"Physics of Auroral Phenomena", Proc. XXXI Annual Seminar, Apatity, pp. 73- 78, 2008

Polar Geophysical Institute

MODEL STUDY OF TRANSITION FROM IMPULSIVE TO STEADY-STATE RECONNECTION

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Abstract. Observations of magnetic reconnection in the Earth's magnetosphere show that reconnection is very seldom stationary or quasi stationary, more often it has impulsive character. The purpose of this paper is to study the transition from Petschek-like to quasi steady-state reconnection. For this purpose, we use the time-dependent reconnection model for a symmetric current layer. Reconnection is produced by a time-varying reconnection electric field along the x-axis. The temporal variations of the magnetic field and the plasma velocity are computed for a) a one pulse of electric field, b) a steady-state electric field and c) a series of electric field pulses. At small distances from the current layer we find for case c) all signatures of impulsive reconnection, for intermediate distances signatures of steady-state reconnection, and, finally, for large distances it looks like the usual one pulse reconnection.

1. Introduction

Petschek gave in his work (Petschek, 1964) a solution for a steady-state reconnection model. The global evolution of magnetic flux tubes is described by a local reconnection across an initially magnetically closed current carrying surface, the current sheet. Within ideal magnetohydrodynamics (MHD) a local dissipative electric field, which is tangential to the surface, produces a broken tangential discontinuity. In detail this means that the surface breaks into a thin boundary layer which collects plasma from the near flux tubes and accelerates the plasma with Alfvénic speed v_A. This kind of shock structure propagates then outward along the current sheet during the switch-off phase (Figure 1). The magnetic fields above and below the current sheet, which are initially antiparallel directed, are connected via the shocks, both bound the outflow region (OR). The surrounding area is then called the inflow region (IR).

In nature reconnection has more often an unsteady and patchy behavior of impulsive character. If there is a series of several pulses propagating in time the reconnection flux increases nearly linear like for steady-state reconnection with the proportionality

$$E^* \approx \frac{\partial F}{\partial t}.$$

E^* stands for the reconnection field and F is the flux. And if the time duration is in average bigger than the pulse itself then the impulsive reconnection can be considered as a quasi steady-state reconnection.

We study in this paper, how we can get a Petschek-like reconnection with a chain of pulses, and at what distance z above the current layer an observer will recognize this transition from impulsive to steady-state reconnection.

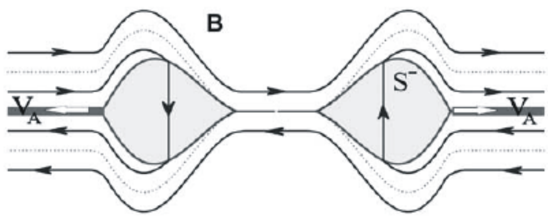

Fig. 1: Time-dependent Petschek-reconnection after Ivanova et al. (2007) and Semenov et al. (2004) in switch-off phase. Heated and accelerated plasma, enclosed by the shocks (S^-), leaves inside the outflow regions (grey) the reconnection scene with v_A. The magnetic fields are connected via the shocks. The dotted line represents the separatrix.

2. Model and calculations

Analytical solutions for impulsive reconnection can be found by using the ideal MHD equations and Rankine-Hugoniot jump relations for incompressible plasma with a constant density ρ (Semenov et al.,2004). Our considerations are based on a 2D-current sheet. It is a tangential discontinuity, which separates two incompressible plasmas with opposite oriented magnetic fields, which are undisturbed and stationary at begin. Inside the diffusion region the electric field $E^*(t)$, which is much less than the Alfvénic electric field E_A, is an arbitrary function of time

$$E^* << \frac{1}{c} B_0 v_A = E_A,$$

and generates moving of discontinuities through the plasmas along the current sheet. Here should be mentioned generally that c is the speed of light, B_0 is the undisturbed magnetic field and v_A stands for the specific Alfvénic speed.

