Stability of MHD Effects on Surface Waves in Liquid Gallium

W. Fox[1], H. Ji[2], D. Pace[3], H. Rappaport[4]
[1]*Physics Department, Princeton University*
[2]*Princeton Plasma Physics Laboratory, Princeton University*
[3]*University of Pacific*
[4]*University of Texas at Austin*

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Outline

- Motivations
- Goals of Liquid Metal Experiment (LMX)
- Initial experimental results
  - Measurements of dispersion relations
  - Measurements of wave amplitudes
- Upgraded experimental device
  - Preliminary results
- Conclusions and future work

Motivations

- Fusion applications of liquid metal wall have raised interests in physics understanding of MHD effects on
  - **Surface stability**
  - **Flow stability**
  - **Thermal convection**
- Better understanding of free-surface MHD could provide more **controls** of liquid metals.
- MHD physics in liquid metals is also relevant to **basic plasma physics** and **astrophysics**.

Many Astrophysical Phenomena Controlled by Interfacial Mixing

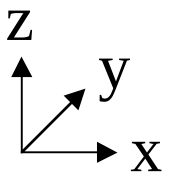
- **Mixing efficiency of fuels and ashes determines**
  - **Burning rate** of nuclear runaways (novae, supernovae, x-ray burst…)
  - **Composition** of ejecta or material on star surfaces
- **Possible physical mechanisms for efficient mixing**
  - **Rayleigh-Taylor instability,** when heavier unburned fuels sit on top of lighter nuclear ashes
  - **Kelvin-Helmholtz instability** in shear flows, common in differentially rotating stars
  - **Thermal convection,** driven by a temperature gradient created by internal heating via nuclear reactions
  - **Wave-breaking** of interfacial gravity waves driven by shear motion between two fluids

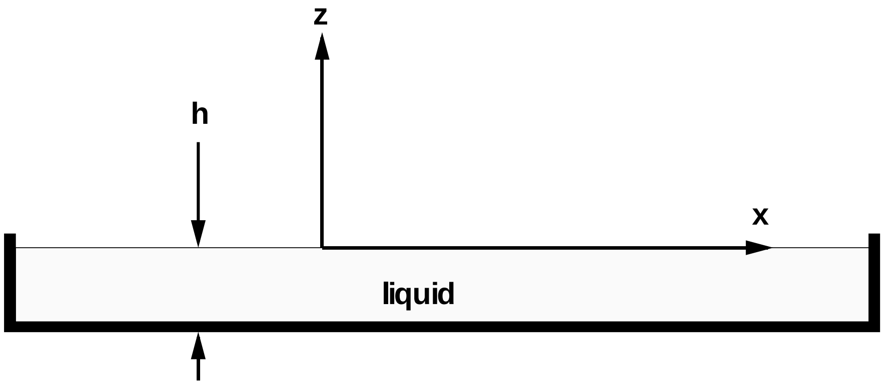
Goals of Liquid Metal Experiment (LMX)

Small-scale experiments using easy-to-handle metals to study:

- When and how do MHD effects modify surface stability, either in linear or nonlinear regimes?
- When and how do MHD effects modify a free-surface flow?
- When and how do MHD effects modify thermal convection?

A Simple Theory of Dispersion Relation of Gallium Surface Waves





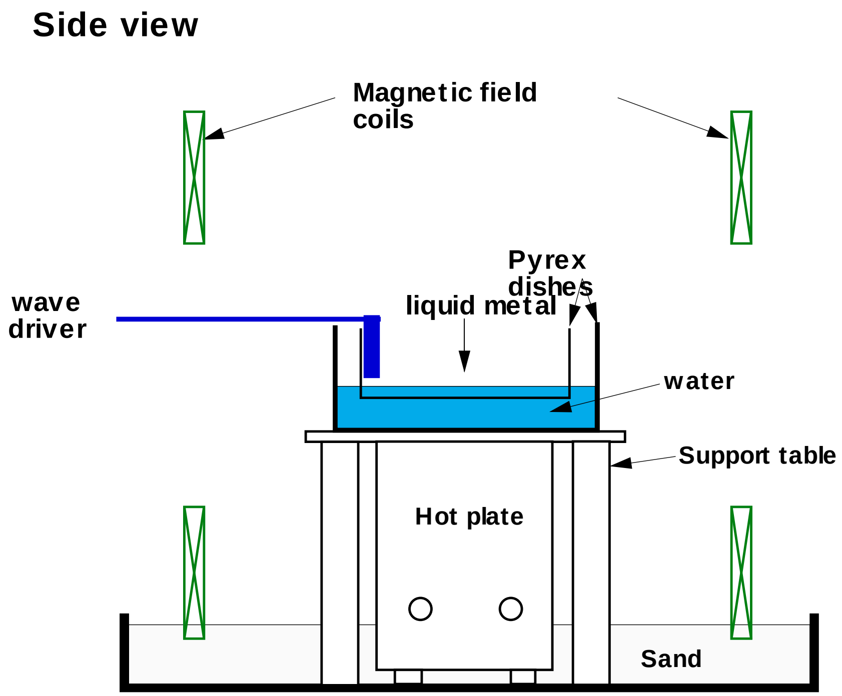
- **Basic assumptions**
  - **Boundary is at infinity**
  - **Incompressibility: ∇·V=0**
  - **Uniform j=(**j_x, j_y, 0**) and B=(**B_x,B_y,0**) imposed**
  - **Ignore V×B and self-generated field → Zero vorticity: ∇×V=0**
- **Dispersion Relation:**

$$\rho\omega^2 = \left(\rho g + Tk^2 + j_y B_x\right) k \tanh kh$$

(ρ: density, g: gravity, T: tension force coefficient)

