ANALYSIS AND MODELING OF LITHIUM FLOWS IN POROUS MATERIALS

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Outline

- Introduction
- Viscous Linear Stability Analysis
- OpenFOAM VOF-MHD Modelling

Introduction: Flowing Liquid Metal as PFC

- *flowing* liquid metal (LM): *attractive plasma facing component (PFC)* in fusion engineering

➢ benefits of *flowing* LM PFC:

- absorption & removal of *impurities* with LM flow
- absorption of *high heat fluxes* preventing *PFC melting & erosion*

➢ some problems with *flowing* LM PFC:

- need to achieve *smooth* and *controllable* LM flow in magnetic field
- prevent LM *thickness variation* & *formation of dry spots*
- mitigate LM *splashing* & *plasma contamination* by LM droplets formed during ELMs or plasma disruptions

Introduction: Motivation for Research

- goals of research: *quantitative theoretical & computational analysis* of *LM free surface flows* in both porous & non-porous media

➢ **Flow of LM on substrate *without impact of gas or plasma*:**

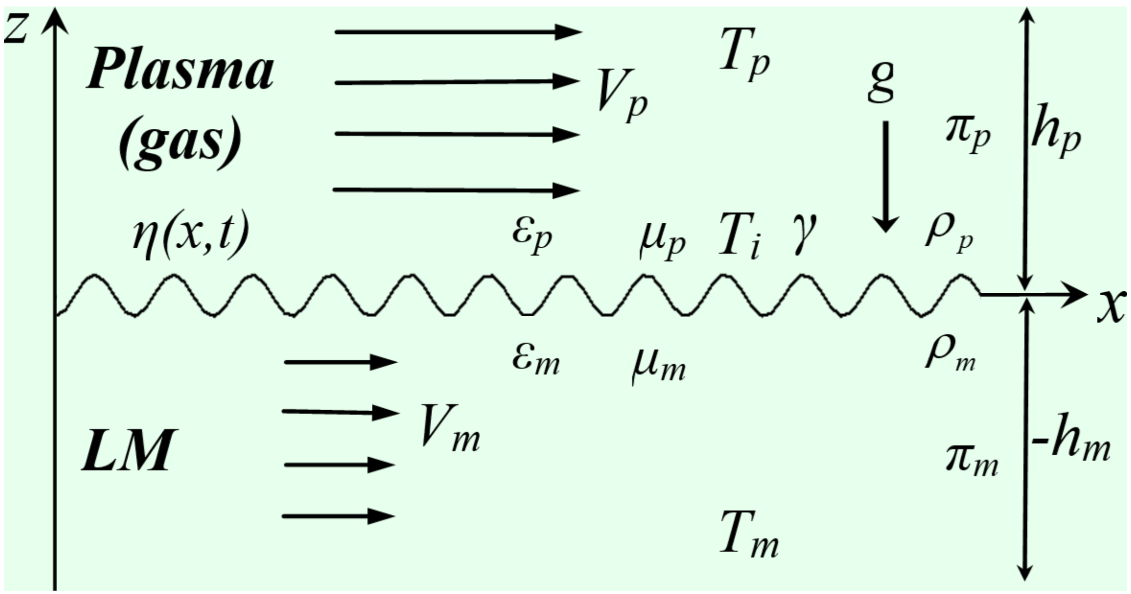
- dependence of flow regime on *speed* & *thickness* of LM layer
- development/suppression of *waves* on the surface & their *wavelength*
- influence of *magnetic field* on LM flow stability & surface waves
- effects of *medium porosity* & *permeability* on LM flow

➢ **Flow of LM on substrate *under impact of gas or plasma*:**

- development of *waves* & their *wavelengths* affected by gas or plasma flowing over LM layer with increasing speed
- conditions for *LM splashing* & *droplet development*

Viscous Linear Stability Analysis (VLSA)

- viscous instability in porous media



Sketch of the plasma-LM system

index m - LM

index p - plasma (gas)

V_p & V_m - velocities

ρ_p & ρ_m - mass densities

μ_p & μ_m - viscosities

h_p & h_m - thicknesses

ε_p & ε_m - porosities

π_p & π_m - permeabilities

T_p & T_m - temperatures

γ - surface tension g - gravity constant T_i - interfacial temperature

➢ stability analysis: includes *viscosity*, *thermal effects*, and *porosity*

- linearize *Navier-Stock equations* & apply *harmonic normal modes*

Viscous Linear Stability Analysis (VLSA)

- final expression for *the relative velocity* $\Delta V=|V_p-V_m|$ of viscous instability in porous media

$$k^2\Big[\alpha^2\left(\varepsilon_p\rho'_p\coth^2(kh_m)+\varepsilon_m\rho'_m\coth^2(kh_p)\right)+4k^4\left(\varepsilon_p\rho'_p\mu'^2_m+\varepsilon_m\rho'_m\mu'^2_p\right)+$$
$$4k^2\varepsilon_m\varepsilon_p\left(\frac{\rho'_p}{\pi_m}\mu'^2_m+\frac{\rho'_m}{\pi_p}\mu'^2_p\right)+2\alpha\varepsilon_m\varepsilon_p\left(\frac{\rho'_p}{\pi_m}\mu'_m\coth(kh_m)+\frac{\rho'_m}{\pi_p}\mu'_p\coth(kh_p)\right)+$$
$$4\alpha k^2\left(\varepsilon_p\rho'_p\mu'_m\coth(kh_m)+\varepsilon_m\rho'_m\mu'_p\coth(kh_p)\right)+\varepsilon_m\varepsilon_p\left(\frac{\varepsilon_p\rho'_m\mu'^2_p}{\pi_p^2}+\frac{\varepsilon_m\rho'_p\mu'^2_m}{\pi_m^2}\right)\Big]\Delta V^2=$$
$$\left[\left((\rho_m-\rho_p)kg+\gamma k^3\right)+2k^2\alpha\left(\frac{\mu'_m}{\varepsilon_m\rho_m}+\frac{\mu'_p}{\varepsilon_p\rho_p}\right)+\alpha\left(\frac{\mu'_m}{\pi_m\rho_m}+\frac{\mu'_p}{\pi_p\rho_p}\right)\right]\times$$
$$\left[\alpha\left(\varepsilon_p\coth(kh_m)+\varepsilon_m\coth(kh_p)\right)+2k^2\left(\varepsilon_p\mu'_m+\varepsilon_m\mu'_p\right)+\varepsilon_m\varepsilon_p\left(\frac{\mu'_m}{\pi_m}+\frac{\mu'_p}{\pi_p}\right)\right]^2$$

$$\rho'_p=\rho_p\coth(kh_p)\qquad \rho'_m=\rho_m\coth(kh_m)\qquad \mu'_p=\mu_p\coth(kh_p)\qquad \mu'_m=\mu_m\coth(kh_m)$$

