Enhancement of heat transfer in duct flows exposed to strong magnetic fields

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with
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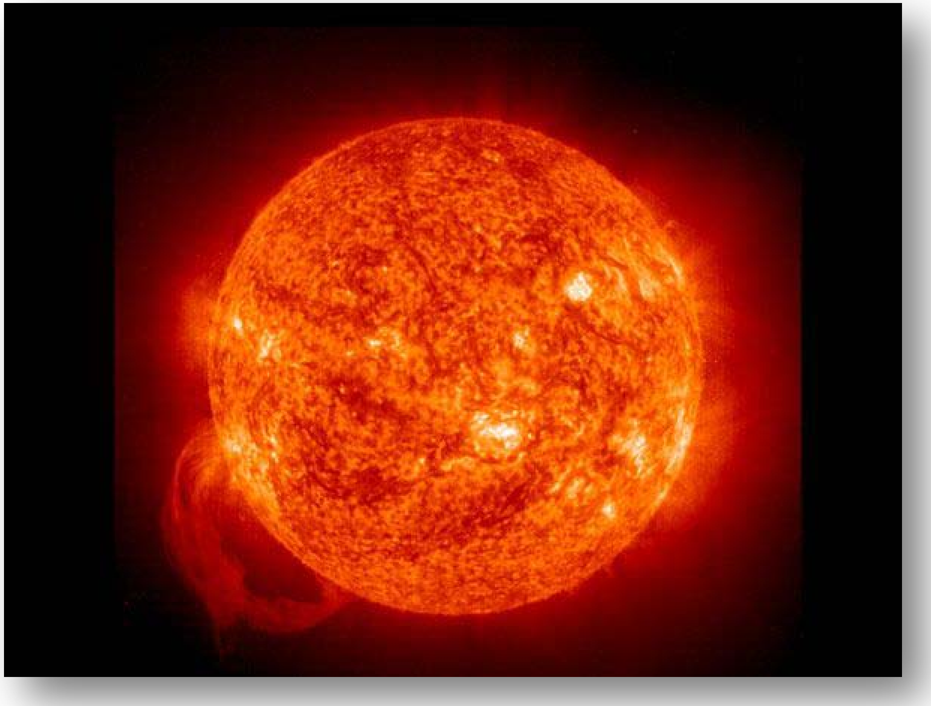
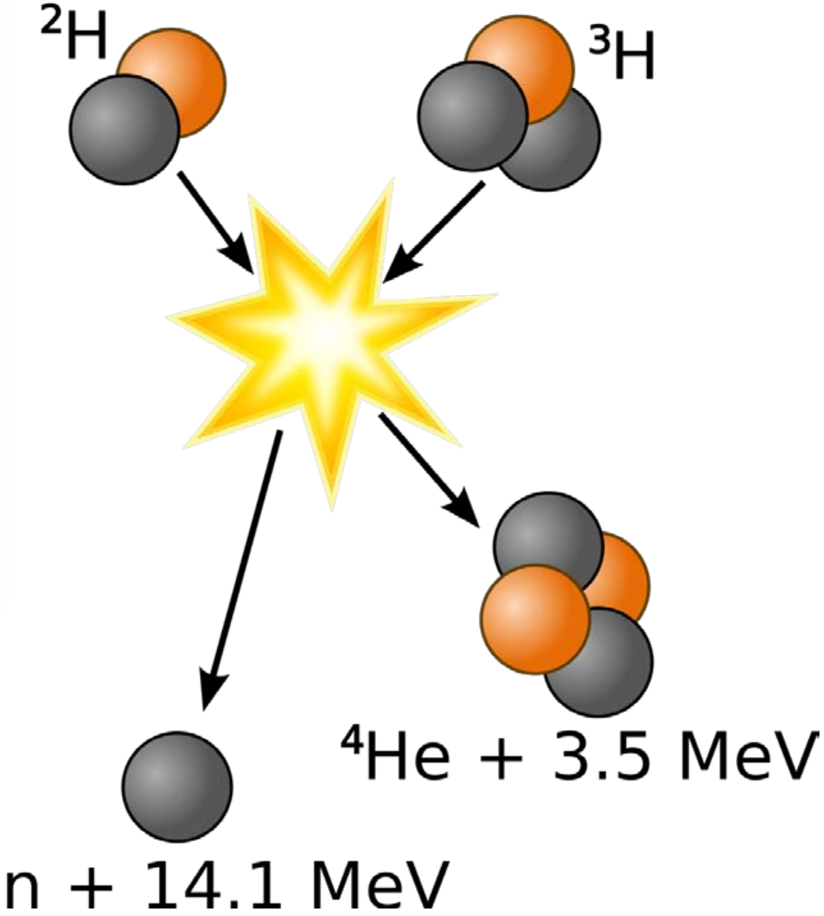
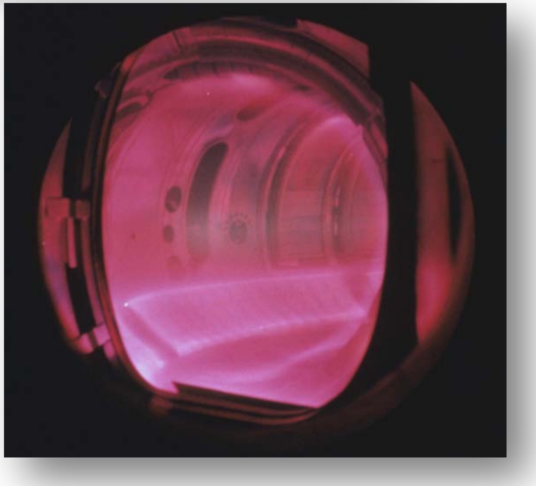
Nuclear fusion of hydrogen