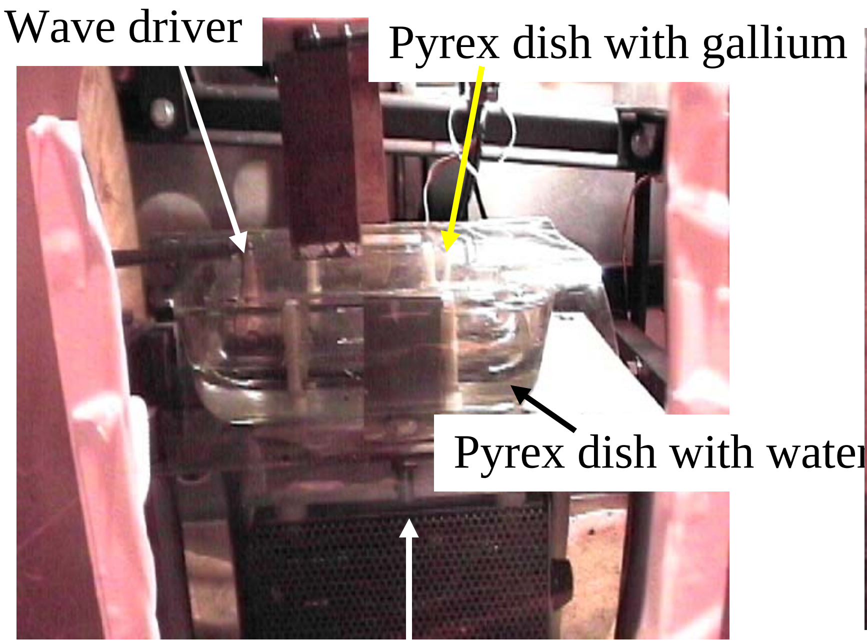
Initial Experimental Setups

- **The gallium** is melted in a smaller Pyrex dish placed in water housed by another Pyrex dish, heated by a hot plate.
- **A wave driver system** (including a copper paddle, support tubing, amplifier, and speaker) is used to drive the wave.
- **Two pairs of magnetic field coils** are placed on either side of the gallium to provide up to 600G of magnetic field around the liquid metal.

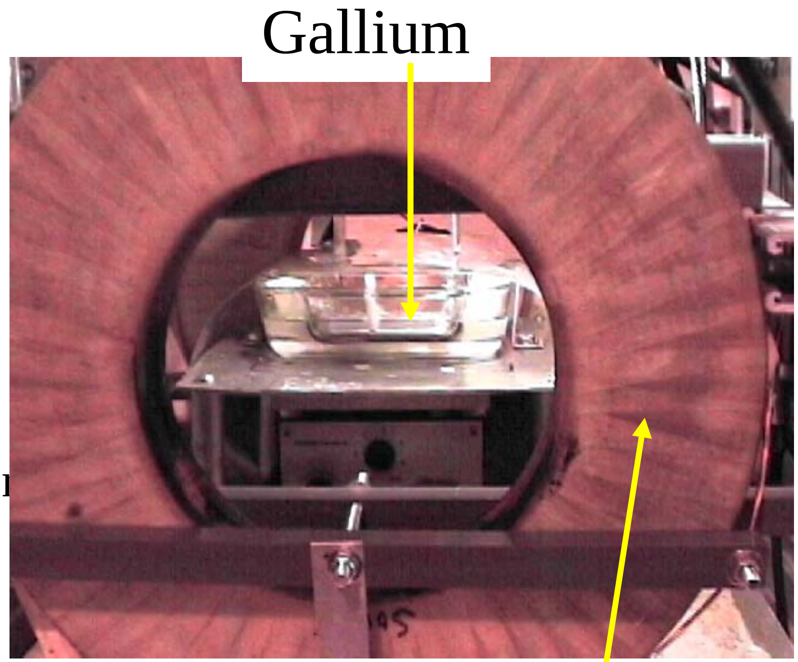


Initial Experimental Apparatus

Side View

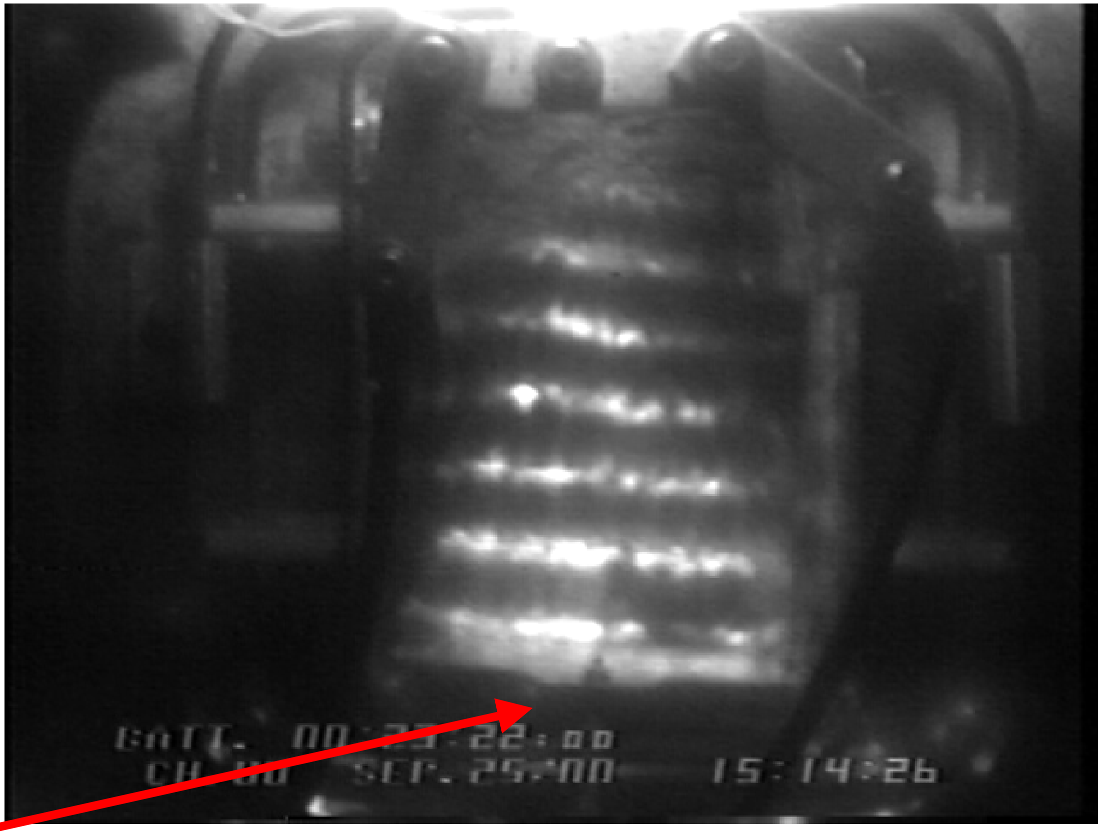


Front View



Gallium Surface Waves are Generated by Wave Driver

- An **ICCD** camera is used to monitor the waves
- **Magnetic field** up to 600 Gauss can be imposed in the wave direction

