Two-fluid modeling of waves and shocks in the solar chromosphere

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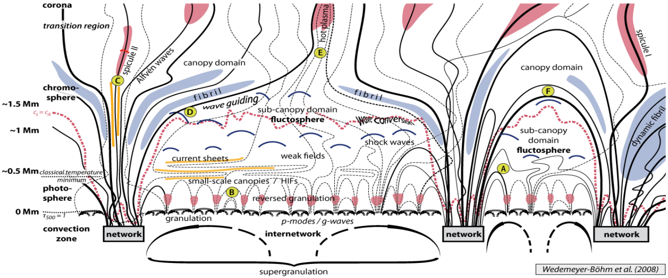
September 4, 2018

Previous work

- Analytical multi-fluid models of waves with application to the chromosphere, under assumption of homogeneous, unbounded plasma (Zaqarashvili et al. 2011,2013; Soler et al. 2013a,2013b; Martínez-Gómez et al. 2016, 2017; Ballester et al. 2018, 2018b), or through magnetic flux tybes: (Zaqarashvili et al. 2012; Soler et al. 2017)
  Conclusion: damping and cutoff frequencies
- Numerical models using the single-fluid approach introducing the partial ionization effects through a generalized Ohm's law (Khomenko & Collados (2012); Cheung & Cameron (2012); Martínez-Sykora et al. (2012,2016); Khomenko et al. (2014,2017); Shelyag et al. (2016);)
  Conclusion: heating

Motivation



- Evaluate how the chromospheric waves and shocks are affected by the two fluid effects
- Use realistic chromospheric stratification
- Full numerical treatment of nonlinearities

Two-fluid equations

$$\begin{aligned}
\frac{\partial \rho_n}{\partial t} + \nabla \cdot (\rho_n \vec{u}_n) &= 0 \\
\frac{\partial \rho_c}{\partial t} + \nabla \cdot (\rho_c \vec{u}_c) &= 0
\end{aligned}$$

$$\begin{aligned}
\frac{\partial (\rho_n \vec{u_n})}{\partial t} + \nabla \cdot (\rho_n \vec{u_n} \otimes \vec{u_n} + p_n) &= -\rho_n \vec{g} + \vec{R}_n \\
\frac{\partial (\rho_c \vec{u_c})}{\partial t} + \nabla \cdot (\rho_c \vec{u}_c \otimes \vec{u}_c + p_c) &= \vec{J} \times \vec{B} - \rho_c \vec{g} - \vec{R}_n
\end{aligned}$$

$$\begin{aligned}
\frac{\partial}{\partial t}\left(e_n + \tfrac{1}{2}\rho_n u_n^2\right) + \nabla \cdot \left(\vec{u}_n (e_n + \tfrac{1}{2}\rho_n u_n^2) + p_n \vec{u}_n\right) = \\
-\rho_n \vec{u}_n \vec{g} + M_n \\
\frac{\partial}{\partial t}\left(e_c + \tfrac{1}{2}\rho_c u_c^2\right) + \nabla \cdot \left(\vec{u}_c (e_c + \tfrac{1}{2}\rho_c u_c^2) + p_c \vec{u}_c\right) = \\
\vec{v}_c \cdot (\vec{J} \times \vec{B}) - \rho_c \vec{u}_c \vec{g} - M_n
\end{aligned}$$

$$\vec{E} + \vec{u}_c \times \vec{B} = 0$$

$$\vec{J} = \frac{1}{\mu_0} \nabla \times \vec{B}, \qquad \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

Two-fluid equations

Continuity: $$\begin{cases} \frac{\partial \rho_n}{\partial t} + \nabla \cdot (\rho_n \vec{u}_n) & = 0 \\ \frac{\partial \rho_c}{\partial t} + \nabla \cdot (\rho_c \vec{u}_c) & = 0 \end{cases}$$

Momentum: $$\begin{cases} \frac{\partial (\rho_n \vec{u_n})}{\partial t} + \nabla \cdot (\rho_n \vec{u_n} \otimes \vec{u_n} + p_n) & = -\rho_n \vec{g} + \boxed{\vec{R}_n} \\ \frac{\partial (\rho_c \vec{u_c})}{\partial t} + \nabla \cdot (\rho_c \vec{u}_c \otimes \vec{u}_c + p_c) & = \vec{J} \times \vec{B} - \rho_c \vec{g} \quad \boxed{-\vec{R}_n} \end{cases}$$

