Simulation of a plasmoid penetrating a magnetic barrier

Herbert Gunell[a], Jeff Walker[a], Tomas Hurtig[b], Mark Koepke[a], Nils Brenning[c], and Hans Nilsson[d]

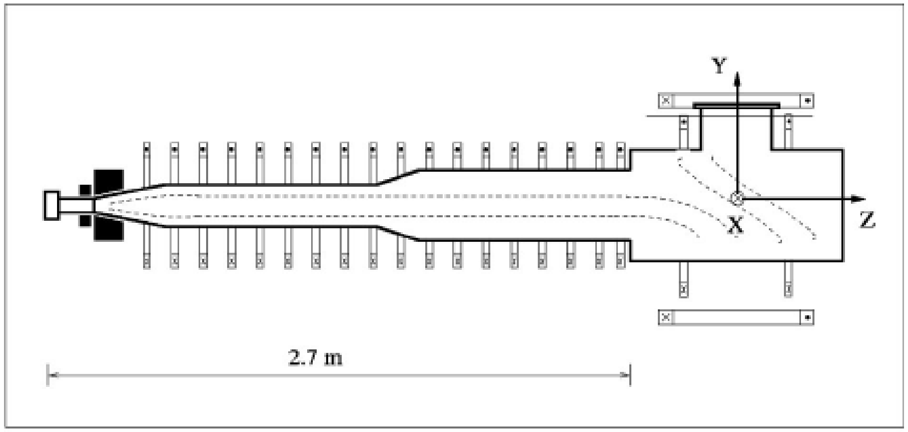
[a] West Virginia University, Morgantown, WV, USA
[b] Swedish Defence Research Agency, Stockholm, Sweden
[c] Royal Institute of Technology, Stockholm, Sweden
[d] Swedish Institute of Space Physics, Kiruna, Sweden

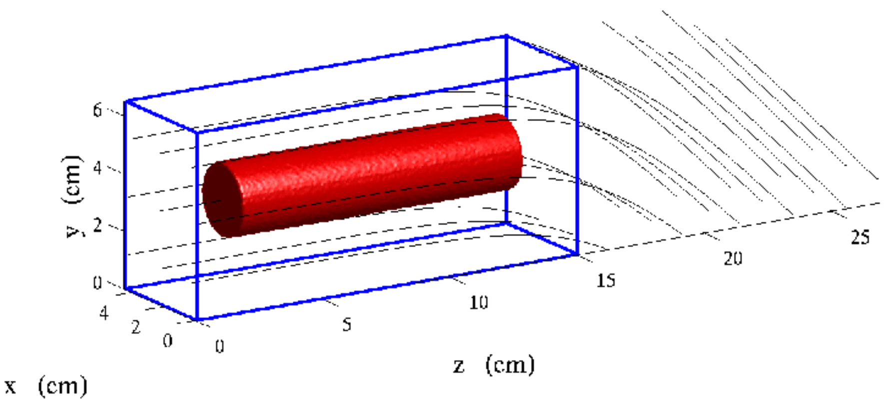
WestVirginiaUniversity

Abstract

Plasma structures, here typified by the term "plasmoids", in the solar wind impacting on the magnetopause, i.e., the boundary between the solar wind and the earth's magnetosphere, can penetrate this boundary and be injected into the magnetosphere. This can happen either by expulsion of the magnetic field from the structure and subsequent diffusion of the magnetic field into the structure, or by formation of a polarisation electric field that lets the plasmoid $\vec{E} \times \vec{B}$-drift in the earth's magnetic field. In both cases a collisionless resistivity is required at some stage of the process. While magnetic expulsion requires electromagnetic models for its description, polarisation can be modelled electrostatically. Both processes can be studied in laboratory experiments. We present three-dimensional electrostatic particle-in-cell simulations that reproduce large-amplitude waves, in the lower-hybrid range, that have been observed in laboratory experiments. Simulations of plasmoids that are longer than those previously published have been run over longer periods of time. We find that waves are propagating upstream from the barrier, and also that the penetration process causes the part of the plasmoid that is upstream of the barrier to rotate. The application of theoretical predictions to the magnetopause environment shows that a plasma structure penetrating via polarisation needs to be small, i.e., less than 10–100 km wide for typical parameters, and that wave processes at the magnetopause are needed to create such small structures [1]. The interchange Rayleigh–Taylor instability is a candidate for producing these structures.