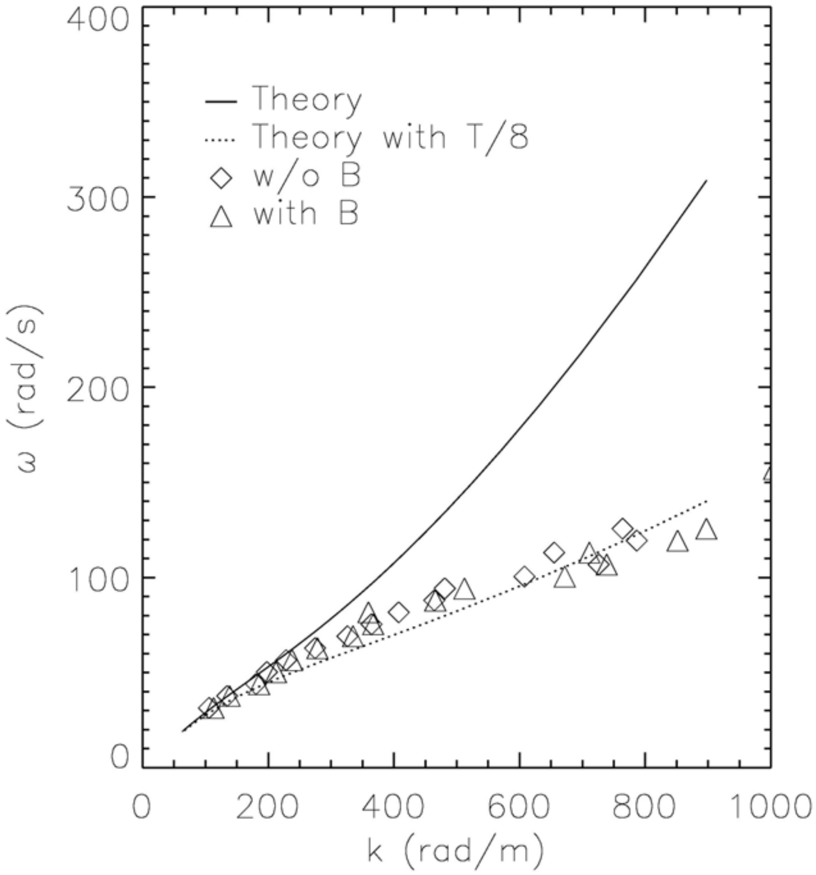


Wave driver

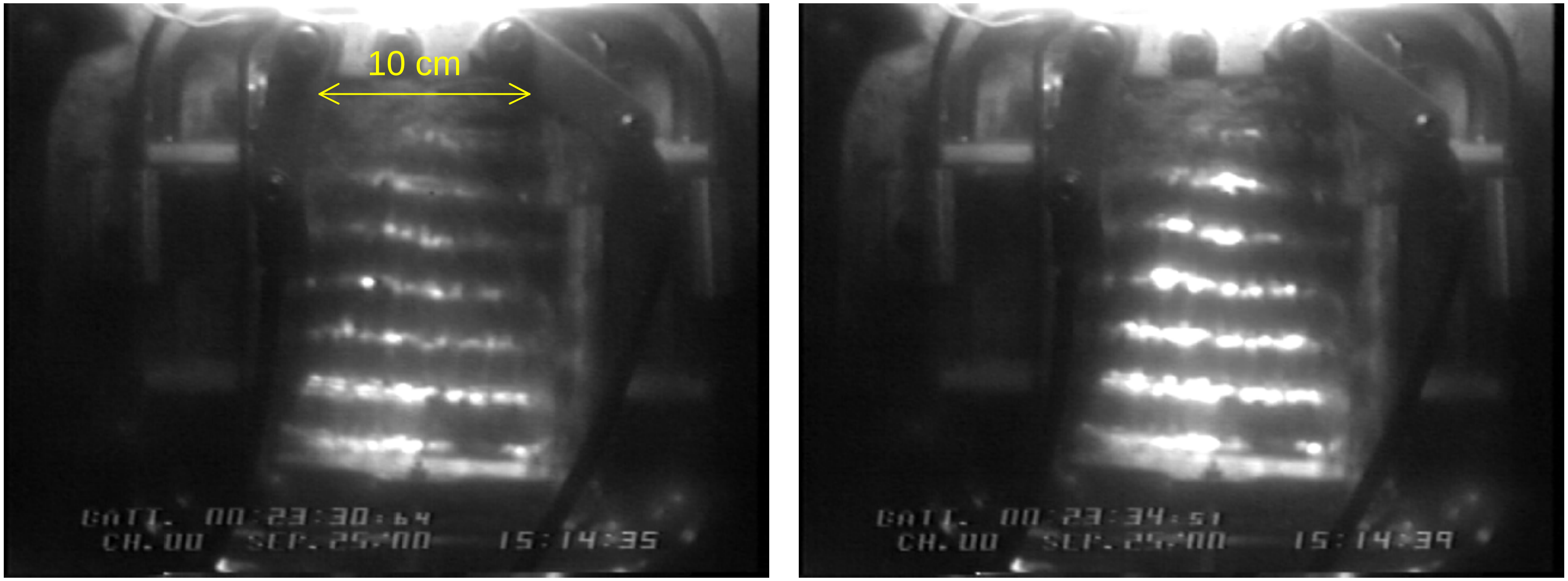
f=10Hz

Preliminary Measurements of Dispersion Relation and Comparison with a Theory

- Good agreement with theory at low frequency and long wavelength (gravity waves)
- Large discrepancy at high frequency and short wavelength (capillary waves) → Change in tension coefficient due to surface oxidization



Waves With And Without Magnetic Field



f=10Hz

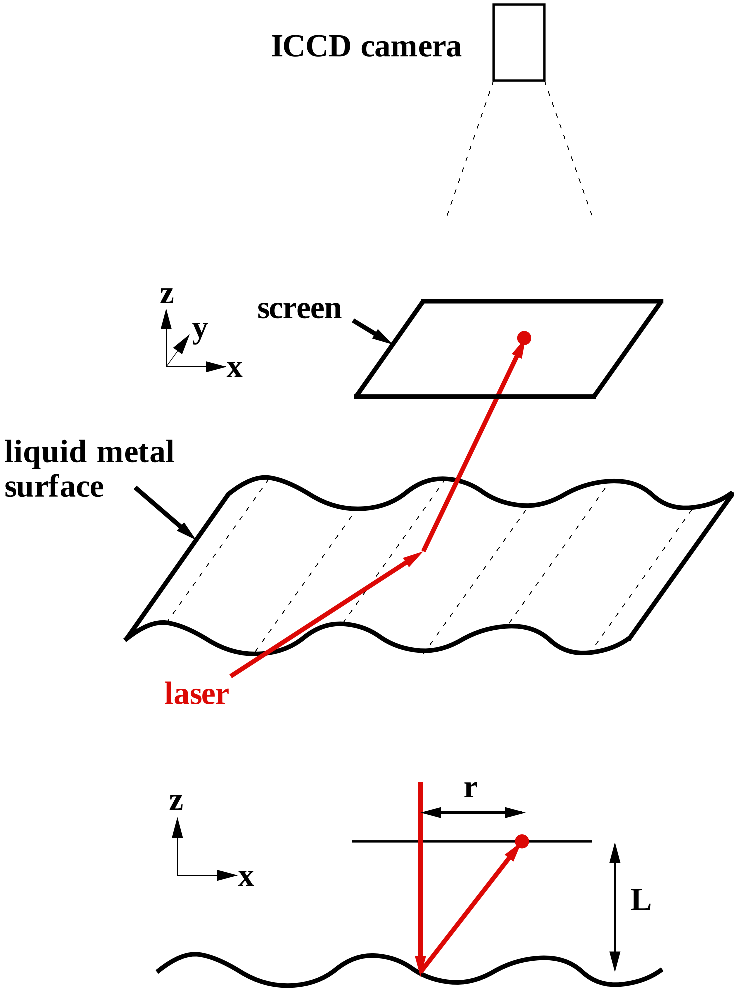
With Magnetic Field **Without Magnetic Field**

