MHD wave propagation in localised magnetic flux tubes connecting the photosphere to corona

Viktor Fedun, Robert Erdélyi and Sergiy Shelyag

SP[2]RC, Department of Applied Mathematics, University of Sheffield, Hounsfield Road, Hicks Building, Sheffield, S3 7RH, UK

email: (Robertus, V.Fedun)@sheffield.ac.uk, http://robertus.staff.shef.ac.uk

We examine numerically the linear and non-linear propagation of magneto-acoustic waves in flux tube embedded into the two-dimensional solar atmosphere. To perform the modelling we employed our newly developed MHD code SAC (Sheffield Advanced Code) which exploits numerical variable separation and advanced hyper-resistivity and diffusivity techniques. The plasma equilibrium is constructed by a combination of the VAL IIIC and McWhirter solar atmosphere and corona density profiles. The localised magnetic flux tubes, embedded in the stable background, are modelled as a self-similar non-potential magnetic field configuration. Harmonic wave sources, located at the bottom of the magnetic flux tube representing photospheric motions at the solar temperature minimum, are incorporated to excite and drive a range of typical transverse and vertical (longitudinal) periodic motions propagating from the photosphere to the corona in this building box of the solar atmosphere. The following results will be discussed in detail:

- The rich pattern of mode conversion at the region where the plasma beta is equal to unity;
- The slow and fast magneto-acoustic modes in the chromosphere form shock waves which then hit the transition region (TR). This impulsive impinging causes strong perturbations of the TR and forms shock wave fronts in the solar corona;
- High-frequency magneto-acoustic waves propagate from the lower atmosphere through the transition region, experience relatively low reflection, and transmit most of their energy into the corona;
- The thin transition region acts as a good wave guide for horizontally propagating surface waves for all types of drivers investigated.

With the above forward modelling we serve as impetus for magneto-seismologic acquisition of the complex and dynamic solar atmosphere.

Introduction

In the present work, we show 2D simulations of linear and non-linear wave propagation through **an open magnetic flux tube embedded in the solar atmosphere from the surface to the corona.** A joint VAL IIIC [1] and McWhirter [2] solar atmosphere and corona density profiles is used as the background model in our simulations (see Fig. 1). In general, the numerical domain consists of four physically different parts: photosphere, chromosphere, transition region and solar corona. A typical simulation domain is shown in Fig. 2. The box is 4 Mm wide in the *x* direction and 4 Mm high in the vertical *z* direction, and has a resolution of 400 × 1976 grid points, respectively. As a background magnetic field we use a self-similar non-potential magnetic field configuration, which can be obtained from the following set of equations [3], [4]:

$$B_x = -\frac{\partial f}{\partial z}\cdot G(f) \quad ,B_z = \frac{\partial f}{\partial x}\cdot G(f),$$

and

$$f = x \cdot B_{0z}(z),$$

where B_{0z} describes the decrease of the vertical component of magnetic field towards the top of the model, and G is the function which defines how the magnetic field opens up with height. The magnetic field constructed in this way is divergence-free by definition. The structure of the background magnetic field is shown in Fig. 2. Initially and during each simulations, **magneto-acoustic waves** are excited by a harmonic driver located just under the height corresponding to the temperature minimum of the solar atmosphere. The vertical or horizontal velocity component of the perturbation has a Gaussian spatial distribution in the x and z directions, i.e.:

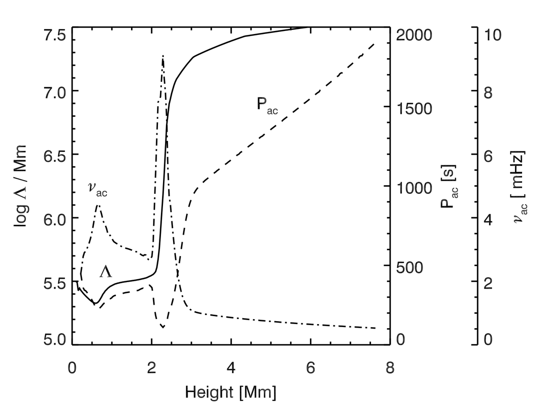

Fig. 1: Variation in the pressure scale-height Λ, the acoustic cutoff period P_{ac} and the cyclic frequency ν_{ac} with changing height as derived from the solar atmosphere model.

$$V_{z,x} = A\sin\left(\frac{2\pi t}{\Delta t}\right)\exp^{-\left(\left(\frac{x}{\Delta x}\right)^2+\left(\frac{z-z_0}{\Delta z}\right)^2\right)}.$$

To perform the modelling we employed our newly developed MHD code SAC (Sheffield Advanced Code) which exploits the variable separation and numerical resistivity and diffusivity techniques [5].