For OR we use the following list of definitions for each component of the plasma velocity and the magnetic field:

$$v_x = v_A = \frac{B_0}{\sqrt{4\pi\rho}},$$
$$v_z = 0,$$

$$B_x = 0,$$
$$B_z = \frac{c}{v_A} E^*\left(t - \frac{x}{v_A}\right).$$

In this case the electric field inside the diffusion region looks like

$$E_y = \frac{v_A}{c} B_z = E^*\left(t - \frac{x}{v_A}\right).$$

On the other hand for IR, the vector components of the magnetic field and the plasma velocity have the form:

$$\vec{B} = (B_0 + B_x^{(1)}, B_z^{(1)})$$

$$\vec{v} = (v_x^{(1)}, v_z^{(1)})$$

The components with index *(1)* are the perturbations of the magnetic field and velocity.

For them we adopt the following from Biernat et al., 1987:

$$B_x^{(1)}(t,x,z) = \frac{1}{\pi}\int_{-\infty}^{\infty} d\xi \frac{(x-\xi) B_z^{(1)}(t,\xi,0)}{(x-\xi)^2 + z^2},$$

$$B_z^{(1)}(t,x,z) = \frac{z}{\pi}\int_{-\infty}^{\infty} d\xi \frac{B_z^{(1)}(t,\xi,0)}{(x-\xi)^2 + z^2},$$

$$v_x^{(1)}(t,x,z) = \frac{1}{\pi}\int_{-\infty}^{\infty} d\xi \frac{(x-\xi) v_z^{(1)}(t,\xi,0)}{(x-\xi)^2 + z^2},$$

$$v_z^{(1)}(t,x,z) = \frac{z}{\pi}\int_{-\infty}^{\infty} d\xi \frac{v_z^{(1)}(t,\xi,0)}{(x-\xi)^2 + z^2}.$$

While for z = 0 we put

$$B_z^{(1)}(t,x,0) =$$
$$2\frac{c}{v_A} E^*\left(t - \frac{x}{v_A}\right) - \frac{c}{v_A^2} x E^{*\prime}\left(t - \frac{x}{v_A}\right)$$

for the disturbed magnetic field and for the analogue velocity

$$v_z^{(1)}(t,x,0) =$$
$$-\frac{v_A}{E_A} E^*\left(t - \frac{x}{v_A}\right) + \frac{x}{E_A} E^{*\prime}\left(t - \frac{x}{v_A}\right).$$

All calculations are done with a scaling of T, $v_A T = L$, B_0, and v_A.

3. Results

For modelling the pulses we use this periodic function

$$E^*(t) = \varepsilon \sin^2(\pi t), \qquad 0 \le t < 1$$

to avoid further jumps in generating shock structures in regard to its derivation.

Here we compute the electric fields and their derivations with $\varepsilon = |E^*|/|E_A| = 0.1$.

For all pictures *t* is the normalized time *T* and the distances are measured in units of *L*. *z* defines the height of the observer (e.g. satellites in the tail of the magnetosphere of Earth) above the current layer.

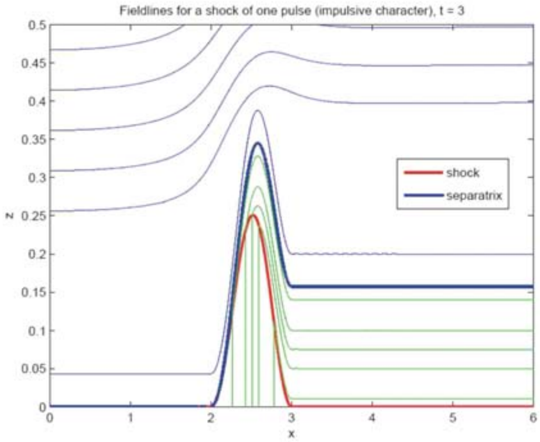

Fig. 2: Model of the shape of one impulsive shock, which propagates in x direction through space after a time period of t = 3, and the magnetic field lines influenced by it.

Figure 2 illustrates an impulsive reconnection for one pulse. It shows a solitary wave with a specific length of one. This comes from a short switch-on and -off of an electric field in the current layer. But we made this picture only for the first quadrant of a Cartesian system.