A Laser Reflection Scheme to Measure Wave Amplitudes

- **Projection of reflected laser provides measurements of the wave amplitude, a:**

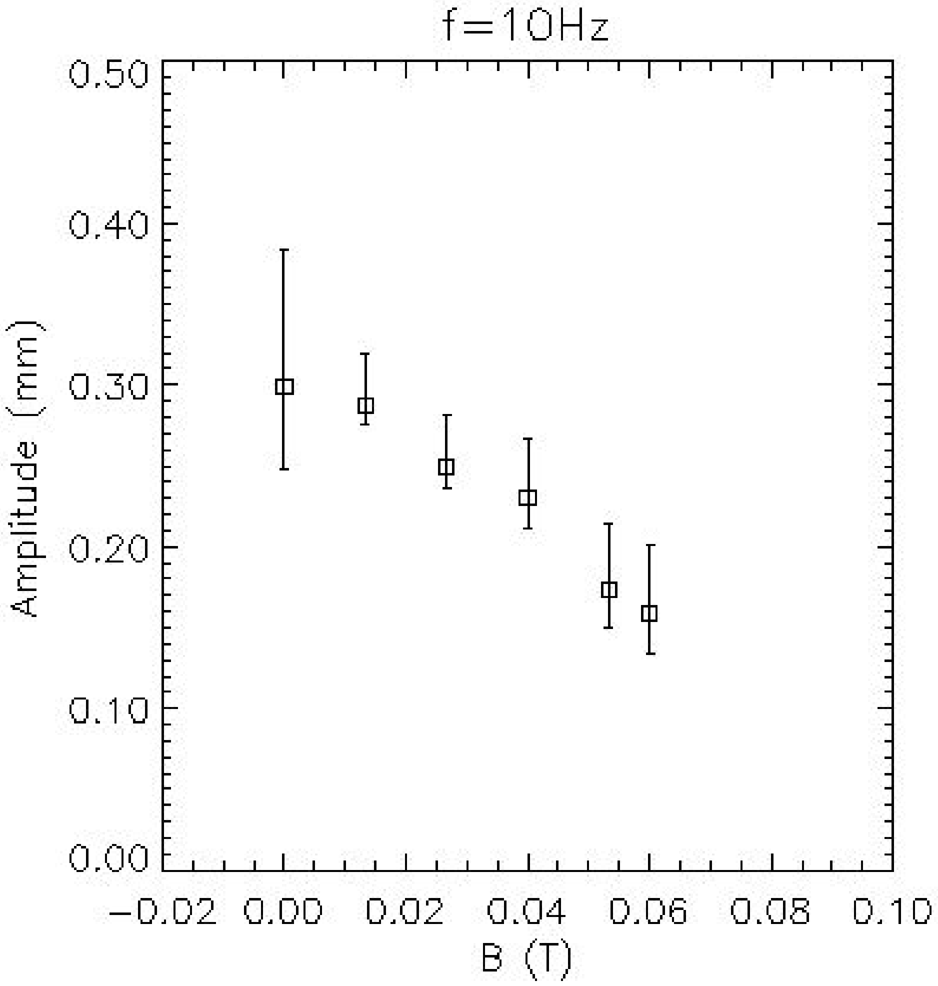
$$ka \approx \frac{1}{2}\frac{r_{\max}}{L} - \frac{1}{8}\left(\frac{r_{\max}}{L}\right)^3$$

(when a,r << L)



Effects of Magnetic Field on Wave Amplitude

- Wave amplitude decreases by a factor of 2 with magnetic field up to 600 gauss.

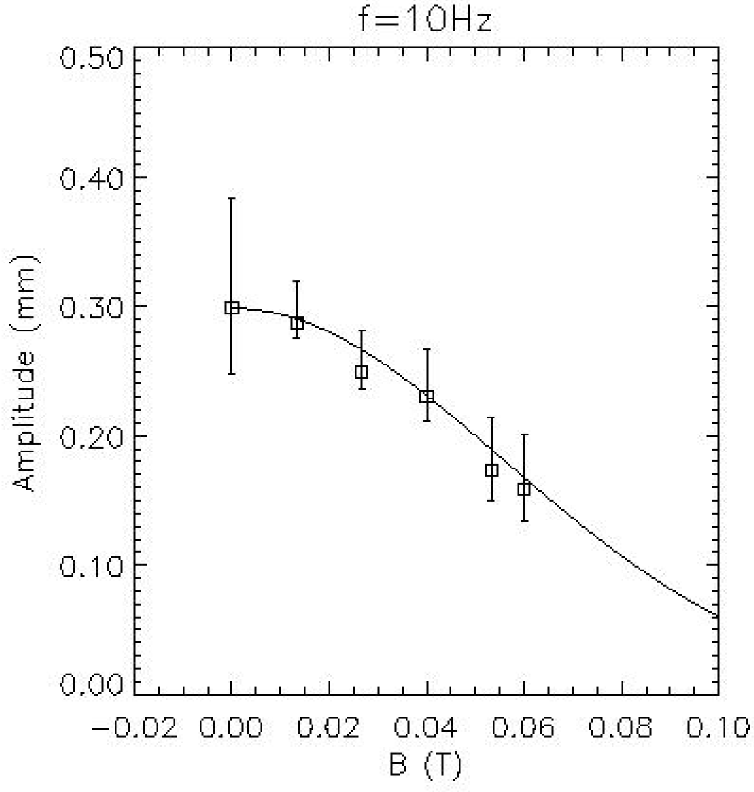


Inclusion of V×B Term Explains Wave Damping Due to Magnetic Field

$$\rho\omega^2 = \left(\rho g + Tk_x^2 + j_y B_x\right)k_x \tanh k_x h\left[1 + i\,\frac{B_x^2}{2\rho\eta\omega}\left(1 - \frac{2k_x h}{\sinh(2k_x h)}\right)\right]$$

