Control of MHD instabilities in plasmas and liquid metals

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Outline

• Motivation for Locked Mode (LM) Research - Relevance to disruptions
• How LMs initiate thermal quenches
• Statistics/prediction of LMs disruptions
• LM control by magnetic perturbations & ECCD

• Motivation for Liquid Metal (LM) Control
• Sensors of LM thickness
• Passive, active & f/back stabilization
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NTMs form at high pressure
...and limit pressure at inner radii

Modified Rutherford Eq.:
\[
\frac{\tau_R}{r^2} \frac{dw}{dt} = \Delta' + \text{destab. BS current term} \times \text{correction for small isl.}
\]
Electrical circuits interact with magnetic fields (Ampere, 1822)

DITE [Morris 1990]
COMPASS-C [Hender 1992]
HBT-EP [Navratil 1998]
TEXTOR [Koslowski 2006]
DIII-D [Volpe 2009]
J-TEXT [Rao 2013]
Current-field and current-current interactions \( \rightarrow \) electromagnetic torques on island

e.m. torques \( d\vec{T} = \vec{r} \times d\vec{F} = \vec{r} \times (I \, dl \times \vec{B}) \)
Current-field and current-current interactions $\rightarrow$ electromagnetic torques on island

- Island(s) = non-axisymmetric distribution of $\vec{j}$ at rational surface(s)
- Wall = non-axisymmetric distribution of $\vec{j}$ at at the wall, resistively delayed w.r.t. $d\vec{B}/dt$ that caused it (e.g. from rotating $\vec{j}$ at rational surface(s))
- EF, RMP = non-axisymmetric $\vec{B}$

\[
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\]
Current-field and current-current interactions → electromagnetic torques on island

- Island(s) = non-axisymmetric distribution of $\vec{j}$ at rational surface(s)
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- EF, RMP = non-axisymmetric $\vec{B}$

\[
e.m. \text{ torques } \vec{T} = \int \vec{r} \times d\vec{F} = \int \vec{r} \times (I \ dl \times \vec{B})
\]

\[
I\ddot{\phi} = T_{EF} + T_{MP} + T_{wall} + T_{NTM} + T_{NBI} + T_{visc}
\]

- Moment of inertia of frozen-in plasma
- Non-e.m. torques on frozen-in plasma
- Low NBI torque, Low rotation
All e.m. torques except wall torque are angle-dependent. Wall torque $\Rightarrow$ magnetic braking, mimics viscous torque.

$$I_h = \pm 2|B_R(b)|b \left( \frac{b}{r_{mn}} \right)^m \frac{1}{m\mu_0}$$

$$T_{wall} = -\frac{2\pi R B_R(b) r_{mn}}{\mu_0 b} \left[ \frac{r_{mn}}{b} \right]^{2m-1} \frac{\Omega \tau}{1 + (\Omega \tau)^2}$$

$$T_{EF} = -\pi^2 R^2 m a \frac{a}{r_{mn}} I_{EF} B_R(a) \sin[n\phi(t)]$$

$$T_{RMP} = -\pi^2 R^2 m b \frac{b}{r_{mn}} I_{RMP} B_R(b) \sin[n\phi(t) - n\phi_{RMP}(t)]$$

$$T_{TM} = -\pi^2 R^2 m \sum_{m',n'} \frac{r_{m'n'}}{r_{mn}} \sin[n\phi(t)] I_{m'n'} B_R[r_{m'n'}]$$

- Wall torque decelerates rotating island
- $T_{wall} \rightarrow 0$ as $\Omega \rightarrow 0$
- EF, RMP and other TMs cause final locking
- Final phase minimizes potential energy of multipole-multipole system (generalization of compass in terrestrial field)
Inertia of and torques on partly frozen-in plasma

- Note: here $\Omega$ is plasma rotation, not mode rotation!
- Non-rigidity

Coupled rotation-stability problem
- Growth/decay affects locking/unlocking
- Rotation $\Rightarrow$ stabilization by rotation shear, effect of rotating wall, ...