For the following Figures of one pulse it is the same, the shock wave only disturbs only for a short period and very locally the magnetic fields above and under the current sheet.

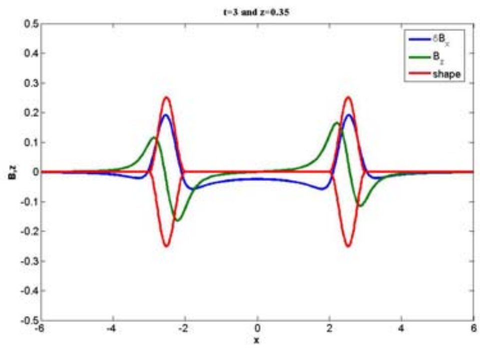

Fig. 3: Position of magnetic field components in space after a time t = 3.

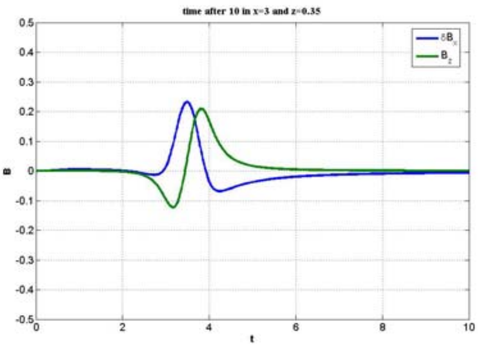

Fig. 4: Magnetic field components, seen by an observer at a position of x = 3 and z = 0.35 above the current layer.

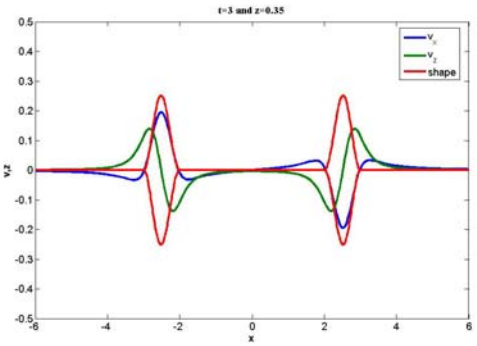

Fig. 5: Velocity components of the plasma flow in space after a time period of t = 3.

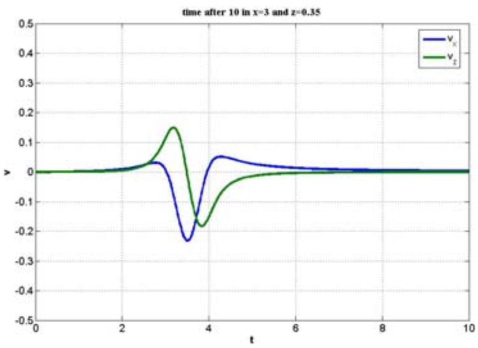

Fig. 6: Plasma velocity components, seen by an observer at a position of x = 3 and z = 0.35 above the current layer.

We create the following Figures (7 – 11) for the case of a typical steady-state reconnection, where the electric field is switched on one time and keeps its value constant during its whole life of propagation along the current sheet.
As a consequence even the disturbance of the magnetic field and plasma velocity components assume a constant level after several time duration, Only at the begin of the shock wave (switch-on) the components react a little bit impulsive.

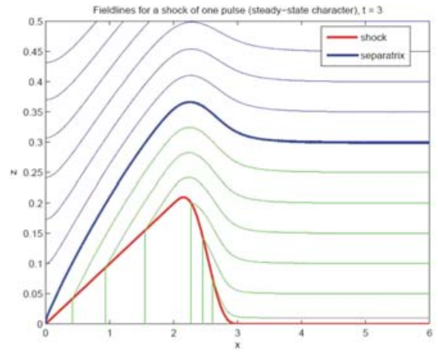

Fig. 7: Model of the shape of one steady-state shock, which propagates in x direction through space (shown for a time after t = 3), and the even here with the influenced magnetic field lines.