- **Shallow water waves** ($k_x h \ll 1$): **no damping**
- **Deep water waves** ($k_x h \gg 1$) **damping rate:**

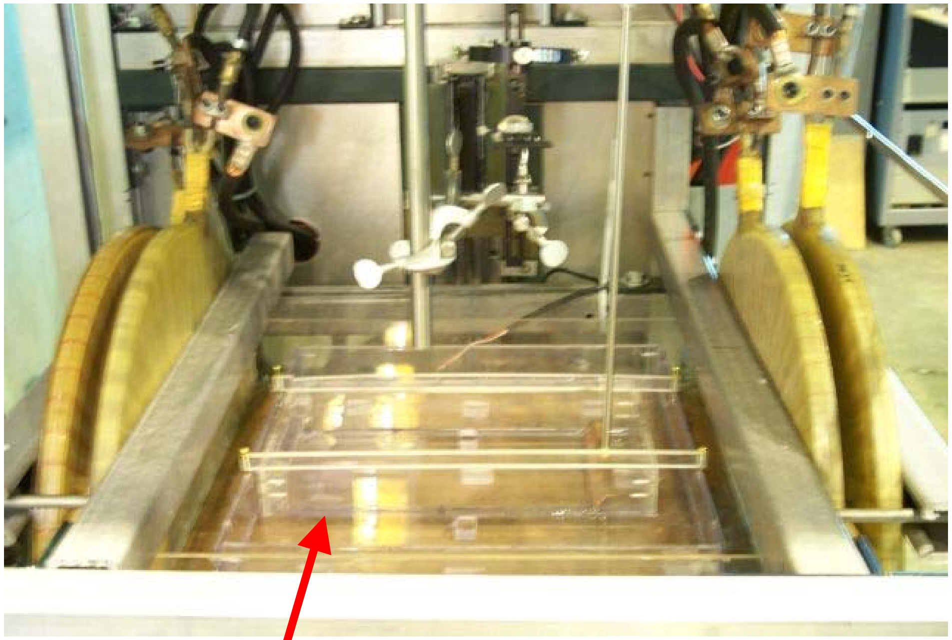
$$e^{-\frac{B_x^2\omega k_x \delta x}{2\eta\left(\rho\omega^2 + 2Tk_x^3\right)}}$$

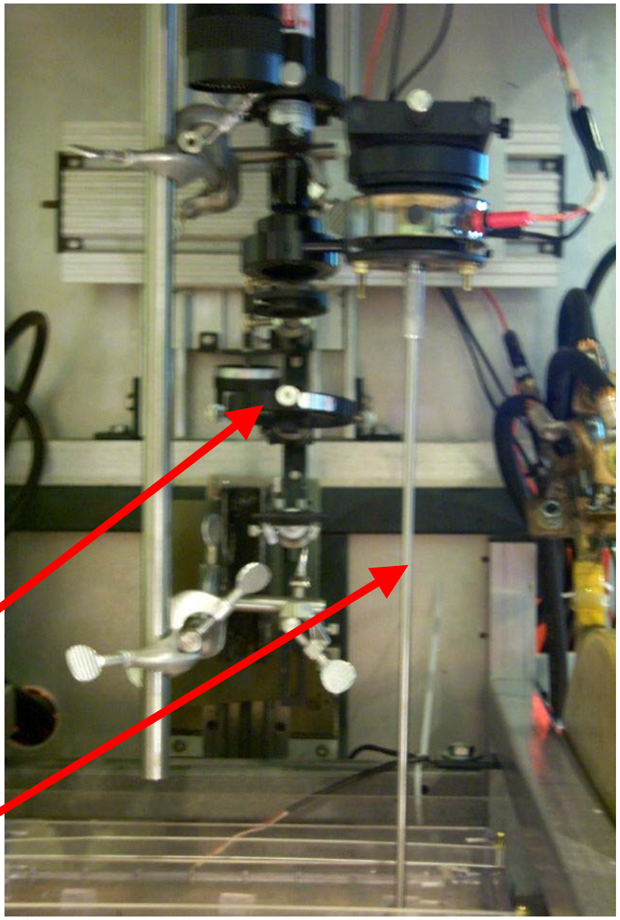


Major Upgrades Completed

- Robust and flexible wave driver system capable of large amplitude waves
- Larger containers to minimize boundary effects and also for 2D waves
- Surface diagnostics: multiple-point laser reflection system
- Experimental controls by a PC-based system including data acquisition
- Upgrade coils and power supplies for wave damping and growth (planned)

New Experimental Setups





multi-point laser system
(maximum: 7x7)