Original model for RWM [Fitzpatrick 02] can be adapted to NTM

+ other torques/l

Single-fluid momentum equation + eq. for flux evolution (at island, wall & coils) have several advantages

$$\nabla \times \vec{r} \times \dot{\vec{r}} = \sum_{i} \vec{t}_{i} + \nabla \times \vec{\omega} \times \vec{r}$$

Or non-linear generalization

$$\frac{d\hat{\Omega}}{dt} + \nu_{*}(\hat{\Omega} - \hat{\Omega}^{(0)}) = -\nu_{*}\hat{\Omega} \cdot \vec{\omega}$$

$$\frac{d^2\Psi_{a}}{dt^2} + (\nu_{*} - 2i\hat{\Omega} \cdot \vec{\omega}) \frac{d\Psi_{a}}{dt} + [(1 - \kappa)(1 - md) - \hat{\Omega}^2] \Psi_{a} - iv_{*}\hat{\Omega} \cdot \vec{\omega} \Psi_{a} = \sqrt{1 - (md)^2} \Psi_{w}$$

$$S_{*} \frac{d\Psi_{w}}{dt} + (1 + md)\Psi_{w} = \sqrt{1 - (md)^2} \Psi_{a} + 2md\Psi_{c}$$
Locked islands cool plasma edge mostly by convection
Locked islands cool plasma edge mostly by convection

F.C Schüller, PPCF 1995
Nearly all JET disruptions eventually exhibit Mode Locking

P. De Vries et al., NF 2011
About a quarter of DIII-D disruptions is due to LMs with rotating precursors

- Study performed on shots 122000 to 159837 (2005 to 2014)

(a) Survey of 22511 plasma discharges

- Shots with IRLM
  - excluded IRLM
  - non-disruptive IRLMs
  - disruptive IRLMs

- Shots without IRLM
  - disruptions without LMs
  - normal discharge
  - 2/1 rotating NTMs

(b) Survey of 16123 discharges of $\beta_N > 1.5$

- Shots with IRLMs
  - excluded IRLM
  - non-disruptive IRLMs
  - disruptive IRLMs

- Shots without IRLMs
  - disruptions without LMs
  - normal discharge
  - 2/1 rotating NTMs

- 18% of disruptions due to IRLMs
- 28% of disruptions with $\beta_N > 1.5$

- Fraction due to LMs without rotating precursors ("born locked modes") unknown, left as future work
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Locked overlapping islands cause edge thermal collapse. Sometimes plasma recovers (minor disr.)…

- TS and ECE at different toroidal locations allow simultaneous profile measurements at O-point and close to X-point
- Collapse is axisymmetric
...and sometimes it does not (thermal quench, current quench, major disruption)
Nonlinear MHD simulations show that initial 3/2, 2/1, 3/1 and 4/1 islands grow, overlap and stochasticize B
Energy loss is a combination of conduction, convection and radiation

1. Total loss of \(\sim 32\) kJ estimated using kinetic EFITs

2. \(\sim 10\) kJ of energy measured by divertor infrared camera

3. \(25 \pm 5\) kJ of energy measured by bolometers, localized in divertor

Divertor infrared (IR) camera
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Example of an initially rotating locked mode (IRLM)

1. \(m/n = 2/1\) rotating mode

2. Mode locks

3. Exists as locked mode
   - Few to thousands of milliseconds
   - Referred to as **survival time** for disruptive IRLMs

4. Disrupts or...
   ...ceases to be a locked mode
   - decays
   - or spins up

---

(a)

![Disruption](image)

(b)

![Frequency](image)
66% of 2/1 NTMs rotating at 2 kHz will lock in 45 ± 10 ms

- **Slow down time** = time between 2 kHz rotation and locking

- Indication of time available to prevent locking

- Larger $T_{wall}$ results in shorter slow-down time
LMs “survive” 270 ± 60ms before causing a disruption. Survival correlates inversely with proximity to edge.

