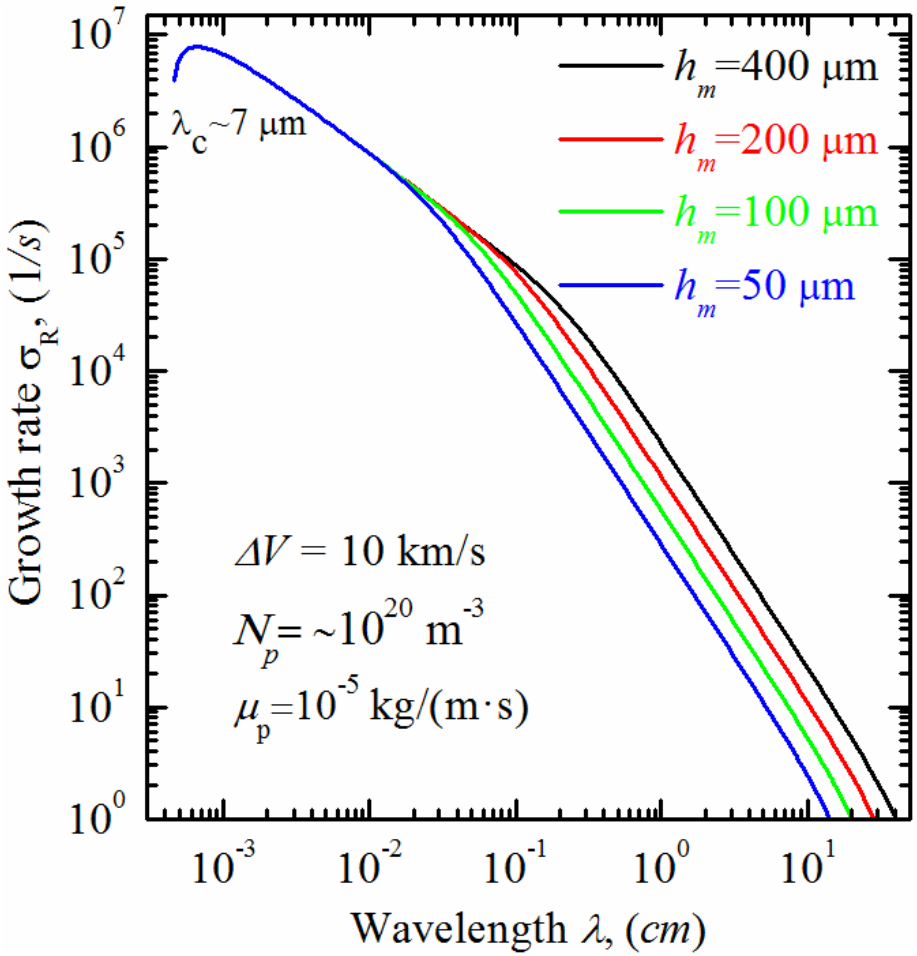


fastest growing dangerous wave shifts toward shorter wavelengths with the increase in plasma velocity

stabilization due to magnetic tension is much less pronounced compared to inviscid plasma

K-H Instability of Viscous Potential Plasma-Melt Flow





critical velocity is affected by the thickness of melt layer! thinner melt layers are more stable

growth rate of long waves decreases with decreasing the depth of melt layer; short waves are not affected