water and gallium tanks

wave driver

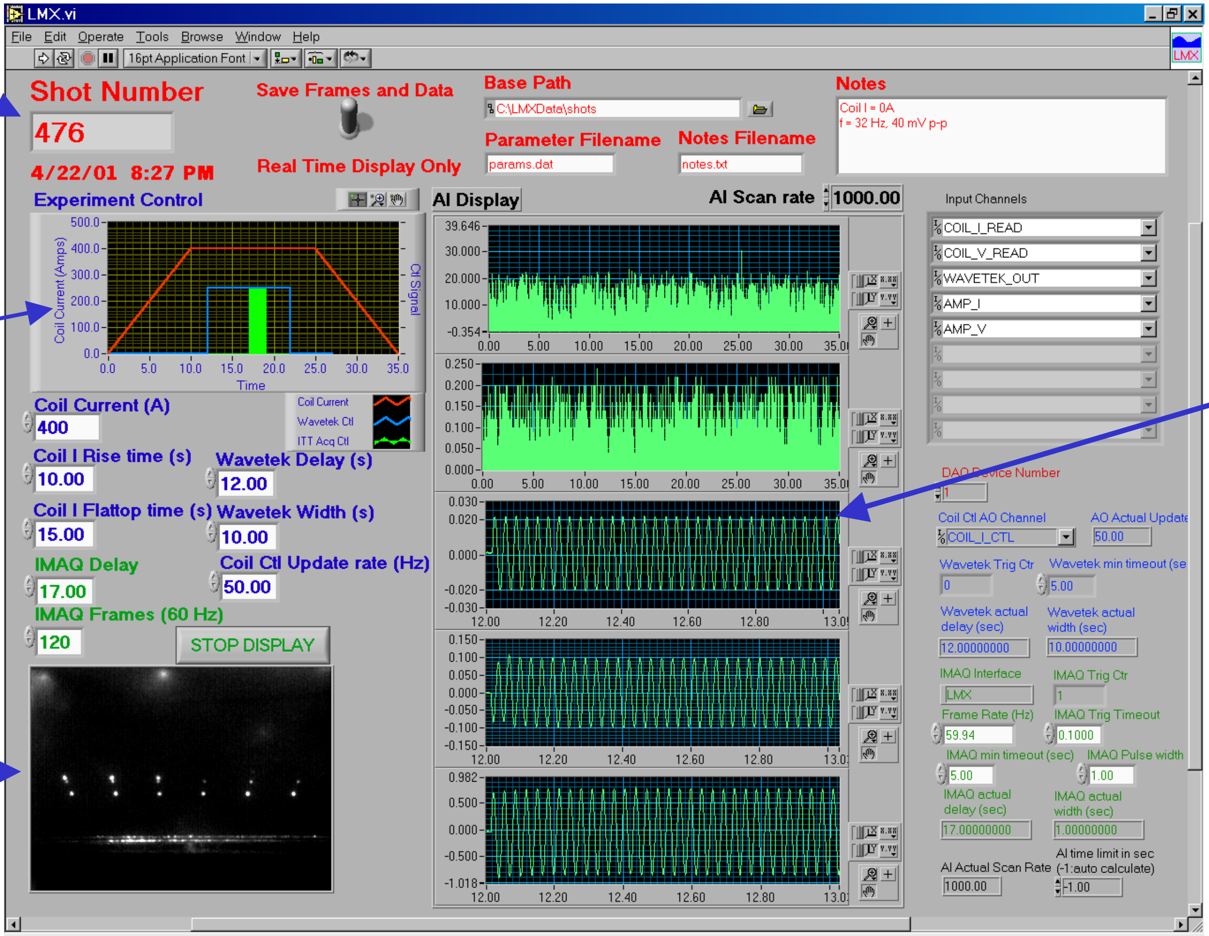
Full Automation of Experimental Sequencing and Data Acquisition