Energy: $$\begin{cases} \frac{\partial}{\partial t}\left(e_n + \frac{1}{2}\rho_n u_n^2\right) + \nabla \cdot \left(\vec{u}_n (e_n + \frac{1}{2}\rho_n u_n^2) + p_n \vec{u}_n\right) = \\ \qquad -\rho_n \vec{u}_n \vec{g} + \boxed{M_n} \\ \frac{\partial}{\partial t}\left(e_c + \frac{1}{2}\rho_c u_c^2\right) + \nabla \cdot \left(\vec{u}_c (e_c + \frac{1}{2}\rho_c u_c^2) + p_c \vec{u}_c\right) = \\ \qquad \vec{v}_c \cdot (\vec{J} \times \vec{B}) - \rho_c \vec{u}_c \vec{g} \quad \boxed{-M_n} \end{cases}$$

Ideal Ohm's law: $\vec{E} + \vec{u}_c \times \vec{B} = 0$

Maxwell equations: $\vec{J} = \frac{1}{\mu_0} \nabla \times \vec{B}, \qquad \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$

Two fluid equations

$$\alpha = \frac{\rho_e \nu_{en} + \rho_i \nu_{in}}{\rho_n \rho_c}$$

$$\vec{R}_n = \rho_n \rho_c \alpha (\vec{u}_c - \vec{u}_n)$$

$$M_n = \frac{1}{2}({u_c}^2 - {u_n}^2)\rho_n \rho_c \alpha + \boxed{\frac{1}{\gamma - 1}\frac{k_B}{m_n}(T_c - T_n)\rho_n \rho_c \alpha}$$

ideal gas laws

Two fluid equations

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neutrals: $\frac{1}{2}({u_c}^2 - {u_n}^2)\rho_n \rho_c \alpha = \tfrac{1}{2}(u_c - u_n)^2 \rho_n \rho_c \alpha + \vec{u}_n \rho_n \rho_c \alpha (\vec{u}_c - \vec{u}_n)$

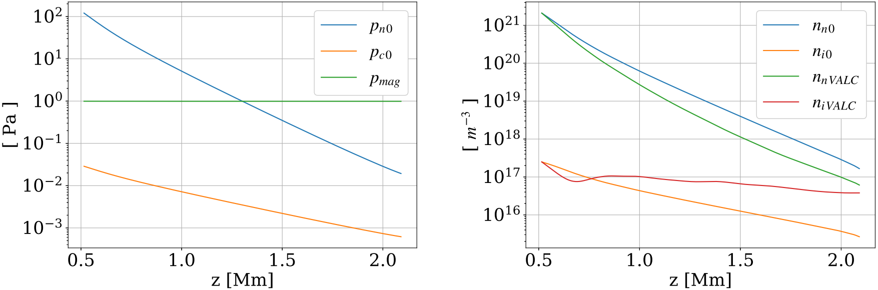
charges: $\frac{1}{2}({u_n}^2 - {u_c}^2)\rho_n \rho_c \alpha = \tfrac{1}{2}(u_c - u_n)^2 \rho_n \rho_c \alpha + \vec{u}_c \rho_n \rho_c \alpha (\vec{u}_n - \vec{u}_c)$