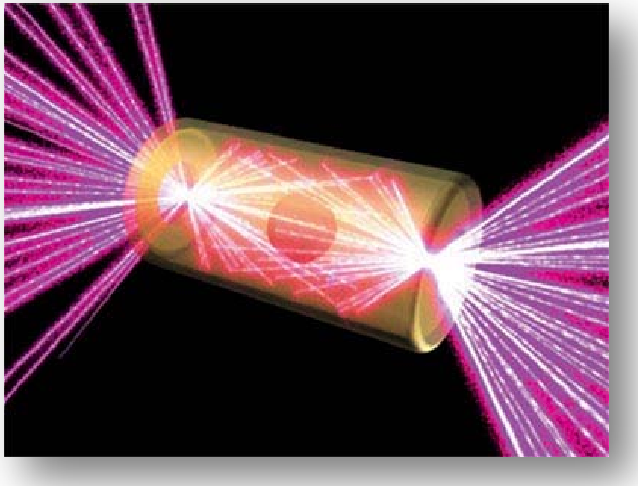
Harnessing fusion

Magnetic confinement



Plasma heated > 150 million°C confined by magnets 200,000 times Earth's field

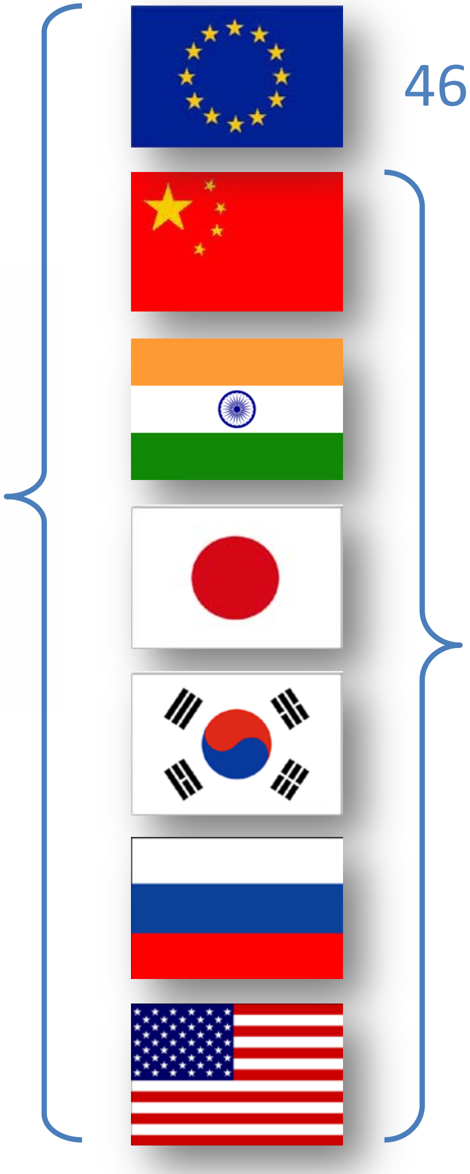
Inertial confinement



NIF 500 TW laser shot July 2012

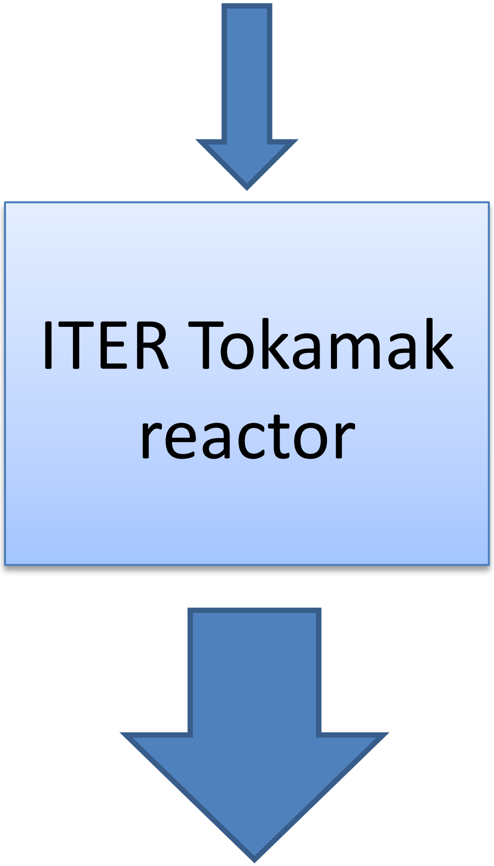
ITER project

> €15
billion



46%

9% each

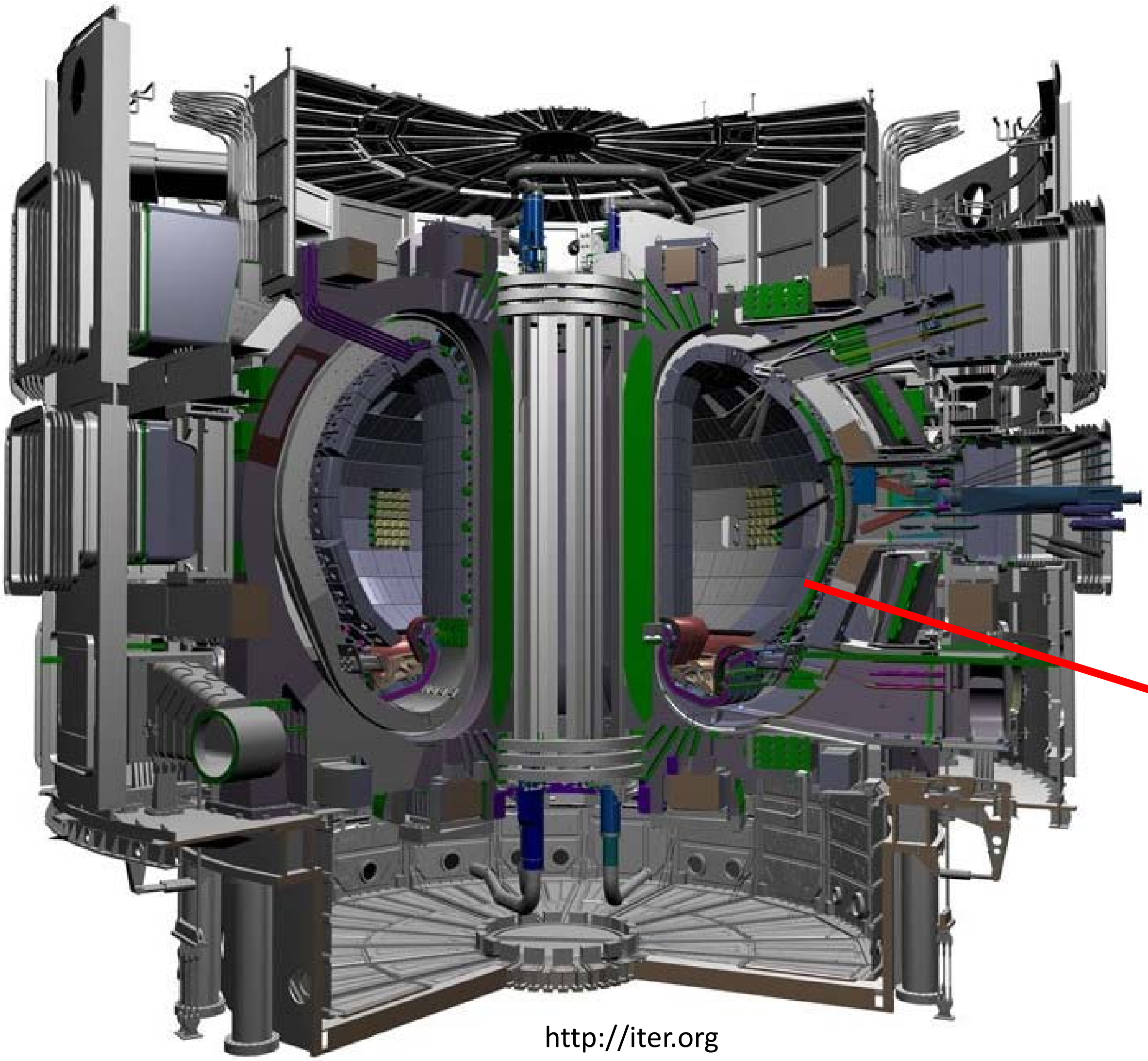


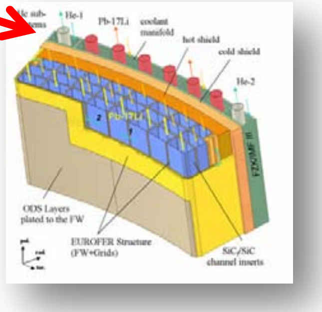
50 MW in

ITER Tokamak
reactor

500 MW out

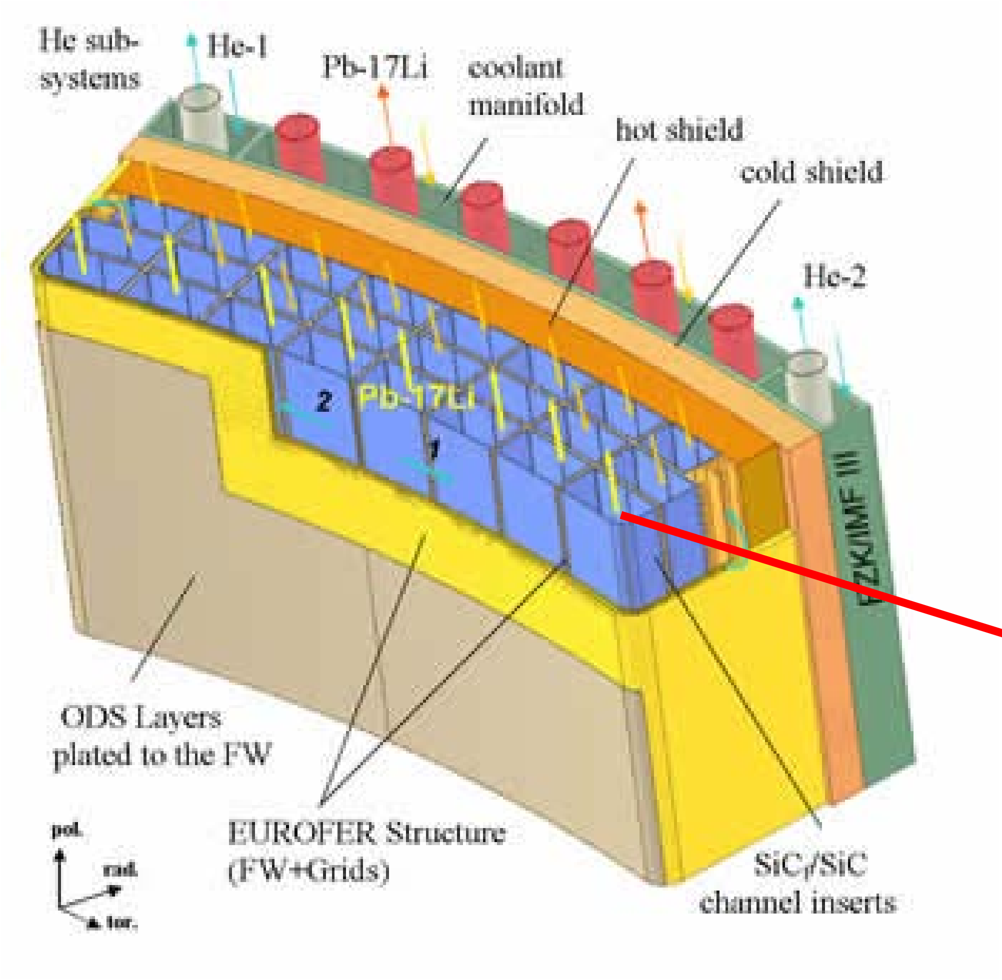
Inside the ITER Tokamak





http://iter.org

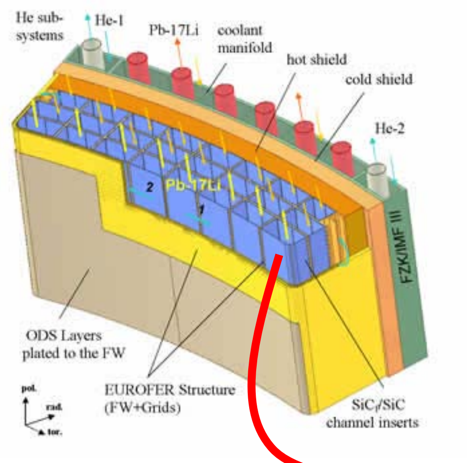
Blankets remove heat and breed tritium from lithium