- **Survival time** = time between locking and disruption
- 66% of disruptive modes terminate between 150 to 1010 ms

![Histogram and Scatter Plot](image-url)
Long survival gives time to safely ramp discharge down
From 100 to a few milliseconds before the thermal quench, the $n=1$ field typically grows

- **(a)** Most IRLMs show increasing $n=1$ field within 100 ms of disruption (5 random IRLMs)
- **(b)** Distributions of $n=1$ field shift higher as disruption approached
- **(c)** Median of (b) grows exponentially in last 50 ms
- Preliminary results suggest $m$ is often even during growth
IRLM disruptivity scales strongly with normalized $q=2$ radius $\rho_{q2}$ (fixing $q_{95}$), and weakly with $q_{95}$ (fixing $\rho_{q2}$).

(a) In 1D projections (blue histograms), IRLM disruptivity appears to depend on both $\rho_{q2}$ and $q_{95}$

(b) Fixing $\rho_{q2}$ shows that IRLM disruptivity scales weakly with $q_{95}$

(c) Fixing $q_{95}$ shows IRLM disruptivity depends strongly on $\rho_{q2}$
Bhattacharyya Coefficient informs on best and worst separators

**Best performing**

For discrete probability distributions $p$ and $q$ parameterized by $x$, the BC value is given by,

$$BC = \sum_{x \in X} \sqrt{p(x)q(x)}$$

- $BC=0$: $p$ and $q$ do not overlap
- $BC=1$ means $p$ and $q$ are identical (completely overlapping)

**Poor separation**

(solid 100 ms prior to disruption, dotted is 20 ms prior)
IRLM disruptions might be explained by $\Delta'$ becoming marginal, or unstable, as a result of the increasing $l_i$.

Theoretical stability limit for tearing mode onset [Cheng, Furth, Boozer PPCF 1987]
- Limit for IRLM disruptions in DIII-D
- Limit for high-density disruptions in JET [Wesson, NF 1989]

Fig. 4 — The range of permissible internal inductance $\frac{l_i}{2}$ as a function of $q(a)$ for $q(0) = 1.01$ is contained by a jigsaw boundary. The maximum $\frac{l_i}{2}$, which corresponds to a uniform current profile up to $r/a = [q(0)/q(a)]^{1/2}$, is also shown. Steady-state data from TFTR operations are found to fall inside the permissible domain.
$l_i/q_{95}$ and $d_{\text{edge}}$ can be used for disruption prediction

<table>
<thead>
<tr>
<th>Condition with IRLM</th>
<th>Missed disruptions (%) at 100 [20] ms</th>
<th>False alarms (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_i/q_{95} &gt; 0.28$</td>
<td>6 [6]</td>
<td>13</td>
</tr>
<tr>
<td>$d_{\text{edge}} &lt; 9 \text{ cm}$</td>
<td>6 [4]</td>
<td>14</td>
</tr>
<tr>
<td>None (i.e. all LMs assumed disruptive)</td>
<td>0 [0]</td>
<td>29</td>
</tr>
</tbody>
</table>

Graph showing $B_R$ and $l_i$ over time with disruptive and non-disruptive markers.
Some LMs self-stabilize through minor disruptions. Typically $q_{\text{min}} > 1.2$ and $q_0 > 2$ (Double 2/1 LM)

Classically stable. Change in pressure profile makes it neoclassically stable too?