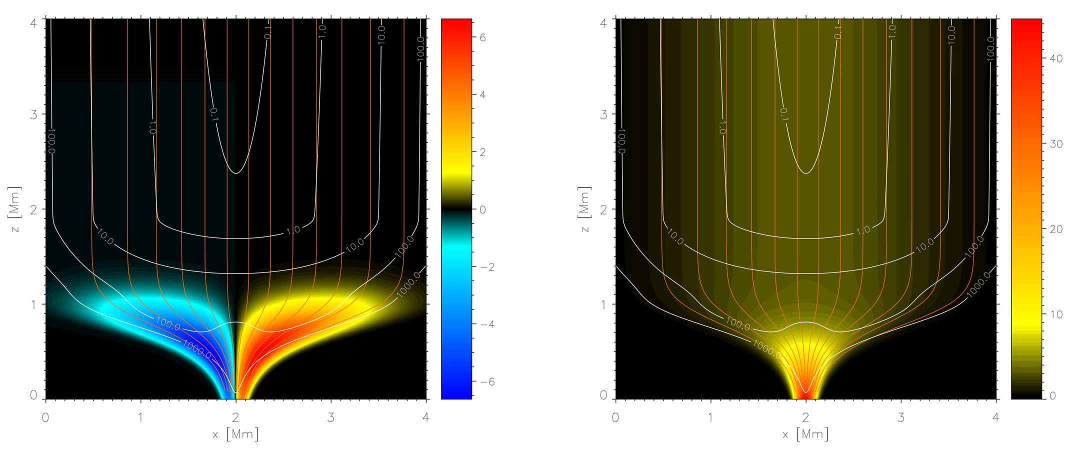

Fig. 2: The magnetic field distribution in the computational domain. The magnetic field components B_{x0} and B_{z0} are shown at the left and right panels of the image respectively. The x axis corresponds to longitude measured in Mm and the z vertical axis are perpendicular to the solar surface. Colours represent the magnetic field strength. The orange curves represent the field structure of the open magnetic flux tube. The black lines are the plasma *iso*-β contours, labelled by their appropriate value.

Simulations and results

In this section we show examples of 2-D simulations of linear and non-linear wave propagation through an open magnetic flux tube embedded in the solar atmosphere from the surface to the corona. We examine the wave pattern that develops in an open magnetic flux tube due to periodic **horizontal** (Figs. 3, 4) and **vertical** (Figs. 5, 6) motions, with an amplitude 500 m/s. We consider a typical high-frequency driver with a characteristic period of 30 second. The driver's period is well below the acoustic cut-off period at any point in the model (and in the real solar atmosphere), and therefore it allows us to investigate the strong wave coupling of the photosphere to corona.

