University of St Andrews

Solar & Magnetospheric Theory Group
University of St Andrews

Resonant Absorption in Expanding Magnetic Flux Tubes

Thomas Howson

Ineke De Moortel Patrick Antolin

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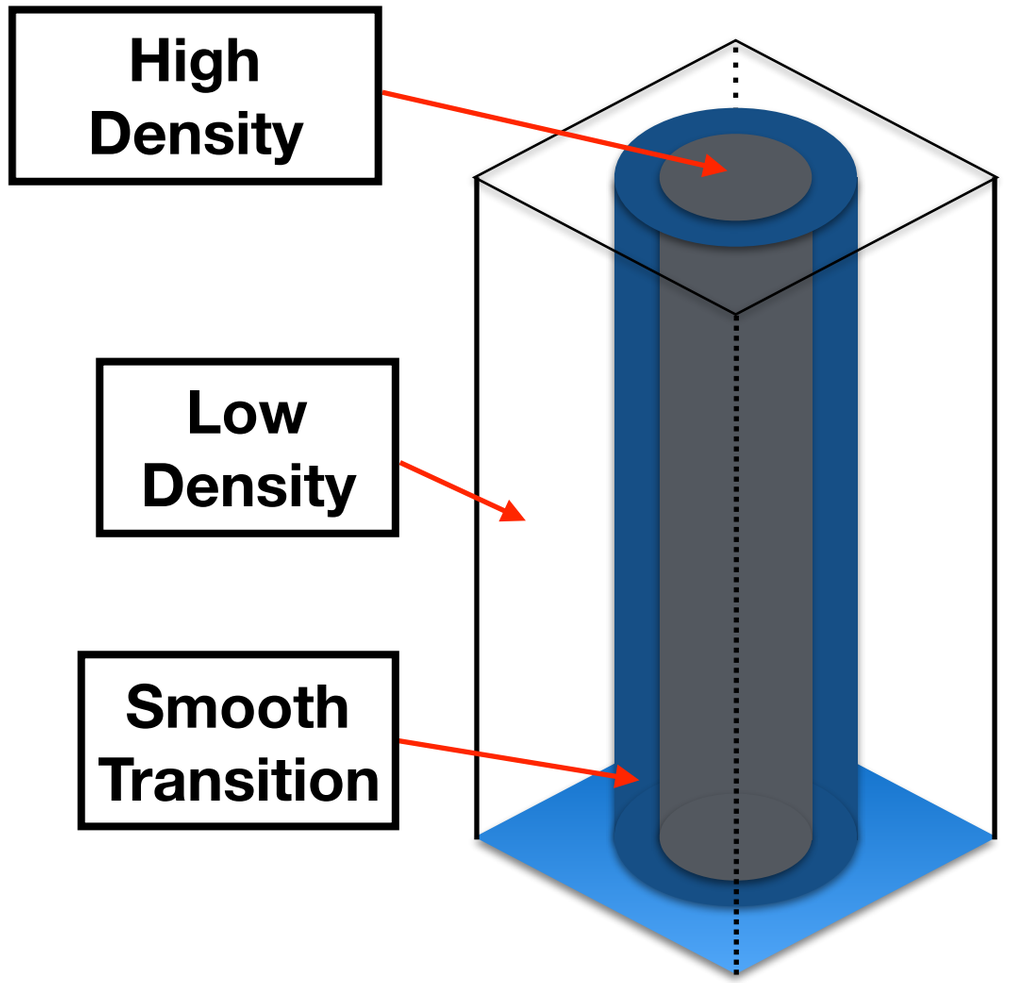
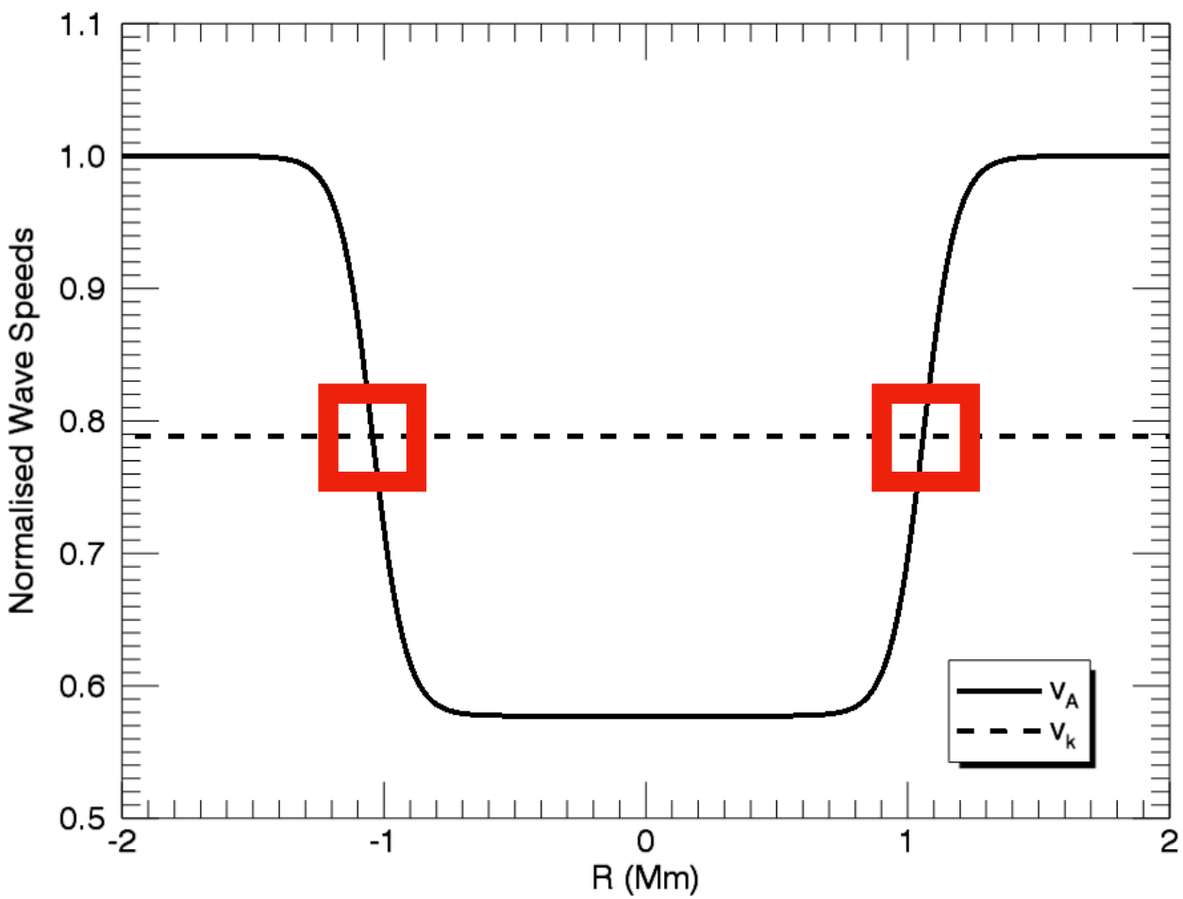
Resonant Absorption

Transverse oscillations observed to decay rapidly.

Energy transfer from kink mode to azimuthal Alfvén waves. Requires **non-uniform Alfvén frequency**.

Wave decay but no dissipation.





Assume non-uniform density.

Frequencies match when

$$\rho = \frac{\rho_e + \rho_i}{2}$$

$\Longrightarrow$ **Resonance**

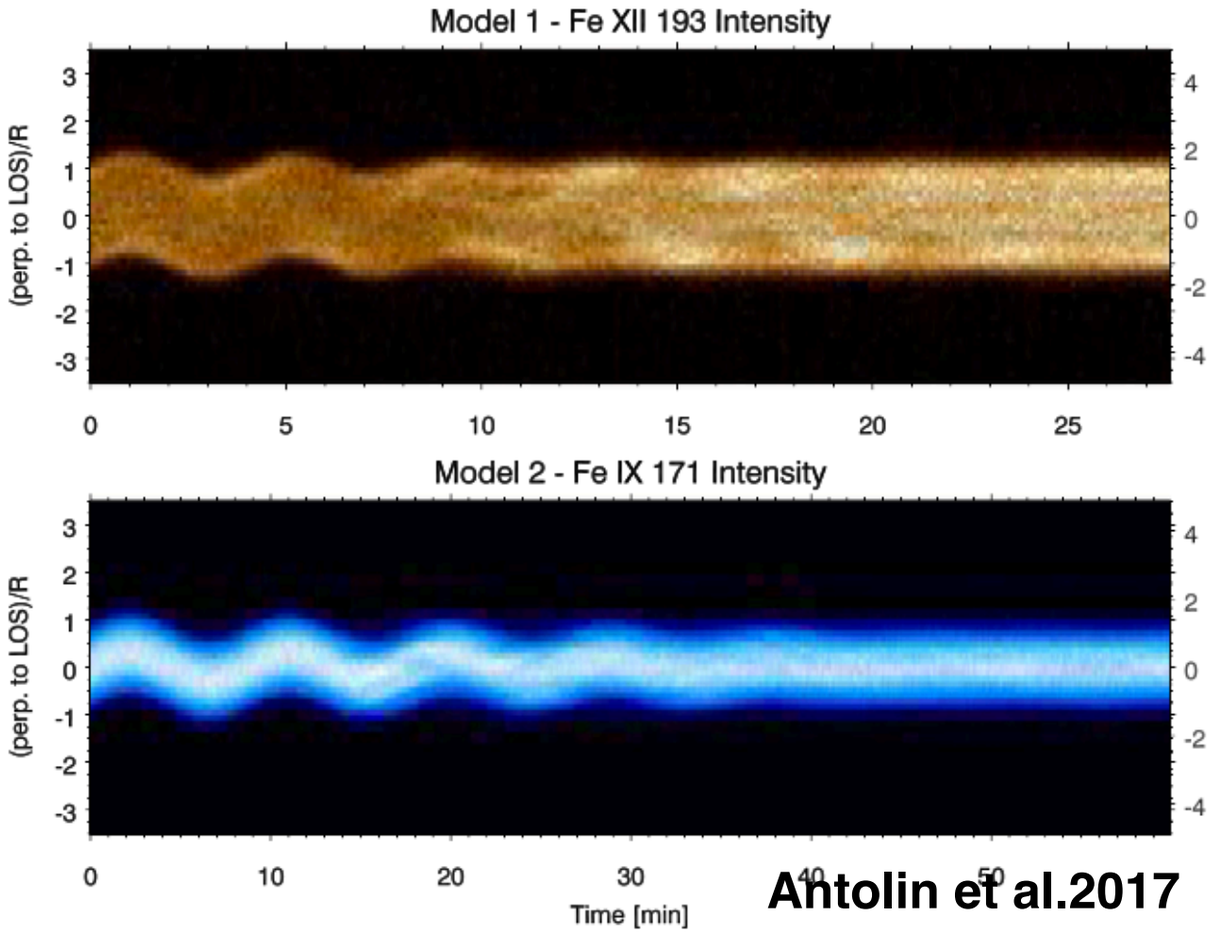
Problem:

Models of Wave Heating typically require density profiles that the heating cannot sustain (Cargill et al. 2016).