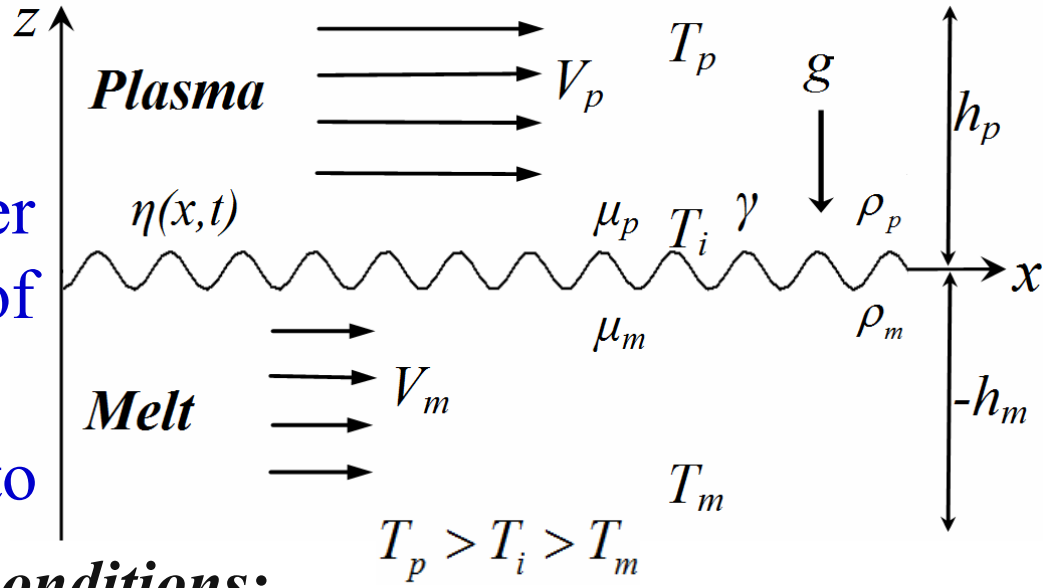
Outline

- Brief Overview of Previous Results
- Viscosity Effects on Kelvin-Helmholtz Instability
- **Mass & Heat Effects on Kelvin-Helmholtz Instability**
- OpenFOAM Modelling
- Summary

K-H Instability of Viscous Potential Plasma-Melt Flow

Effects of Mass & Heat Transfer Across the Interface:

- thermal effects due to mass transfer across the interface & release of latent heat during phase change
- immiscibility is not held due to phase change



The interfacial conditions:

➢ mass transfer:

$$\left\| \rho_\alpha \left(\frac{\partial \phi_\alpha}{\partial z} - \frac{\partial \eta}{\partial t} - \frac{\partial \eta}{\partial x}\frac{\partial \phi_\alpha}{\partial x} \right) \right\| = 0$$

$$\alpha = (p, m)$$

➢ energy transfer:

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

$$\rho_m \left(\frac{\partial \phi_m}{\partial z} - \frac{\partial \eta}{\partial t} - \frac{\partial \eta}{\partial x}\frac{\partial \phi_m}{\partial x} \right) = \delta\eta$$ - Hsieh model

with $\delta = \frac{F}{L}\left(\frac{1}{h_m} + \frac{1}{h_p} \right)$ - coefficient of heat transfer

➢ conservation of momentum (dynamic condition) modified by mass transfer:

$$\left\| \rho_\alpha \left(\frac{\partial \phi_\alpha}{\partial t} + g\eta + \frac{\partial \phi_\alpha}{\partial x}\frac{\partial \phi_\alpha^0}{\partial x} \right) + 2\mu_\alpha \frac{\partial^2 \phi_\alpha}{\partial z^2} \right\| = -\gamma \frac{\partial^2 \eta}{\partial x^2}$$ with $\phi_\alpha^0 = V_\alpha x$

K-H Instability of Viscous Potential Plasma-Melt Flow

Effects of Mass & Heat Transfer Across the Interface

Critical Velocity:

$$\Delta V > \sqrt{\frac{2(\delta(\coth(kh_m)+\coth(kh_p))+2k^2(\mu'_m+\mu'_p))^2 \times}{\delta^2(\rho'_p\coth^2(kh_m)+\rho'_m\coth^2(kh_p))+4k^4(\rho'_m\mu'^2_p+\rho'_p\mu'^2_m)+}}$$