ideal gas laws

Equilibrium athmosphere

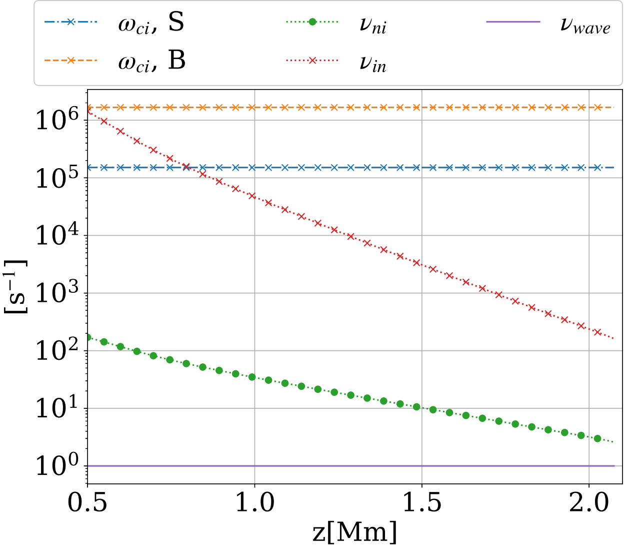
- model of hydrogen plasma with horizontal magnetic field, $B_{x0}(z)$, stratified in the vertical z direction.
- VALC model atmosphere for the background atmosphere, starting from z $\approx$ 500 km, and ending just below the transition region temperature increase, trimming the temperature at 9000 K, at z $\approx$ 2.1 Mm
- number density of neutrals and charges at the base of the atmosphere from the VALC model at $z \approx 500$ km, having $n_{c00} = 5 \times 10^{17}$ /m^3, and $n_{n00} = 2.1 \times 10^{21}$ /m^3
- neutral and charges pressure obtained by integrating the hydrostatic and magnetohydrostatic equilibrium equations, respectively
- two magnetic field profiles almost flat: S of $\approx$ 15 G, and B of $\approx$ 174 G.
- densities obtained by the EOS using the temperature profile from VALC for both neutrals and charges

Equilibrium athmosphere



Equilibrium athmosphere

Characteristic frequencies

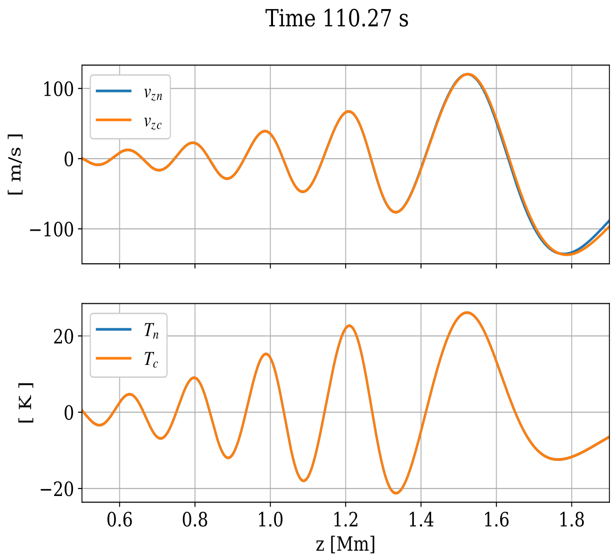


Parameters of the simulations:

- Wave amplitude: the value of the velocities amplitudes at the base is equal to A * 10^{-3} * c_0, and A has values: 0.5, 1, 2, 10, 100
- Wave period (1,5,20 s)
- Background magnetic field(S, B)