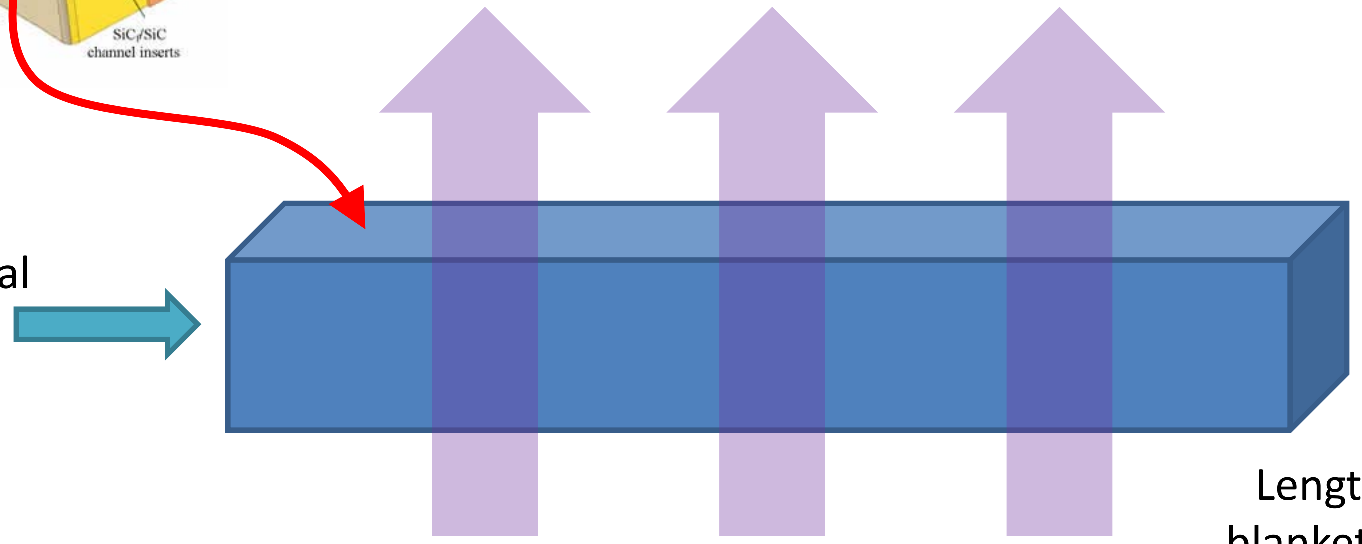


Liquid metal duct flow

Image courtesy: FZK/ IMF III

MHD duct flow with strong perpendicular magnetic field



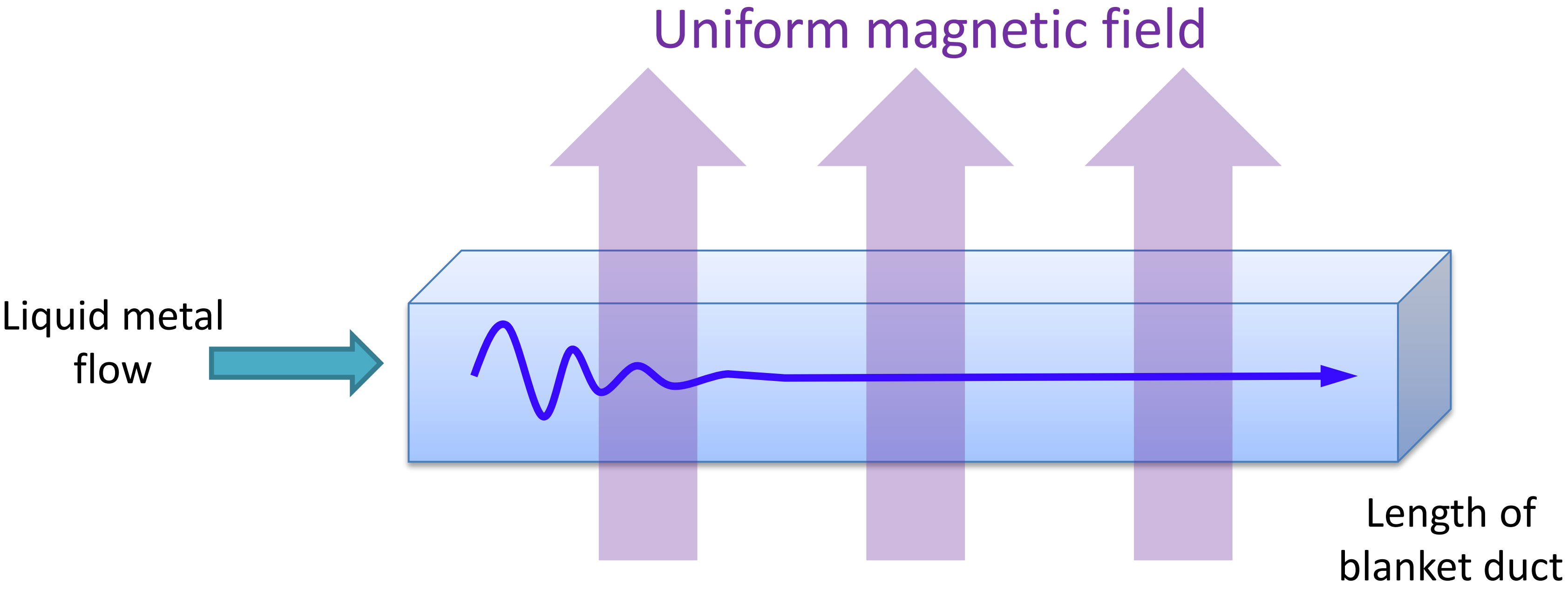


Uniform magnetic field

Liquid metal flow

Length of blanket duct

Magnetic field damps disturbances parallel to field direction

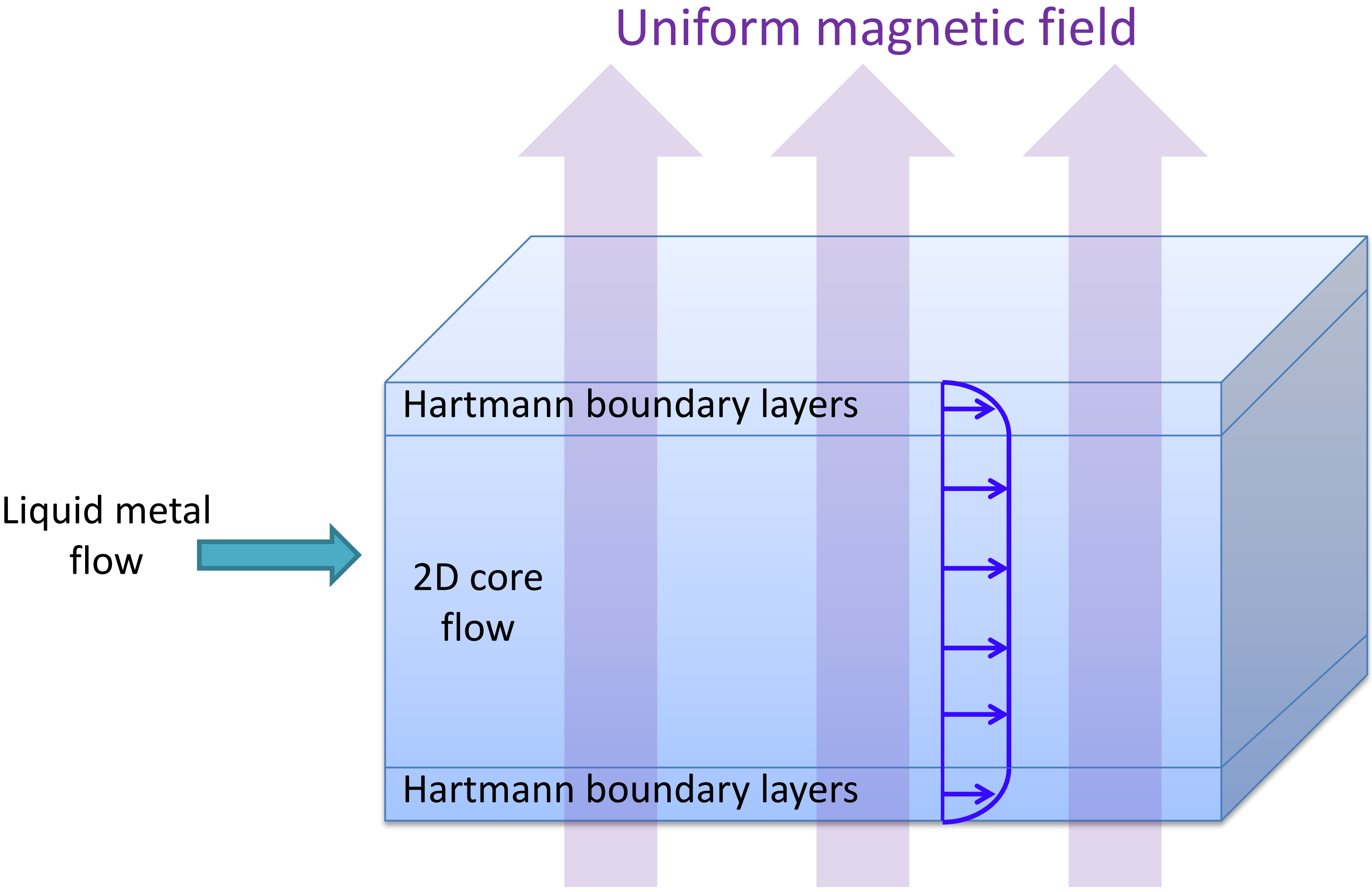


Uniform magnetic field

Liquid metal flow