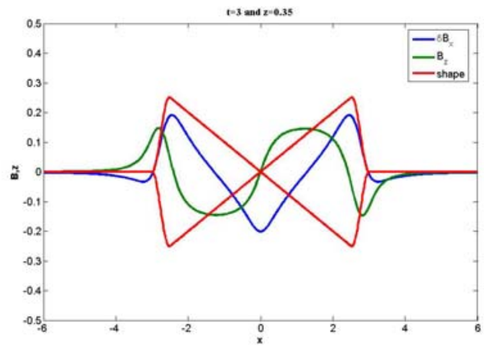

Fig. 8: Position of the magnetic field components in space after a time t = 3.

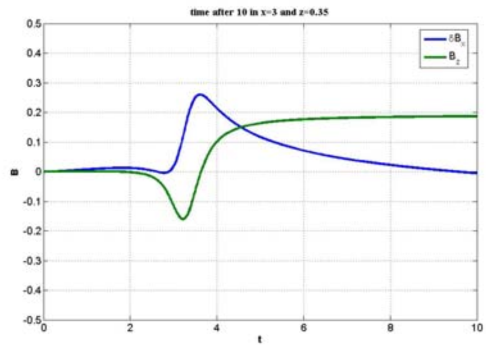

Fig. 9: Magnetic field components, seen by an observer at a position of x = 3 and z = 0.35 above the current layer.

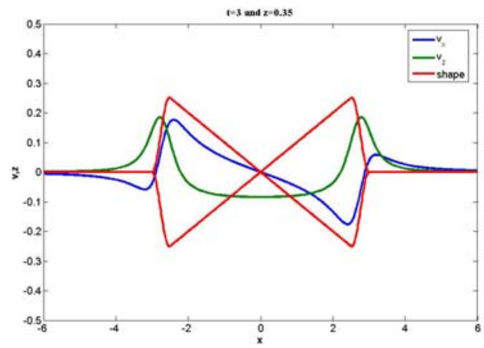

Fig. 10: Velocity components of the plasma flow in space after a time period of t = 3.

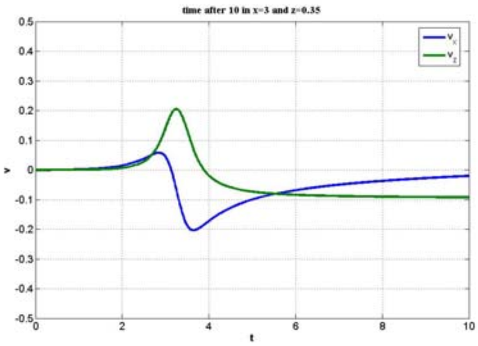

Fig. 11: Velocity components, seen by an observer at a position of x = 3 and z = 0.35 above the current layer.

We use the Figures 2 – 11 to give the reader of this article an imagination about the transition from impulsive to steady-state character during the reconnection process with multiple pulses, when he is looking at our results for a series of many pulses.

The last Figures should now gain a short insight, what is happening if the observer moves away from the current layer with increasing z, when he is confronted with a series of seven pulses. We compute for all formulas with a time delay Δt = 1.5 between each shock wave. That means after the switch-on of a pulse the next pulse follows after Δt.

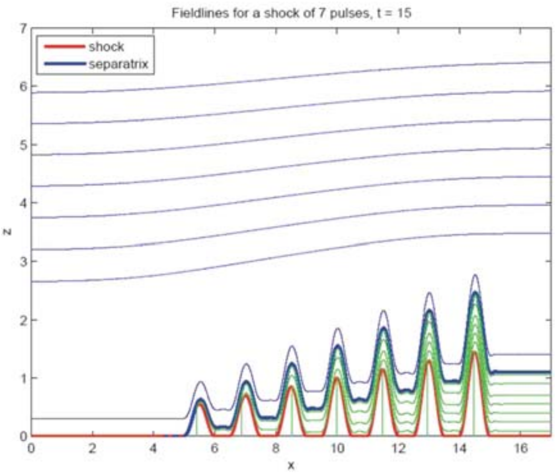

Fig. 12: Model of the shape of seven shocks in the upper half of the coordinate system, propagating in x direction.