$k=2\pi/\lambda$ - wave number λ - wavelength α - coefficient of heat transfer

Viscous Linear Stability Analysis (VLSA)

- case of *viscous Li instability* in porous medium with parameters:

$\rho_m \approx 0.516\, g/cm^3$ at $T_m = T_p = 454\, K$

$\rho_p \approx 1.06 \cdot 10^{-7}\, g/cm^3$ => $N_p \approx 1.6 \cdot 10^{15}\, cm^{-3}$ for Ar gas

$\mu_m \sim 6.4 \cdot 10^{-3}\, g/(cm \cdot s)$ and $\mu_p \sim 3.2 \cdot 10^{-5}\, g/(cm \cdot s)$

$h_m = 1\, cm$ $h_p \to \infty$ $\alpha = 0$ $\gamma = 331.3\, g/s^2$ $g = 981\, cm/s^2$

$\varepsilon_m \to 0 \div 1$ <0.01 *for solids* and ~1 *for non-porous medium*

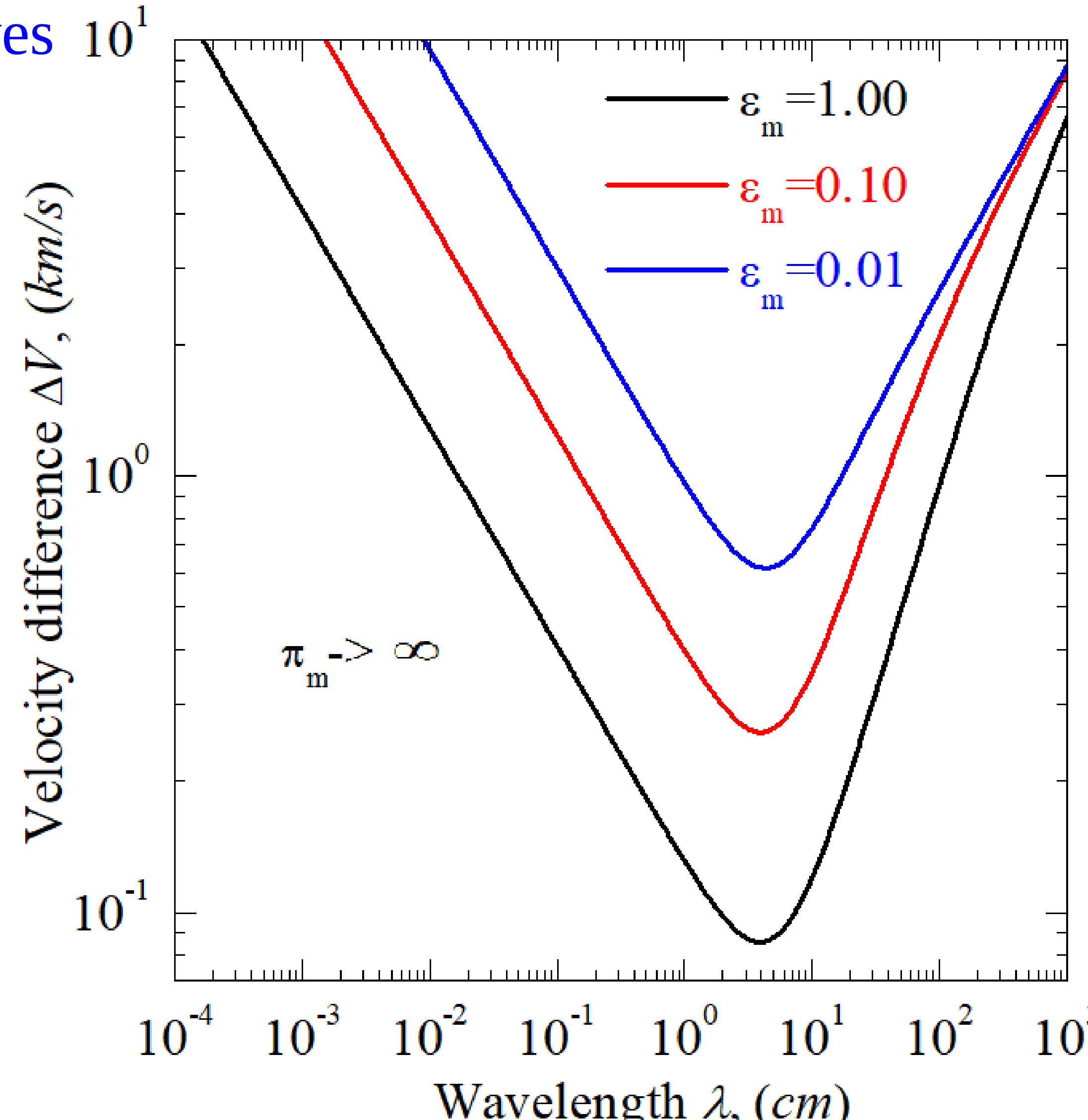
$\varepsilon_p = 1$ - *no porosity* for Ar gas