- "Hiccup" in $I_p$
- $q_0$ drops at minor disruption
- Significant drop in $\beta_N$
- Beams appear in feedback
- $I_i/q_{95}$ below empirical disruption limit
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- LM control by **static** magnetic perturbations & **cw** ECCD
  
  - Motivation for Liquid Metal (LM) Control
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Control-coils, magnetic diagnostics and ~3MW of steerable Gyrotron power were used at DIII-D.
Magnetic steering aligns locked mode O-point to stabilizing ECCD
Static applied RMP make Locked Mode O-point accessible to stabilizing ECCD

- (a) Magnetic island decelerates and locks
- (b) No stabilization (no ECCD)
- (c) Locking to controlled phase
- (d) Magn. perturbations applied
- (e) 2/1 island, q=2 surface
- (f) Disruption

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DIII-D National Fusion Facility
Locked-mode-controlled discharges do not lose H-mode, or rapidly recover it.
Incomplete recovery of pre-locking confinement is probably due to ECCD and RMPs still on.

Best Disruption Avoidance should maintain high fusion gain $Q$. 
\( \beta_N \) is recovered after locked mode suppression.

**Locked mode stabilized:**
- High \( \beta \) and no disruption

**Locked mode not stabilized:**
- Disruption at \( \beta \sim 1.7 \)

ECCD at \( q=2 \) prevents reappearance of 2/1, whether locked or rotating.
• Motivation for Locked Mode (LM) Research - Relevance to disruptions
• How LMs initiate thermal quenches
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• LM control by rotating magnetic perturbations & modulated ECCD

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Modeling effect of rotating RMPs on locked or nearly-locked mode

\[ I \frac{d^2 \phi}{dt^2} = T_{wall} + T_{EF} + T_{RMP} + T_{TM} + T_{visc} + T_{NBI} \]

E.M. Torques on Island

Other Torques

Simplified equation of motion

\[ I \frac{d^2 \phi}{dt^2} = T_{wall} + T_{EF} + T_{RMP} \]

Smooth entrainment

\[ \theta = T_{wall} + T_{RMP} \]
Entrainment can be lost due to failure of applied torque to counteract braking torque from the wall at high frequency.

Max frequency increases with coil current and decreases with island width.
Loss of entrainment is more complicated than loss of torque balance

- Entrainment lost at different times and frequencies in similar discharges.  
  - Possibly due to MHD events.

- While it lasts, it avoids disruptions w/o using ECCD
Magnetics array analysis and ECE diagnostic confirm entrainment and spin-up of 2/1 mode

- \( m/n = -2/1 \) mode tracks l-coil frequency

- Entrainment frequency is modulated by EF on sub-period timescale (not shown)
Improved confinement: edge pedestal forms during entrainment.

At entrainment <

Electron density ($10^{19}$ m$^{-3}$)

- 2240 ms
- 2340 ms

Electron temperature (keV)

- 0
- 1

At loss of entrainment >

Electron density ($10^{19}$ m$^{-3}$)

- 3260 ms
- 3340 ms

Electron temperature (keV)

- 0
- 1
5 tokamaks, 2 spherical tokamaks, 2 RFPs and a helical device are involved in WG-11

Different Machines
- Sizes
- Aspect ratios
- Elongations
- Wall times

Different Coil sets
- Internal or external
- Narrow or broad in angular spread
- Dense or sparse arrays
- Partial/full toroidal/poloidal coverage
ITER 2/1 mode entrained by external coils

- **coils:**
  - External coils: 3 sets of 6
  - Internal coils: 3 sets of 9
- **major radius:** 6.2 m
- **wall time:** 188 ms
- **density:** $7.2 \times 10^{19} \text{ m}^{-3}$
- **$B_t$:** 5.3 T

Larger island results in stronger torque
ITER model – NTM slows and locks in about 7 seconds