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

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

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 $T_i \sim 5933\ K$

$T_m = 3683 \div 300\ K$

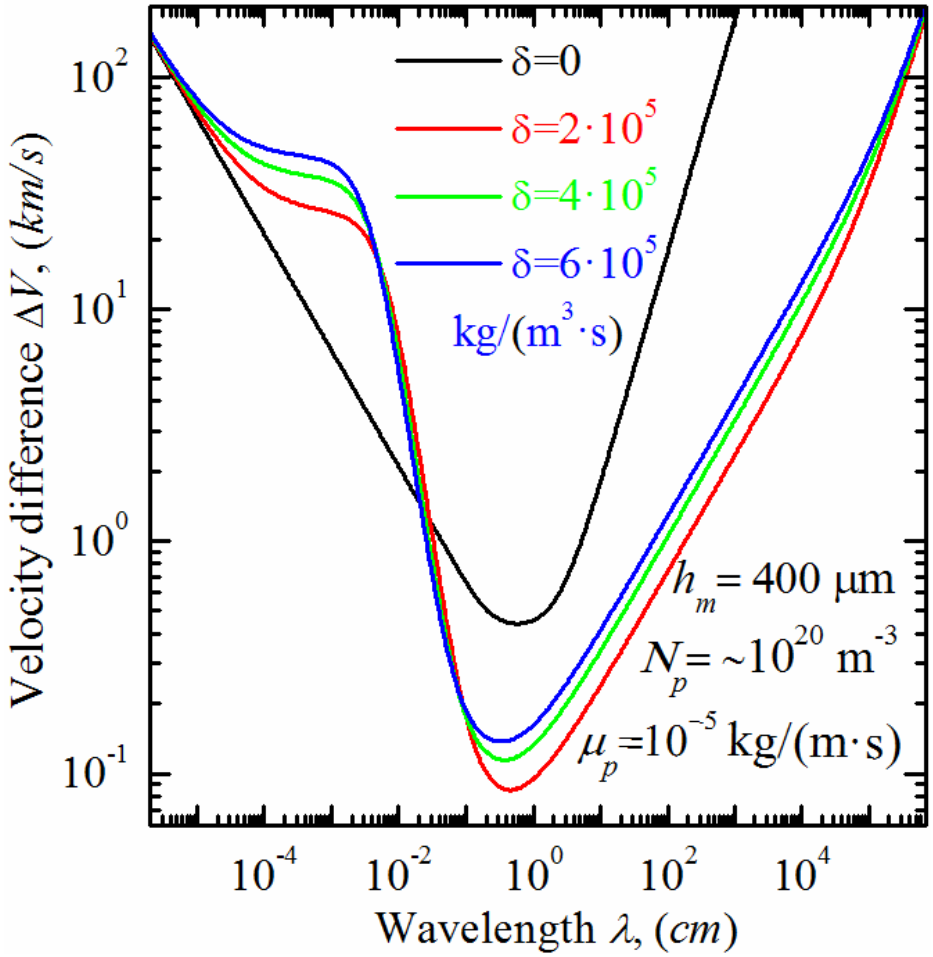
$\delta \sim 2.1\cdot 10^5 \div 5.3\cdot 10^5$