1. Density **structure destroyed by plasma cooling** and draining faster than wave energy dissipation time scales.
2. Wave heating occurs in the **‘wrong’ place** - deposits energy in regions of high density gradient rather than high density.

Plausible Solutions?

- Wave-based mechanisms are not the dominant mechanism for heating dense loops.
- Loop density structure is **not constant** through time. Turbulence (e.g. generated by dynamic instabilities’).



Antolin et al.2017

Not a solution, but a question:

How can resonant absorption proceed **without** a density enhancement?

We would like a radial gradient in the Alfvén frequency:

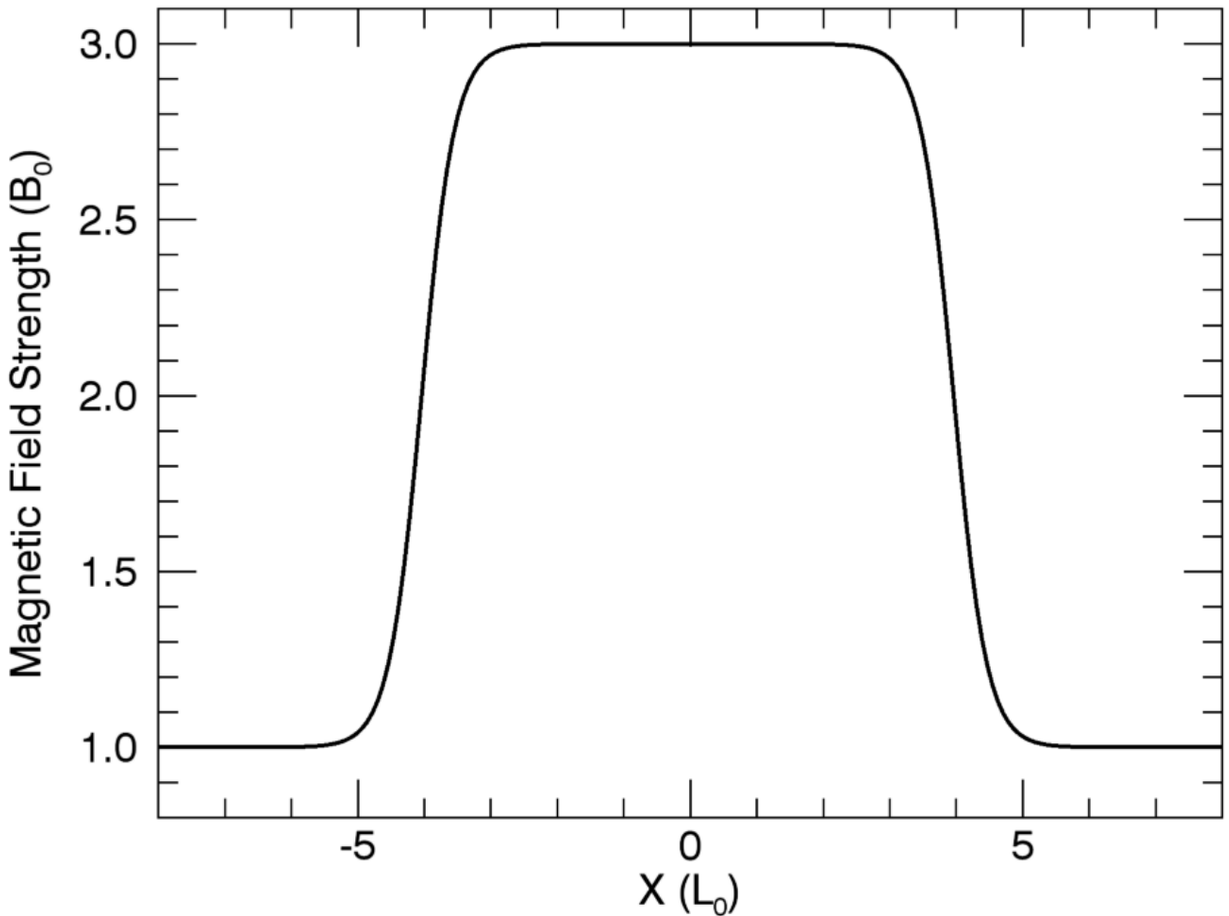
$$\omega_A = \sqrt{\frac{k_z^2 B^2}{\mu\rho}}$$

Previously we used the density to achieve this. Can we use the **magnetic field strength** (and field line length) instead?

We would like

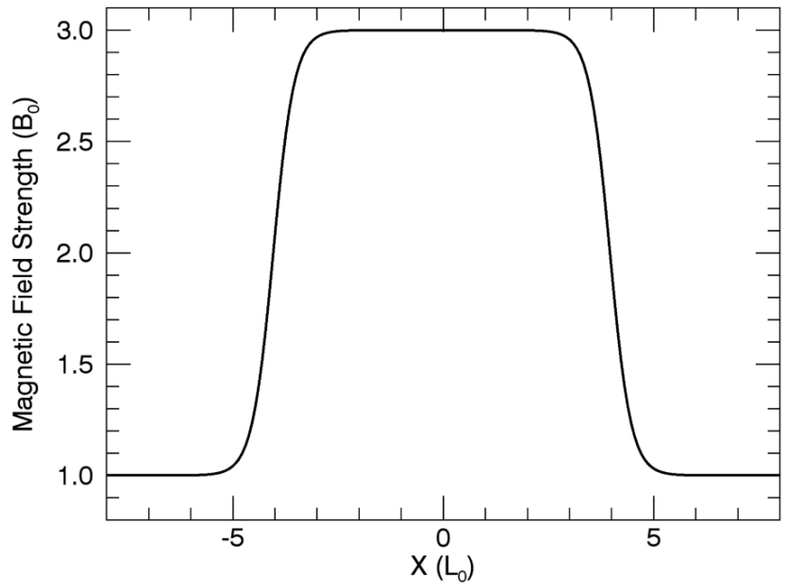
How can we balance the magnetic pressure force to form an **initial equilibrium**?

1. High external gas pressure.
2. Twisted magnetic field.
3. Allow flux tube to expand and **tension confines field enhancement**.



Relaxation to Initial Equilibrium

Pre-Relaxation



Azimuthally and vertically invariant field profile.
Uniform Density.
Uniform Temperature.

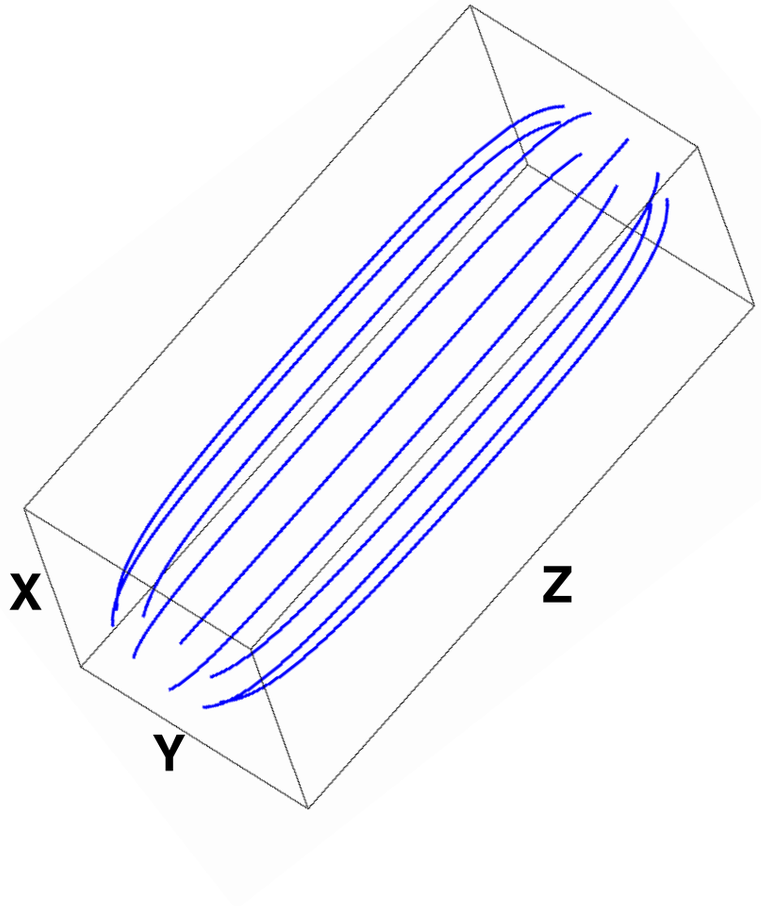
$$0.02 < \beta < 0.2$$

Loop length is 10x radius.

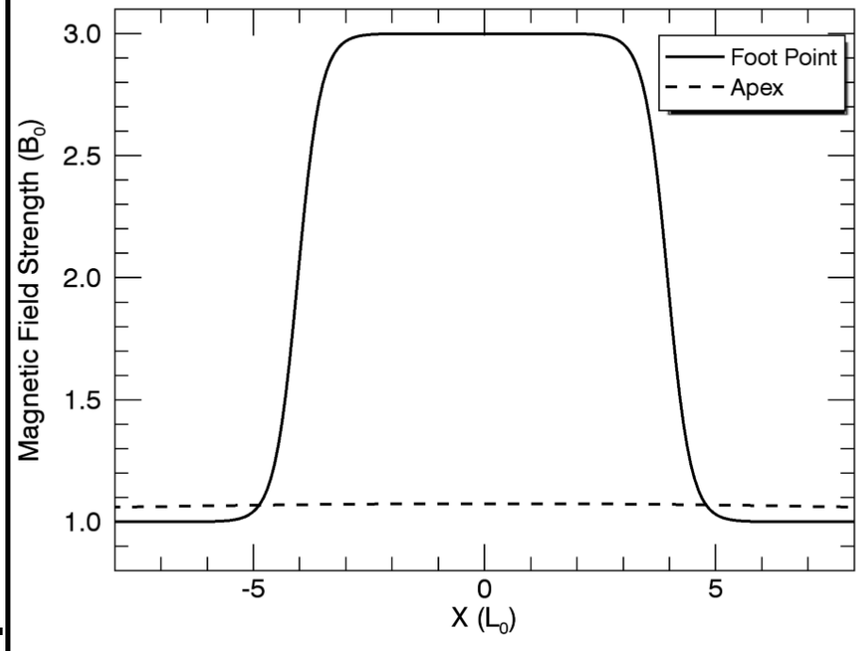
Post-Relaxation

Relax to $\mathbf{j} \times \mathbf{B} = \mathbf{0}$

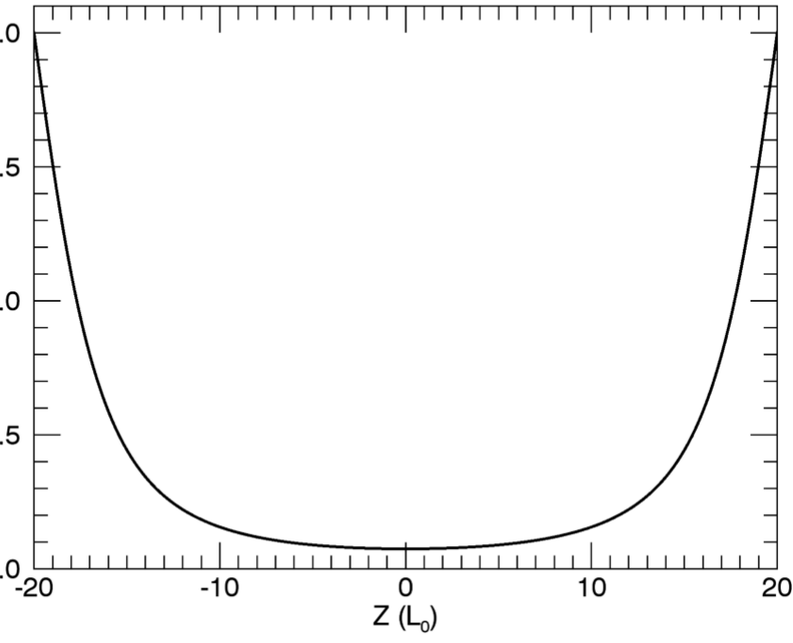
Maintain constant density and temperature during relaxation.