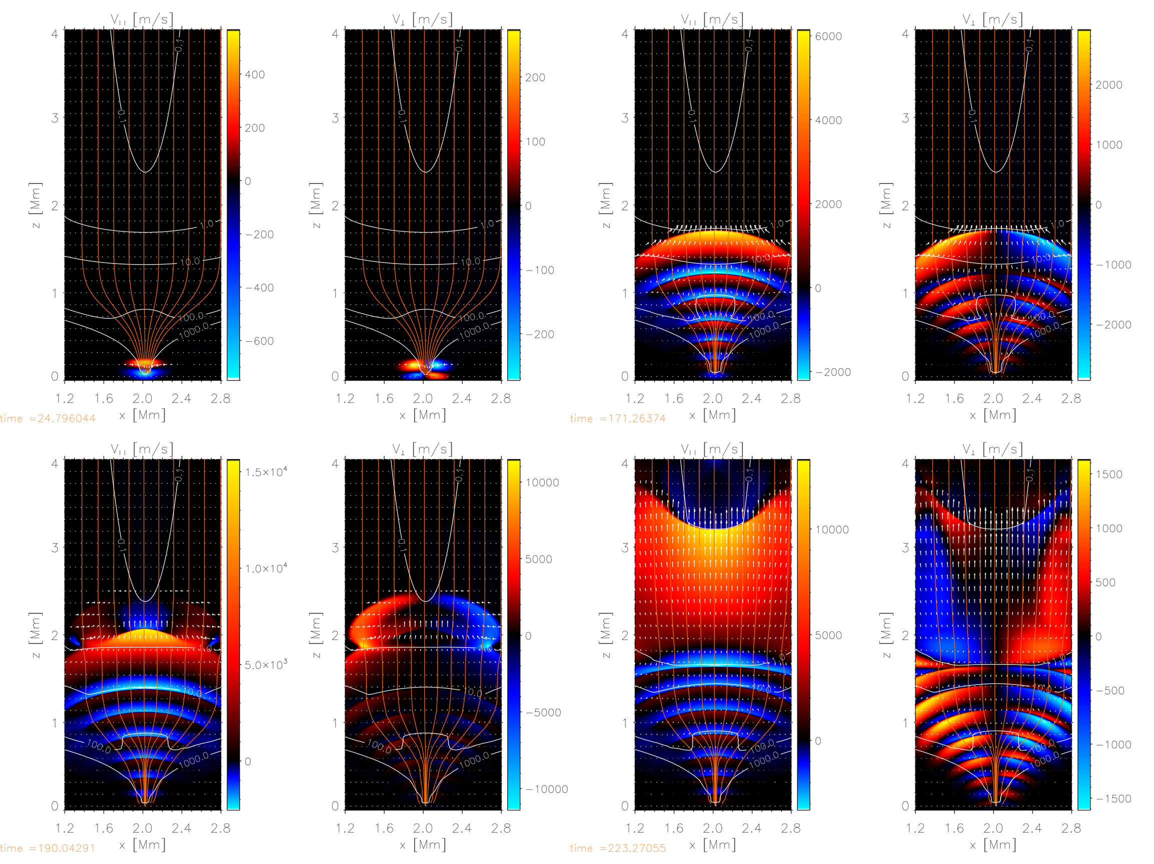

Fig. 3: Field-aligned ($V_{\|}$) and transverse ($V_{\perp}$) components of the velocity images showing the development of the initial perturbation in the open magnetic flux tube generated by the 30 s vertical periodic driver at different times. The colour scale shows the $V_{\|}$ and $V_{\|}$ perturbations in m/s. The colour curves are the same as on Fig. 2. The angle and length of the white arrows correspond to the velocity vector field.