ITER treated with 2 walls:
1) vacuum vessels
2) tiled Be first wall

5 cm island slows from 420 Hz and locks in 7 seconds

Agrees with La Haye NF2009

5 Hz entrainment with 10 kA in external coils
Decelerating island can be “preemptively entrained” by rotating fields applied in feed-forward.
Proportional-integral controller controls LM phase in feedback with LM phase measurements

\[ \phi_{\text{error}} = \phi_{\text{ref}} - \phi_{\text{mode}} \]

\[ \phi_{\text{correction}} = \text{PI control} (\phi_{\text{error}}) \]

\[ \phi_{\text{RMP}} = \phi_{\text{mode}} + \phi_{\text{corr.}} \]

limit to \( \phi_{\text{mode}} \pm 90^\circ \) for max torque

applied to coils
Phase controller locked mode where desired and entrained it at 20 Hz as desired.
Different phasing gives different behavior. Deposition slightly outside $q=2$ location.
Amplitude feedback can prevent locking and sustain NTM rotation at 15-60 Hz

Mode rotates at ~15 Hz

Feedback settings:
- Low-pass filter, $\tau_p=40\text{ms}$
- Gain $G_p=60$
Locked modes can also be controlled non-magnetically, or w/o ECCD

- Increase NBI torque → Stabilization by rot.shear or rot.wall
- Drop in power (NBI and ECH) → Reduce $\beta$ → Neoclassical stability
- Full $I_p$ ramp down → Safe shutdown
- Partial $I_p$ ramp down → Reduce $q_{95}$. Increase $d_{edge}$, $l_i/q_{95}$
- Change in shape → Affect stability & rotation
- Some/all of the above
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Why study the MHD of liquid metals?

- Outer core of Earth is liquid Fe
- Geodynamo B protects life from Solar wind and cosmic rays
Adaptive optics with liquid mirrors?
Technological and medical applications of liquid metals

3D printing

Reconfigurable antennas
Tunable metamaterials
Flexible electronics
Nanomedicine
Metallurgical, nuclear, aerospace applications

Cast & flow control

Recovery of precious & toxic spill

Coolants in fission reactors.

Refractory walls for furnaces?

Rockets?
Liquid metal walls

1. Reduce impurities and recycling [≪ 1mm thick, 1mm/s to 1cm/s]
Liquid metal walls

1. Reduce impurities and recycling [≪ 1mm thick, 1mm/s to 1cm/s]

“Thick” walls

2. Remove heat [~1m, 1mm/s (turbulent) to 1m/s (laminar)]

3. Attenuate neutrons [~1m, 1mm/s (turbulent) to 1m/s (laminar)]

4. Increase survivability to disruption

5. If rotating, they stabilize the plasma → higher plasma $\beta$ [~1cm, >10m/s]

Here: [1-10 mm, 10-60 cm/s]
Liquid walls will tend to be uneven

- **Instabilities**
  - Rayleigh-Taylor
    - 1-100 cm, 13-130 ms
  - Kelvin-Helmholtz
    - >1 cm, \(\lesssim 3\) ms

- **Turbulence**

[Image: Narula 2006]
Liquid walls will tend to be uneven

- **Instabilities**
  - Rayleigh-Taylor
    - 1-100 cm, 13-130 ms
  - Kelvin-Helmholtz
    - >1 cm, $\lesssim$3 ms

- **Turbulence**

- **Non-uniform forces**
  - Non-axisymmetric “error” fields
  - Inhomogeneous temperature $\rightarrow$ inhomogeneous...
    - ...resistance $\rightarrow$ current $\rightarrow$ TEMHD
    - ...viscosity $\rightarrow$ shear-flow, convection
    - ...density $\rightarrow$ convection
  - Modes in plasma

[Narula 2006]
LM becomes uneven under effect of time-varying non-uniform field, fast flow and solid wall roughness

Link: https://www.youtube.com/watch?v=oXp4JsFWqt0
Liquid walls will need to be stabilized

Otherwise, they could

1. “bulge” and interact with plasma
   - Contaminate it
   - Cool it
   - Act as limiter
   - Disrupt it

2. “deplete” and expose substrate to heat and neutrons, and plasma to less benign plasma-facing material
   - Increased sputtering, erosion, recycling, Tritium retention...
Of forces considered, only $jxB$ are rapidly, locally adjustable