Field Strength



Radial Profile

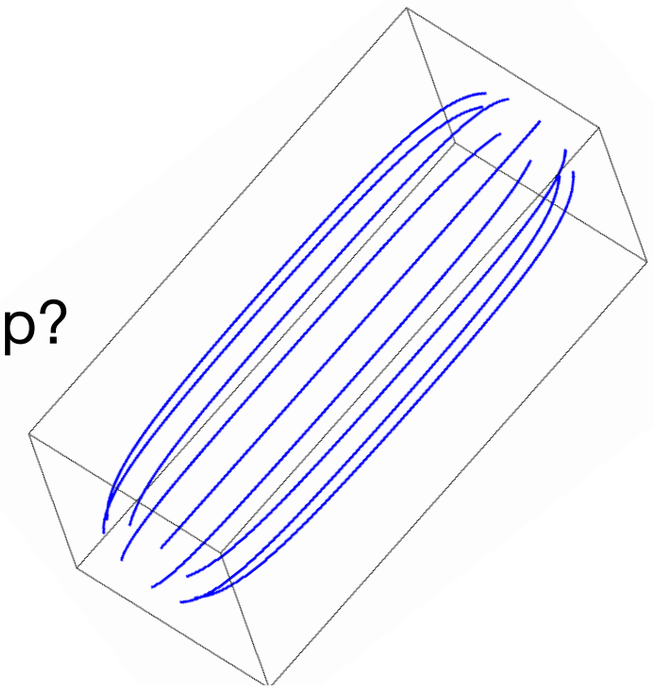


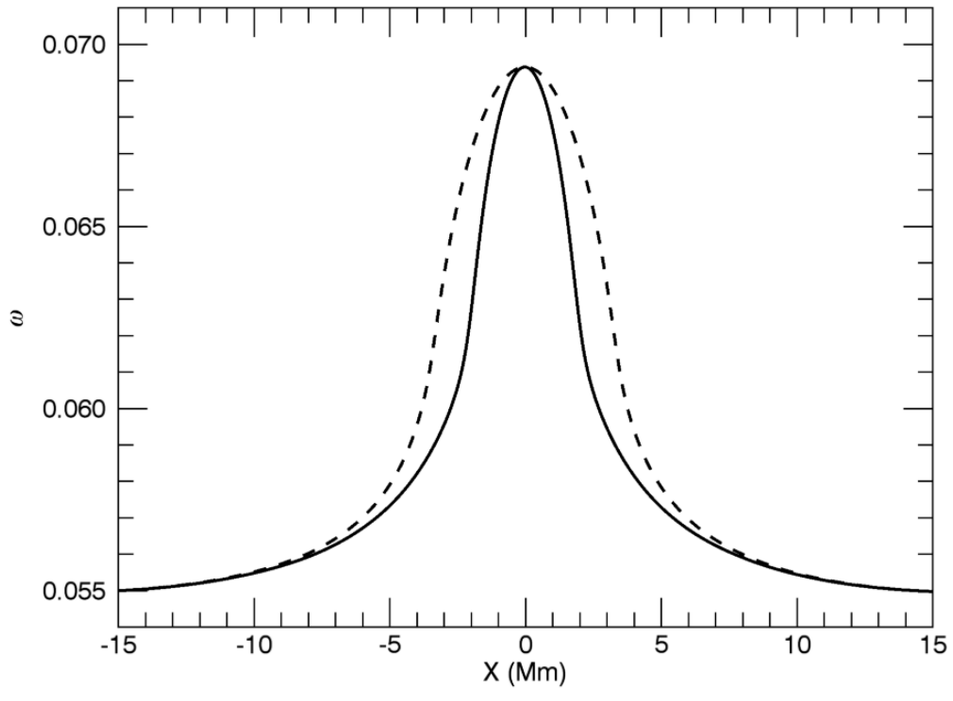
Vertical Profile

Model Comparison

Expanding Field

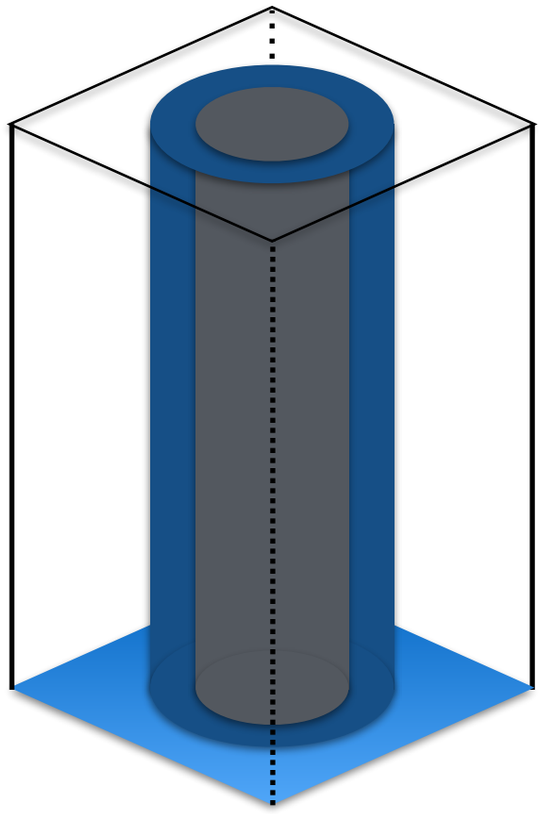
- Non-uniform along loop axis.
- Higher wave speed inside loop.
- Short - 20 Mm.
- Transition region loop?
- Not currently observable.

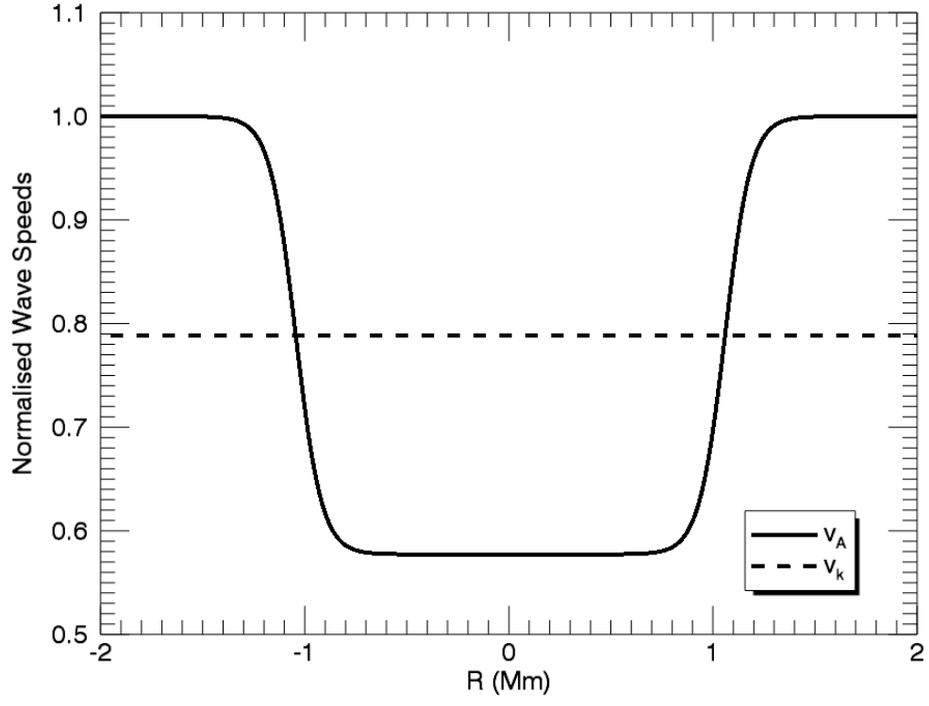




Straight Field

- Uniform along loop axis.
- High wave speed inside loop.
- Long - 200 Mm.
- Observable as a dense loop.