Length of blanket duct

In field direction, flow is 2D except near walls



Uniform magnetic field

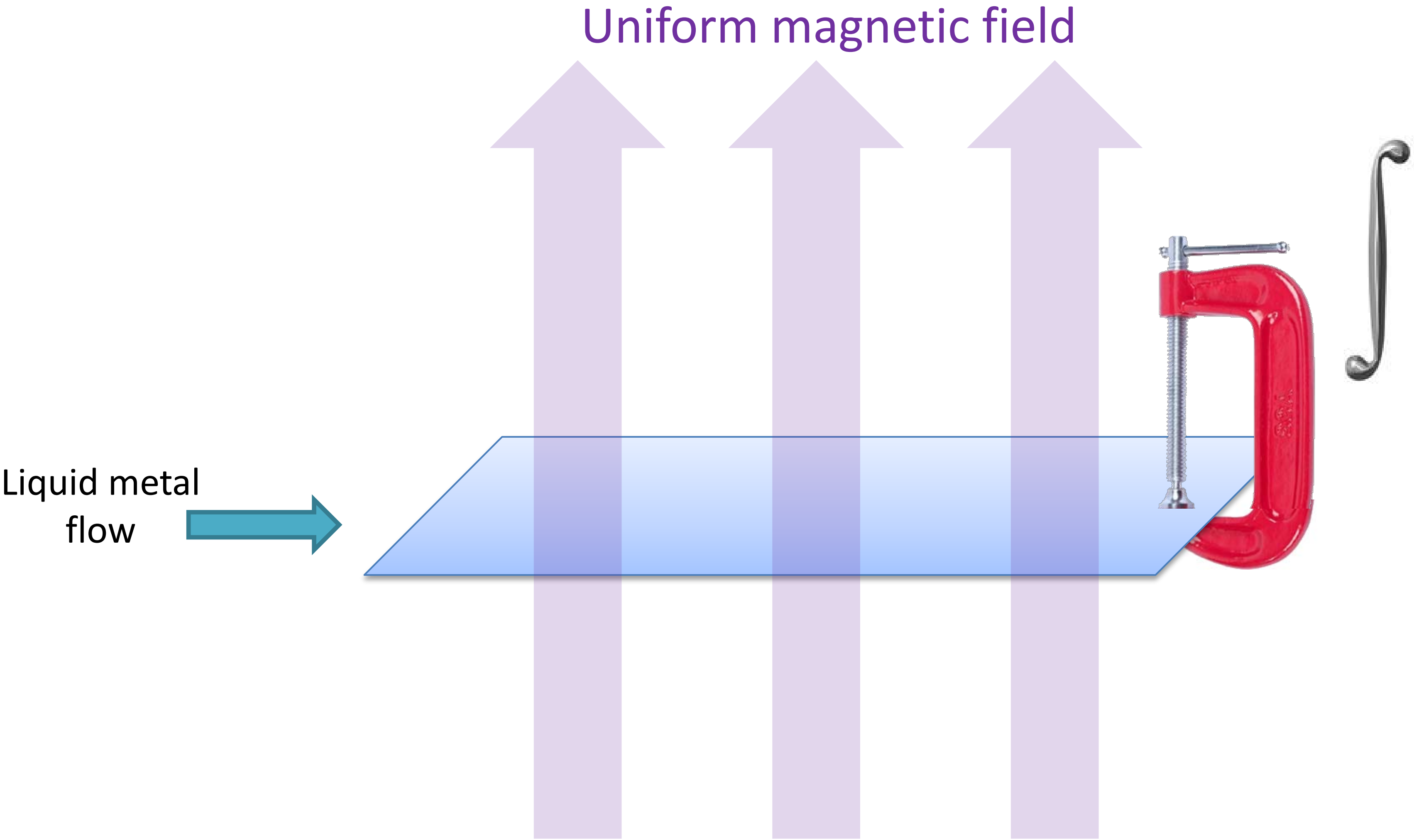
Hartmann boundary layers

Liquid metal flow

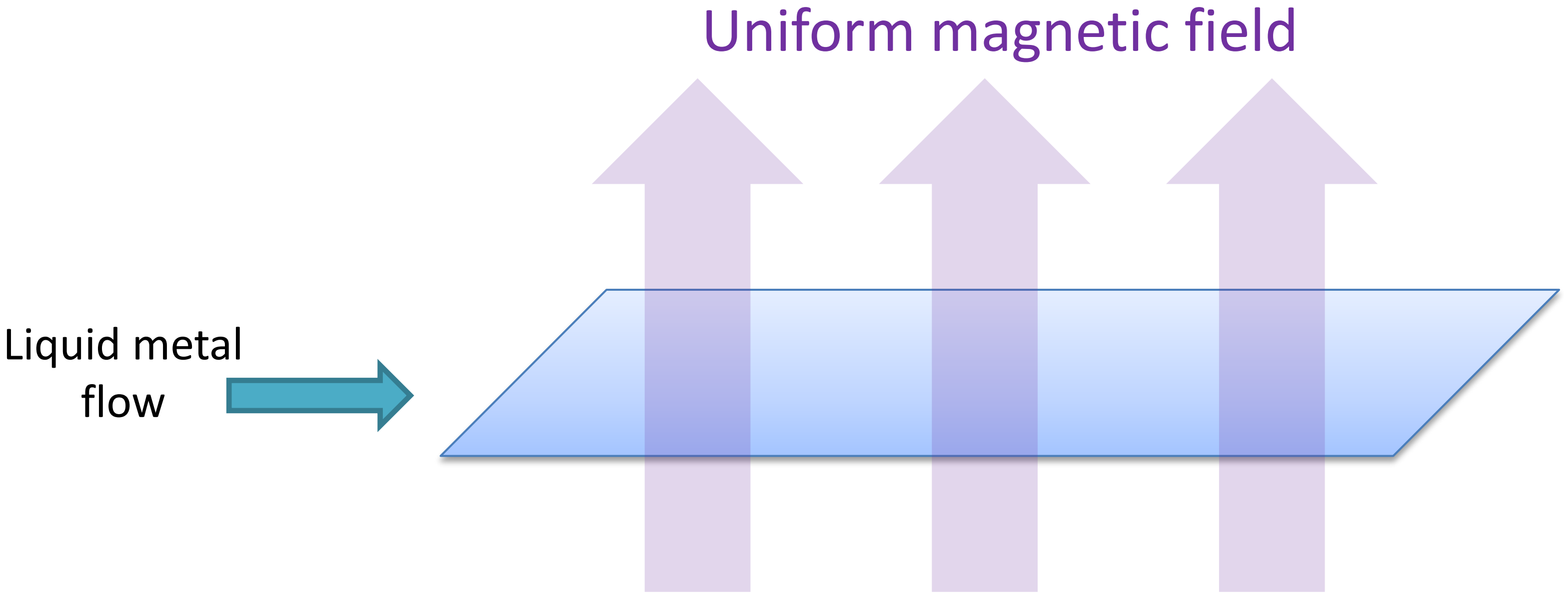
2D core flow

Hartmann boundary layers

Integrating along field direction reduces problem to 2D



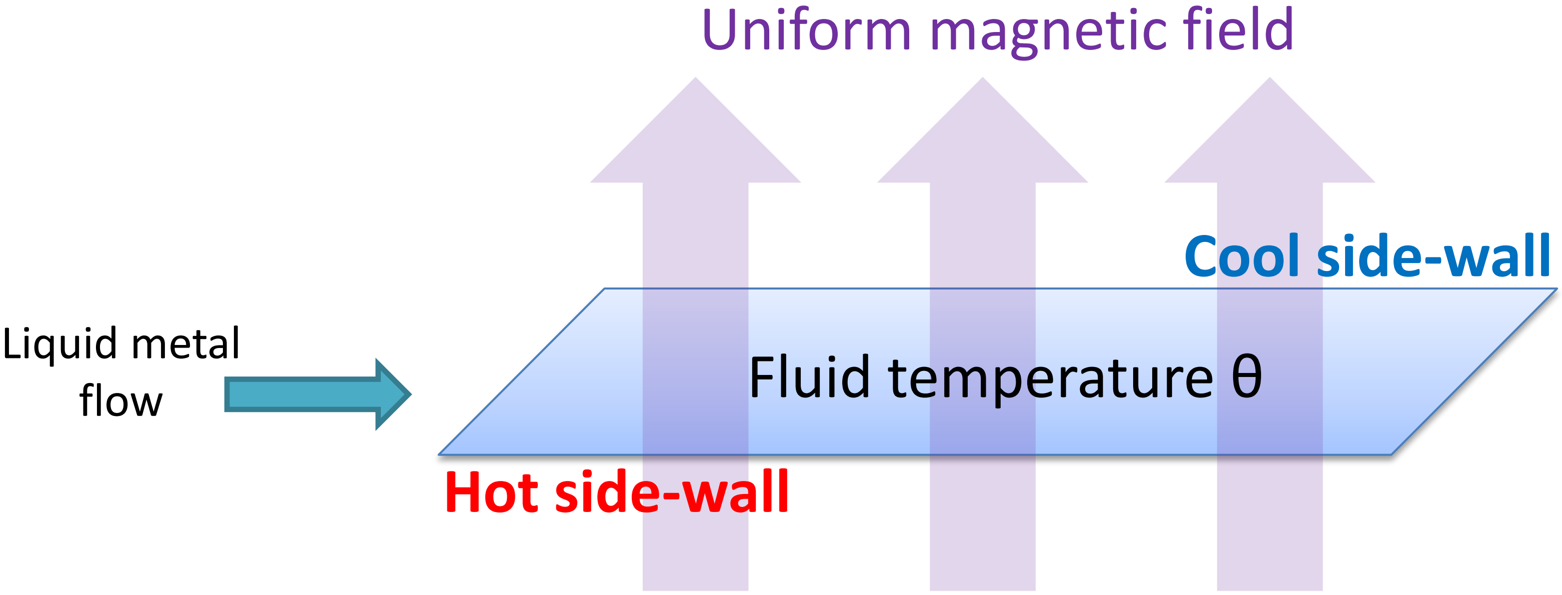
Friction in Hartmann layers accommodated by linear friction term