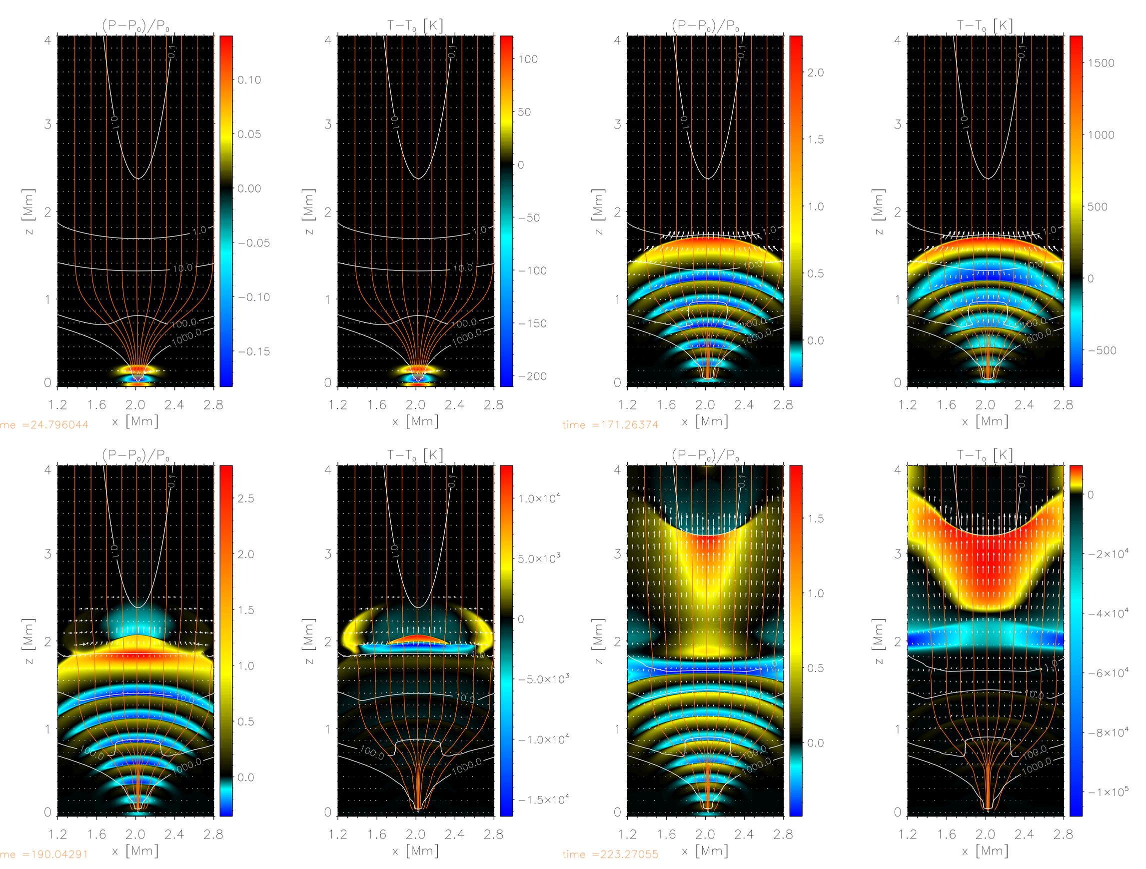

Fig. 4: The relative pressure difference $\triangle P/P_0$ and temperature $\triangle T$ perturbation from the initial state in a single magnetic flux tube at different times. Wave excitation is due to periodic vertical motion. The colour scale shows the relative difference pressure and temperature perturbations. The colour curves are the same as in the Fig. 2.