$\pi_p \to \infty$ - *no resistance* for Ar gas to permeate in porous medium

$\pi_m \to \infty \div 0$ - *range of permeability* of Li in porous medium

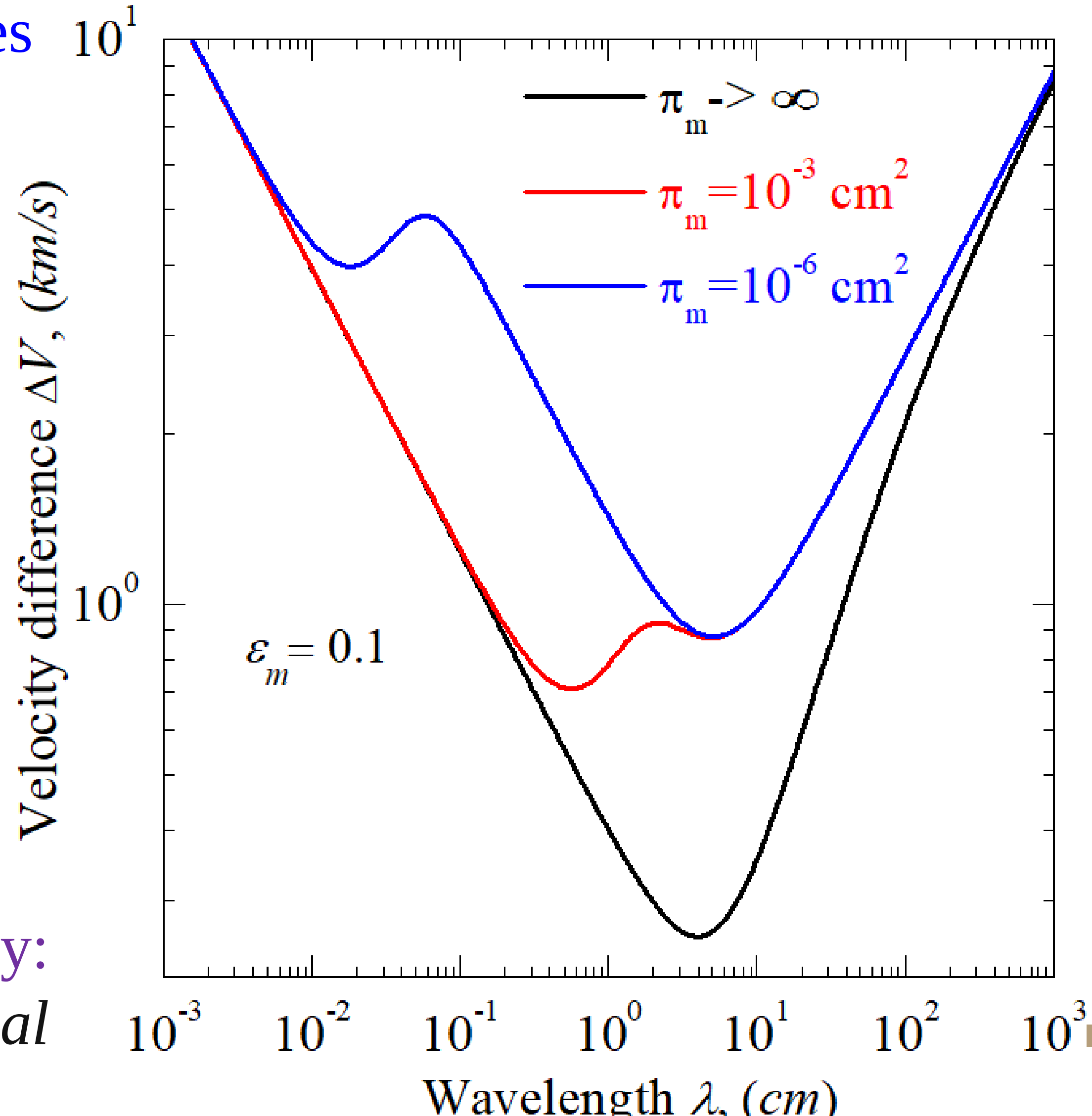
Viscous Linear Stability Analysis (VLSA)

- effects of *porosity of medium* with very large permeability for Li on stabilization of surface waves
  - case with $\varepsilon_m = 1$ (non-porous medium): Ar gas flow with velocity of $V_p > 100\ m/s$ induces *instability* with critical wavelength ~*4 cm*
  - with decrease in porosity: *whole range of wavelengths becomes more stable*
  - porous medium: *has stabilizing effect* on Li flow



Viscous Linear Stability Analysis (VLSA)

- effects of *permeability* of Li in the medium with porosity $\varepsilon_m = 0.1$ on stabilization of surface waves



- case with π_m -> ∞ (full permeability): Ar gas flow with velocity of V_p > *300 m/s* induces *instability* with *critical wavelength ~4 cm*
- with decrease in Li permeability π_m:
  - short wavelengths *<4 cm:* become *more stable*
  - π_m independent instability: at V_p > *1 km/s* with *critical wavelength ~4 cm*

Viscous Linear Stability Analysis (VLSA)

- **Summary**

➢ VLSA: predicts only *the onset conditions* for development & growth of surface waves

- values of *relative velocity* ΔV as a function of *wavelength* λ
- unstable & stable regions: located *above* & *below* the ΔV curve
- *fastest growing wave* with "dangerous" wavelength λ_{cr}

➢ VLSA: can not predict *the nonlinear stage* of wave growth, wave breakage & droplet ejection

➢ VLSA: can be used to investigate *Li flow behavior* as a function of

➢ *velocity*, *mass density*, and *temperature* of gas (plasma)

➢ thickness, *velocity*, and *temperature* of Li

➢ *porosity* & *permeability* of porous medium

OpenFOAM VOF-MHD Modelling

- OpenFOAM: Open Source CFD Toolbox with *extensive multi-physics capabilities*
- C++ library of finite volume solvers & utilities: under active development with capabilities of commercial CFD software
- 2D or 3D structured/unstructured mesh & parallel running
- possibility 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*:

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

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

http://www.openfoam.com/

OpenFOAM VOF-MHD Modelling

Equations governing two-fluid flow:

$$\boxed{\frac{\partial}{\partial t}(\varepsilon\rho u)} + \nabla\cdot(\rho uu) = -\nabla p + \nabla\cdot(\mu(\nabla u + (\nabla u)^T)) + \gamma\kappa\nabla\alpha_m + \rho g + \boxed{J\times B} + \boxed{\Pi}$$

$$\frac{\partial\alpha_m}{\partial t} + \nabla\cdot(\alpha_m u) + \nabla\cdot(\alpha_m(1-\alpha_m)u_c) = 0$$

$$\boxed{\vec{J}\times\vec{B} = -\nabla\left(\frac{\vec{B}^2}{2\mu_m}\right) + \frac{1}{\mu_m}\nabla\cdot\left(\vec{B}\vec{B}\right)}$$

$$\nabla\cdot\vec{u} = 0$$

$$\boxed{q = \frac{J\cdot J}{\sigma}} \qquad \boxed{\vec{J} = \frac{1}{\mu_m}\nabla\times\vec{B}}$$

$$\boxed{\frac{\partial\rho CT}{\partial t} + \nabla\cdot(\rho C\vec{u}T) = \nabla\cdot(K\nabla T) + q}$$

$$\boxed{\begin{aligned}
\alpha_p &= 1-\alpha_m\\
\rho &= \alpha_m\rho_m + \alpha_p\rho_p\\
\mu &= \alpha_m\mu_m + \alpha_p\mu_p\\
C &= \alpha_m C_m + \alpha_p C_p\\
K &= \alpha_m K_m + \alpha_p K_p\\
\sigma &= \alpha_m\sigma_m + \alpha_p\sigma_p
\end{aligned}}$$

Magnetic Induction & Divergence equations:

$$\boxed{\frac{\partial\vec{B}}{\partial t} + \nabla\cdot\left(\vec{u}\vec{B} - \vec{B}\vec{u}\right) = \nabla\cdot\frac{1}{\sigma\mu_m}\nabla\vec{B} + \nabla q}$$

$$\boxed{\nabla\cdot\vec{B} = 0}$$

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OpenFOAM VOF-MHD Modelling

Equations governing two-fluid flow: (cont.)