Recent experiments





Schematic of the KTH plasma gun; now at WVU (top) [2], and simulation region and magnetic field lines (bottom). The simulation box moves to the right in the figure with the initial bulk velocity of the plasma, v_0.

parameter	sim.	exp. [2]
$v_0/(\mathrm{km/s})$	300	300
$B_\perp/\mathrm{T}$	0.05	0.015
n_0/m^{-3}	10^{16}	10^{18}
m_i/m_e	92	1836
W_K/W_E	756	$8 \cdot 10^5$
$\frac{1}{10}\frac{W_K}{W_E}\sqrt{\frac{m_e}{m_i}}$	7.9	$2 \cdot 10^3$
$\beta_k = W_K/W_B$	$8 \cdot 10^{-4}$	0.8
$\Pi = \frac{w}{r_{\mathrm{gi}}} K \sqrt{\beta_{\mathrm{ith}}}$	$4.2 \cdot 10^{-3}$	0.1

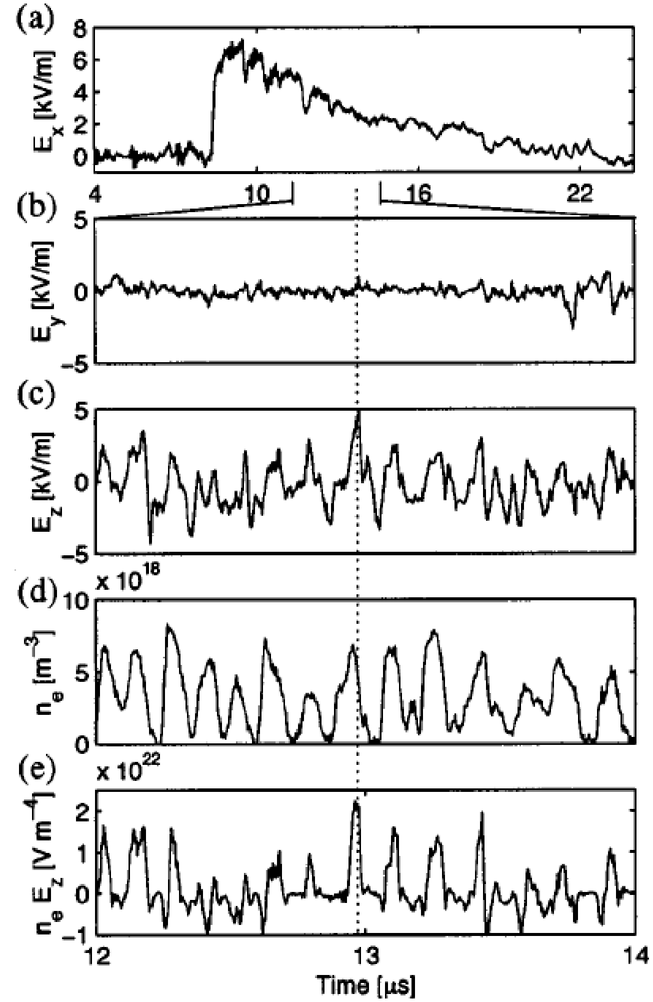
$$W_K = \frac{1}{2} n_0 m_i v_0^2$$

$$W_E = \frac{1}{2} \epsilon_0 \left(v_0 B_\perp\right)^2$$

$$W_B = \frac{B_\perp^2}{2\mu_0}$$

Previous results

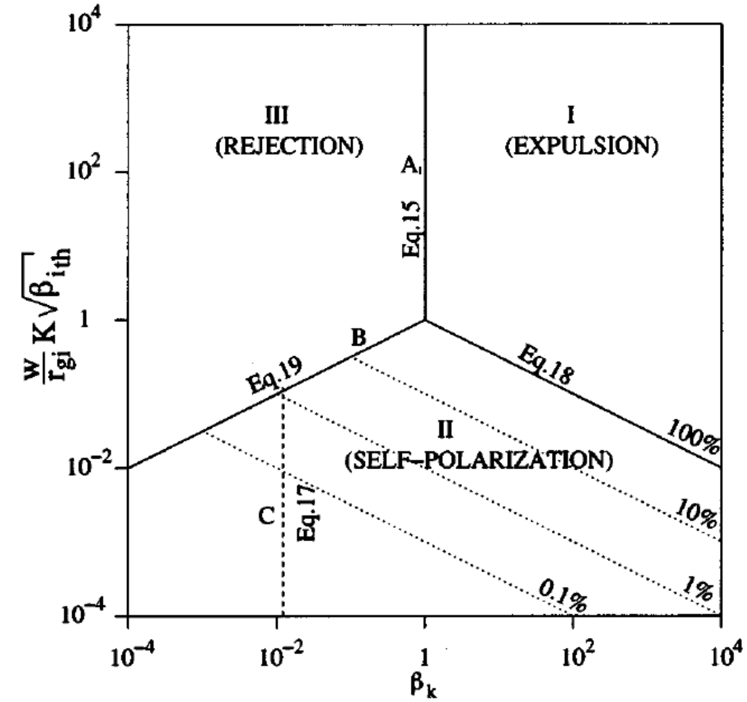
- When $W_K \gg W_E$ an electric field is set up that allows the plasma to $\vec{E} \times \vec{B}$-drift into the transverse magnetic field [3].
- For quasi-neutrality to be maintained one needs to require that $W_K/W_E \gg \sqrt{m_i/m_e}$ [4].
- It was found experimentally that unless $W_K/W_E > 10\sqrt{m_i/m_e}$ longitudinal oscillations and sheath formation prevent penetration [5].
- A recent series of experiments revealed a wave-driven electron transport, perpendicular to $\vec{B}$ and $\vec{v}_0$, into the high potential side [6].
- Waves on the lower-hybrid frequency scale were seen in simulations [1].