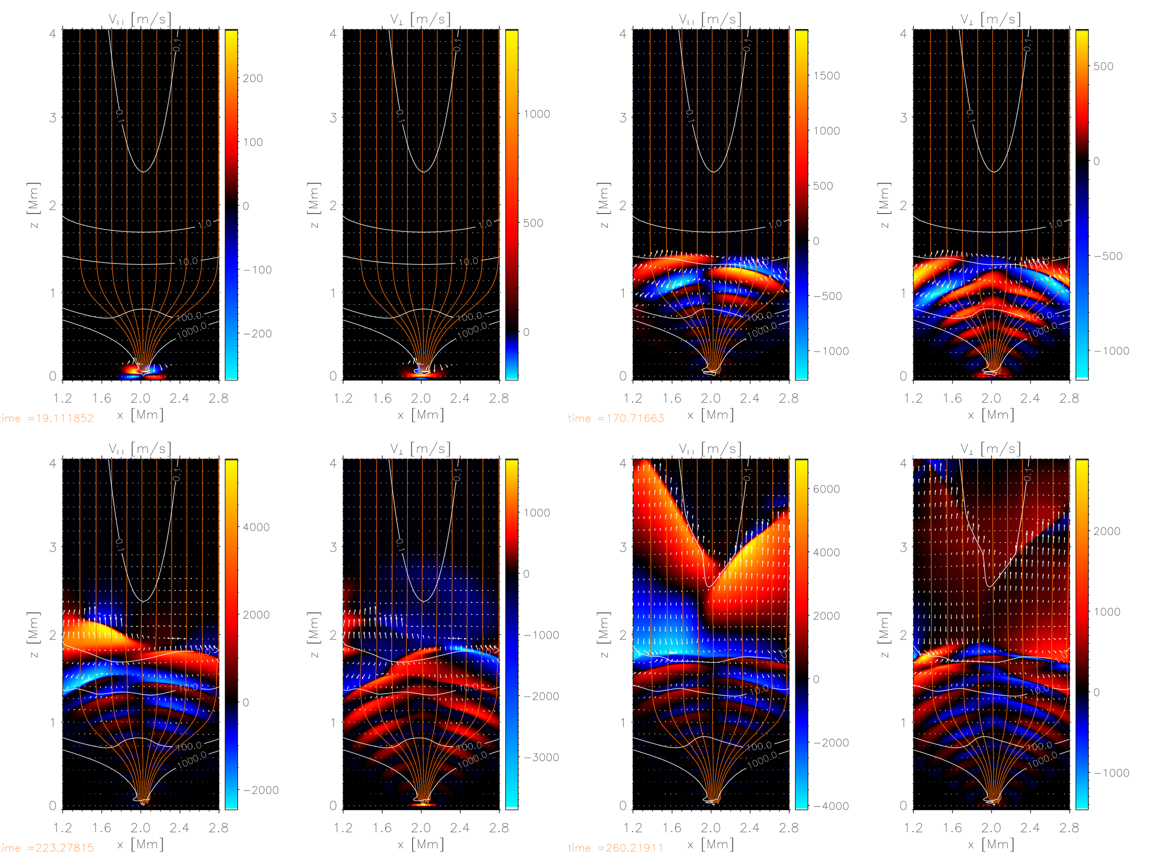

Fig. 5: Field-aligned ($V_{\|}$) and transverse ($V_{\perp}$) components of the velocity showing the development of the initial perturbation in the open magnetic flux tube generated by the 30 s horizontal periodic driver at different times. The format is the same as in previous images.

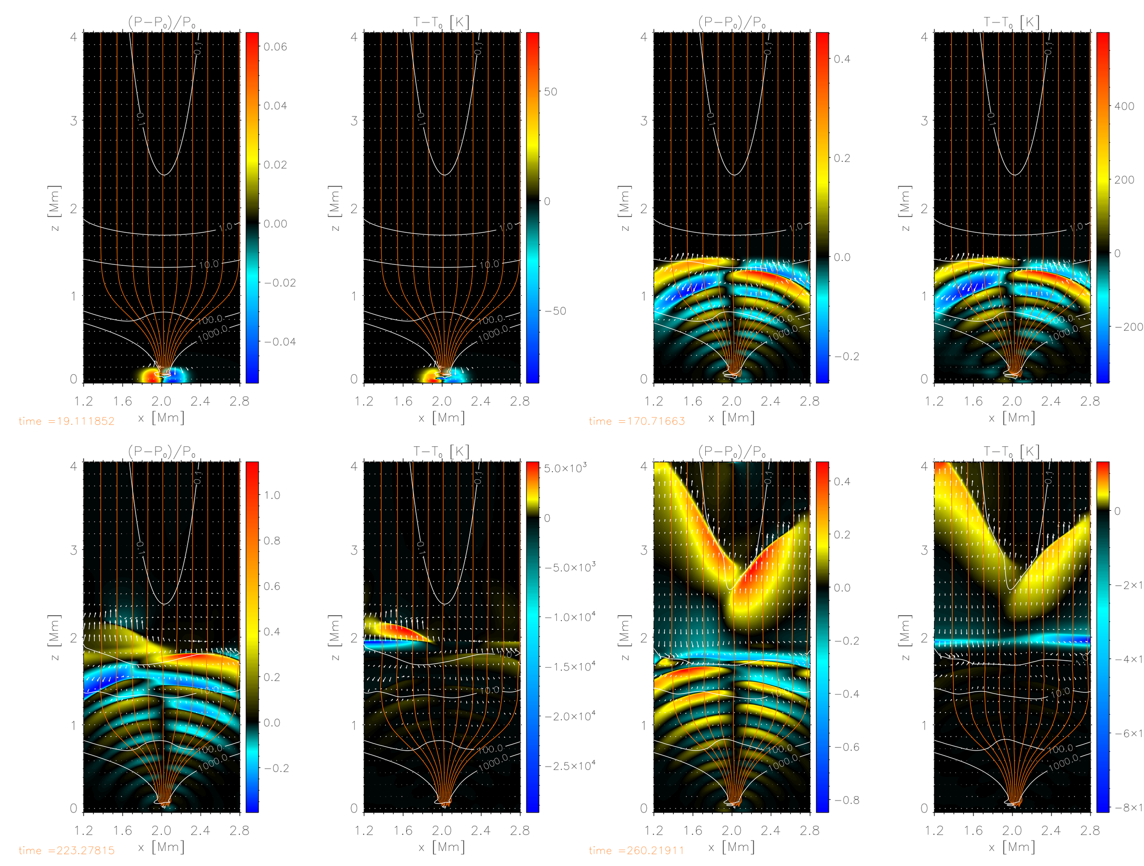

Fig. 6: The relative pressure difference $\triangle P/P_0$ and temperature $\triangle T$ perturbation from the initial state in a single magnetic flux tube at different times. Wave excitation is due to periodic horizontal motion. The colour scale shows the relative difference pressure and temperature perturbations. The colour curves are the same as in the Fig. 2.