The Figure 12 is generated for a series of seven pulses with their disturbing influence to the magnetic field lines. We use a time duration of about t = 15, because after this time all shocks alive and propagate along the current sheet.

The following Figure 13 should give an imagination about the increase of the flux F during time for many pulses (solid line). We put into this picture even the electric field and the flux for the steady-state case (dotted line). As shown in this Figure even in the impulsive case the flux grows nearly linear in time, which allows us to investigate a series of pulses like one pulse of Petschek-like time-dependent reconnection.

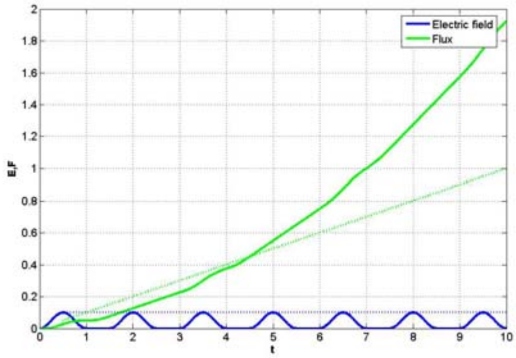

Fig. 13: Electric field and flux in time for impulsive (solid line) and steady-state reconnection (dotted line).

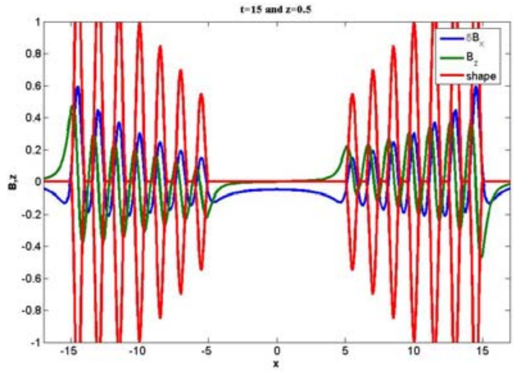

Fig. 14: Position of the magnetic field components in space after a time t = 15 for near observation.

If the observer is near the current sheet, he will see every single pulse of the series with every disturbance of the pulses, which is very well visualised in the Figures 14 – 17.

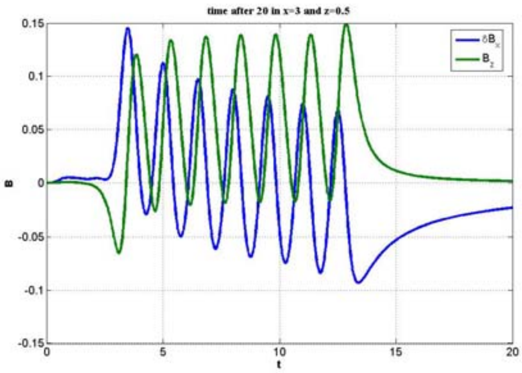

Fig. 15: Magnetic field components, seen by an observer at a position of x = 3 and z = 0.5 above the current layer during a time period of t = 20.

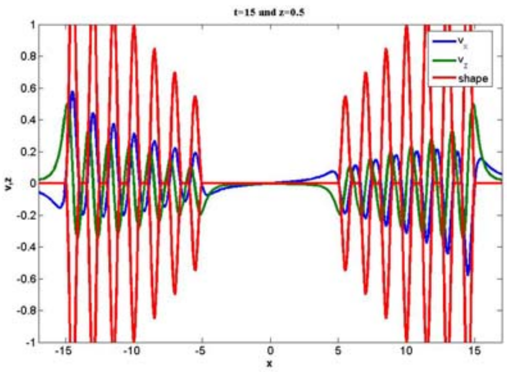

Fig. 16: Velocity components of the plasma flow in space after a time period of t = 15 for near observation.