$$\nabla \cdot \mathbf{u} = 0,$$

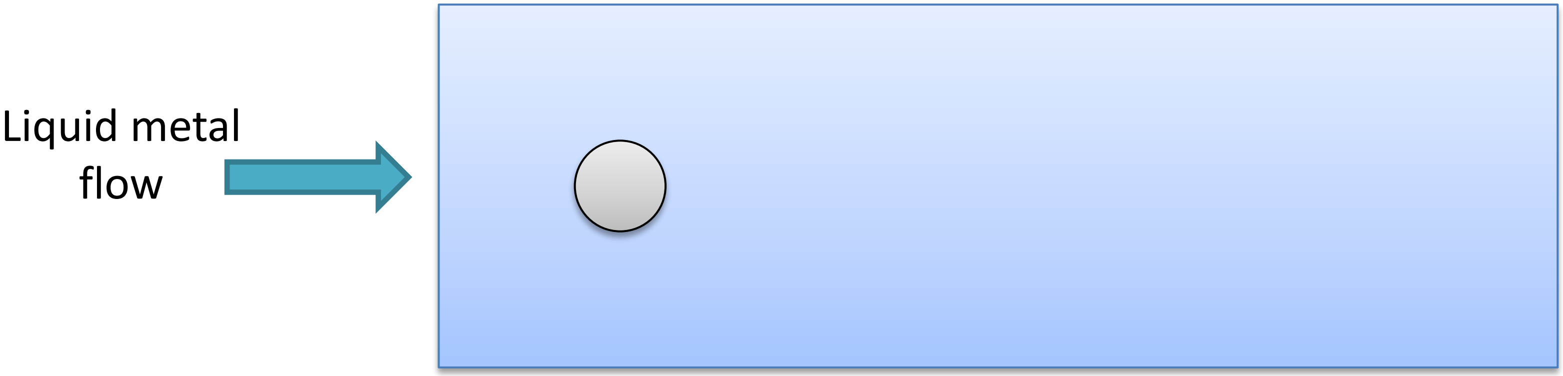
$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla p = \frac{1}{Re}\nabla^2 \mathbf{u} - \boxed{2\left(\frac{d}{a}\right)^2 \frac{Ha}{Re}\mathbf{u}}$$

Describing heat transfer in blanket ducts



$$\frac{\partial\theta}{\partial t} + (\mathbf{u}\cdot\nabla)\theta = \frac{1}{Pe}\nabla^2\theta$$

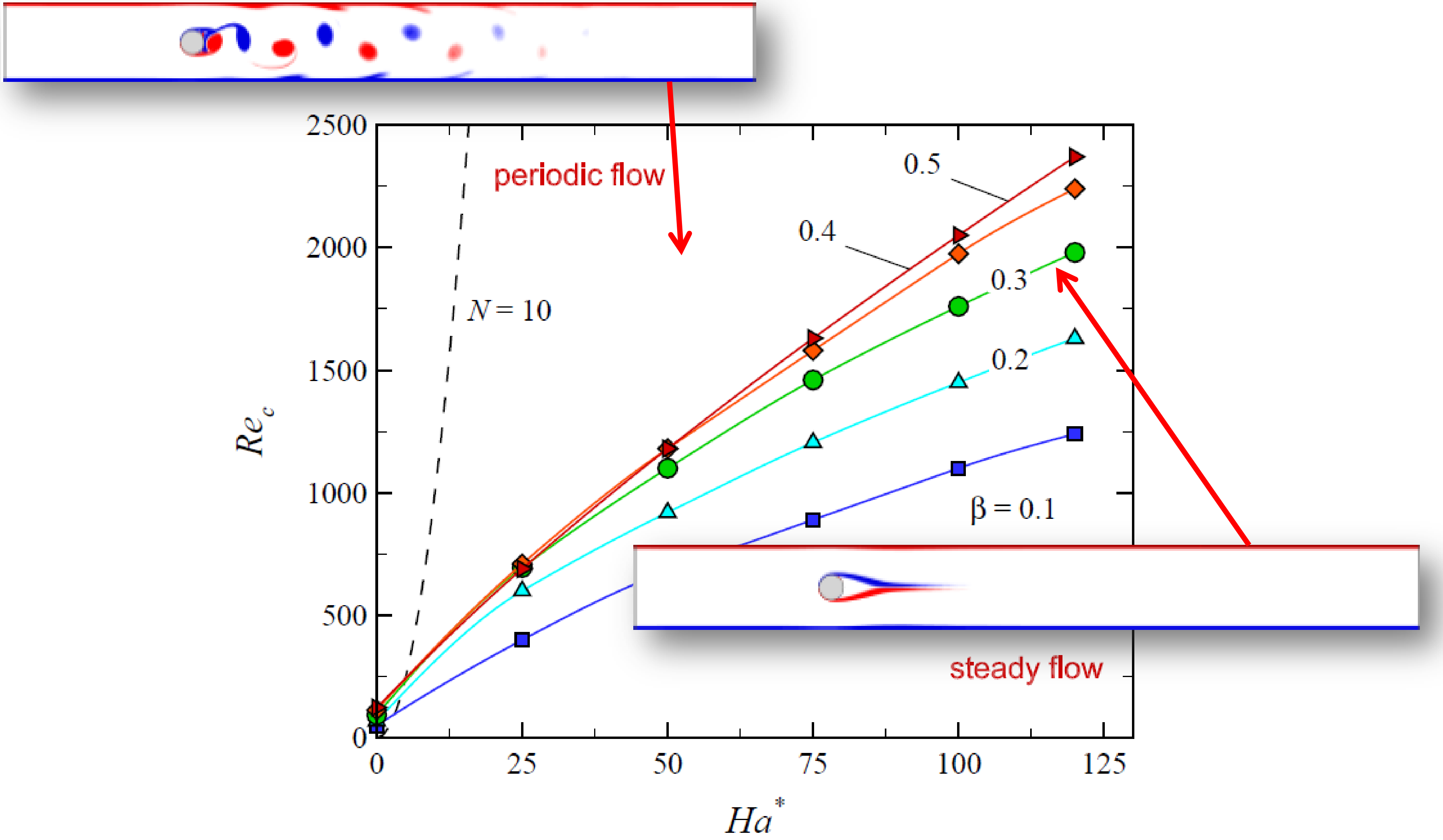
Problem: At high Hartmann numbers, friction term suppresses flow disturbances even in quasi-2D plane



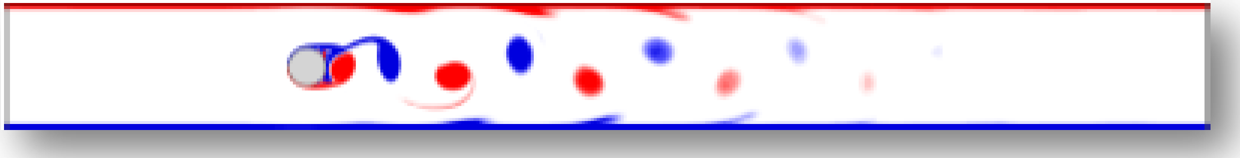
Looking now in the direction of the magnetic field

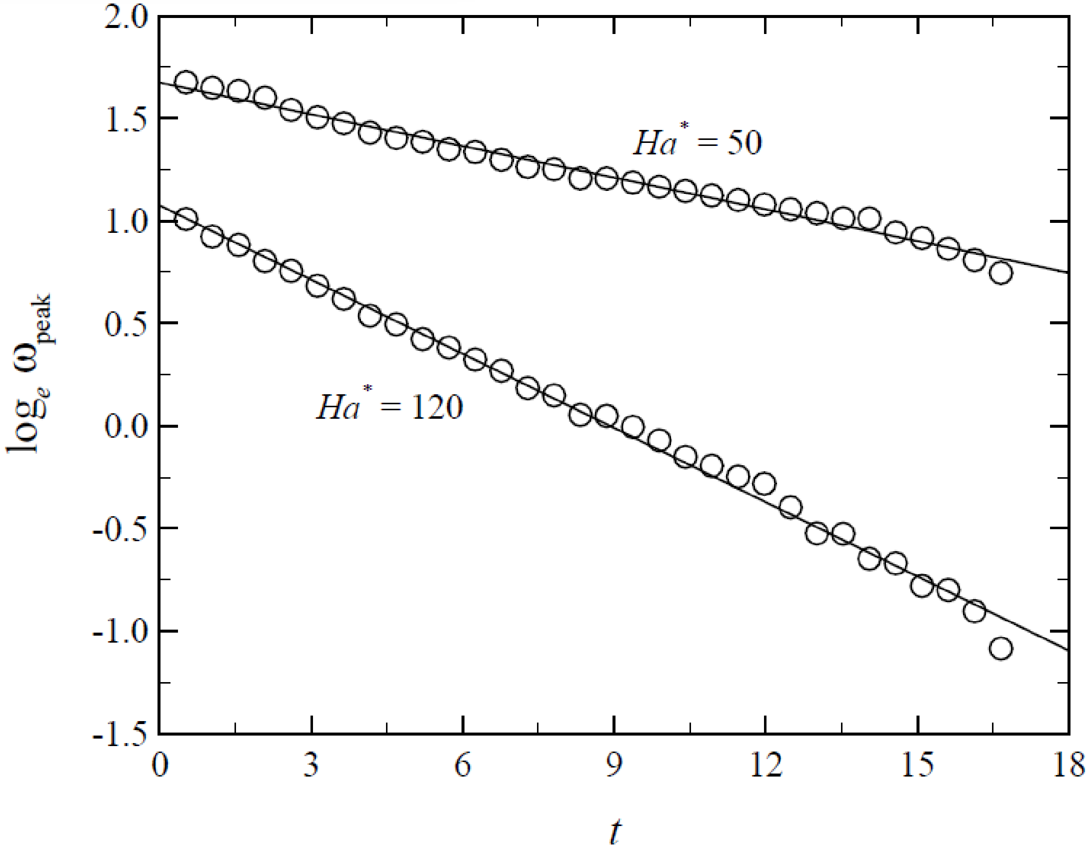
Aim: Investigate the use of cylindrical obstacles to enhance heat transfer