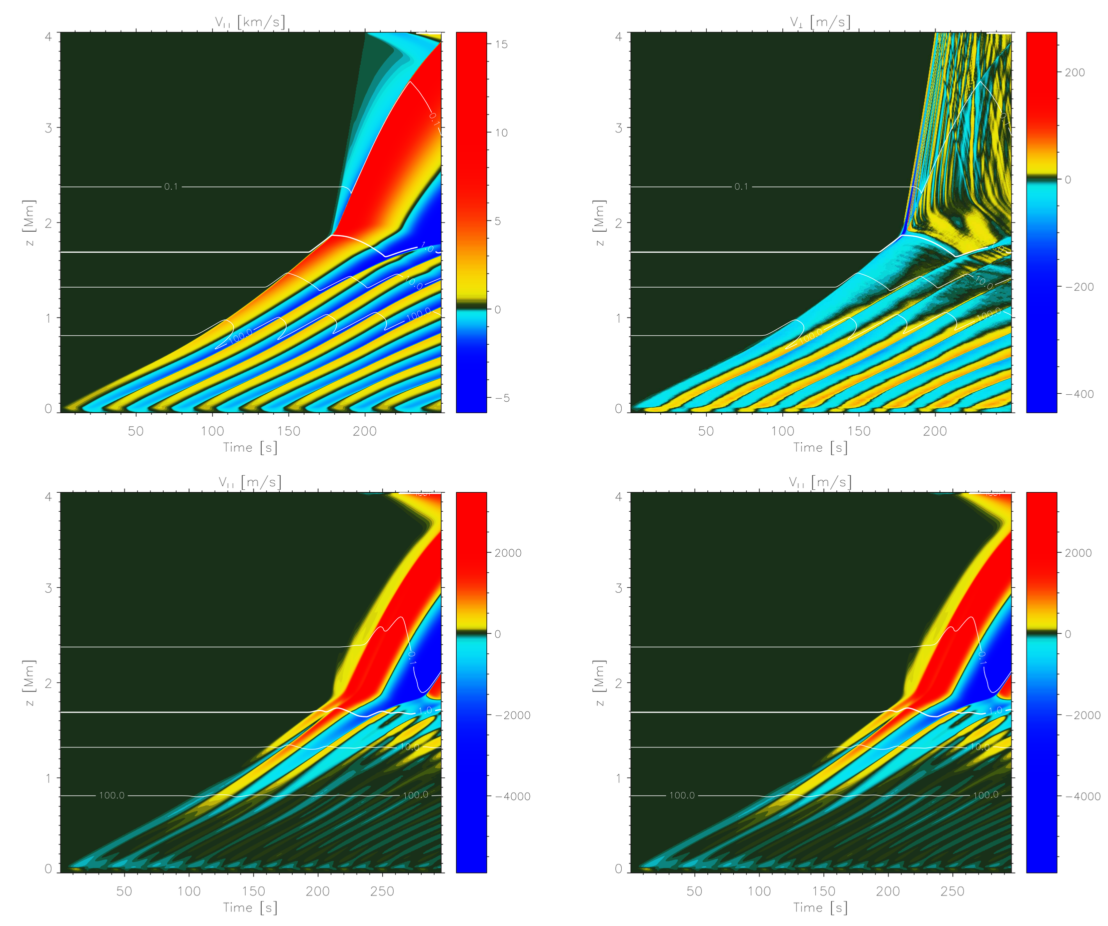

Fig. 7: Altitude vs. time rendering of transverse ($V_{\perp}$) and field-aligned ($V_{\|}$) components of the velocity at $x = 2.0\ Mm$, for vertical (top panels) and transverse driving. The white lines show the altitude variations of selected *iso*-β contours with time, labelled by their appropriate value.

Conclusions

- The magneto-acoustic waves propagate from the photosphere through the transition region to the solar corona, experience relatively low reflection, and transmit most of their energy into the corona;
- The rich pattern of mode conversion and formation of strong shock waves at the region where the plasma beta is equal to unity;
- The thin transition region becomes a wave guide for horizontally propagating surface waves

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