Shot #

Preset waveforms

Images

Measured waveforms



Shot Number: 476

4/22/01 8:27 PM

Save Frames and Data / Real Time Display Only

Base Path: C:\LMXData\shots

Parameter Filename: params.dat

Notes Filename: notes.txt

Notes:
Coil I = 0A
f = 32 Hz, 40 mV p-p

AI Scan rate: 1000.00

Coil Current (A): 400

Coil I Rise time (s): 10.00

Coil I Flattop time (s): 15.00

Wavetek Delay (s): 12.00

Wavetek Width (s): 10.00

IMAQ Delay: 17.00

Coil Ctl Update rate (Hz): 50.00

IMAQ Frames (60 Hz): 120

Input Channels:
COIL_I_READ
COIL_V_READ
WAVETEK_OUT
AMP_I
AMP_V

DAQ Device Number: 1

Coil Ctl AO Channel: COIL_I_CTL

AO Actual Update: 50.00

Wavetek Trig Ctr: 0

Wavetek min timeout (se: 5.00

Wavetek actual delay (sec): 12.00000000

Wavetek actual width (sec): 10.00000000

IMAQ Interface: LMX

IMAQ Trig Ctr: 1

Frame Rate (Hz): 59.94

IMAQ Trig Timeout: 0.1000

IMAQ min timeout (sec): 5.00

IMAQ Pulse width: 1.00

IMAQ actual delay (sec): 17.00000000

IMAQ actual width (sec): 1.00000000

AI Actual Scan Rate: 1000.00

AI time limit in sec (-1:auto calculate): -1.00

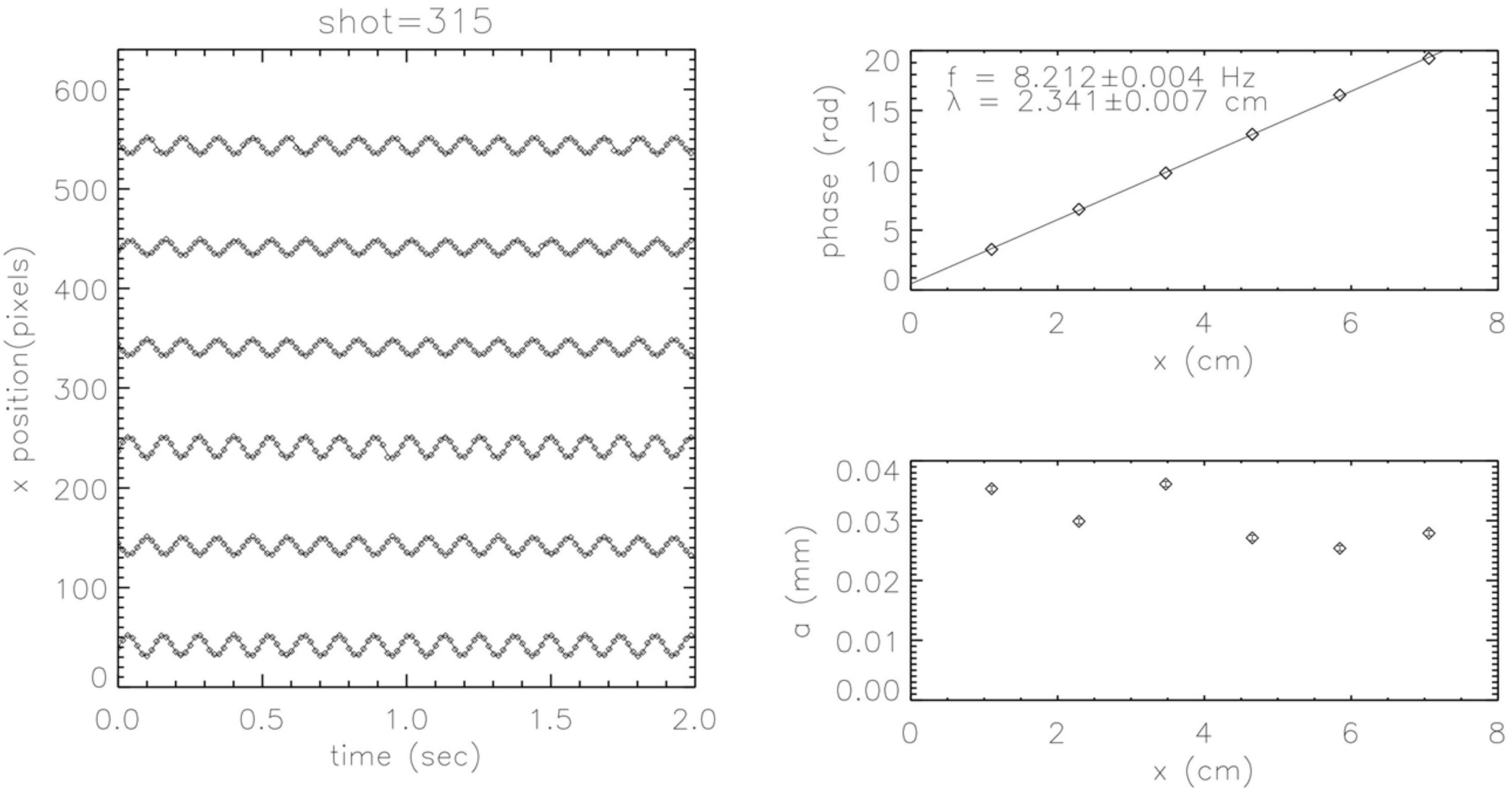
- PC-based Labview

Multiple-point Laser Reflection Measurements

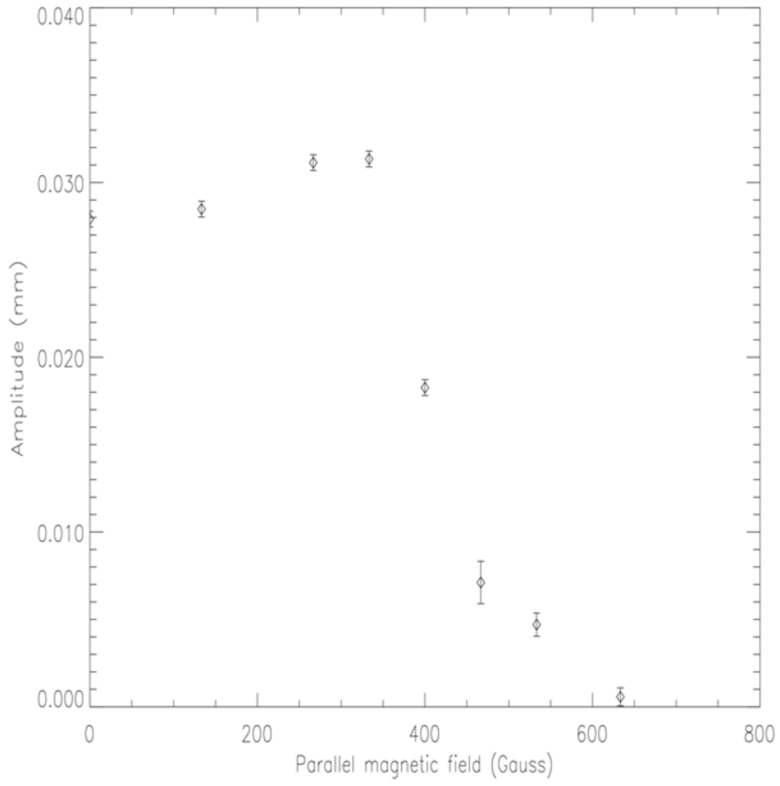
Shot 315: f=8Hz, B=0, gallium waves

- Wave amplitude and phase measured at 6 positions

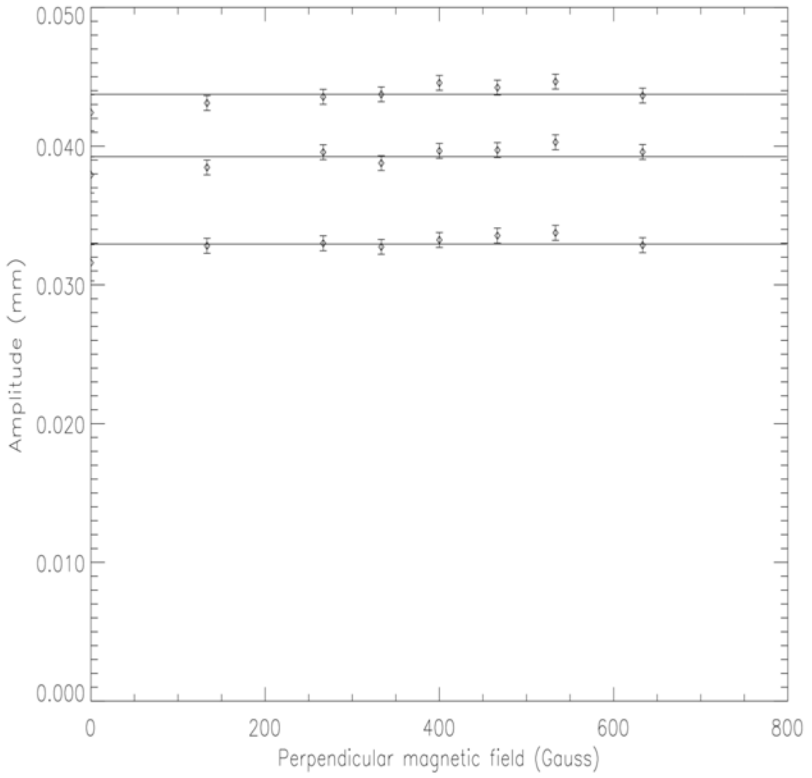
Accurate Determinations of (f, λ, a)



Effects of Magnetic Field on Amplitudes



Damping when $B \parallel k$



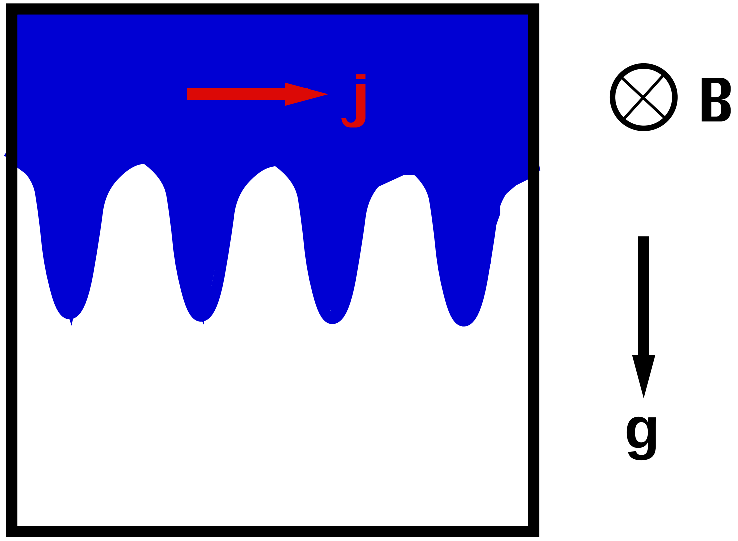
No effect when $B \perp k$

Near Future Work on Surface Waves

- **Linear waves:**
  - **Dispersion**
    - **k ⊥ B, j=0**
    - **Bz ≠ 0, j=0**
    - **j ≠ 0**
  - **Amplitude**
    - **Damping (k // B or k ⊥ B)**
    - **Growth (j ≠ 0): Rayleigh-Taylor instability**
  - **2D, circular waves**
- **Nonlinear waves**
  - **Nonlinear dispersion relations with B and j**
  - **Can we make an MHD solitary wave? (k ⊥ B, j=0, weakly nonlinear regime)**
  - **Can we make breaking waves? (strongly nonlinear regime)**