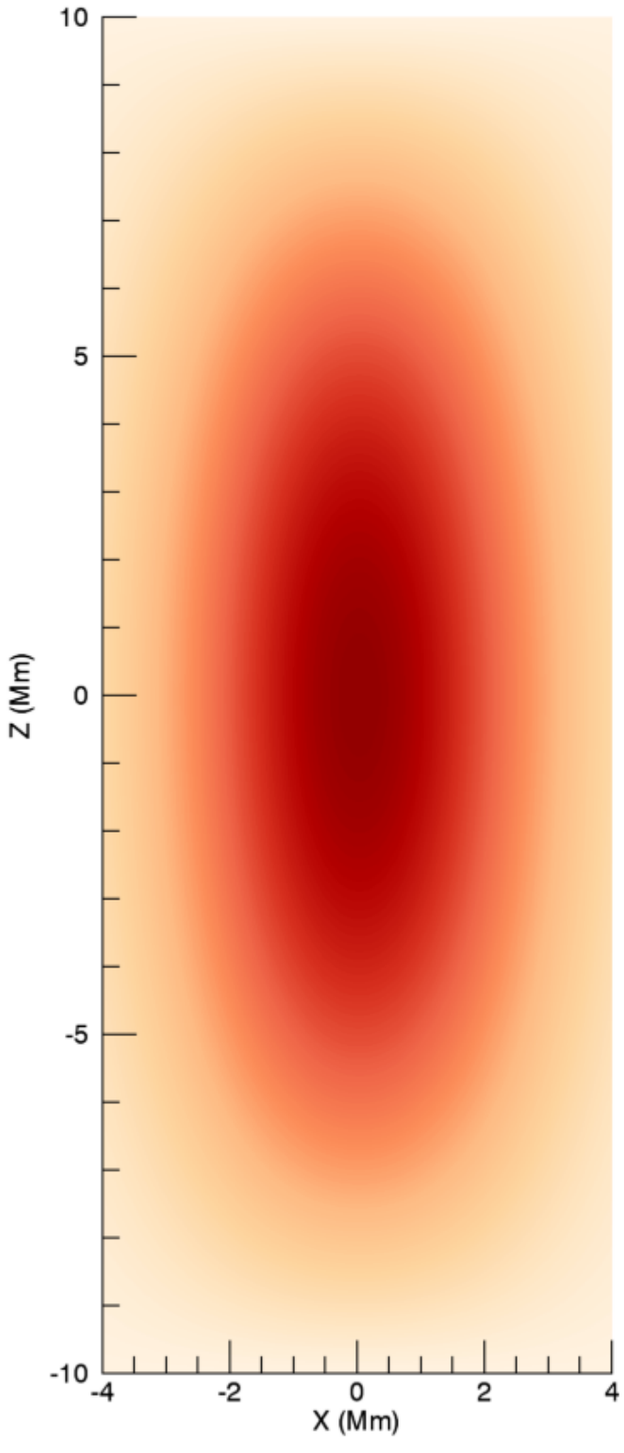


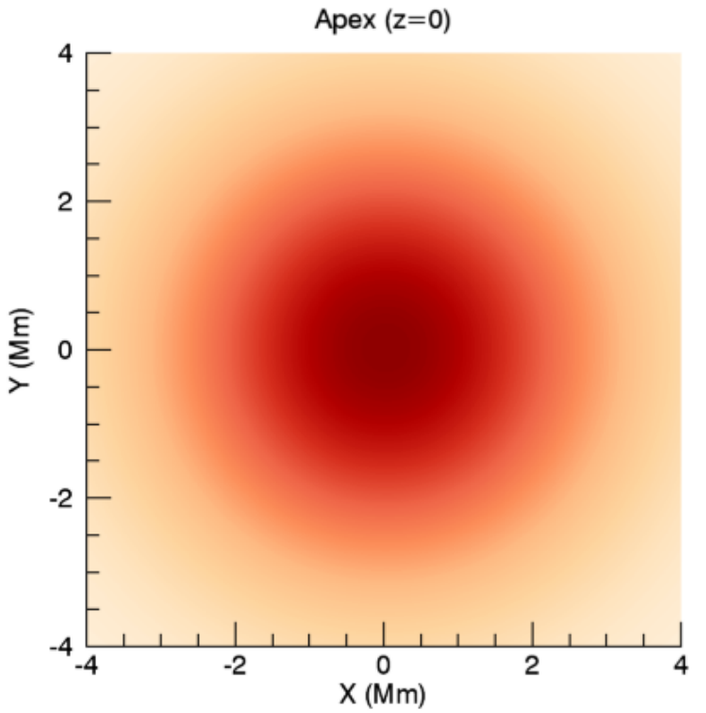


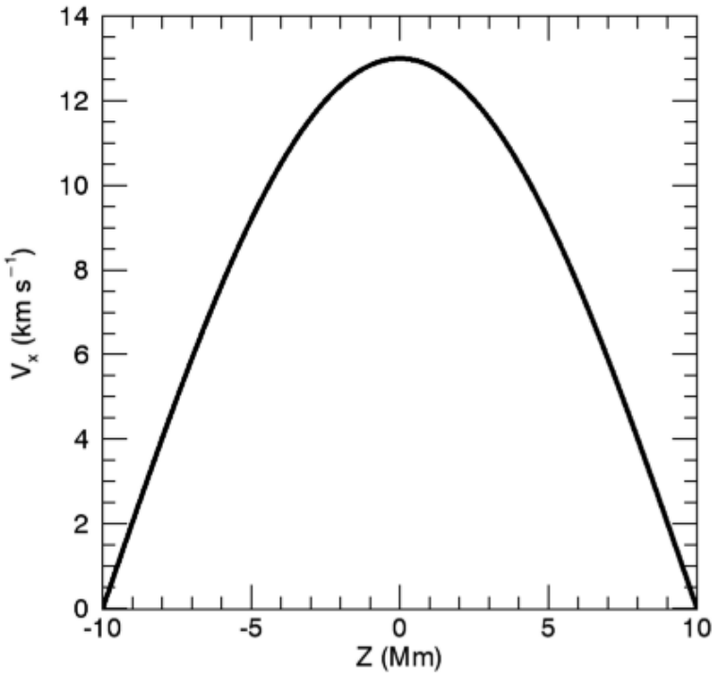
Initial Velocity Profile

How would waves in such coronal structures be excited?

- **External Pulse.**
- **Continuous driving** from foot points to generate (fundamental) standing mode (e.g. Karampelas 2017).
- **Impose a fundamental mode.**

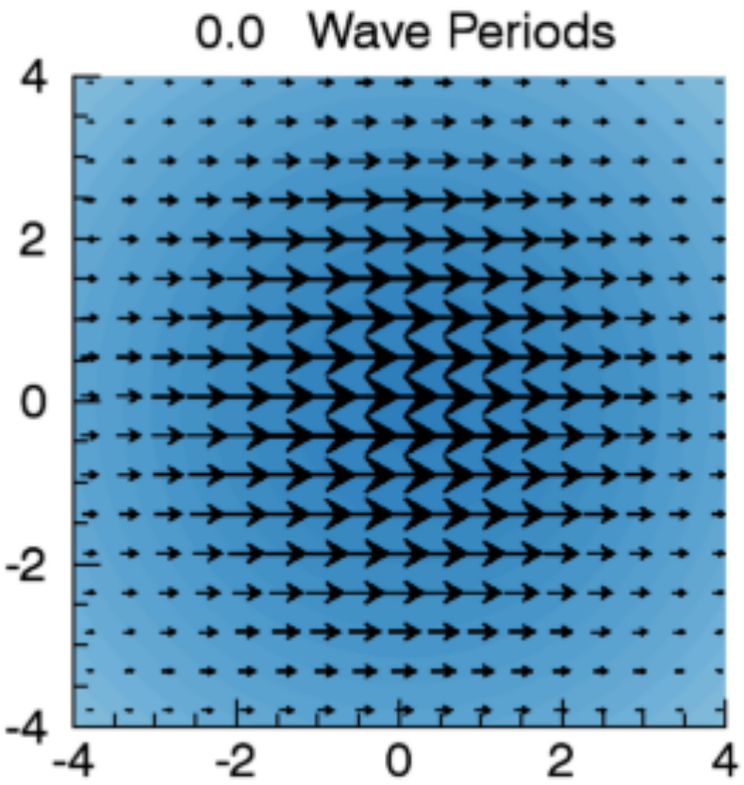




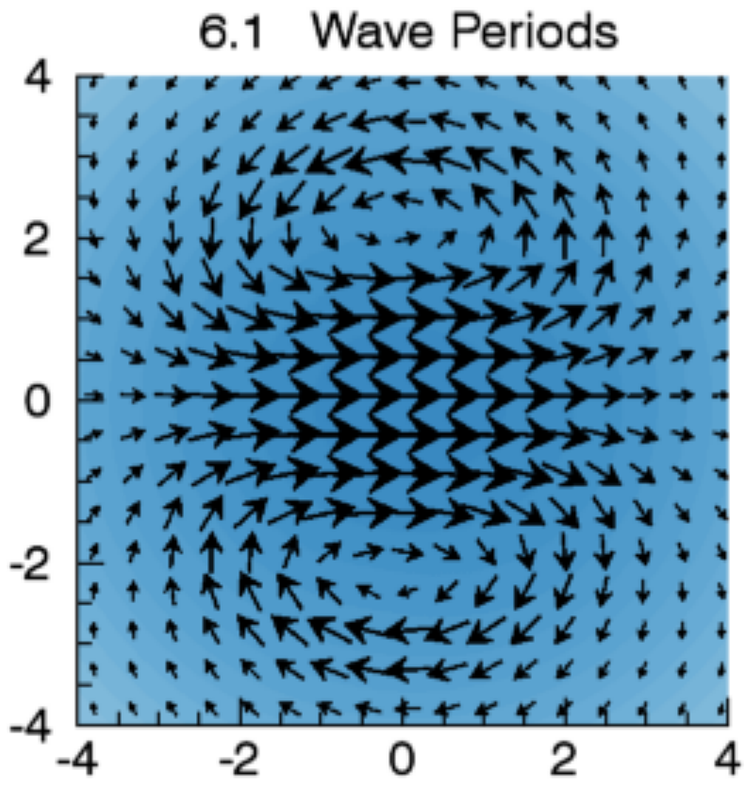


Resonant Absorption in Expanding Flux Tubes

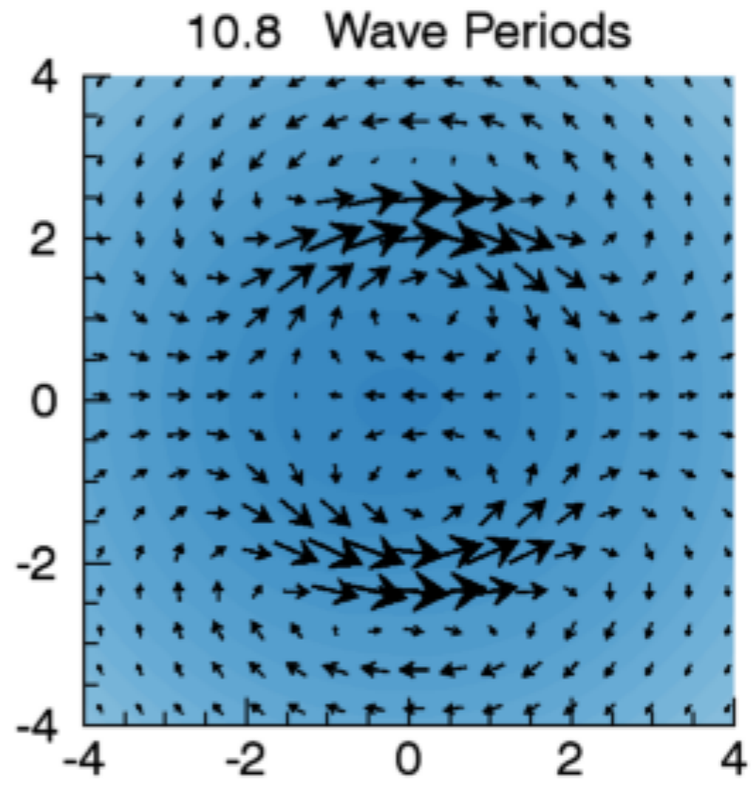
Initial Velocity



Dipole Flow



Alfvén Wave forms



Velocity field initially largest within loop's core.

Return flow forms immediately.