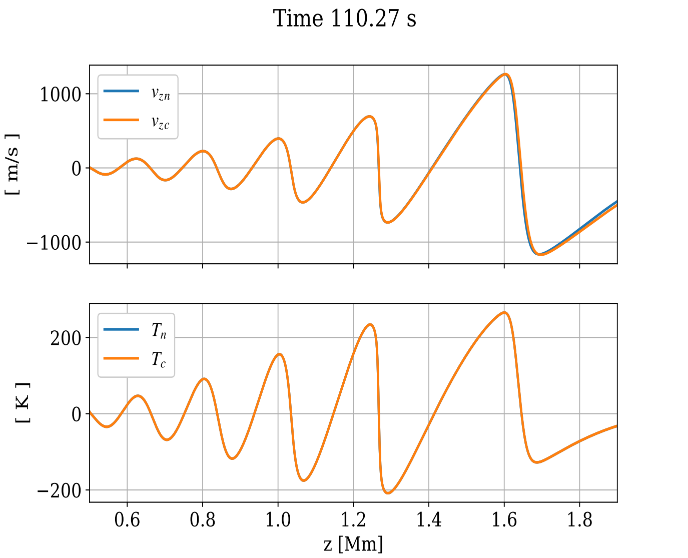
Nonlinear effects. P = 20. S

A = 1



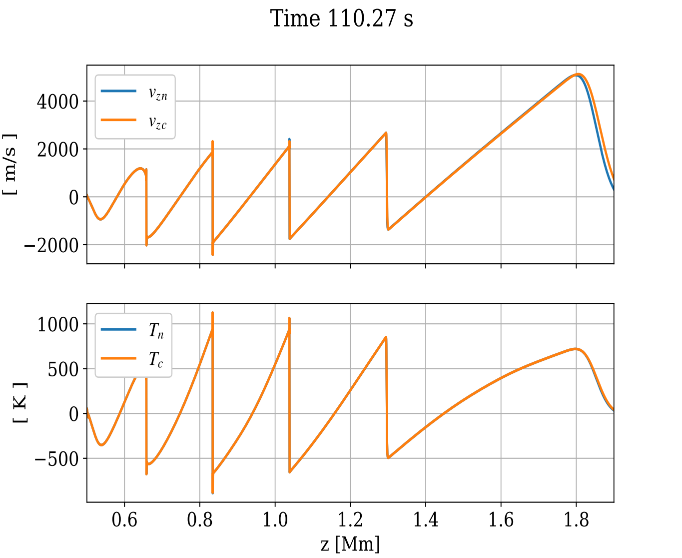
Nonlinear effects. P = 20. S

A = 10



Nonlinear effects. P = 20. S

A = 100



Nonlinear effects. P = 20. S

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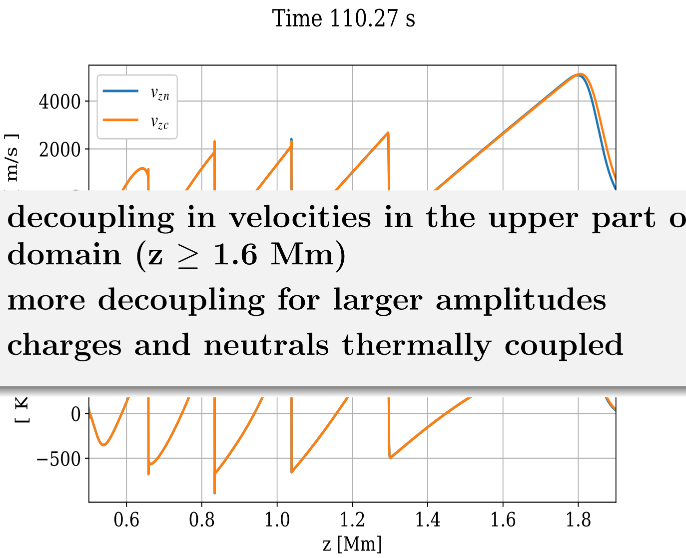
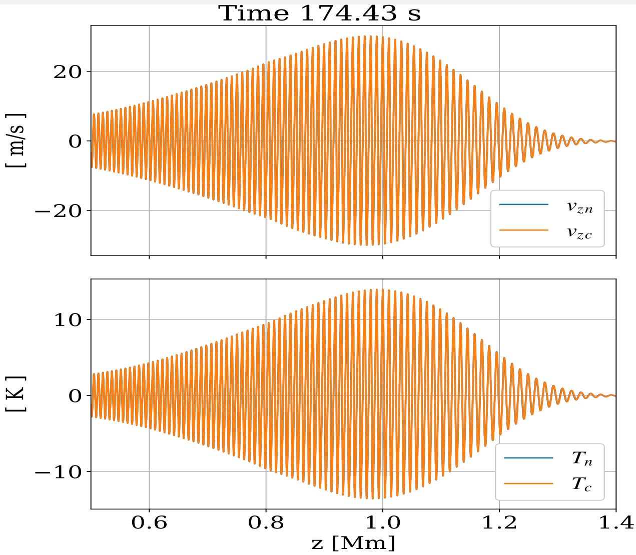


- **decoupling in velocities in the upper part of the domain (z $\geq$ 1.6 Mm)**
- **more decoupling for larger amplitudes**
- **charges and neutrals thermally coupled**