$$\frac{\partial}{\partial t}(\varepsilon\rho u) + \nabla\cdot(\rho u u) = -\nabla p + \nabla\cdot(\mu(\nabla u + (\nabla u)^T)) + \gamma\kappa\nabla\alpha_m + \rho g + J\times B + \Pi$$

$\varepsilon \to 0 \div 1$ - porosity defining *the amount of pore space*

$$\Pi = -\left(\mu D + \frac{1}{2}\rho|u|F\right)u$$

- *Darcy-Forchheimer equation* describing *resistance (permeability)* to LM flow

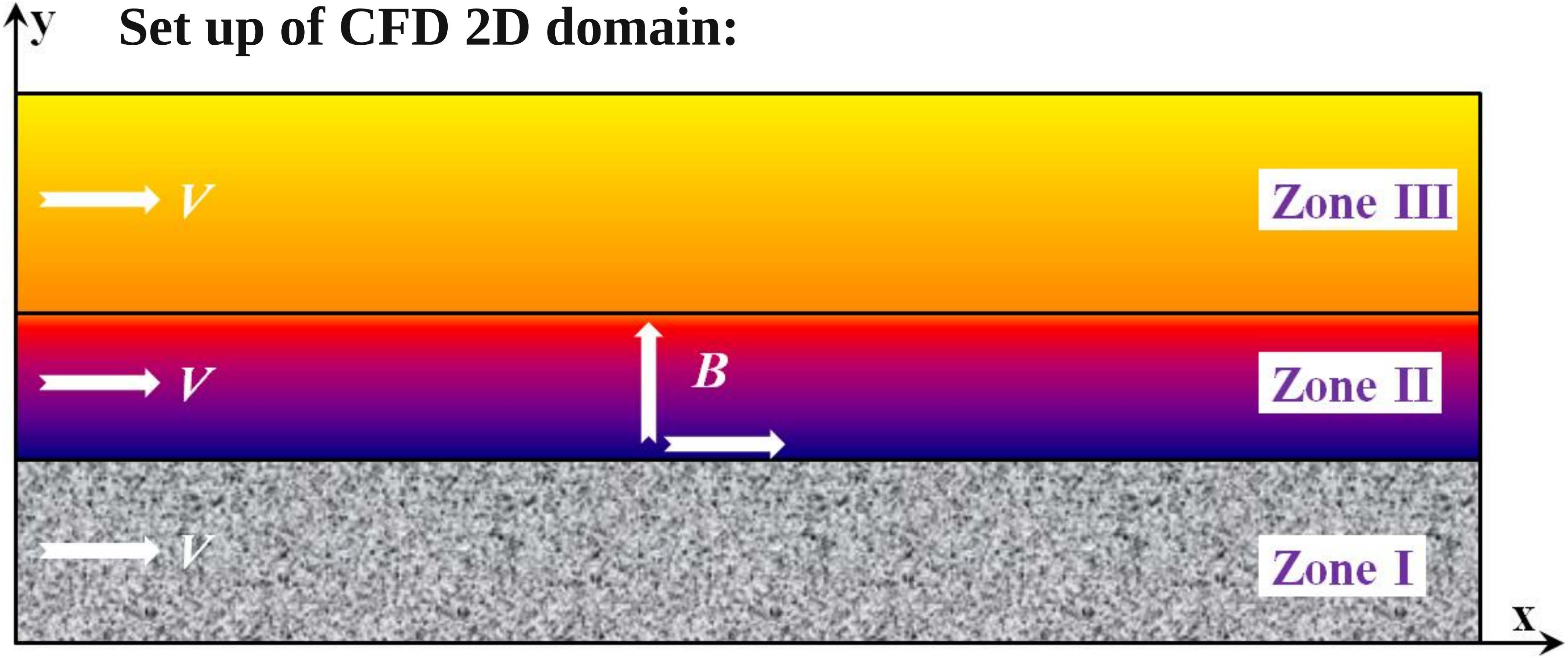
D [1/m^2] - viscous *Darcy* coefficient

F [1/m] - inertial *Forchheimer* coefficient

➢porous media: introduced *in a certain zone* within the computational domain

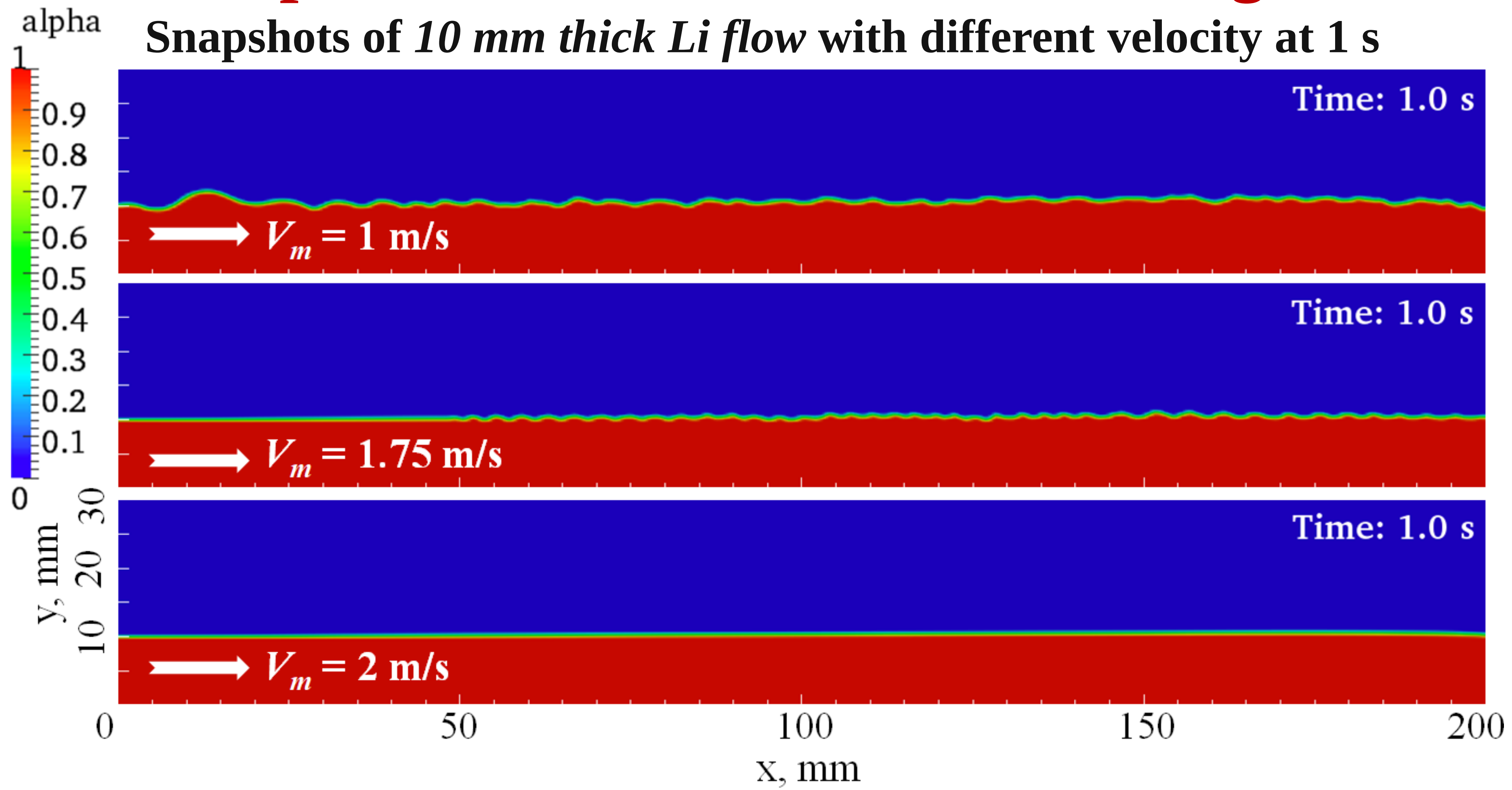
➢porosity of media: introduced as *holes/vanes* at some angle to *change the main flow direction*