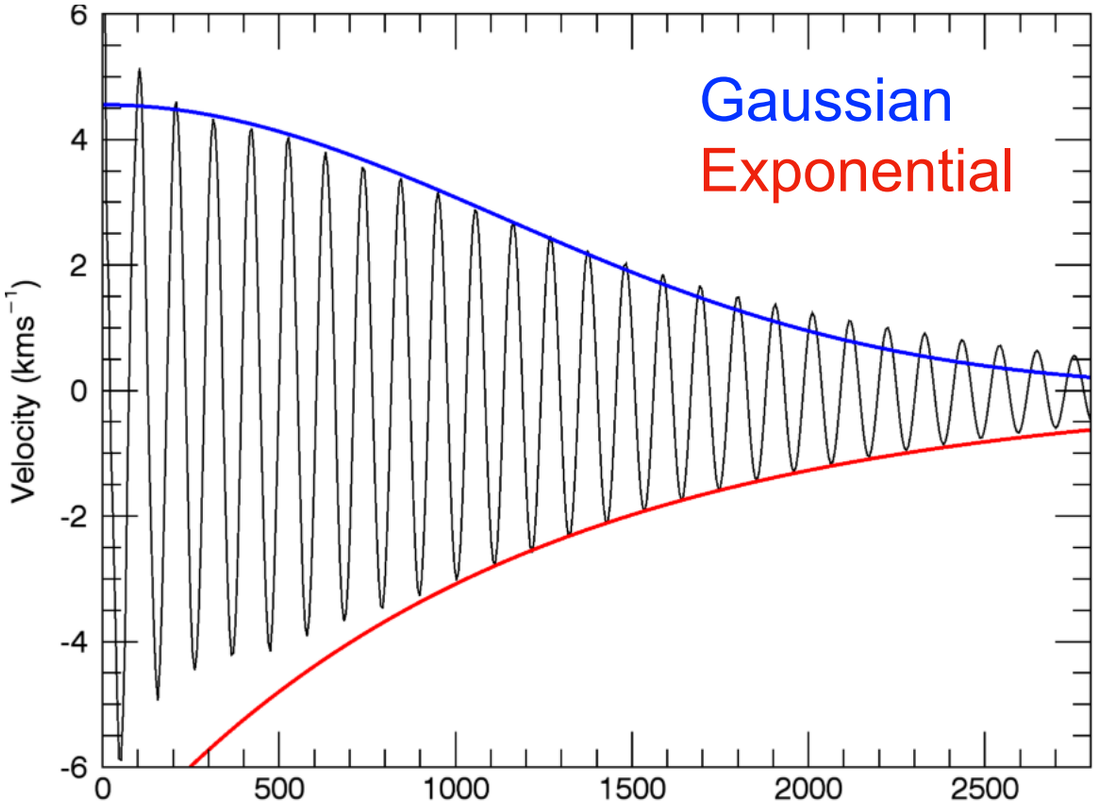
Over several wave periods, **azimuthal Alfvén wave develops** as energy is transferred from the kink mode via a **resonance**.

Kink Wave and Resonant Absorption

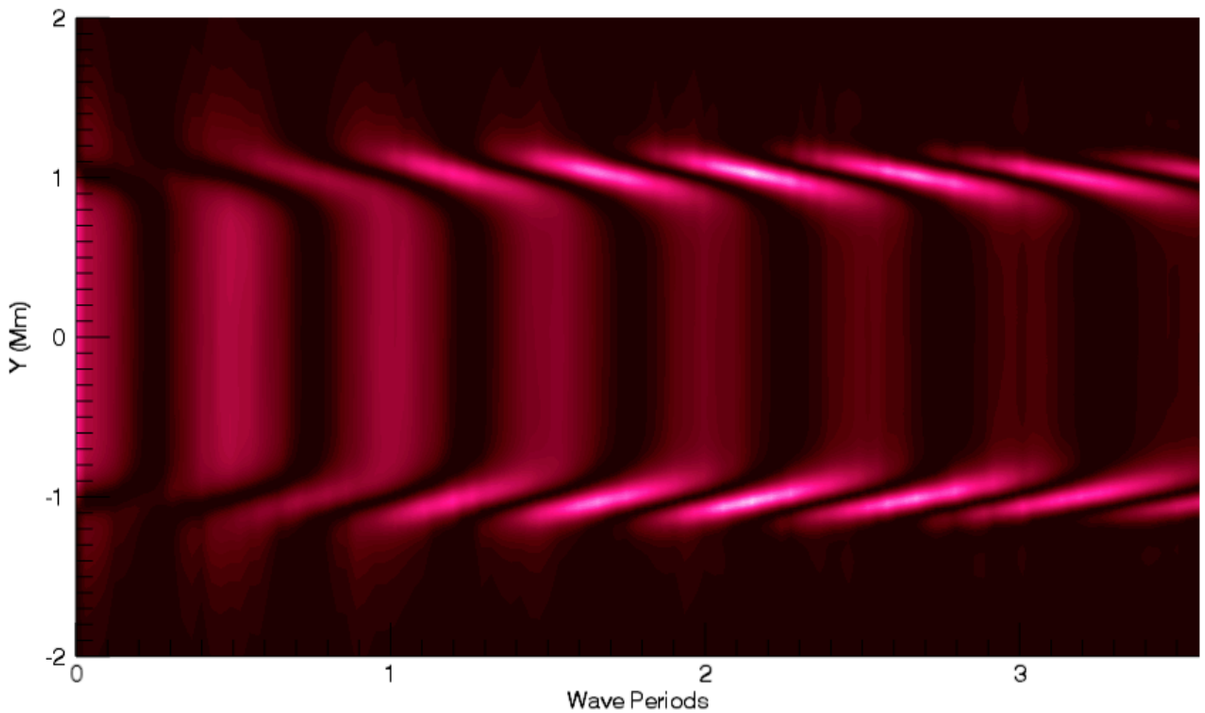
Amplitude of kink wave decays due to resonant absorption.

Initially **Gaussian decay (blue)**.
Later **exponential decay (red)**.

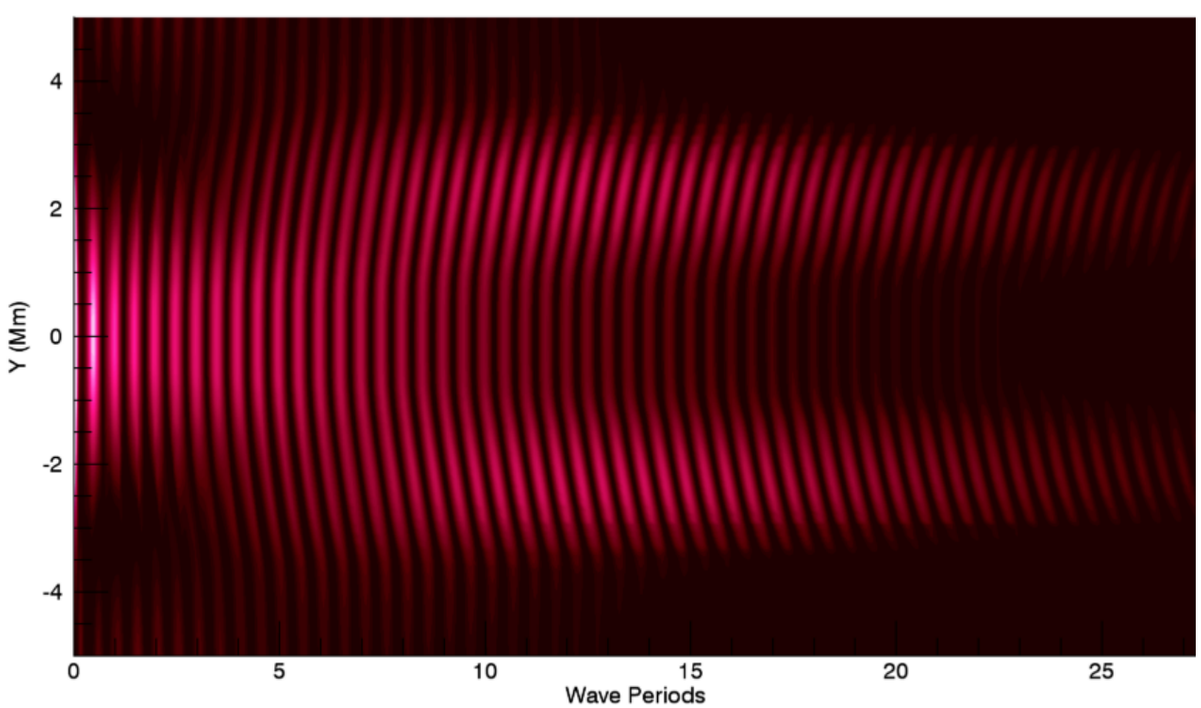
Slower energy transfer than in straight field case.