To sustain the flow:

- Gravity
- Electromagnetic forces
- Magnetic propulsion ($\nabla B_T$)
- Thermoelectric drive ($\nabla T$)

For adhesion to substrate:

- Capillary forces
- Electromagnetic forces
- Centrifugal
Three approaches to electromagnetic stabilization of liquid metal flows

• Passive stabilization (B only)
• Active stabilization (jxB)
• Feedback stabilization
Three approaches to electromagnetic stabilization of liquid metal flows

- Passive stabilization (B only)
- Active stabilization (jxB)
- Feedback stabilization
“Frozen-in” field from rotating permanent magnets propels liquid metal

- CNC-machined from single block
- Duct of constant area but variable shape

Permanent magnets
Ferromagnetic core
PLA plastic, 3D printed
Slots for Fe laminations

Output
Input
Free-surface flow in tiltable "tile" exposed to B

- B from external coil
- Pivot. Inclination can be varied (floor, wall, ceiling)
- Slot for electrodes

LM flow in
LM flow out
Strong B is stabilizing, even in absence of j

\[ B = 0 \, \text{T} \quad u \approx 0.2 \, [\text{m/s}] \]

\[ B = 0.4 \, \text{T} \]
Navier-Stokes and generalized Ohm’s law
\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{v} + \mathbf{g} + \frac{1}{\rho} (\mathbf{j} \times \mathbf{B})
\]

\[
\mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})
\]

Contain a stabilizing term
\[
\frac{\sigma}{\rho} (\mathbf{v} \times \mathbf{B}) \times \mathbf{B} \text{ of order } \sigma U B^2 / \rho
\]
Strong B is stabilizing

Navier-Stokes and generalized Ohm’s law
\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{v} + \mathbf{g} + \frac{1}{\rho} (\mathbf{j} \times \mathbf{B})
\]

\[\mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})\]

Contain a stabilizing term
\[\frac{\sigma}{\rho} (\mathbf{v} \times \mathbf{B}) \times \mathbf{B}\] of order \(\sigma UB^2/\rho\)

that dominates over convective term \((\mathbf{v} \cdot \nabla) \mathbf{v}\) (ratio=44 in our exp)
and over viscous term \(\nu \nabla^2 \mathbf{v}\) \((Ha = BL\sqrt{\sigma/\mu} = 7 \cdot 10^4)\).
Velocity fluctuations are damped by effective viscous drag $\propto B^2$

Simplified Navier-Stokes

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{\rho} \nabla p + \frac{g}{\rho} + \frac{\sigma}{\rho} (\mathbf{v} \times \mathbf{B}) \times \mathbf{B}$$

- pump, thermoel. drive, magn. propulsion...
- gravity
- effective viscous drag

$$\delta v_\perp \xrightarrow{\text{Ohm}} \delta j_\perp = \sigma B \delta v_\perp \xrightarrow{\text{Lorentz}} \delta F_\perp = -\sigma B^2 \delta v_\perp / n$$

Incompressibility $\nabla \cdot \mathbf{v} = 0 \rightarrow \delta v_\parallel$ also small
Three approaches to electromagnetic stabilization of liquid metal flows

• Passive stabilization (B only)
• Active stabilization ($j \times B$)
• Feedback stabilization
jxB acts as effective gravity, stabilizing

\[ I=60 \text{ A} \]
\[ B=0 \text{ T} \]
\[ I=60 \text{ A} \]
\[ B\approx0.2 \text{ T} \]
\[ I=60 \text{ A} \]
\[ B\approx0.4 \text{ T} \]
jxB acts as effective gravity, stabilizing

\[ l = 120 \, \text{A} \]
\[ B = 0 \, \text{T} \]

\[ l = 120 \, \text{A} \]
\[ B \approx 0.2 \, \text{T} \]

\[ l = 120 \, \text{A} \]
\[ B \approx 0.4 \, \text{T} \]

Broader coverage of substrate?
Three approaches to electromagnetic stabilization of liquid metal flows

- Passive stabilization (B only)
- Active stabilization ($j \times B$)
- Feedback stabilization

For Lithium and $B = 5 \, \text{T}$, $j = 0.1 \, \text{A/cm}^2$ suffices to defy gravity.