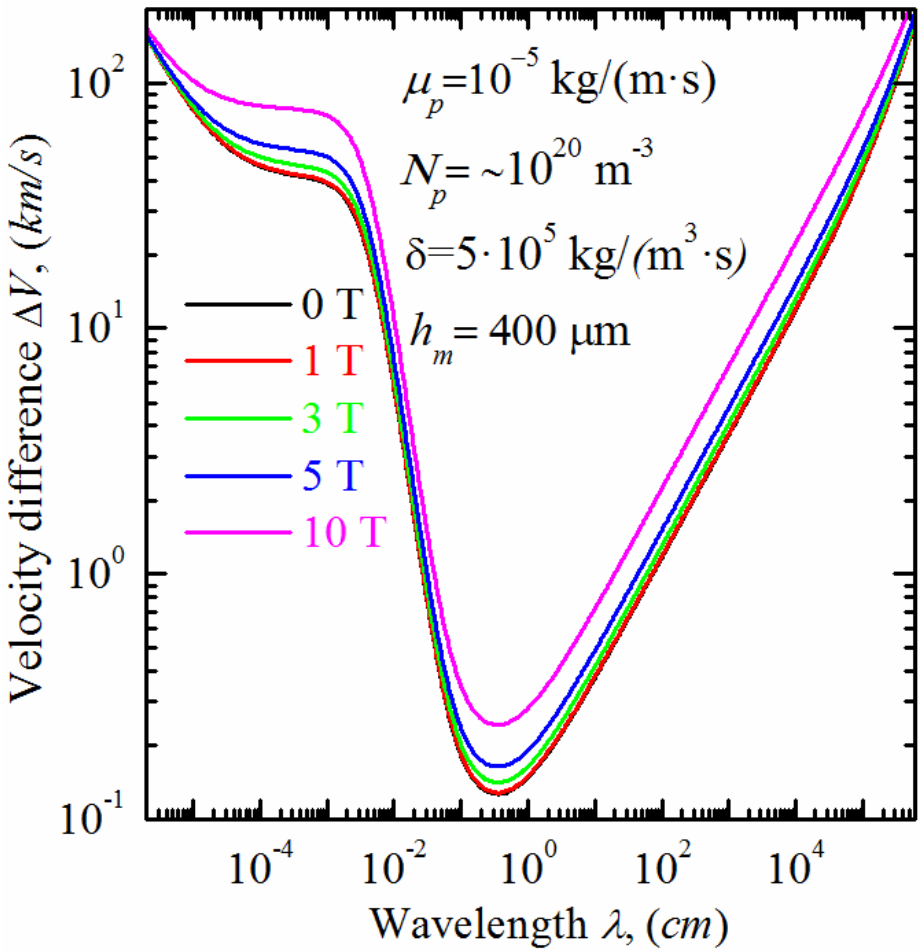
$kg/(m^3\cdot s)$

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

K-H Instability of Viscous Potential Plasma-Melt Flow

Effects of Mass & Heat Transfer Across the Interface



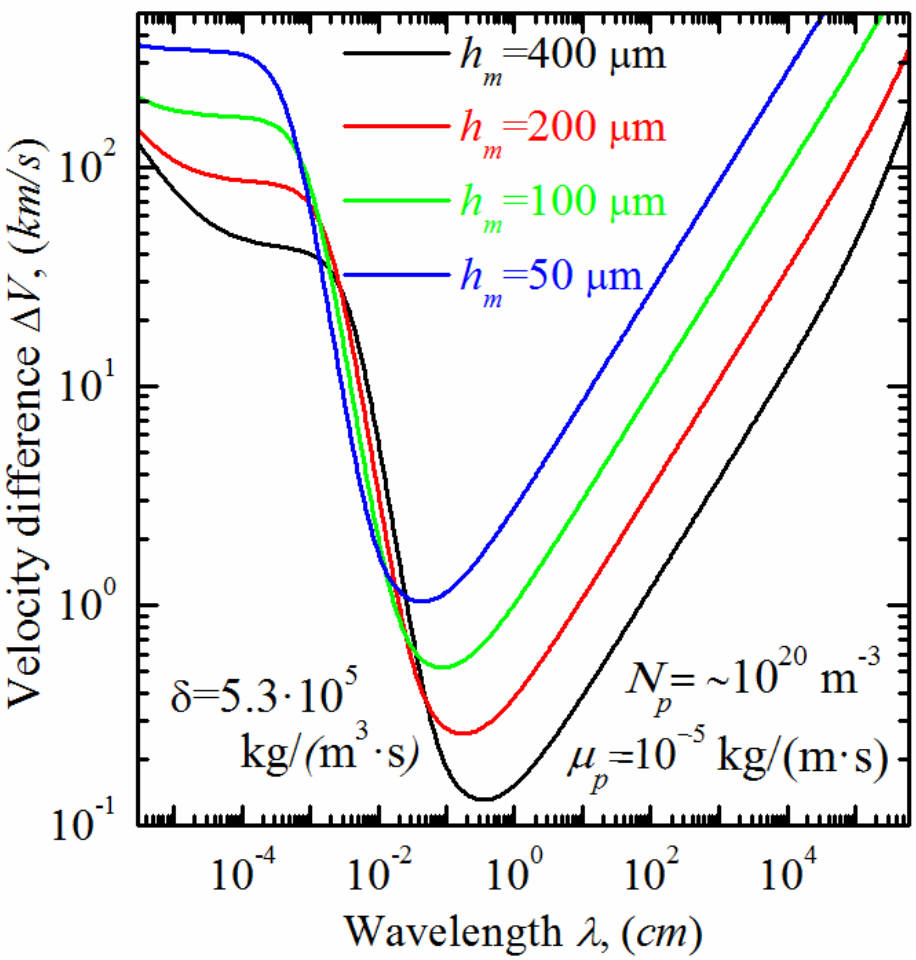


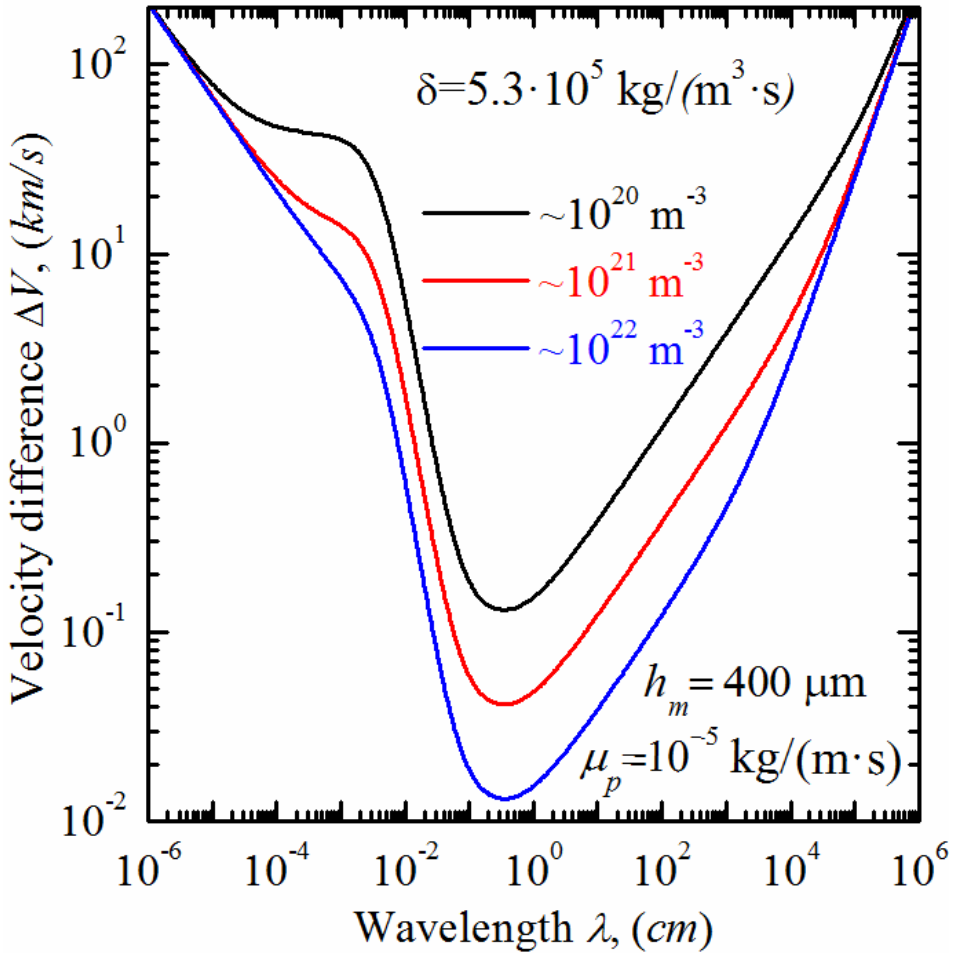
stabilization of short waves & destabilization of long waves

minor stabilization due to magnetic field

K-H Instability of Viscous Potential Plasma-Melt Flow

Effects of Mass & Heat Transfer Across the Interface





melt stabilization with decrease of thickness of melt layer

destabilizing effects of denser plasma

Outline

- Brief Overview of Previous Results
- Viscosity Effects on Kelvin-Helmholtz Instability
- Mass & Heat Effects on Kelvin-Helmholtz Instability
- **OpenFOAM Modelling**
- Summary