Wave-driven electron drift observed in a plasma gun experiment. Picture from [6].

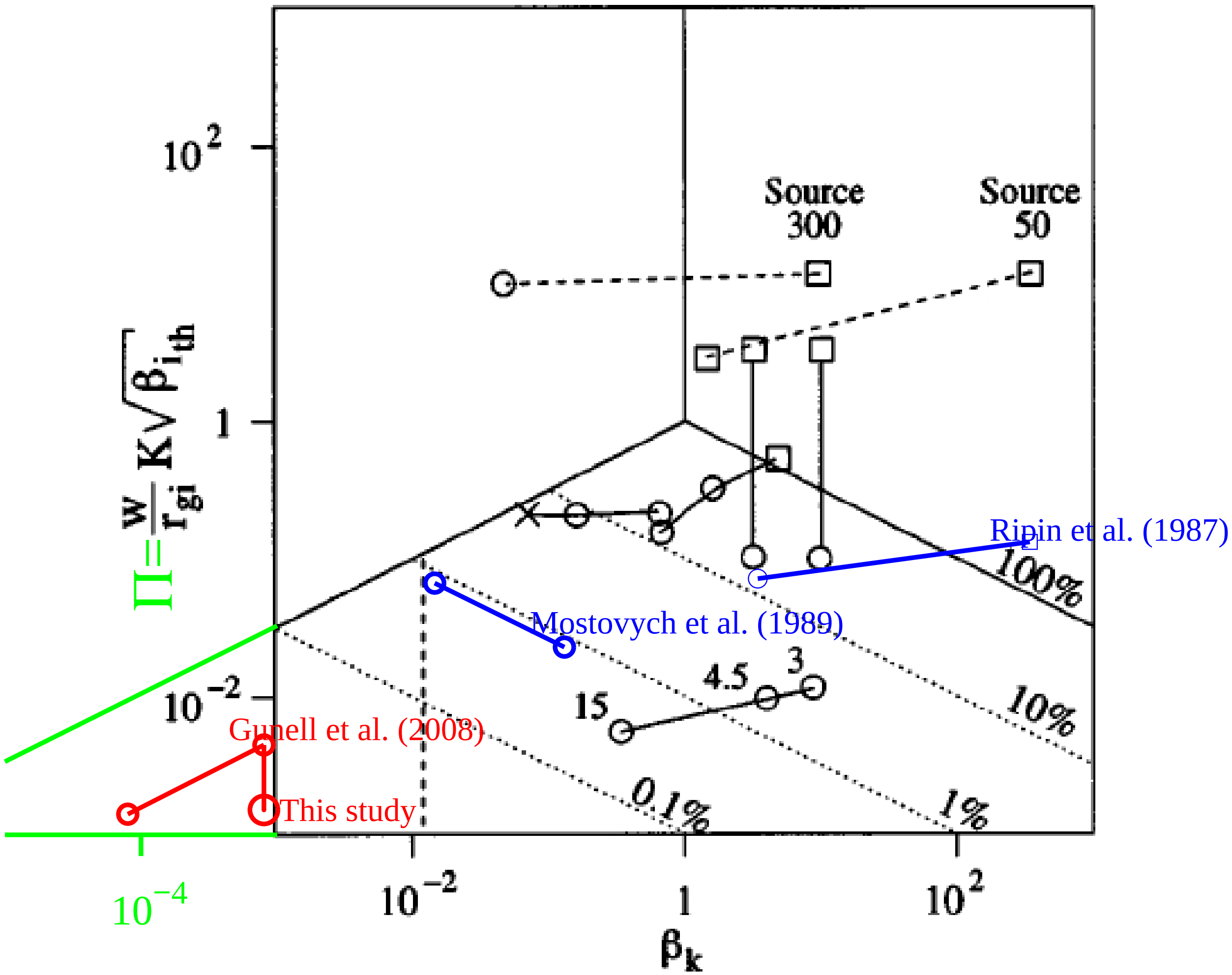
Parameter regions: definitions

Brenning, et al. [7] suggested an analytical model for the non-linear magnetic diffusion, and proposed that experiments and observations can be classified by dividing the parameter space into three regions corresponding to three different outcomes of a penetration experiment. With the width of the plasma equal to w, the ion gyro radius $r_{\mathrm{gi}} = m_{\mathrm{i}} v_0/(\mathrm{e}B_\perp)$, the magnetic energy density $W_B = B_\perp^2/(2\mu_0)$, the kinetic beta $\beta_{\mathrm{k}} = W_K/W_B$, the ion thermal beta $\beta_{\mathrm{ith}} = \frac{1}{2} n_0 m_{\mathrm{i}} v_{\mathrm{ith}}^2/W_B$, the