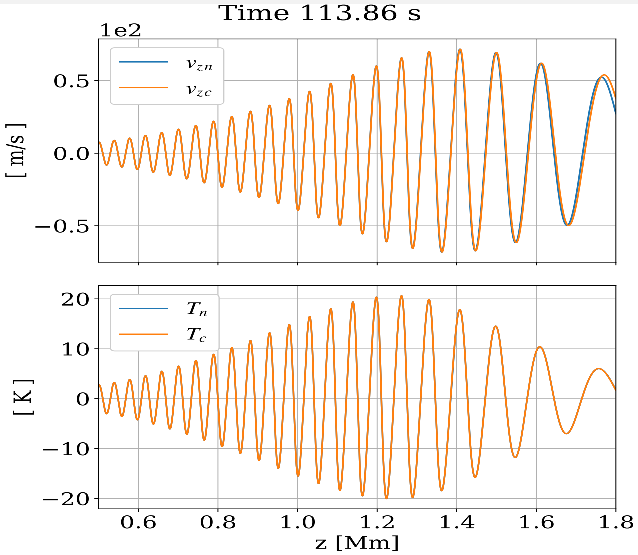
Dependence on frequency. A=1. S

P=1s



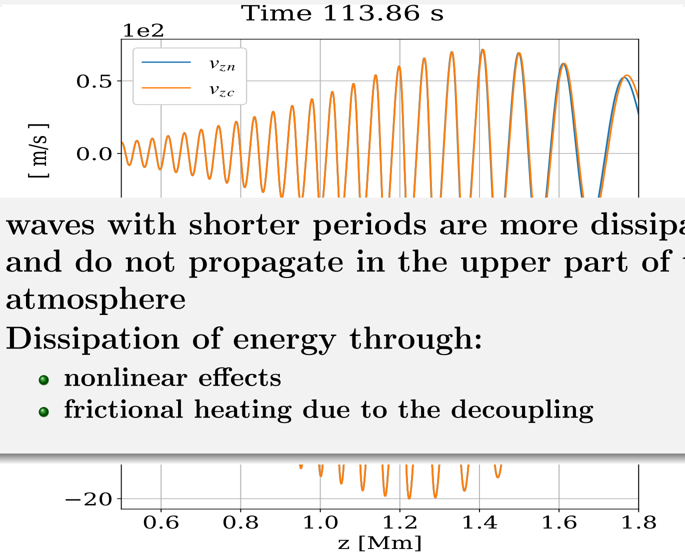
Dependence on frequency. A=1. S

P=5s



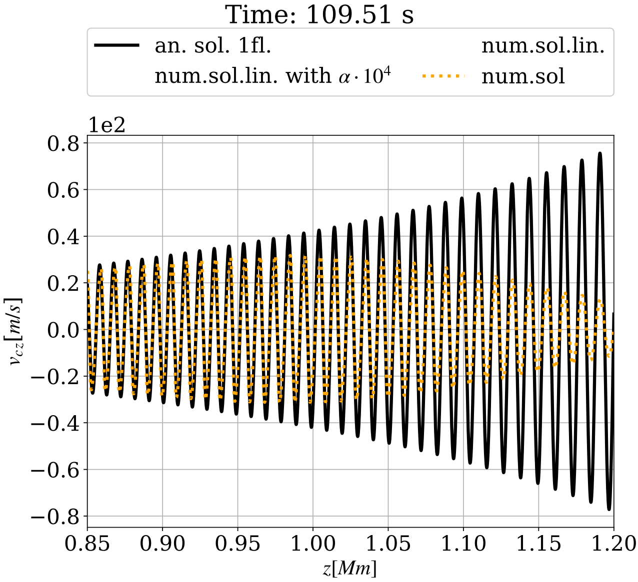
Dependence on frequency. A=1. S

P=5s

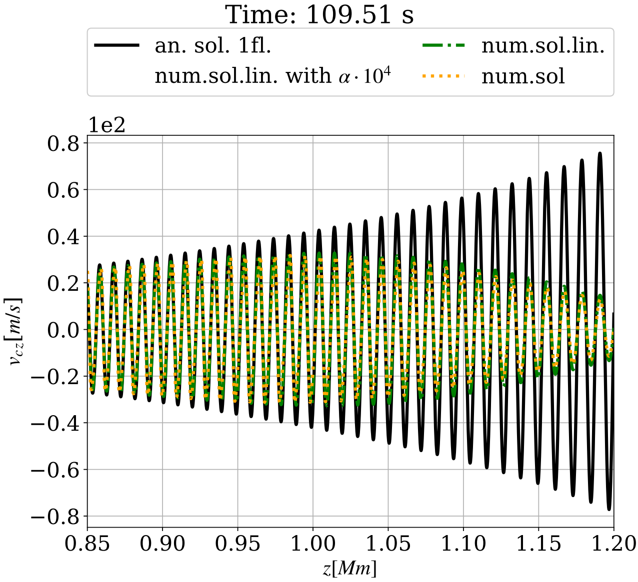


- **waves with shorter periods are more dissipated and do not propagate in the upper part of the atmosphere**
- **Dissipation of energy through:**
  - **nonlinear effects**
  - **frictional heating due to the decoupling**