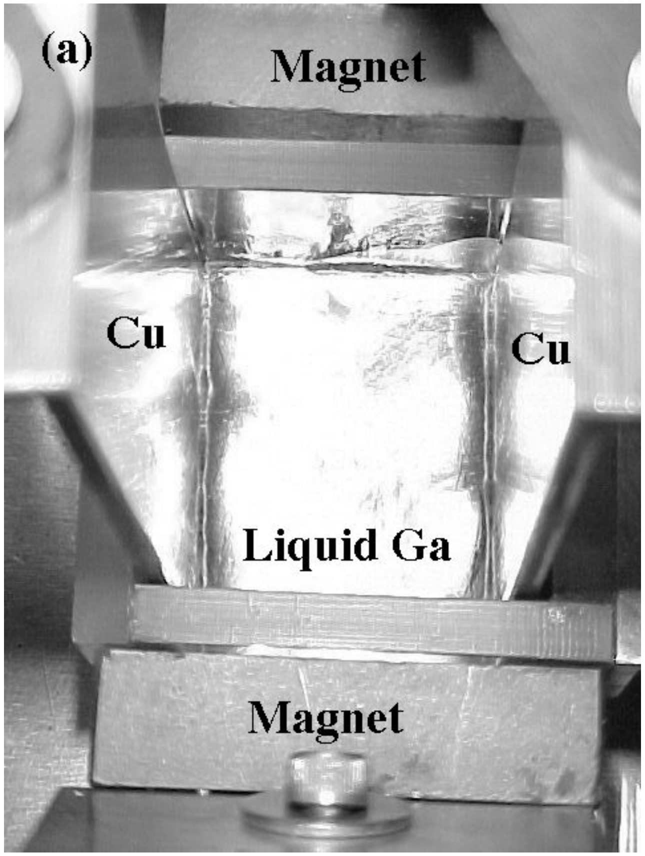
A Rayleigh-Taylor Instability Experiment

- Equilibrium: j×B>ρg
- Choosing x in the j direction, the surface is always unstable: maximum growth rate at certain k → deforming like fingers



$$\rho\omega^2 = \left(-\rho g + T k_x^2\right) k_x \tanh k_x h \left[1 + i \frac{B_x^2}{2\rho\eta\omega}\left(1 - \frac{2k_x h}{\sinh(2k_x h)}\right)\right]$$

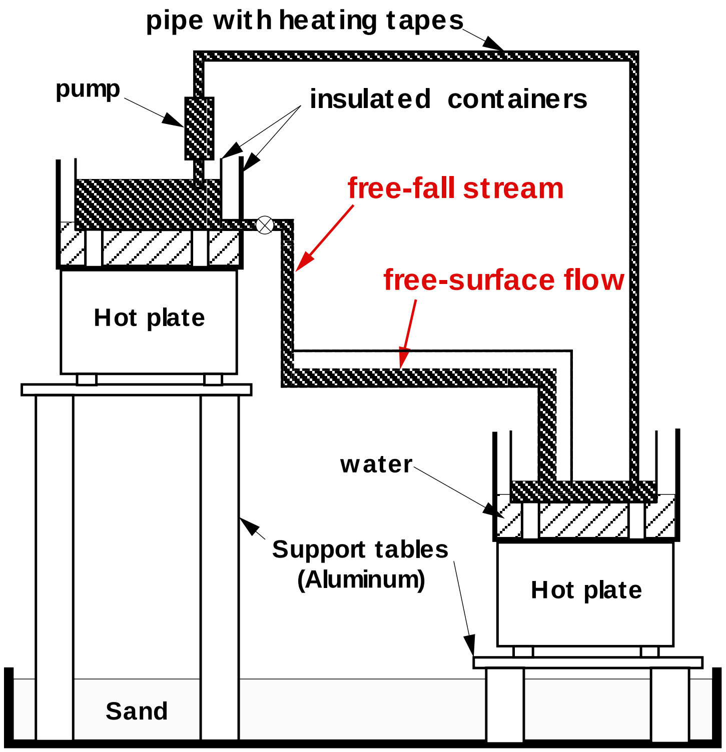
Indications Exist For Current To Introduce Turbulence



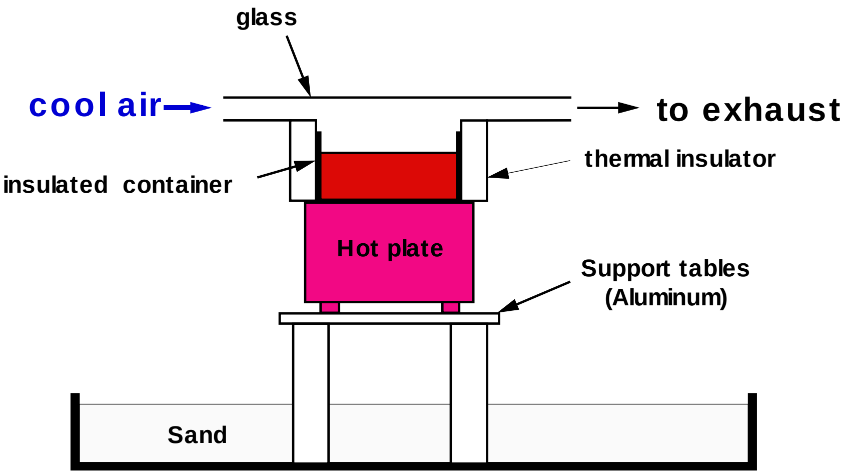
Without Current

With Current of 100A

Other Proposed Work in LMX



Rapid free-surface MHD flow



Turbulent thermal convection

Conclusions

- A new experiment, **LMX** (Liquid Metal Experiment) has been set up to study MHD physics of liquid metals.
- **Surface oxidization** modifies capillary waves at high frequency.
- Waves **damped** by **parallel** (but not perpendicular) magnetic field, consistent with linear theory.
- Wave generation **sensitive** to driving method, needs optimization (also wave reflections?)
- Experiments on **2D** waves and **nonlinear** waves planned
- Experiments on **Rayleigh-Taylor instability** possible when jxB>ρg