Wake instability suppressed by increasing channel blockage and increasing Hartmann number

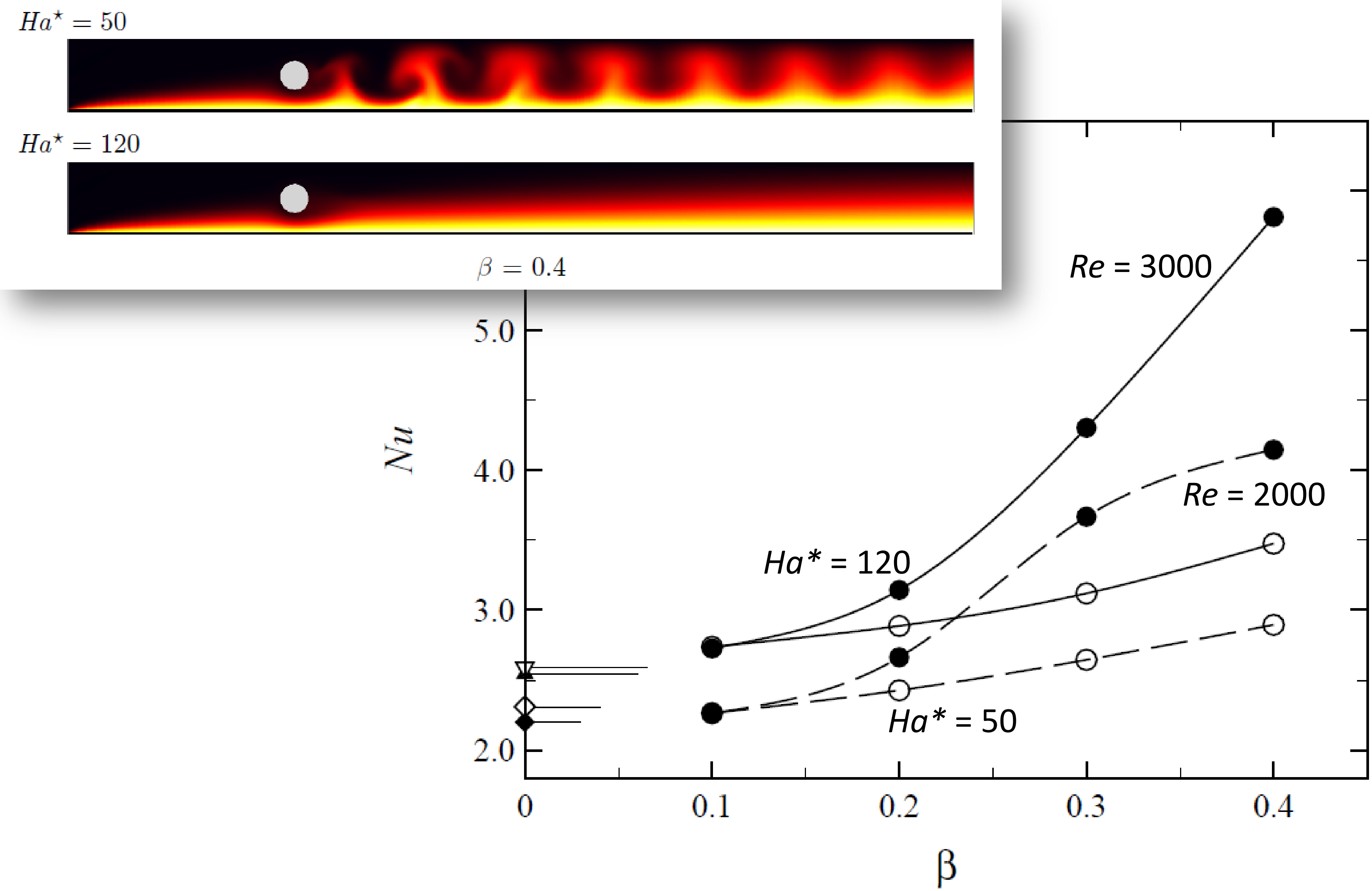


Hartmann friction is responsible for the decay of MHD turbulence

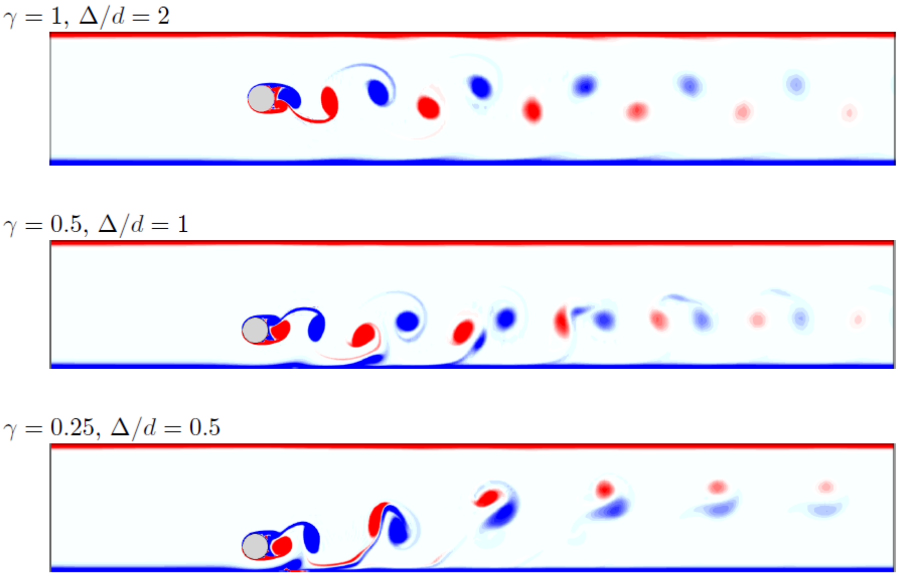




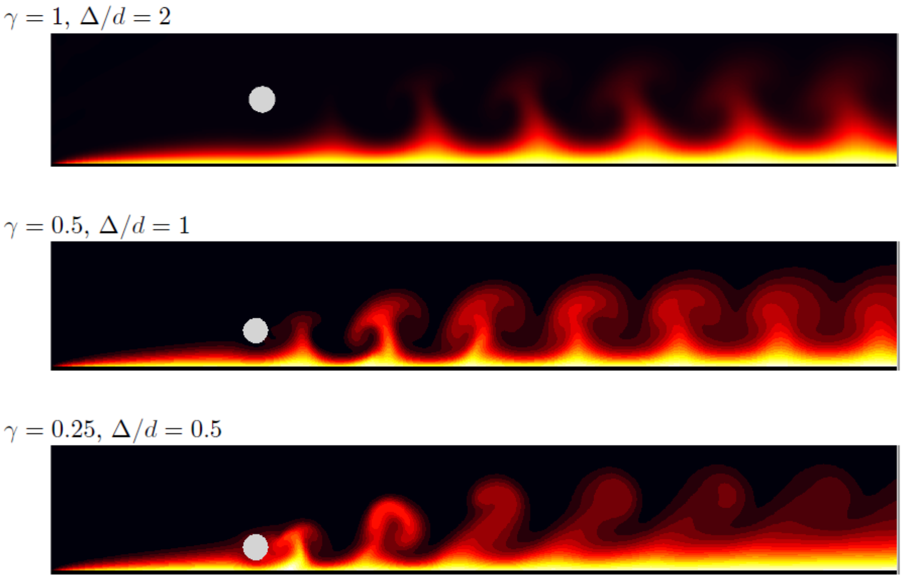
Heat transfer is enhanced by wake instability