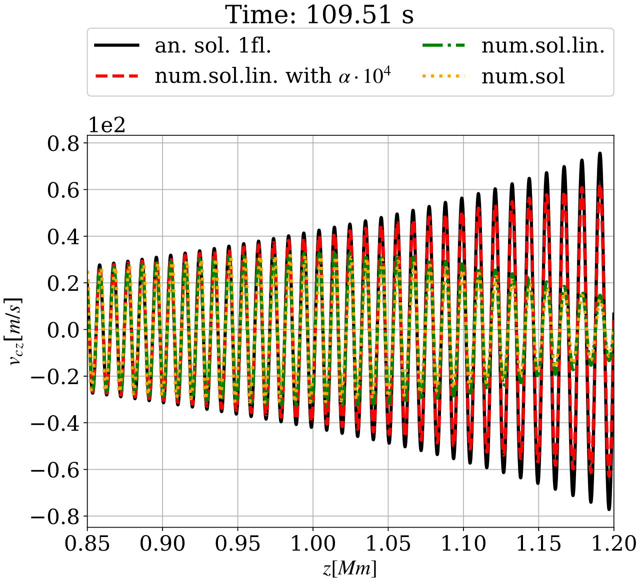
Damping due to nonlinear effects vs. decoupling



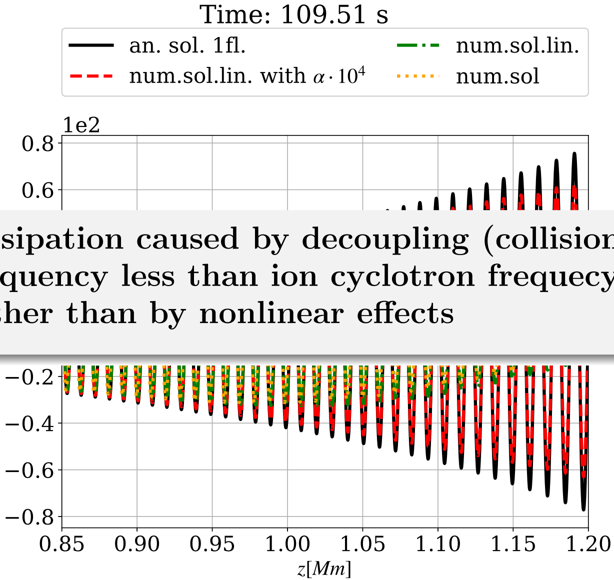
Damping due to nonlinear effects vs. decoupling