OpenFOAM VOF-MHD Modelling



- Zone I: porous or nonporous, Li flow
- Zone II: nonporous, gas or Li flow
- Zone III: nonporous, gas flow

OpenFOAM VOF-MHD Modelling



- for 1 m/s: *wavy surface* over the entire x-range of 200 mm
- for 1.75 m/s: *portion of flat surface* at x < 50 mm
- for 2 m/s: *flat surface* over the entire x-range of 200 mm

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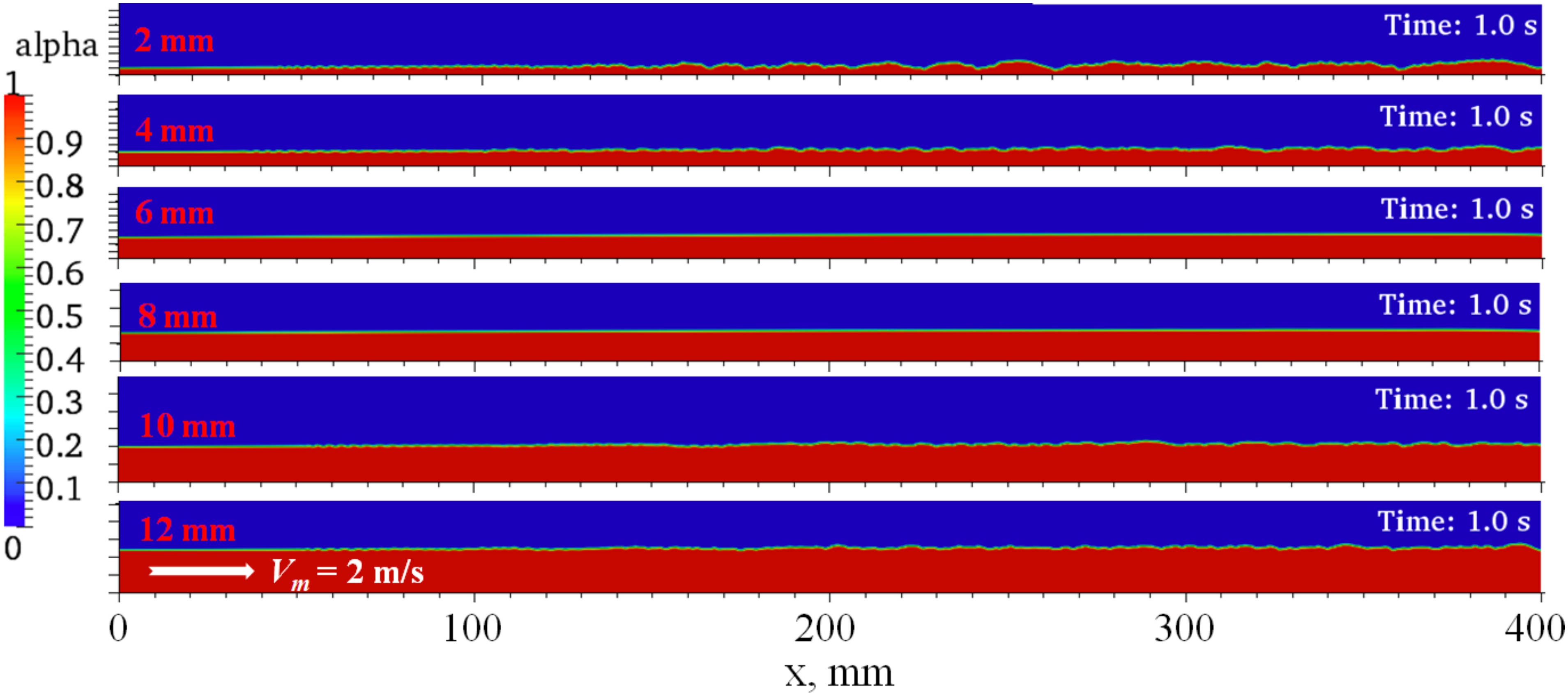
Snapshots of *Li flow of different thickness* with velocity 2 m/s at 1 s



- ≤ 4 mm thick LM: *long waves* with wavelength ~10-20 mm
- ~ 6 - 8 mm thick LM: *no waves, flat Li surface*
- ~ 10 - 12 mm thick LM: *wavy Li surface* with *short-length waves*
- 10 mm thick LM: *flat* & *wavy* Li surface for *200* & *400 mm* x-range