Straight Field



Expanding Field

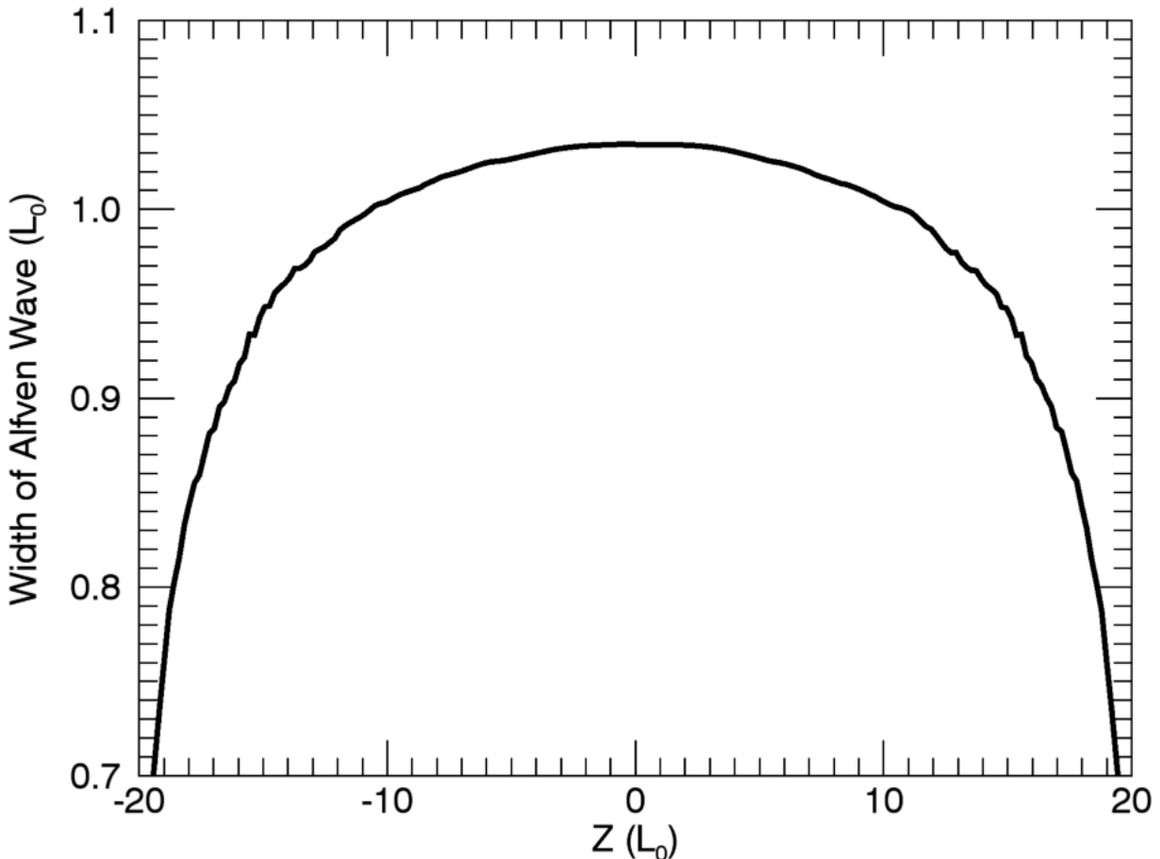


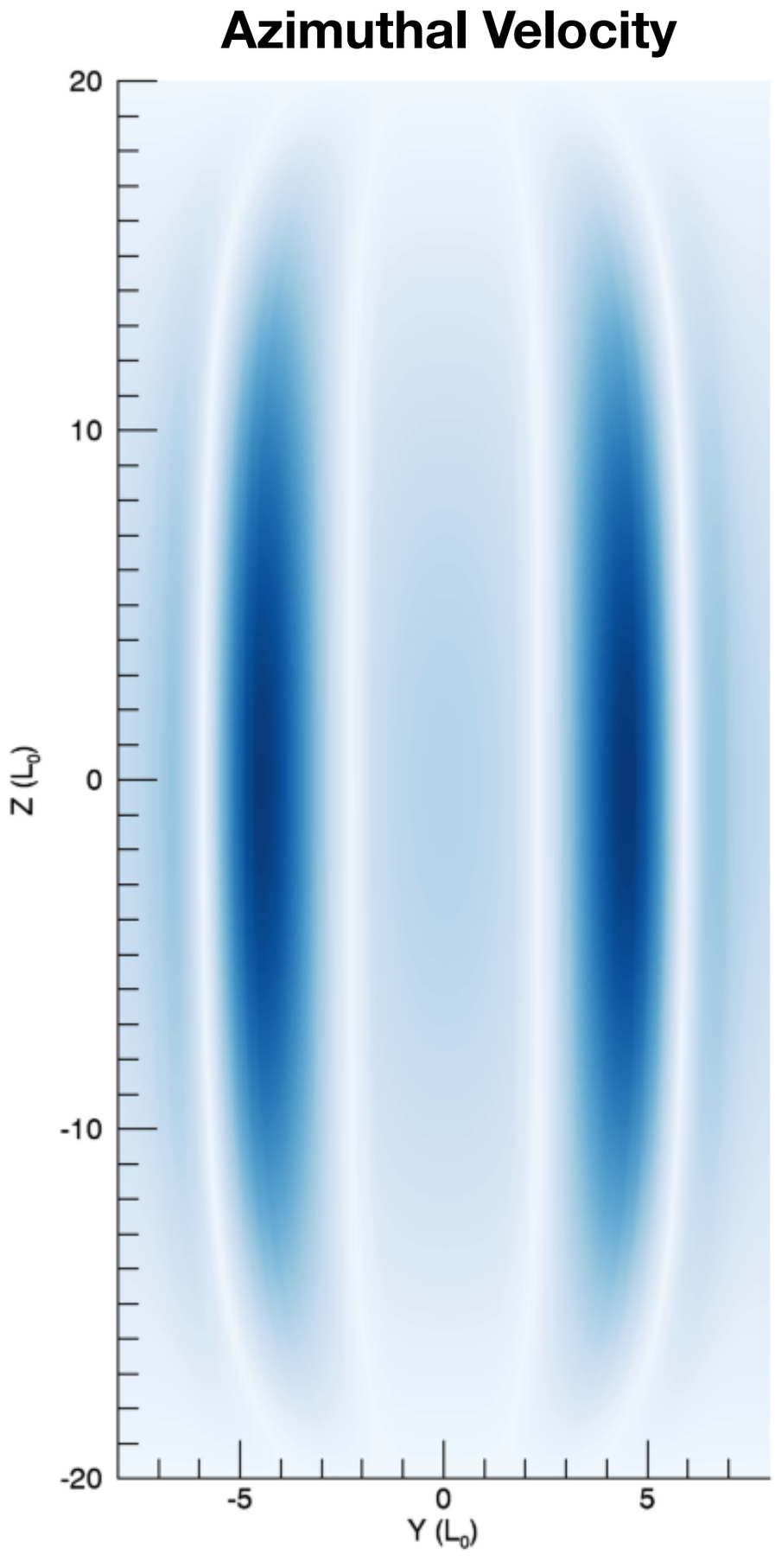
Structure of Alfvén Wave

Expansion of field - narrow layer of resonant field lines at loop foot point map to a wide layer at loop apex.

Resonant layer and azimuthal Alfvén wave are **much wider at loop apex**.

Will smaller scales at loop foot points result in more energy dissipation?





Alfvén Wave Energy

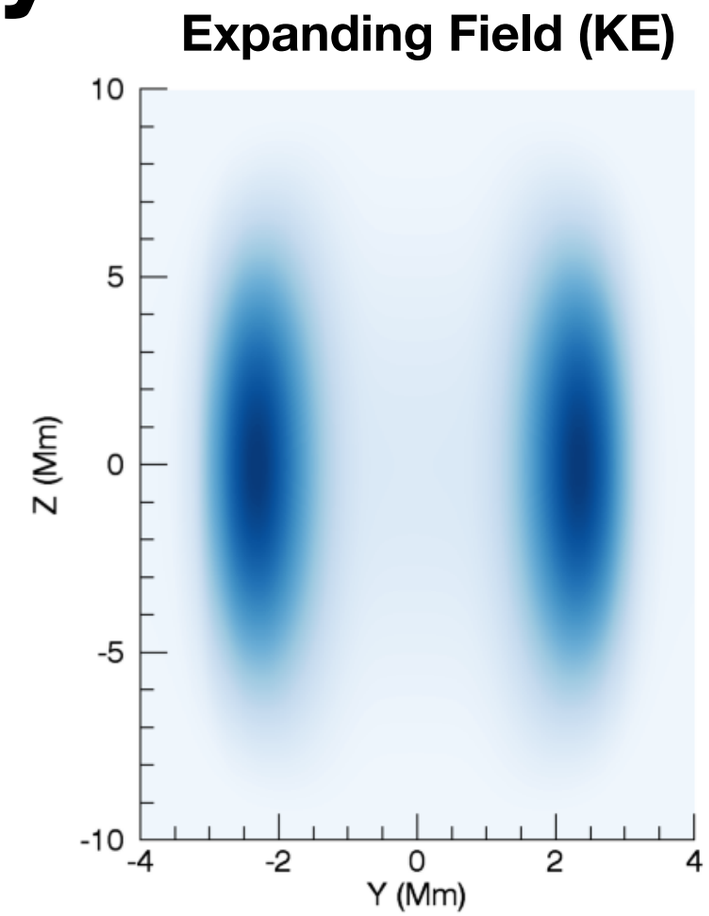
Alfvén wave energy partitioned between kinetic and magnetic.

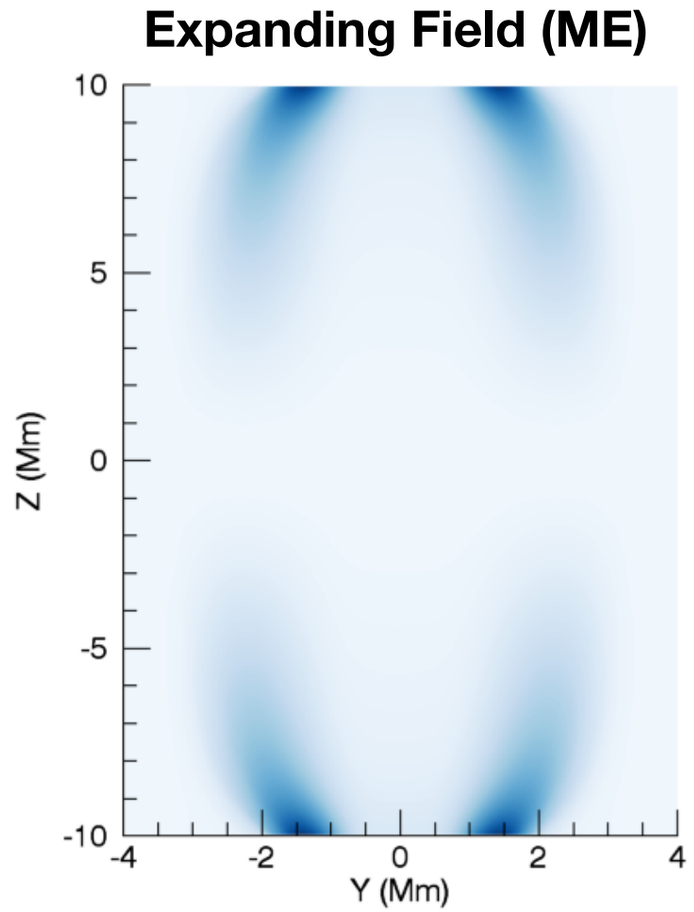
Kinetic energy largest at **apex**. **Magnetic** energy largest at **foot points**.

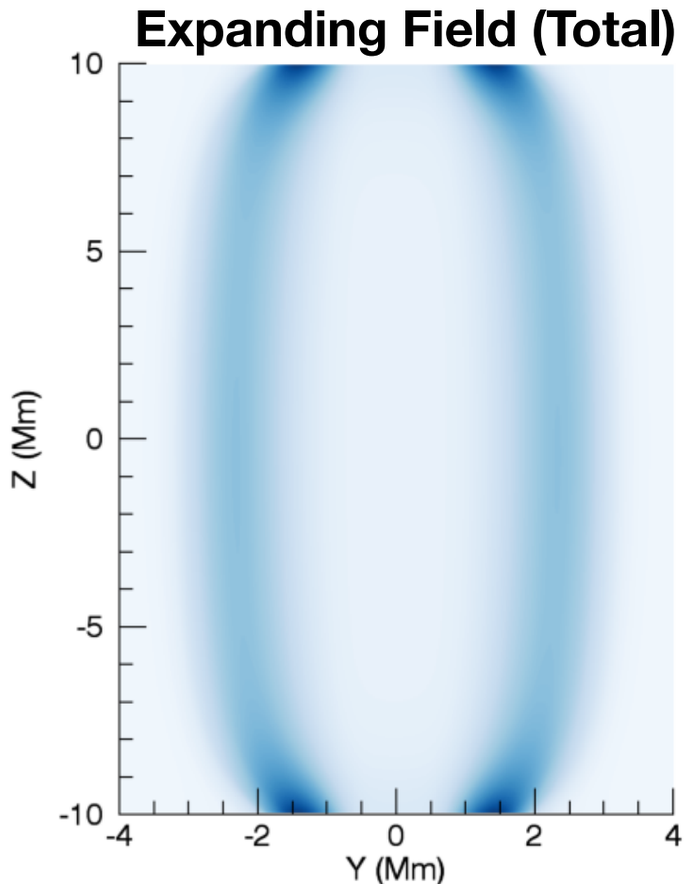
Wave energy uniform with height in straight field case.