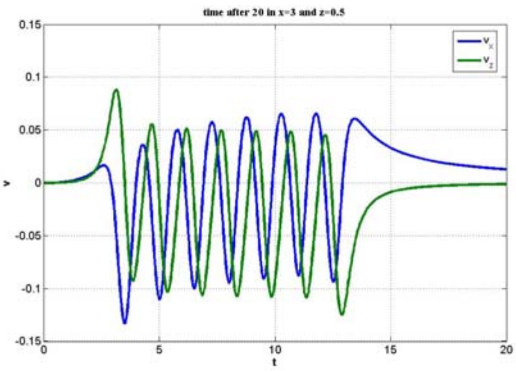

Fig. 17: Velocity components, seen by an observer at a position of x = 3 and z = 0.5 above the current layer during a time period of t = 20.

Looking at the following Figures 18 – 21 for an intermediate distance from the current sheet (z = 1.2) it exposes, like we supposed before, that the impulsive character turns to be steady-state (compare with the Figures for steady-state above).

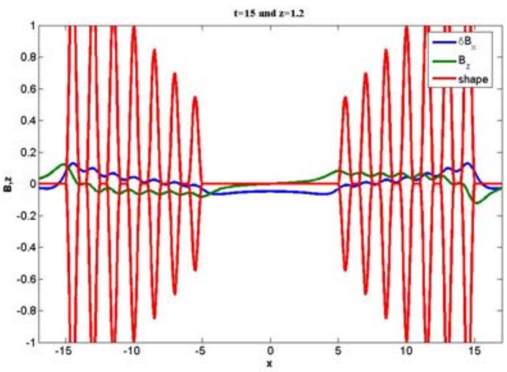

Fig. 18: Position of the magnetic field components in space after a time t = 15 for an intermediate observation.

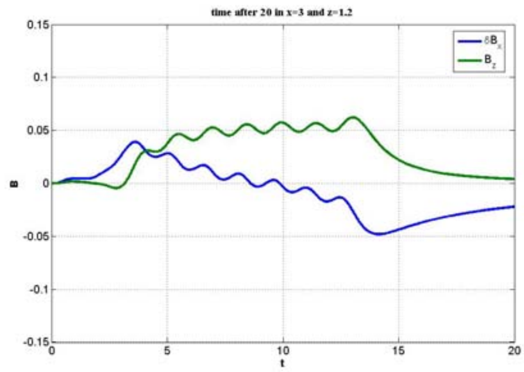

Fig. 19: Magnetic field components, seen by an observer at a position of x = 3 and z = 1.2 above the current layer during a time period of t = 20.

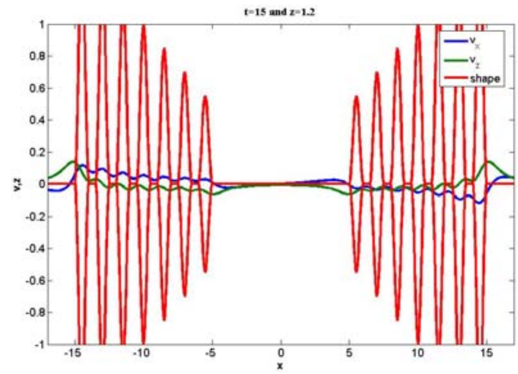

Fig. 20: Velocity components of the plasma flow in space after a time period of t = 15 for an intermediate observation.

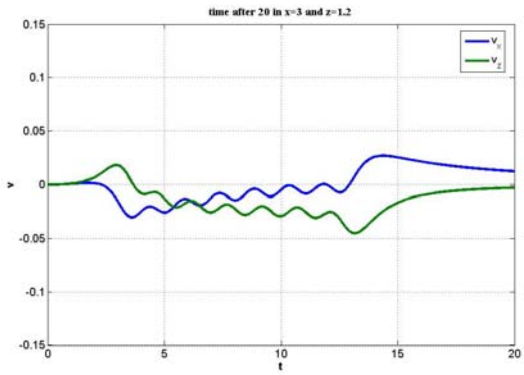

Fig. 21: Velocity components, seen by an observer at a position of x = 3 and z = 1.2 above the current layer during a time period of t = 20.

We proof now this statement with the last Figures in this paper for a real far distance of the observer from the current sheet. And at such far distances we get all signatures again of an impulsive reconnection.