Could be induced by modes in plasma $\rightarrow$ applied currents might need to be adjusted in f/back with thickness.
Feedback control by array of electrodes will enforce uniform thickness under more challenging circumstances.
Feedback control by array of electrodes will enforce uniform thickness under more challenging circumstances.

Similar to feedback control of plasma instabilities by coil.
**jxB actuator pushes LM**

- **I = 0 A**
- **I = 100 A**
- **I = 200 A**

Diagram showing a DC current generator with settings for ON and OFF. The liquid metal (LM) surface and electrode positions are indicated, with an arrow showing the direction of the actuator's push at different current intensities.
Local deformation is linear with applied current

- Surface Level Decrease (cm)
- Applied DC Current (A)

Offset due to surface tension
Same plate electrodes used for actuators succeeded as resistive sensors of LM thickness

Same electrodes as sensors and actuators: 
Imposing uniform resistance = imposing uniform thickness
Measurements of LM thickness were extended to a matrix of pin-electrodes.
Measurements of LM thickness were extended to a matrix of pin-electrodes.
Kirchhoff + generalized Ohm $\rightarrow m \times n$ equations to extract \textit{height} in each electrode

\[
\frac{I_{ij}}{\sigma} = \frac{V_{i,j} - V_{i,j+1}}{dy} h_{i,j+\frac{1}{2}} dx + \frac{V_{i,j} - V_{i,j-1}}{dy} h_{i,j-\frac{1}{2}} dx \\
+ \frac{V_{i,j} - V_{i+1,j}}{dx} h_{i+\frac{1}{2},j} dy + \frac{V_{i,j} - V_{i-1,j}}{dx} h_{i-\frac{1}{2},j} dy
\]

- Where \( \frac{2}{h_{i,j+\frac{1}{2}}} = \frac{1}{h_{i,j}} + \frac{1}{h_{i,j+1}} \)
- Can be rearranged as \( I = Ah \) and inverted: \( h = A^{-1}I \)
Finite poloidal or toroidal $v \times B$ introduce need for coupling with $v$ and $B$ diagnostics

\[
\frac{I_{ij}}{\sigma} = \left[ \frac{V_{i,j} - V_{i,j+1}}{dy} + (v_x B_z - v_z B_x)_{i,j+\frac{1}{2}} \right] h_{i,j+\frac{1}{2}} \, dx \\
+ \left[ \frac{V_{i,j} - V_{i,j-1}}{dy} - (v_x B_z - v_z B_x)_{i,j-\frac{1}{2}} \right] h_{i,j-\frac{1}{2}} \, dx \\
+ \left[ \frac{V_{i,j} - V_{i+1,j}}{dx} + (v_z B_y - v_y B_z)_{i+\frac{1}{2},j} \right] h_{i+\frac{1}{2},j} \, dy \\
+ \left[ \frac{V_{i,j} - V_{i-1,j}}{dx} - (v_z B_y - v_y B_z)_{i-\frac{1}{2},j} \right] h_{i-\frac{1}{2},j} \, dy
\]

- But in our case $|v \times B| \ll E$
- Also, if $v_R = B_R = 0$, then $(v \times B)_\phi = (v \times B)_\theta = 0 \rightarrow \text{no perturbation to } E_\phi$ and $E_\theta$
Measurements of LM thickness were extended to a matrix of pin-electrodes, simultaneously.
~10 ms time-resolution and ±0.5 mm precision were achieved

“Shaker” & Fast camera images →

Waves are non-linear, due to shallow liquid and large lat. oscillation

±0.5 mm noise →
Videos & papers

- [http://pl.apam.columbia.edu](http://pl.apam.columbia.edu)