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)
);
```

See: http://www.openfoam.com/

Modelling: OpenFOAM

VOF model: $\nabla \mathbf{u} = 0$ - continuity

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \mu\nabla^2\mathbf{u} + \rho\mathbf{g} + \gamma K\frac{\nabla\alpha_p}{|\nabla\alpha_p|}$$ - momentum

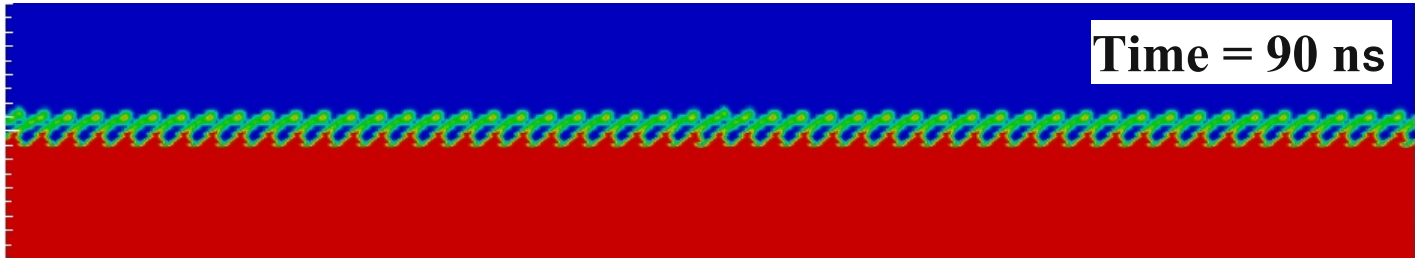
$$\frac{\partial \alpha_p}{\partial t} + \nabla\cdot\left(\alpha_p\mathbf{u}\right) = 0$$ - volume fraction of plasma

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

$$\mu = \alpha_p\mu_p + \alpha_m\mu_m$$

$$\alpha_p + \alpha_m = 1$$

Viscous plasma-melt interface perturbed with fifty wavelengths: $\lambda = 40\ \mu m$



Parameters:

$V_p = 10^5\ m/s \quad V_m = 1\ m/s$

$\rho_p = 10^{-6}\ kg/m^3$

Preliminary data (to be verified): elongation of liquid tungsten ligaments penetrating into plasma

$\rho_m = 17600\ kg/m^3 \quad \mu_m \sim 7\cdot 10^{-3}\ kg/(m\cdot s) \quad \mu_p \sim 5\cdot 10^{-5}\ kg/(m\cdot s)$

$h_m = 400\ \mu m \quad g = 9.81\ m/s^2 \quad \gamma = 2.5\ N/m$

Outline

- Brief Overview of Previous Results
- Viscosity Effects on Kelvin-Helmholtz Instability
- Mass & Heat Effects on Kelvin-Helmholtz Instability
- OpenFOAM Modelling
- **Summary**

Summary

- Viscous potential flow analysis predicts destabilizing effects of viscosity: 1) critical values of plasma velocity required for generation of K-H instability are much lower (~500 m/s) compared to an inviscid case (~90 km/s); 2) fastest growing waves become shifted toward much shorter wavelengths (<100 μm) with sharply increased growth rates (<1 μs); 3) stabilizing effects due to magnetic field are significantly reduced

- Additional effects of boiling and vaporization (mass and heat transfer across the interface) on melt stability: 1) some stabilization of short waves (<100 μm) and destabilization of critical and longer waves ⇒ plasma with ~200 m/s can induce growing waves with wavelengths ~1-10 mm; 2) minor stabilization due to magnetic field

- Predictions of viscous potential flow theory can explain the origin of the fine structure of ligaments observed in TEXTOR; CFD modeling is needed for investigations of these effects at non-linear stage

Thank You for Attention!

Questions?