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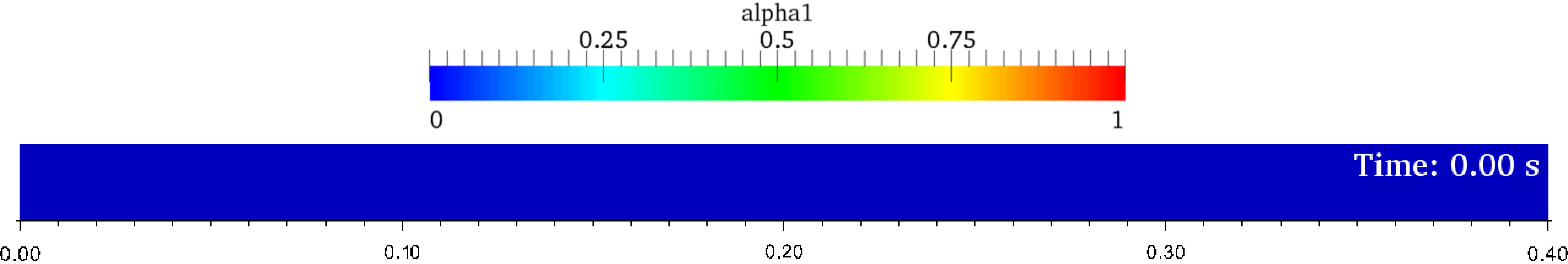
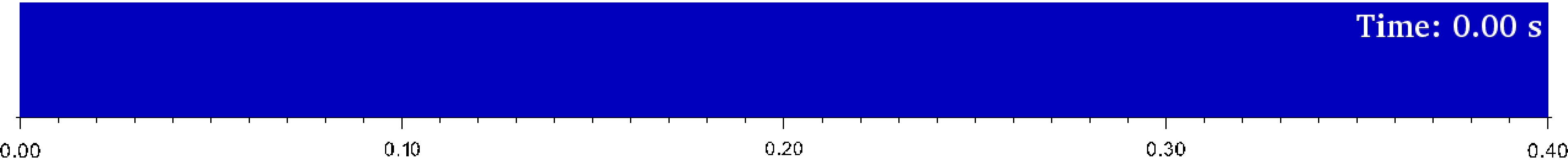
Movies of Li flow on the surface



Li velocity 2 m/s & Li thickness 2 mm

- *large Li blob* in the front of Li flow
- *surface waves* with *long wavelengths* ~10-20 mm



Li velocity 2 m/s & Li thickness 10 mm

- *convex Li shape* in the front of Li flow
- *surface waves* with *very short wavelengths* ~1-5 mm

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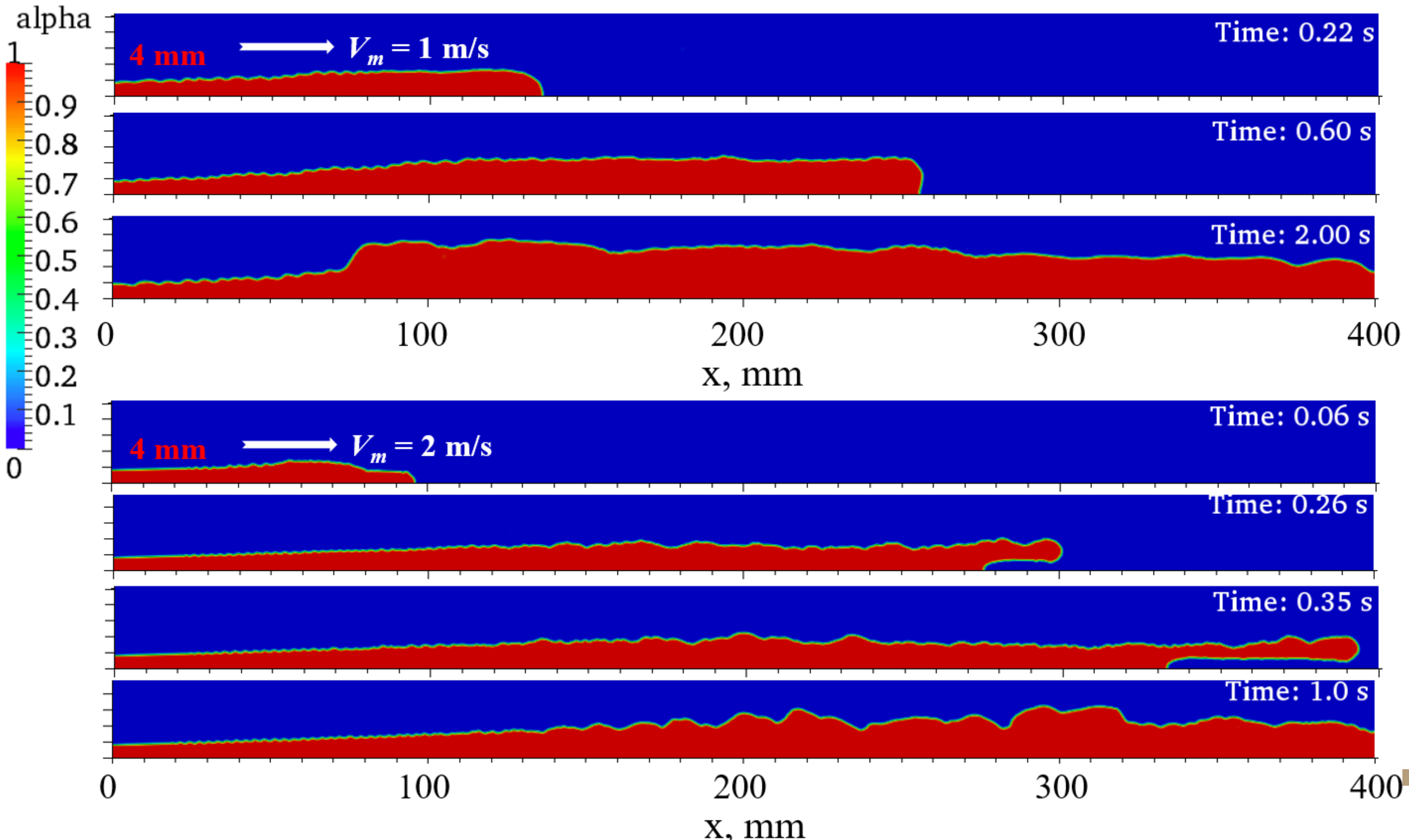
Snapshots of *4 mm Li flow* with 1 & 2 m/s in porous media at various times