Damping due to nonlinear effects vs. decoupling

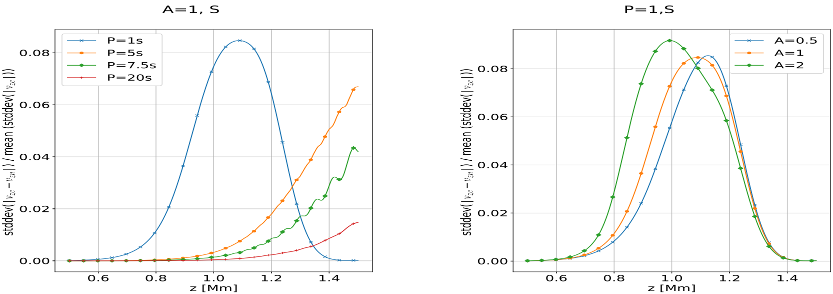


Damping due to nonlinear effects vs. decoupling

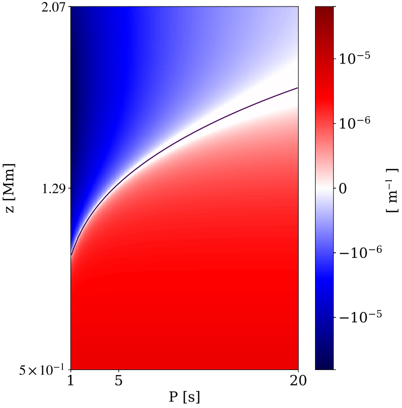


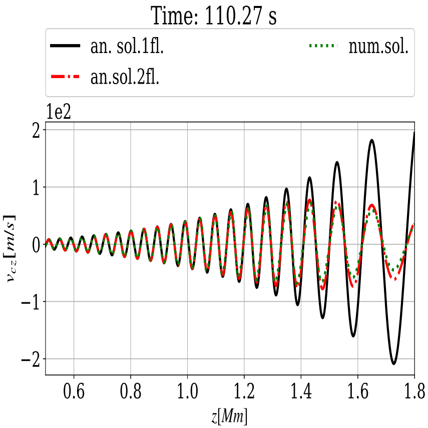
- **dissipation caused by decoupling (collision frequency less than ion cyclotron frequecy) rather than by nonlinear effects**

Decoupling. A=1, S

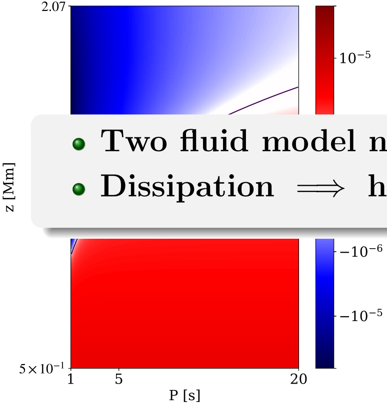


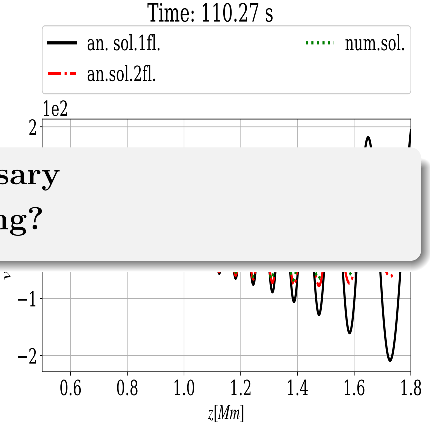
Imaginary part of k. Two fluid solution. S





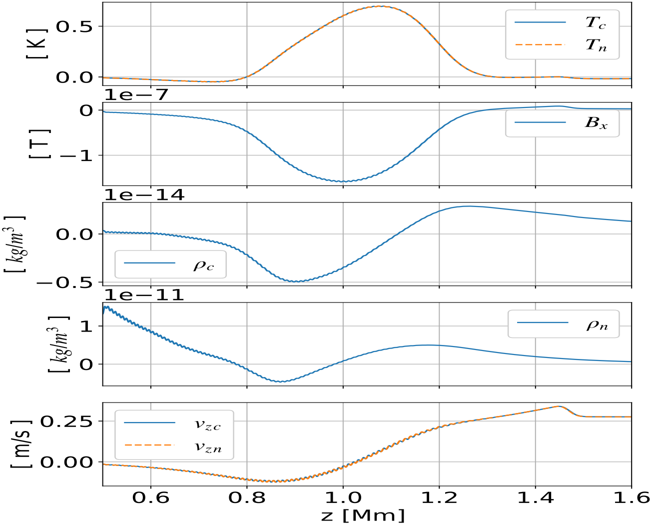
Imaginary part of k. Two fluid solution. S





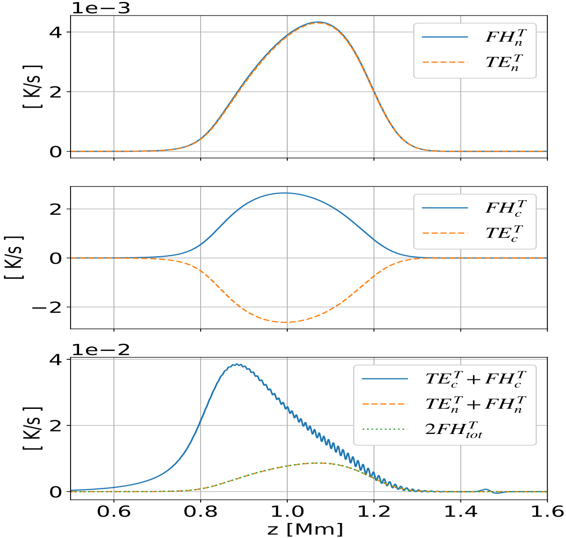
- **Two fluid model necessary**
- **Dissipation $\implies$ heating?**