Proximity of cylinder to wall affects heat transfer

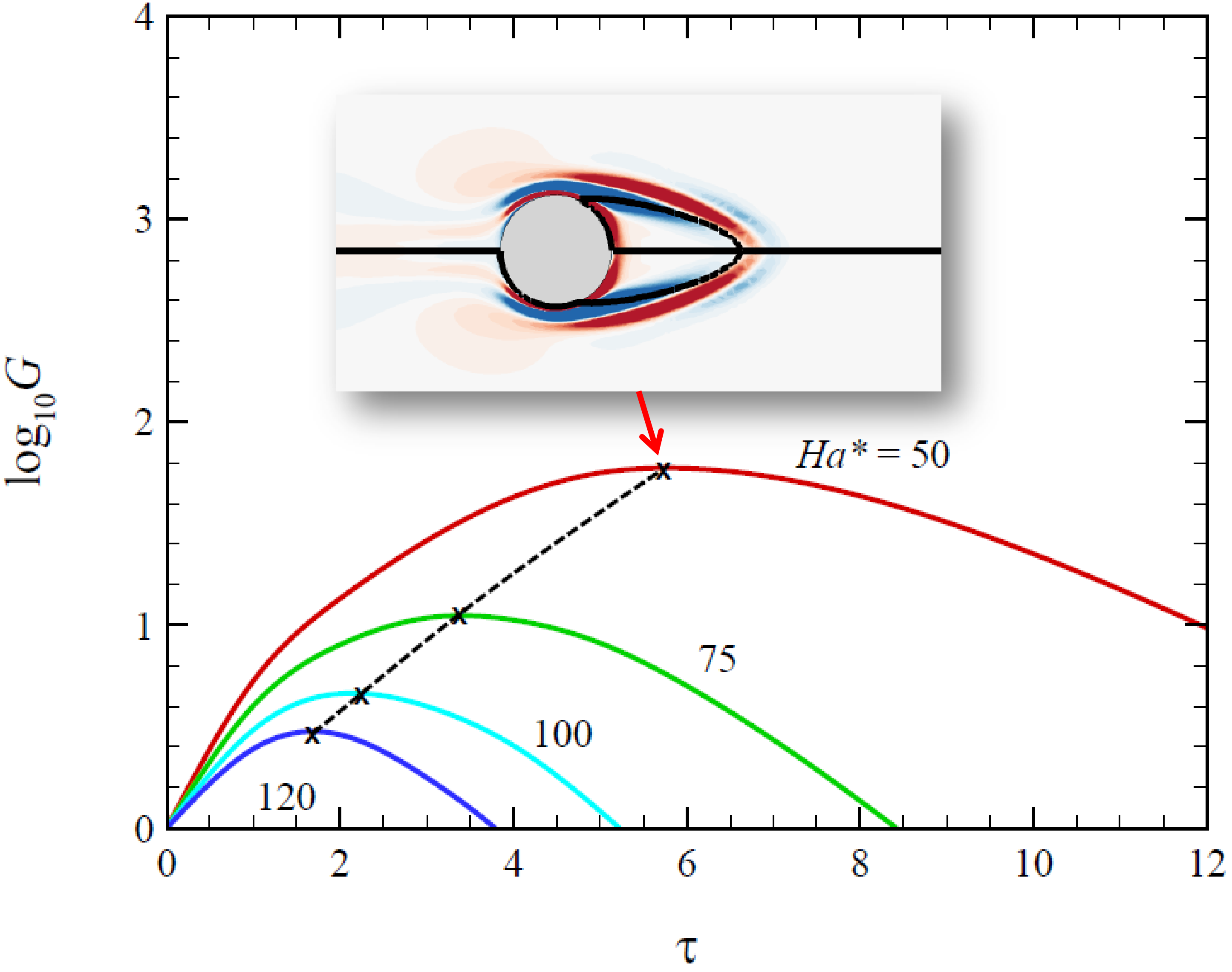


$\beta = 0.2$



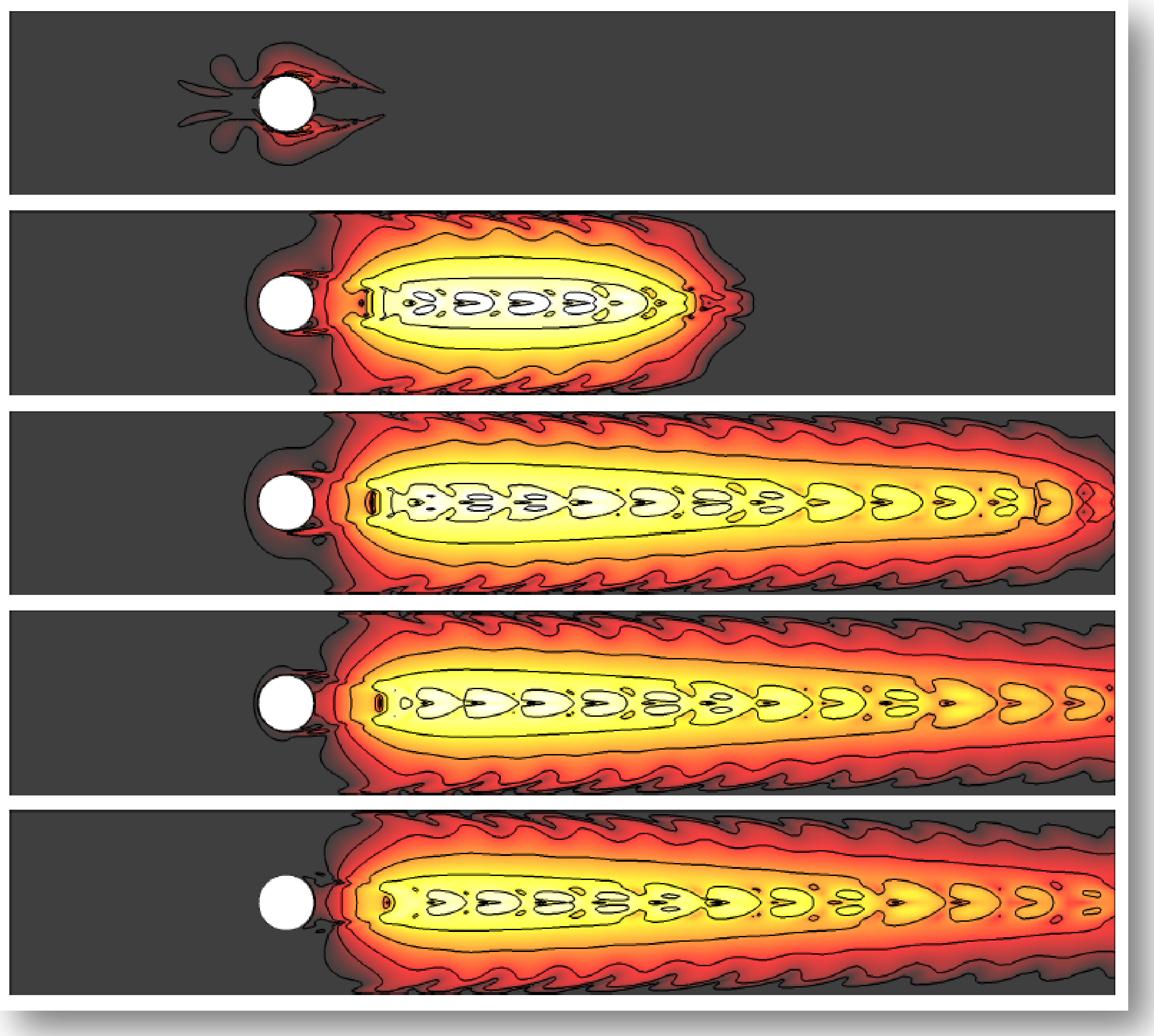
$\beta = 0.2$

Flow stability: Transient disturbances for optimal energy growth



Blockage
ratio
β = 0.1

Optimal disturbances can produce rapid growth in energy of a disturbance



t = 0

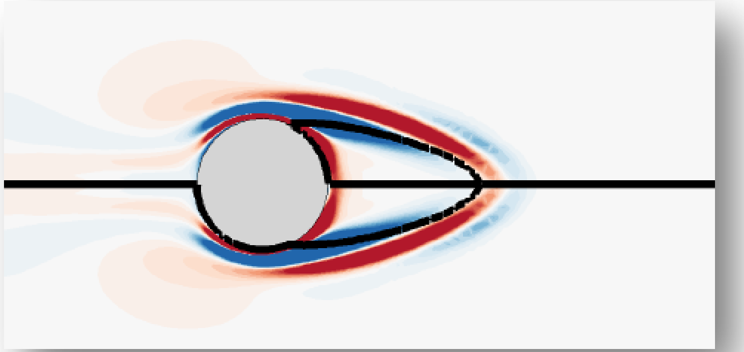
t = 4

t = 8

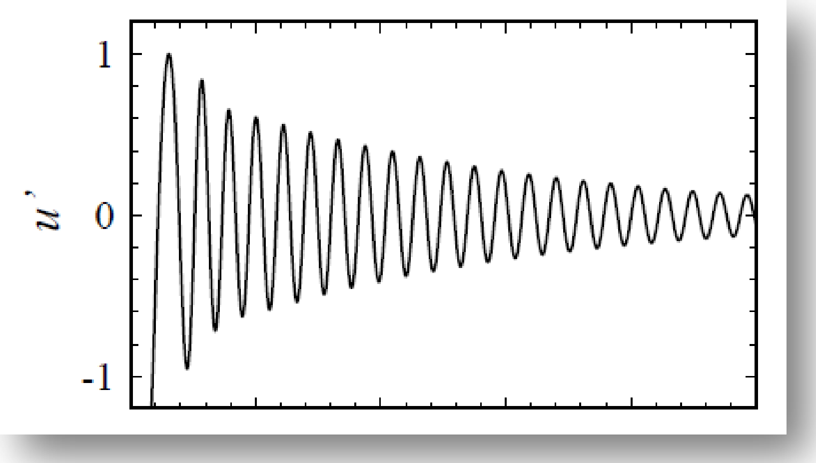
t = 16

t = 32

Can we exploit our understanding of the optimal disturbances to enhance heat transfer?