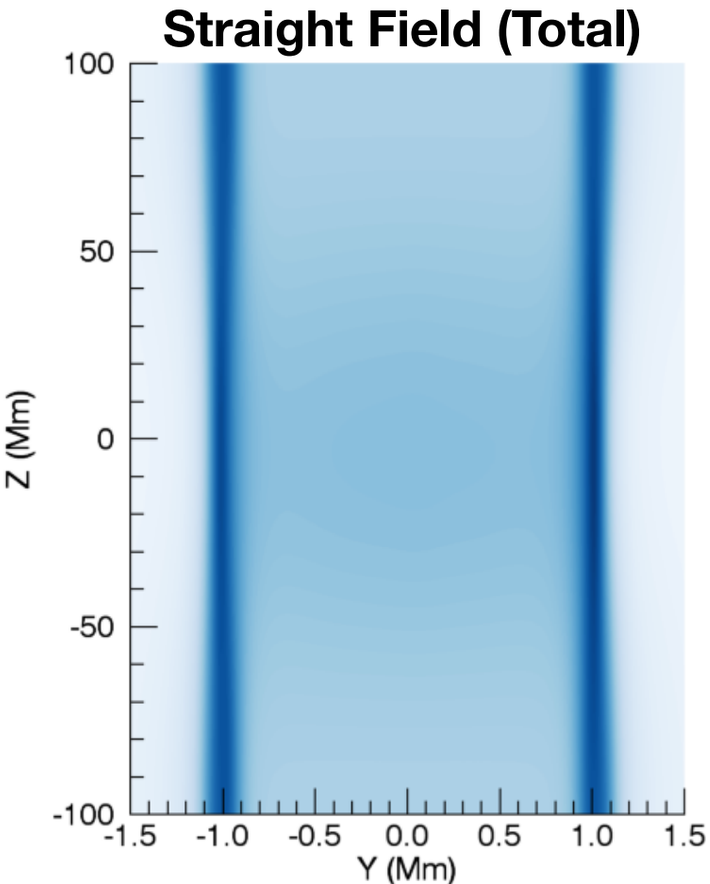
In expanding flux tube case, convergence of field lines concentrates wave energy at foot points.

Smaller scales close to loop foot points - **enhanced heating** here?









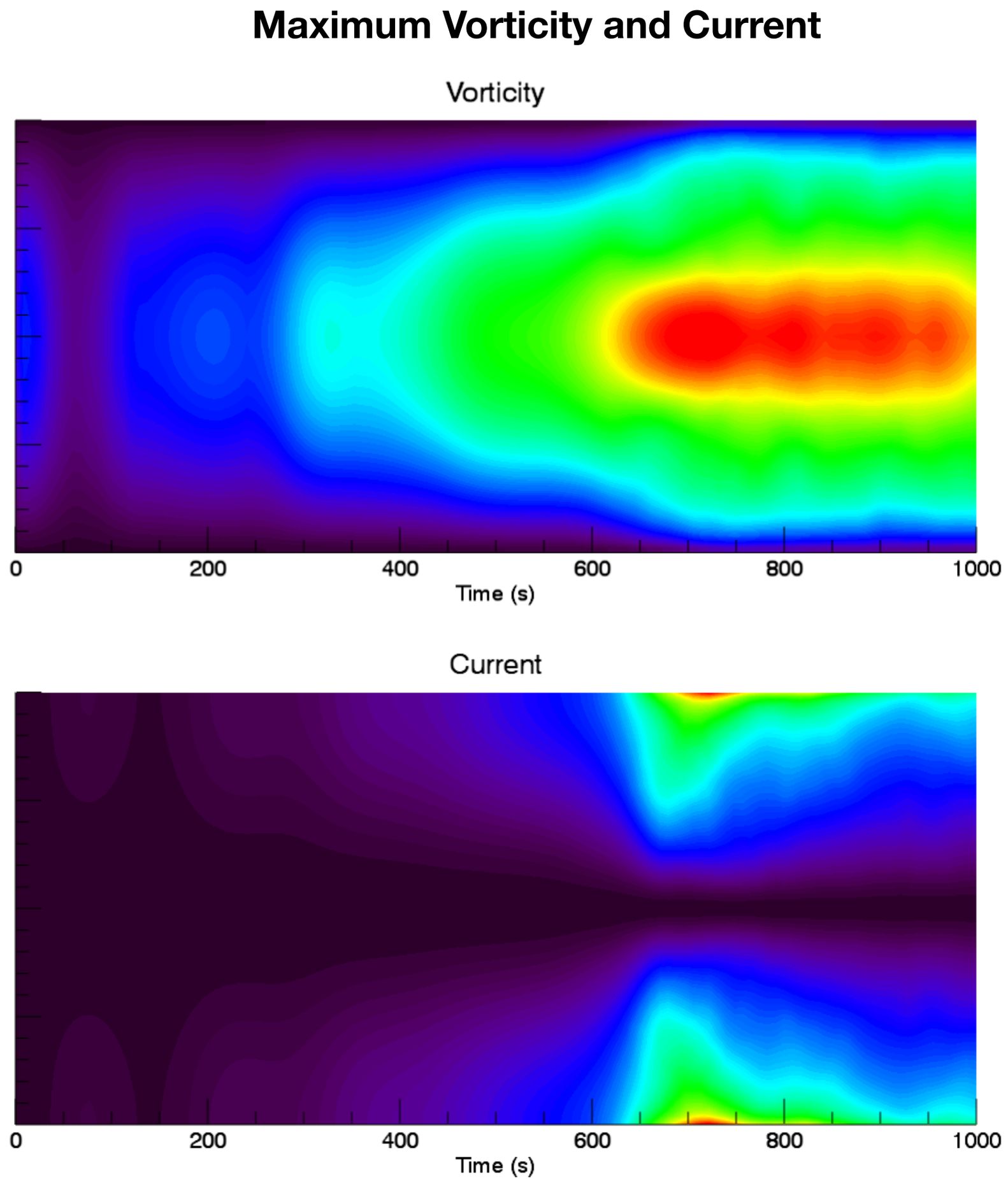
Small scales

Resonant absorption generates small scales in the magnetic (**current**) and velocity (**vorticity**) fields.

In both cases **vorticity** largest at **loop apex**. **Currents** largest at loop **foot points**.

Implications for heating? (See e.g. Karampelas et al. 2017).

Small scales form at a slower rate in expanded field case (~10 wave periods).



Vorticity Formation

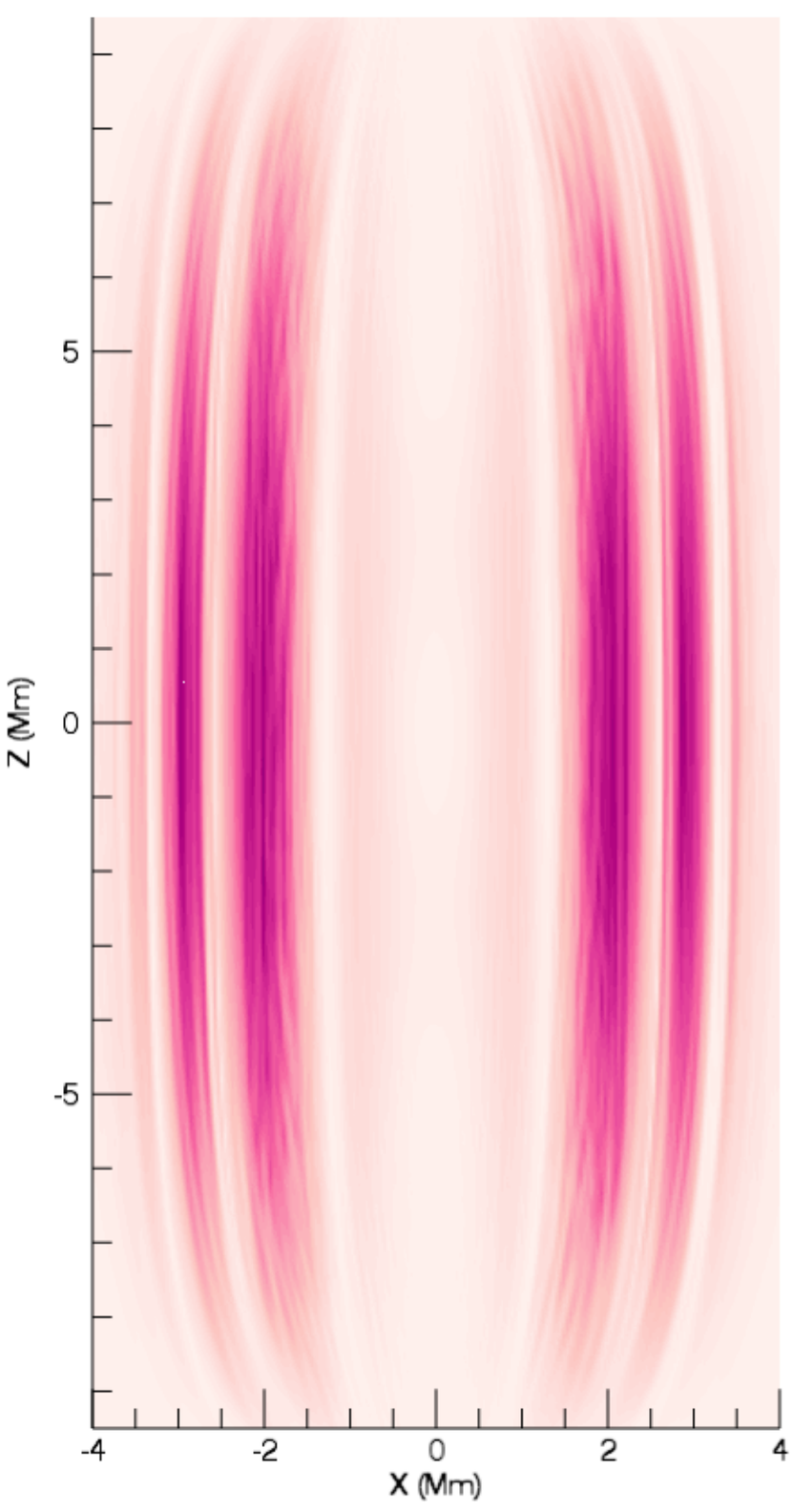
In both cases high vorticity forms throughout resonant layer.

