Langevin Molecular Dynamics of Driven Magnetic Flux Lines

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Motivation

- Type II superconductors exhibit a second order phase transition from superconducting to normal state.
- Magnetic flux penetrates above critical field $H_{c1}$ through vortex lines - each one carries a flux quantum.
- Vortex lines movement generates dissipation.
- Pinning by (artificially introduced) defect sites - optimization.
- Complex and rich system that is accessible in experiments.
- High $T_C$ SC - interesting for technology and applications.
Elastic Line Model

After coarse graining: Vortex lines are interacting elastic lines†

\[
F_{el} = \sum_{j=1}^{N} \int_{0}^{L} dz \left[ \frac{\epsilon_1}{2} \left| \frac{d\vec{r}}{dz} \right|^{2} + \frac{1}{2} \sum_{i \neq j}^{N} V_{I}(|\vec{r}_{ij}|) + V_{D}(\vec{r}_j) \right]
\]

- Elastic energy \( \epsilon_1 \) (stiffness)
- Line interaction energy \( V_{I}(|\vec{r}_{ij}|) \propto K_0(|\vec{r}_{ij}|) \)
- Defects potential \( V_{D}(\vec{r}) \) due to pin sites
- This work: only random point defects

Discretize lines into connected particles \( \rightarrow \) simulations

LMD simulation of interacting vortex lines in clean system
→ form hexagonal lattice
Methods

**Monte Carlo**
Find steady state by performing a biased random walk on the energy landscape

- Problem: external drive enters energy - not well defined for relaxation into non-equilibrium steady-state

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**Langevin Molecular Dynamics Algorithm**
Solve the system of coupled Langevin equations

\[ \ddot{\vec{r}}_i = -\zeta \dot{\vec{r}}_i + \vec{F}(\{\vec{r}_j\}) + \sqrt{2\zeta k_B T} \vec{R}(t) \]

- Additional random force term \( \vec{\eta} \) describing fast degrees of freedom - temperature bath
- Gaussian white noise \( \langle R_i(t)R_j(t') \rangle = \delta_{ij}\delta(t - t') \)
- Problem: also not well defined for non-equilibrium (driven) systems
Time regimes

- **Transient regime**
  - Dependent on initial conditions
  - Dynamical scaling - aging
  - Time translation invariance broken
  - Need two-time quantities to characterize

- **Steady state**
  - Time translation invariance recovered
  - No dependence on initial conditions
  - All quantities stationary in thermodynamic limit
Driven system results

- 16, 32 or 64 initially straight lines placed at random positions
- 34200 randomly distributed point defects
- Driven system, allowed to relax into steady state
- Agreement between MC and LMD good
Two-time height-height autocorrelation

LMD yields similar results as previously performed MC simulations†

No defect sites

Disordered system

- Dynamical scaling - aging exponent $\approx 0.5$

- Disorder leads to glass-like relaxation

Summary

Conclusion
- Complex out-of-equilibrium system
- Important to understand vortex dynamics to optimize technological applications
- Both methods yield comparable results - complementary to each other
- LMD is much more efficient

Outlook
- Aging regime – universality/scaling
- Correlated defects
- Thin films
- Relaxation of driven systems
Thank you for your attention!

References

- D.R. Nelson and VM Vinokur *PRB* 48 13060 (1993)

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