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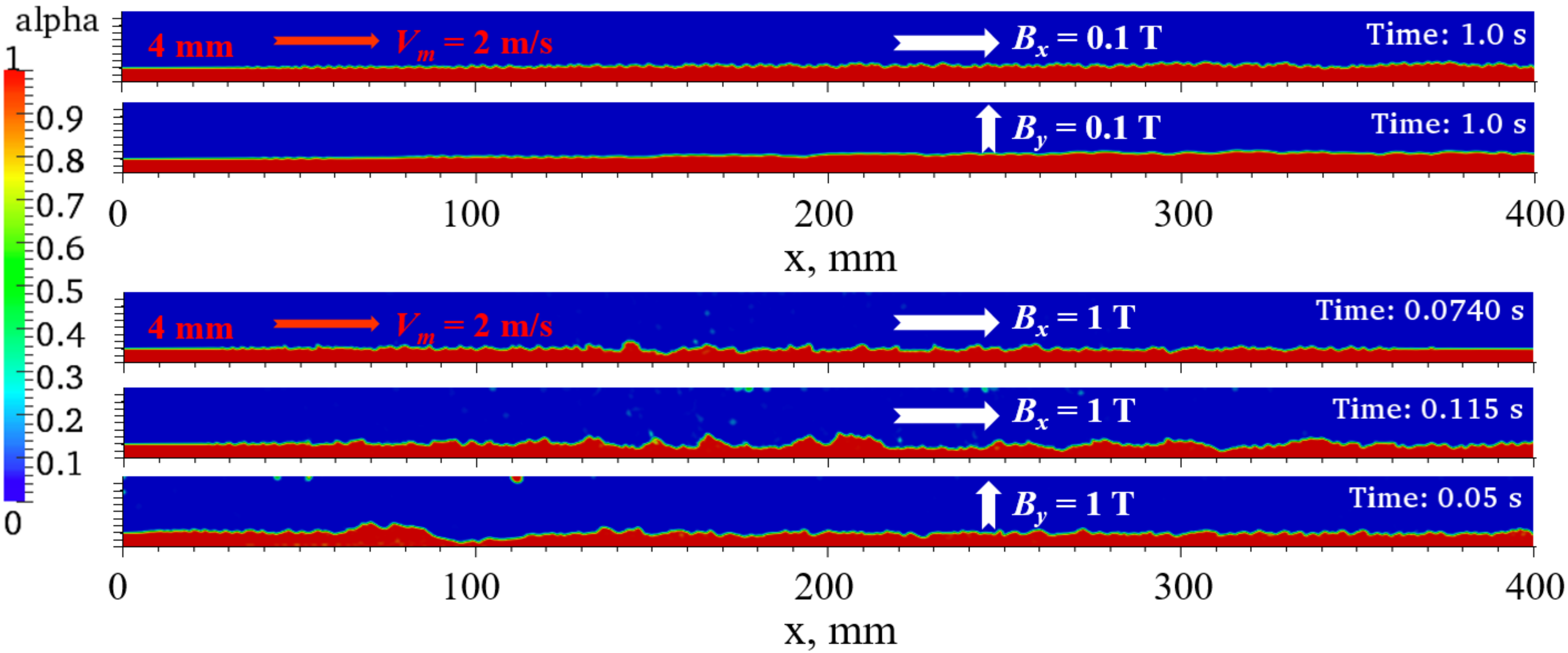
Snapshots of *4 mm Li flow* with 2 m/s in the magnetic field of 0.1 & 1 T



- B_x = 0.1 T: *short-length waves* similar to those in the absence of B
- B_y = 0.1 T: *long-length waves* with *small amplitude*
- B_x = 1 T: *short-length ripples* with *ejection of droplets* from peaks
- B_y = 1 T: *droplet ejection* at early stage of wave development

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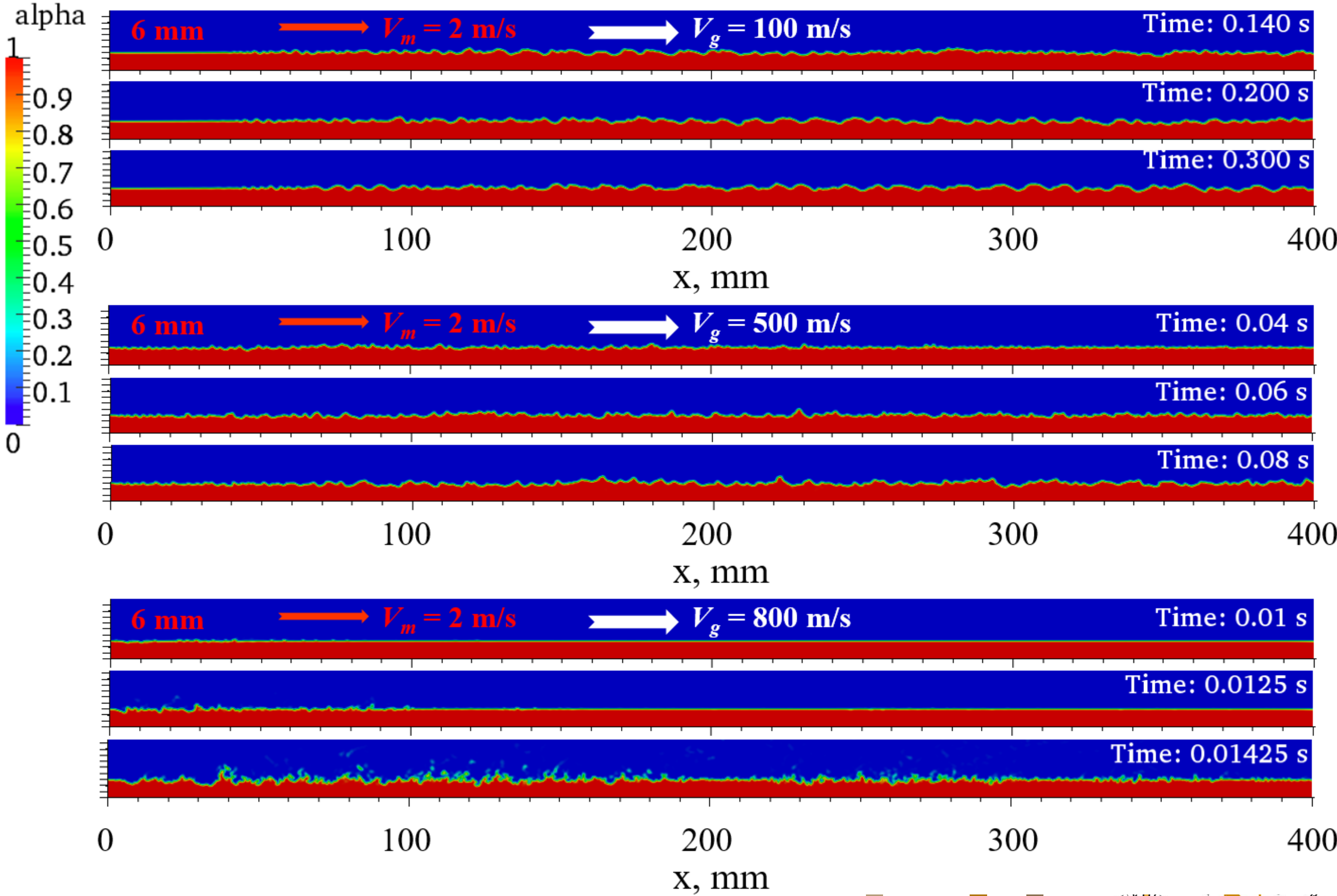
Snapshots of *Ar gas flow* with various speed over 6 mm Li flowing with 2 m/s