- **Videos:**
  - Go to [YouTube](https://www.youtube.com) and search for ‘Volpe Group’

- **Papers:**
  - Sensors and actuators: 
    PPCF **58**, 124005 (2016)
  - Latest on sensors: 
    RSI **87**, 11D427 (2016)
  - Passive and active stabilization: 
    *Magnetohydr.*, submitted (2016)
Ongoing work: put it all together! (sensors, actuators, flow, floor, wall, ceiling)

Flow adhering to “ceiling” ($\theta=14$°)

Cylindrical wall, 90 cm long
Summary & Conclusions on Locked Modes

- Locked modes are non-rotating (growing or saturated) plasma instabilities, typically NTMs.
- Without the benefits of rotation, they grow to the point of significantly degrading confinement.
- One of the main causes of disruptions.
- Ubiquitous, also in disruptions initiated by other phenomena.
- Simple model: helical current-filaments at rational surface, subject to e.m. and non-e.m. torques.
- Advanced model: coupled single-fluid momentum eq. + flux evolution at island location and wall.
- Rotating precursor decelerates due to wall torque, and locks to resultant of EF + applied MP + other TMs.
- Even w/o precursor, above-threshold EF or below-threshold rotation leads to a bifurcation in $B_R \rightarrow$ EF penetration, born LM.
Summary & Conclusions on LMs (Locked Modes)

- Overlap of several islands locked to each other and to EF+MP → Stochastization → Enhanced convection, conduction (and radiation) → Partial thermal quench (TQ) → Full TQ → CQ
- Database analysis suggests that proximity to edge & classical stability determines LM “disruptivity”.
- Real-time monitoring of these parameters could help predicting locking.
- If locking occurs, applied MPs control LM phase, applied ECCD controls LM amplitude.
  - Static/rotating, cw/modulated, in f/fwd, two types of f/back.
  - LM stabilized in DIII-D and entrained in several devices, in agreement with modeling. 5 Hz entrainment possible in ITER.
Summary & Conclusions on LMs (Liquid Metals)

- Liquid metal walls need to be stabilized
- Was stabilized
  - Passively, by strong $\mathbf{B}$
    - Effective viscosity
  - Actively, by applied $\mathbf{jxB}$
    - Effective gravity
- Will be stabilized
  - By $\mathbf{jxB}$ optimized in real-time, in feedback with measurements of LM thickness
    - Sensors and actuators
Melting elements by a resistive furnace in lab to produce Galinstan: a) Tin, b) Indium, c) Gallium and d) Galinstan

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Galinstan (Ga, In, Sn)</th>
<th>Lithium</th>
<th>Tin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>6400 [kg/cm³]</td>
<td>5300 [kg/cm³]</td>
<td>7000[kg/cm³]</td>
</tr>
<tr>
<td>Melting Point</td>
<td>-19°C</td>
<td>181°C</td>
<td>232°C</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>17% of Copper's</td>
<td>16% of Copper's</td>
<td>14% of Copper’s</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Corrosivity</td>
<td>Very high (corrodes all the metals)</td>
<td>Very high</td>
<td>Low</td>
</tr>
</tbody>
</table>
New stainless steel pump with Fe laminations expected to yield faster flows, for centrifugal exp.

Initial test at low speed
3D-printed parts and hoses complete the partly ducted, partly free-surface setup.

Link: https://www.youtube.com/watch?v=W3DANAIdKSU
$j \times B$ force flattens LM flow. Whole solid substrate is covered, and more uniformly.
Other sensors: LIDAR, Ultrasound and Infra-red

LIDAR

- Might not work on shiny surface
- Expensive

Ultrasound

- 1D measurement
- 4D ultrasound medical imaging?

Stereo 3D IR-camera

- Resolution: 1200 x 1000 pixels
- Frames: 30 fps