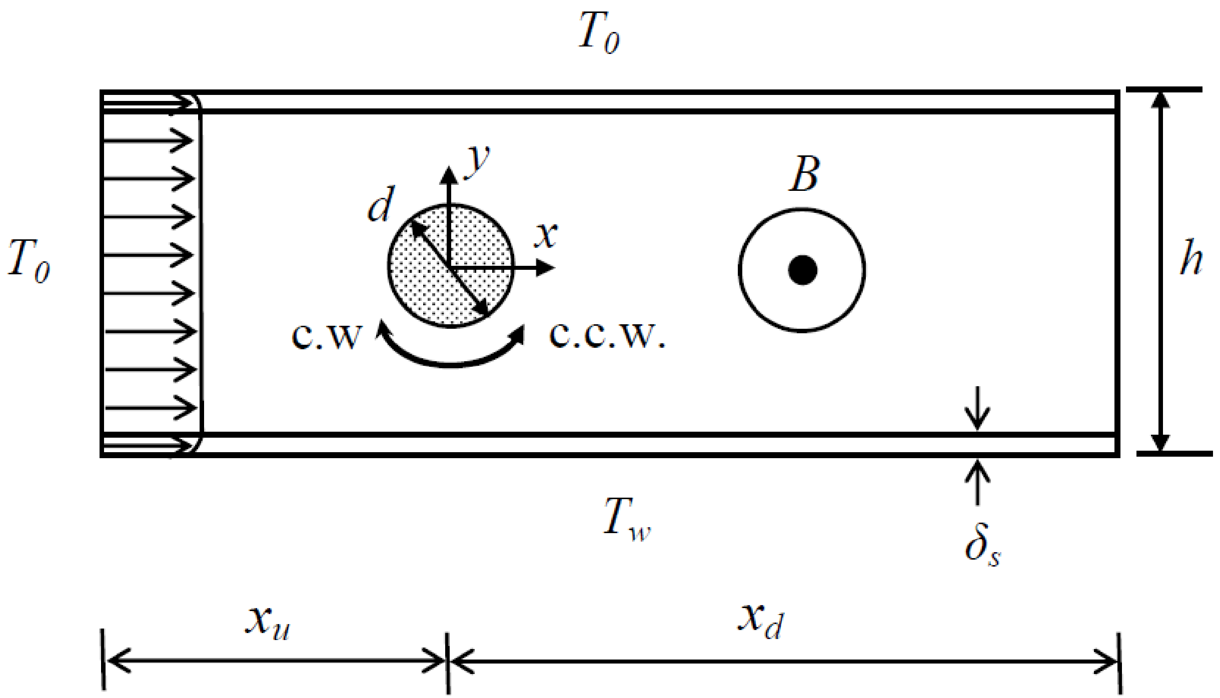


Optimal disturbance field localized to the cylinder

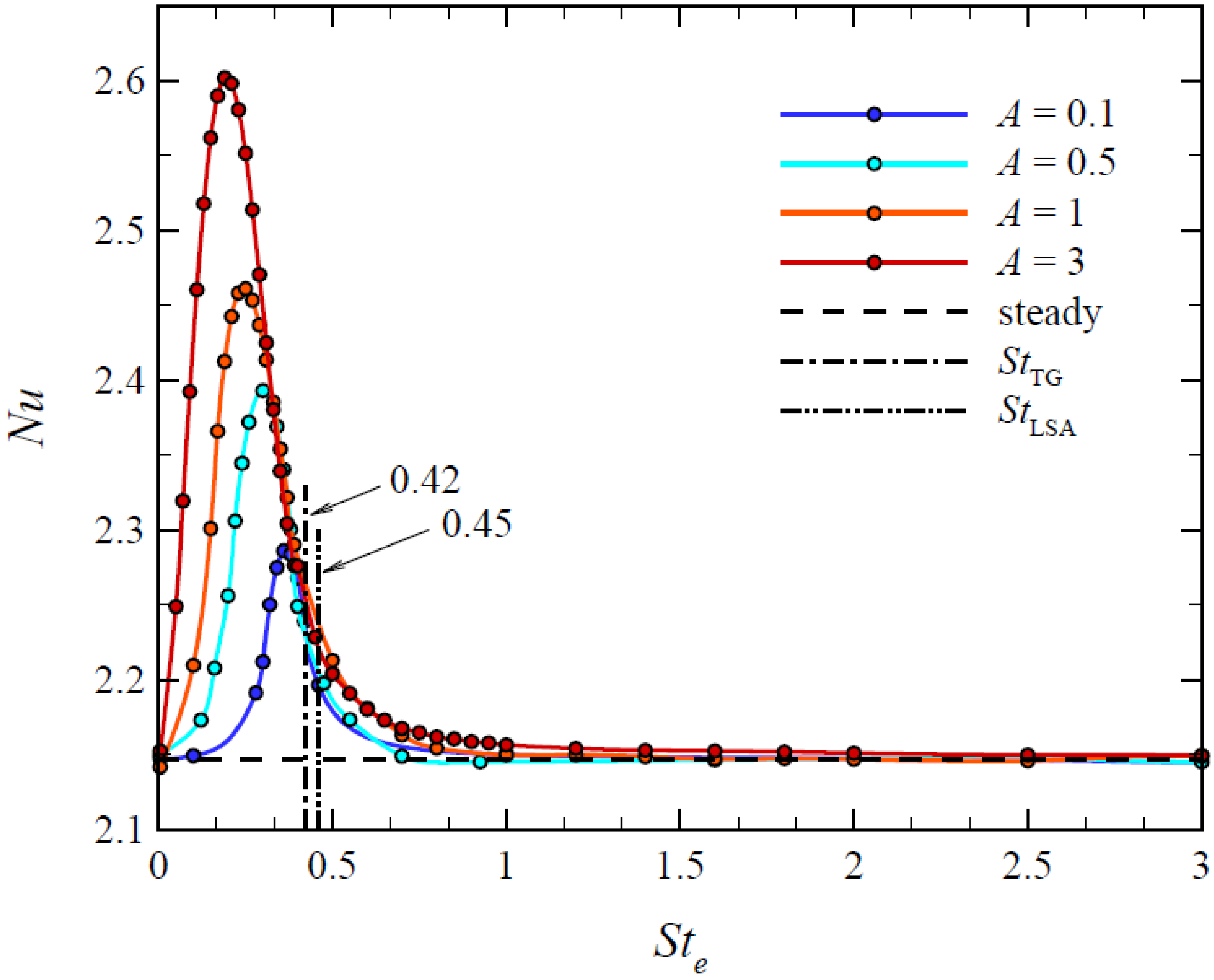


Optimal disturbance creates an oscillation with measurable frequency near to the cylinder surface

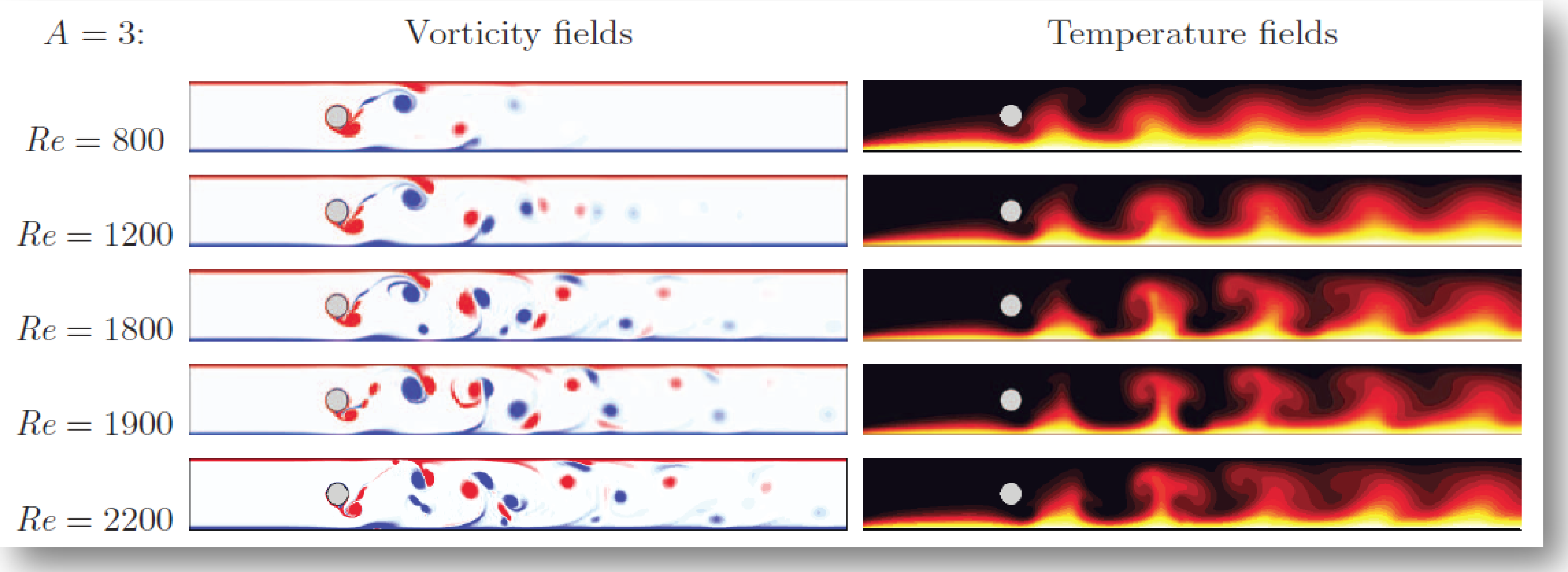
A torsional oscillation mechanism for producing wake instability and enhancing heat transfer



Increasing amplitude of oscillation increases heat transfer



Wake dynamics and heat transport at maximum heat transfer frequencies



Where to from here?

- Much left to explore
  - 3D effects in side-wall boundary layers (not captured by this quasi-2D model)
  - Use of current injection for non-mechanical turbulence promotion
  - Consideration of natural convection effects
  - Other turbulence promoter designs