Evolution of the background variables



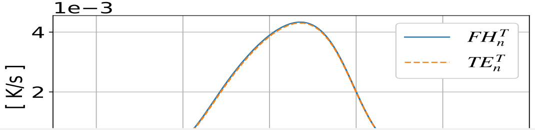
Increase in the background temperature

Dominant terms in temperature equations



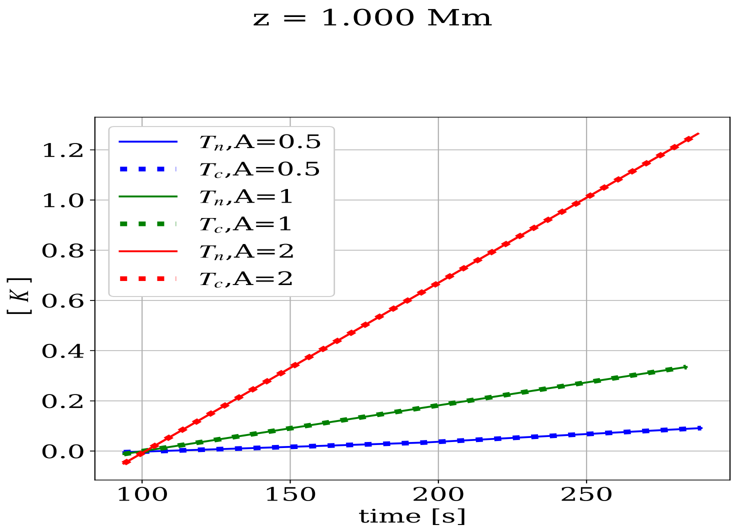
Increase in the background temperature

Dominant terms in temperature equations

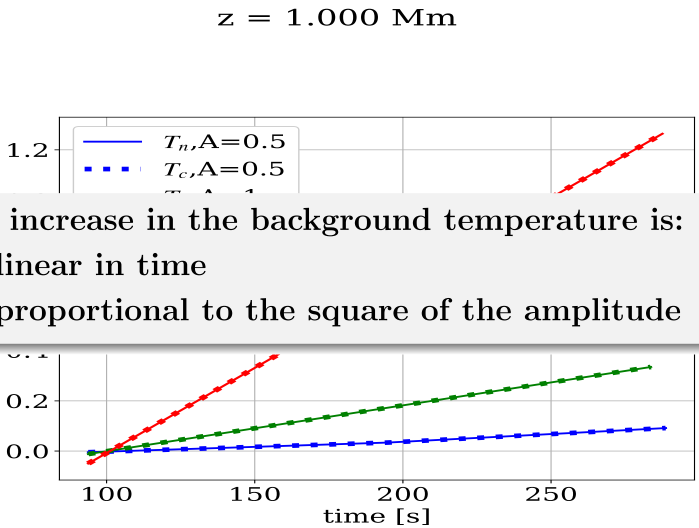


- dominant terms: frictional heating and thermal exchange
- The neutrals density several orders of magnitude larger than the density of charges $\Longrightarrow$
  - charges are heated more efficiently (because of lower density) and transfer heat to the neutrals through the TE term
  - the increase of the temperature, if we sumed the temperature equations, is due to the neutrals
- the peak of charges shifted left because the neutrals number density has a steeper gradient than the charges

Increase in the background temperature



Increase in the background temperature



The increase in the background temperature is:

- **linear in time**
- **proportional to the square of the amplitude**

Conclusions

1. Waves are damped by:
   - decoupling (linear theory)
   - nonlinear effects
2. Dependence on:
   - wave amplitude: (nonlinear effects and decoupling, temperature increase)
   - wave period
   - background magnetic field
3. The increase in the background tempeature is linear in time and depends proportionally on the square of the amplitude.