OpenFOAM VOF-MHD Modelling

- **Summary**

- Li flow in *the absence of gas (plasma) stream*

➢ flat Li surface near inlet: *extending with increasing Li flow speed*

➢ regime of stable (no waves) Li flow: *at a certain Li thickness*

➢ Li flow in porous media: *dependent on porosity & permeability*

➢ **B** effects: development of *short-wavelength ripples with ejection of droplets* at a certain threshold of **B**

- Li flow in *the presence of gas (plasma) stream*

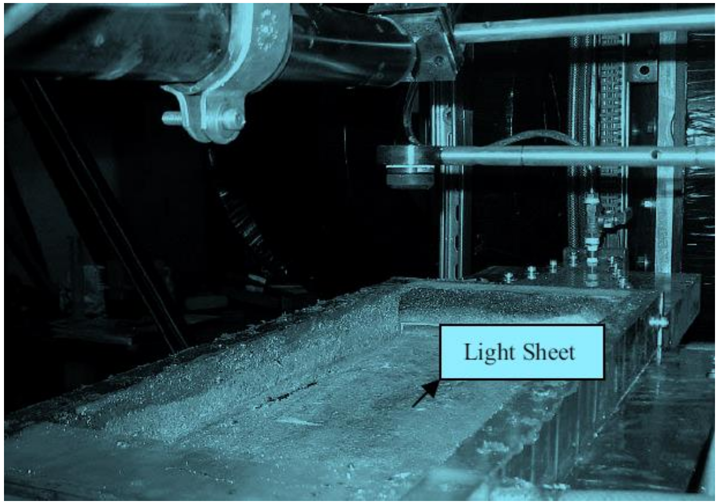
➢ faster development of surface waves: *with increasing gas speed*

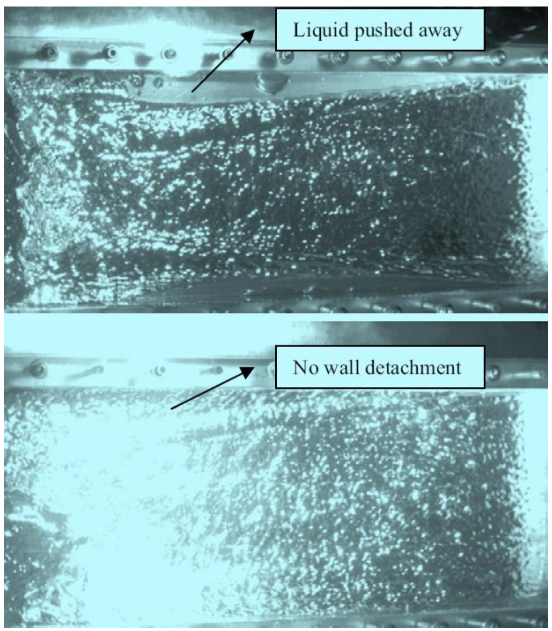
➢ wavelength decrease: *with increasing speed of gas stream*

➢ at very high gas (plasma) speed: *growth of small ripples* and *their disintegration into droplets*

reserved slides

Introduction: LM Flow in Magnetic Field (Exp.)

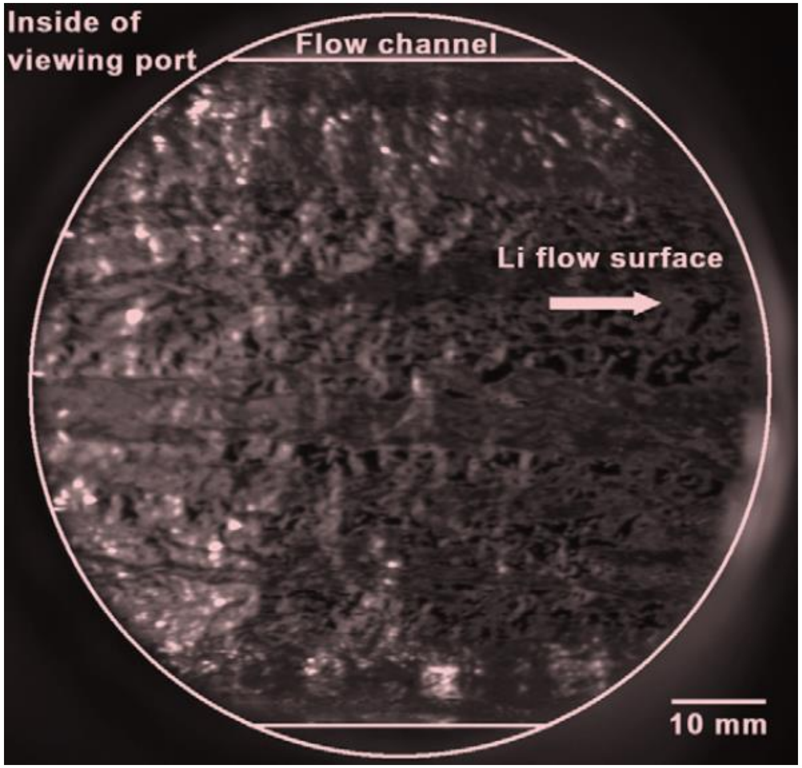




- SS channel: *LxWxH* → *400*x*200*x2 mm
- fusion relevant magnetic field
- LM: Ga-67%, In-20.5% & Sn-12.5%
- hydraulic jump of LM emerging from nozzle: at a particular downstream location
- higher initial velocity (used range 1.0 m/s - 3.0 m/s): farther location of jump from inlet
- wall normal magnetic field: caused LM stream to pinch inward
- formation of separation spots: due to pinching
- increase in LM thickness at 160 mm downstream at high velocity: ~1-2 mm

Narula *et al., A Study of Liquid Metal Film Flow, Under Fusion Relevant Magnetic Fields,* Fusion Sci. Technol. **47**, 564 (2005) **[UCLA]**

Introduction: Liquid Li flow in IFMIF (Exp.)



- IFMIF: generation of 14 MeV neutrons by 40 MeV deuteron beam injection into high-speed liquid Li plane jet
- goal: to study Li surface fluctuations in order to predict the neutron flux
- flat plane jet: thickness of 25 mm, width of 70 mm, guided along a concave wall with a radius of 250 mm
- Li velocity range: from 1 to 15 m/s
- magnitude of Li surface oscillation: from 2.2 to 2.9 mm at 175 mm downstream from nozzle at velocity of 15 m/s
- wavelength of Li surface waves: ~2-3 mm

Kanemura *et al.*, *Investigation of free-surface fluctuations of liquid lithium flow for IFMIF lithium target by using an electro-contact probe*, Fusion Eng. Des. **82**, 2550 (2007) **[Osaka University]**