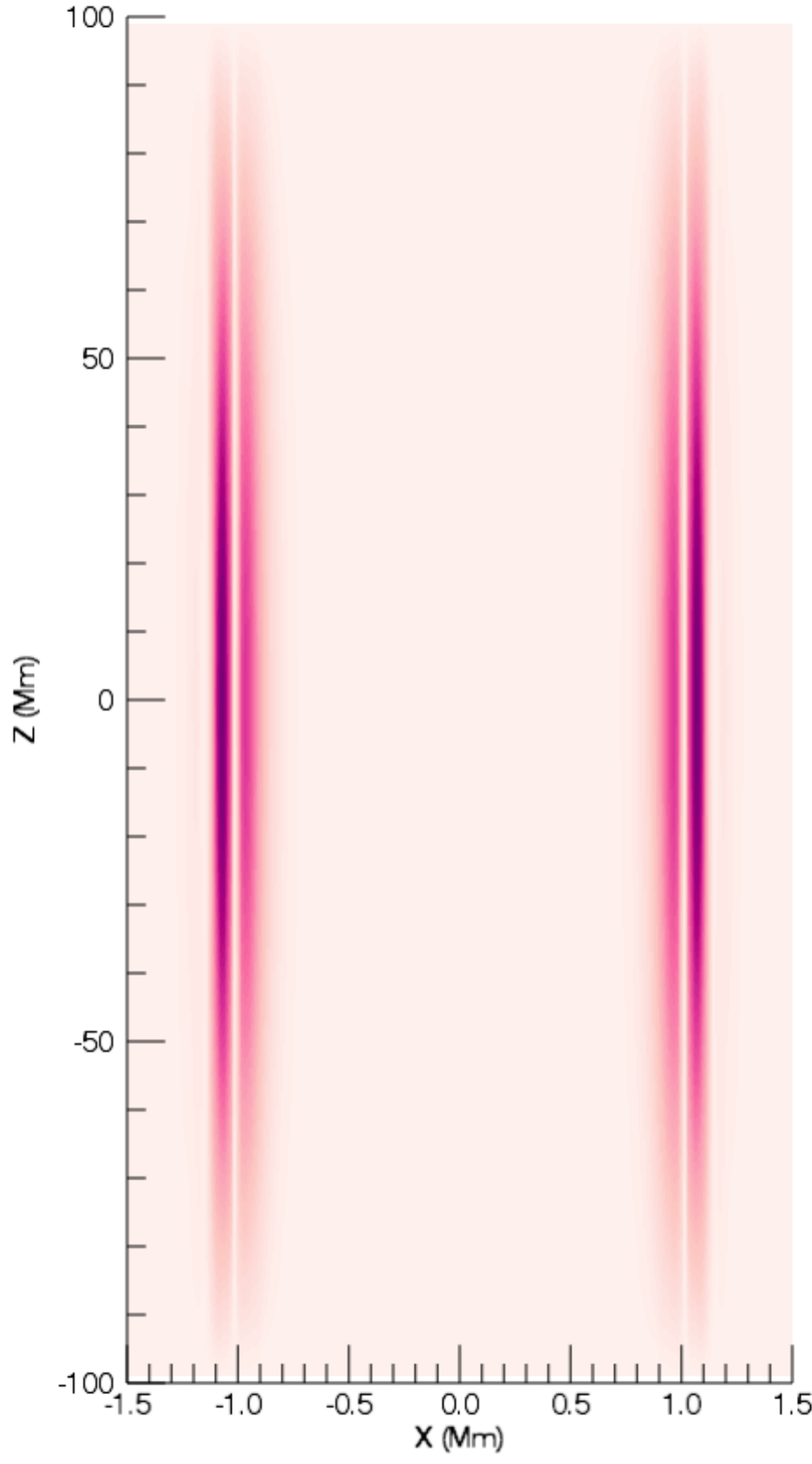
Much **larger region** with high vorticity in expanding field case.

Higher vorticity (and currents) in straight field case.

Phase mixing observed as vertical structures in both simulations.

Vorticity and currents form out of phase **vertically** and **radially**.





Current Formation

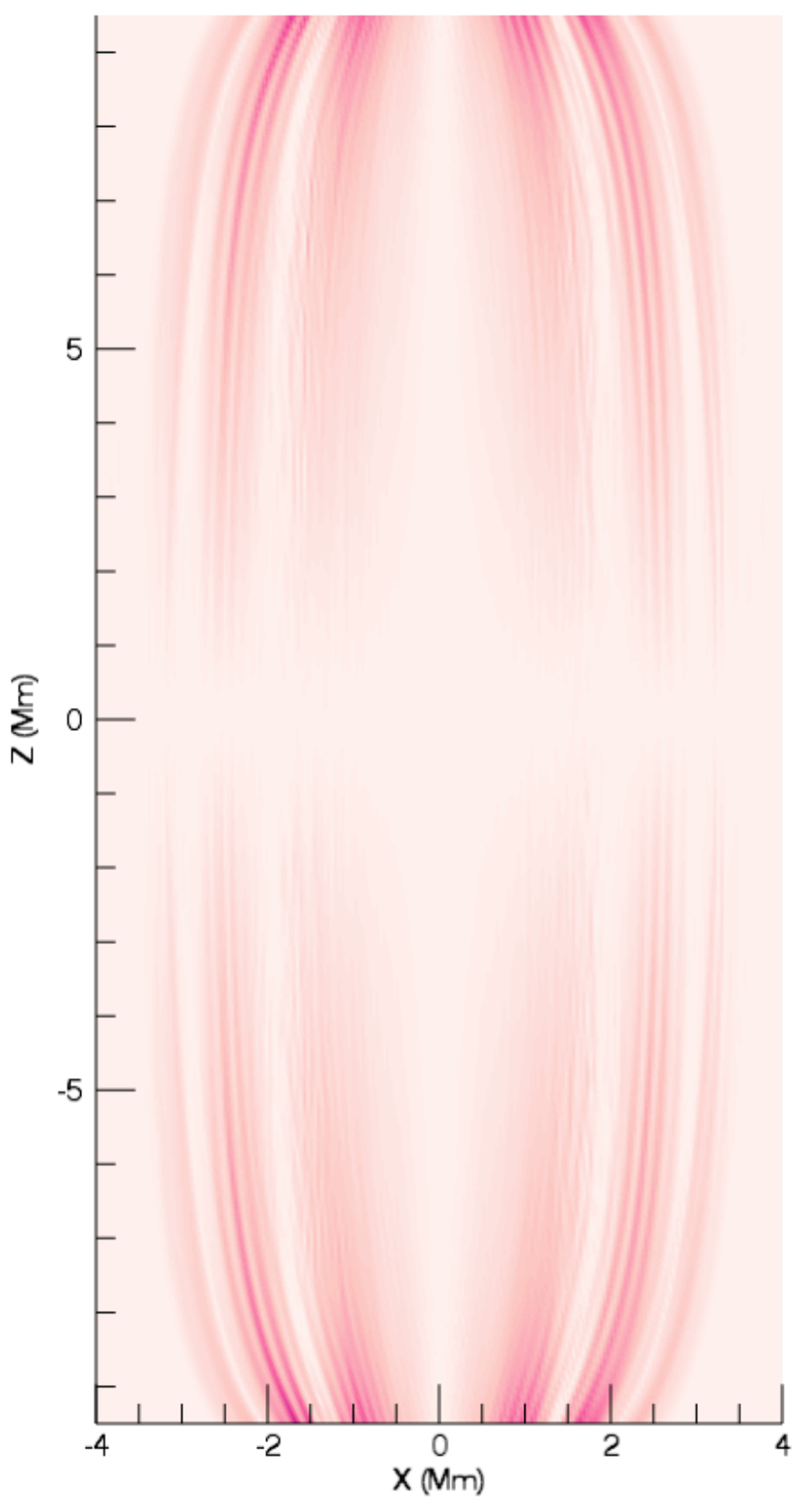
Large currents forms throughout resonant layer.

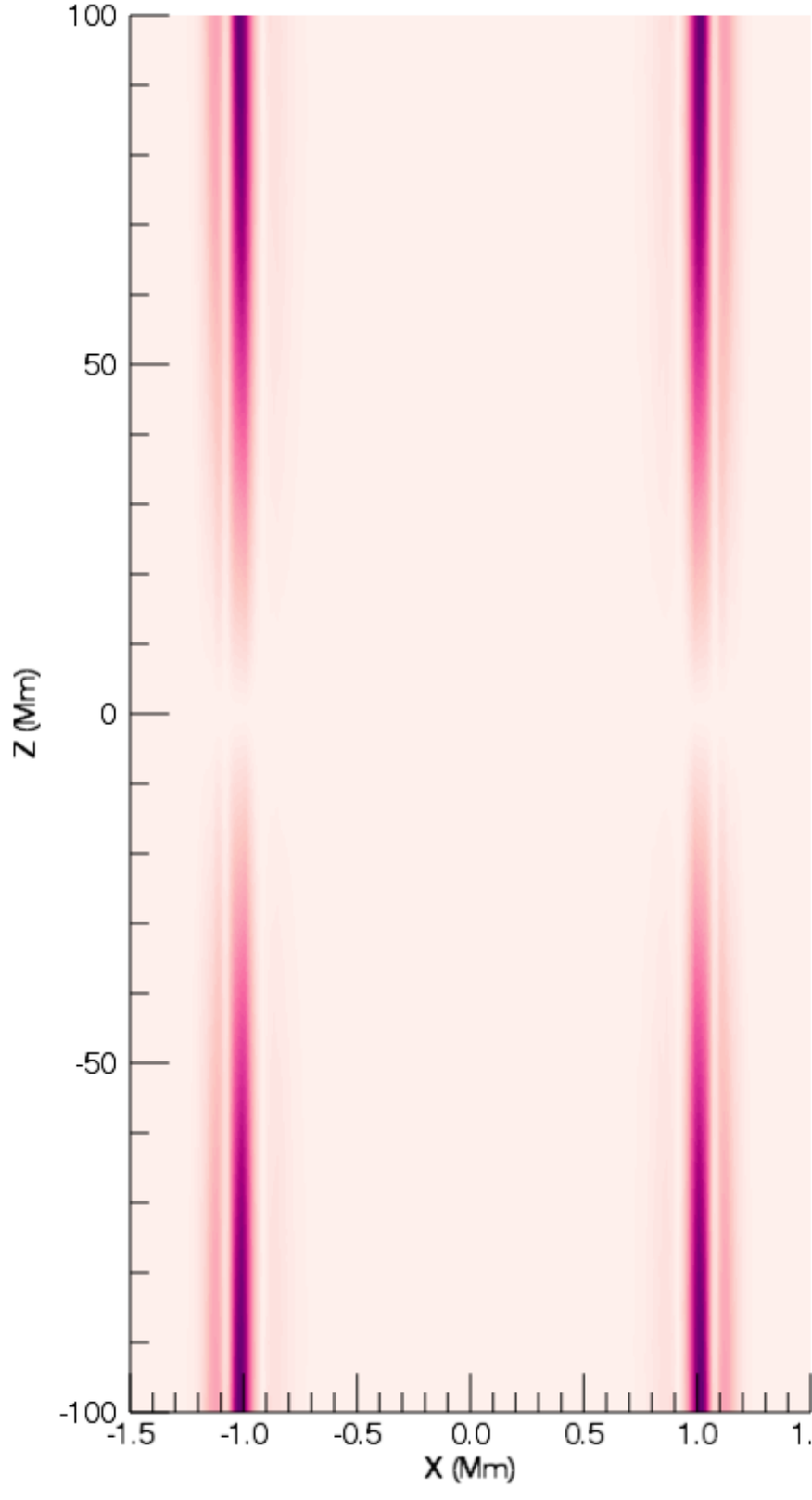
Larger region with high currents in expanding field case.

Vorticities and currents **similar in magnitude** for **straight field** case.

Currents larger than vorticity for **expanding field** simulation.

Observational signatures? Should we detect two narrow loops forming?





Conclusions and Further Thoughts

A **density gradient is not be required** for resonant absorption to proceed in transversely oscillating flux tubes.

Gradients in the magnetic field strength can allow energy to be transferred to azimuthal Alfvén waves.

Resonant absorption and **phase mixing** can occur even if there is **no radial Alfvén speed gradient** over much of the flux tube.

In this model **currents** and **vorticities** form over a larger radial extent than the straight field case.

What consequences does this model have for coronal seismology? How will any plasma heating affect future dynamics e.g. evaporation of plasma? Observational signatures?