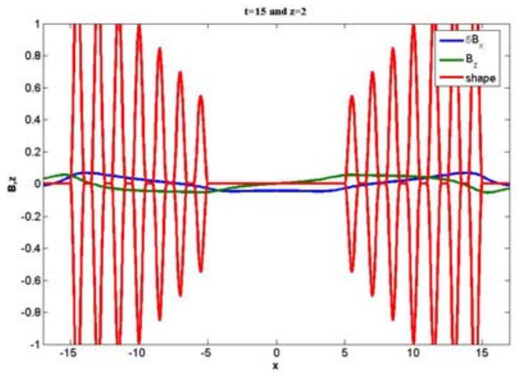

Fig. 22: Position of the magnetic field components in space after a time t = 15 for a far distant observation.

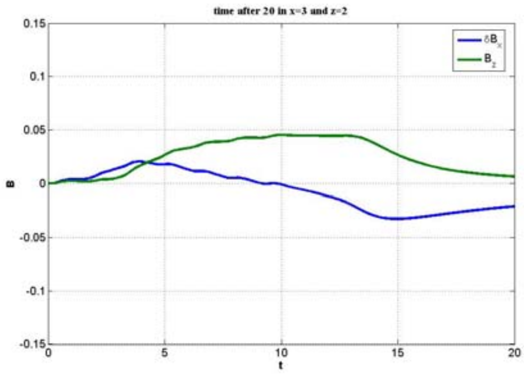

Fig. 23: Magnetic field components, seen by an observer at a position of x = 3 and z = 2 above the current layer during a time period of t = 20.

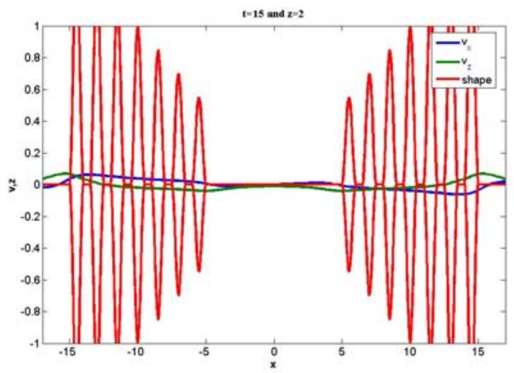

Fig. 24: Velocity components of the plasma flow in space after a time period of t = 15 for a far distant observation.

4. Conclusion

At small distances z from the current layer we find for the case of a series of many pulses all signatures of impulsive reconnection. So an observer can really distinguish between every single pulse by their disturbances in the magnetic field. And he even sees the different velocities in the plasma.

At intermediate distances signatures of steady-state reconnection appear for the observer. So locally we have an impulsive character, but far away it is like Petschek, if the time duration of the whole series is much longer than of one pulse. Therefore we can affirm that we can just use the Petschek steady-state reconnection in a natural completely impulsive case.

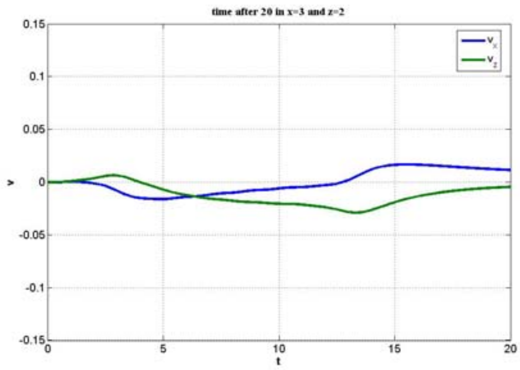

Fig. 25: Velocity components, seen by an observer at a position of x = 3 and z = 2 above the current layer during a time period of t = 20.

Acknowledgements. S.P. acknowledges the "KUWI" funding by the Graz University of Technology, office for "International Relations and Mobility Programs", for a scientific stay at the St.Petersburg State University, department of geophysics.

V.S.S. acknowledges support from the Graz Technical University and thanks the "Institute of Theoretical and Computational Physics" for their hospitality during scientific visits to Graz. His work is supported by the RFBR grants No. 07-05-00776a.

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