penetrability parameter $\Pi = (w/r_{\mathrm{gi}})\, K\sqrt{\beta_{\mathrm{ith}}}$, and $K = 2.3$ being an empirically determined constant, these regions are [7]



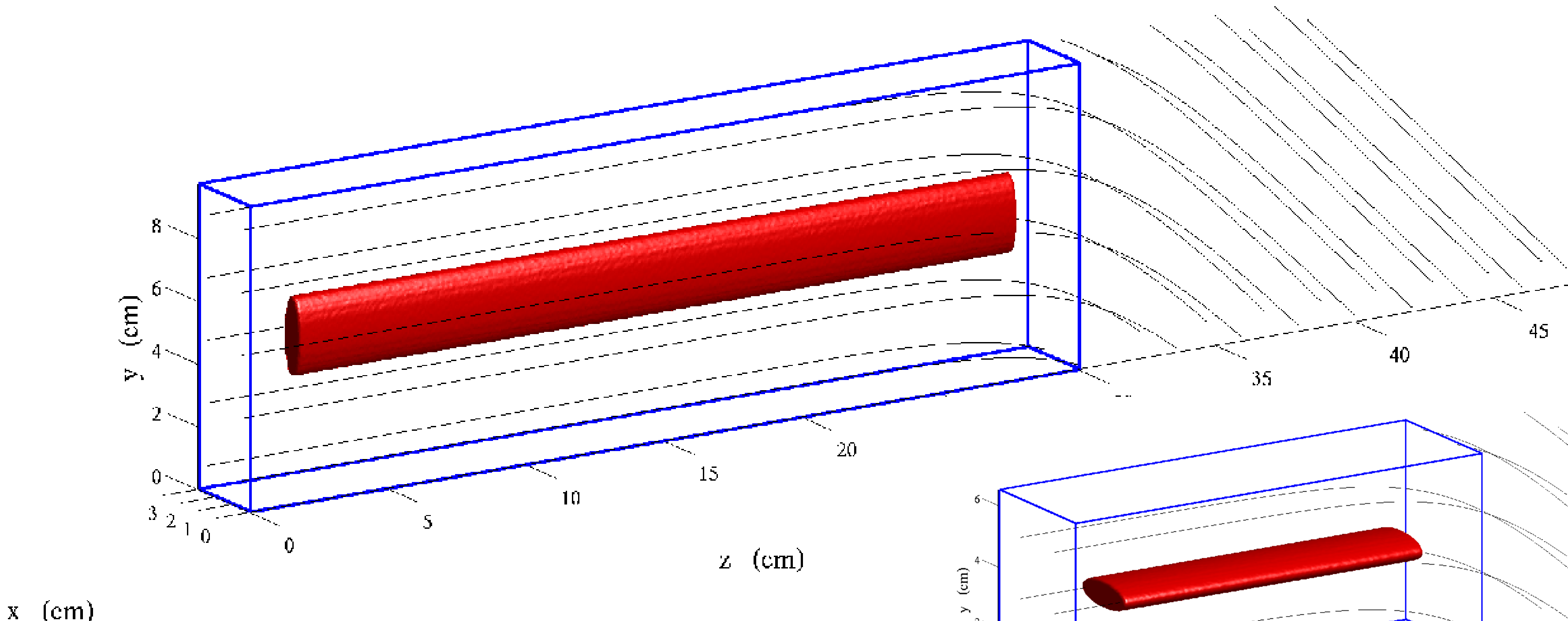
1. **Expulsion.** A plasma structure can penetrate a magnetic barrier by expelling the magnetic field if $\beta_{\mathrm{k}} > 1$ and $\Pi > 1/\sqrt{\beta_{\mathrm{k}}}$.
2. **Self-polarisation.** A plasma structure can penetrate a magnetic barrier by convection in a polarisation electric field if $\Pi < \sqrt{\beta_{\mathrm{k}}}$ for $\beta_{\mathrm{k}} < 1$ and $\Pi < 1/\sqrt{\beta_{\mathrm{k}}}$ for $\beta_{\mathrm{k}} > 1$.
3. **Rejection.** The plasma cannot penetrate the magnetic barrier if $\beta_{\mathrm{k}} < 1$ and $\Pi > \sqrt{\beta_{\mathrm{k}}}$.

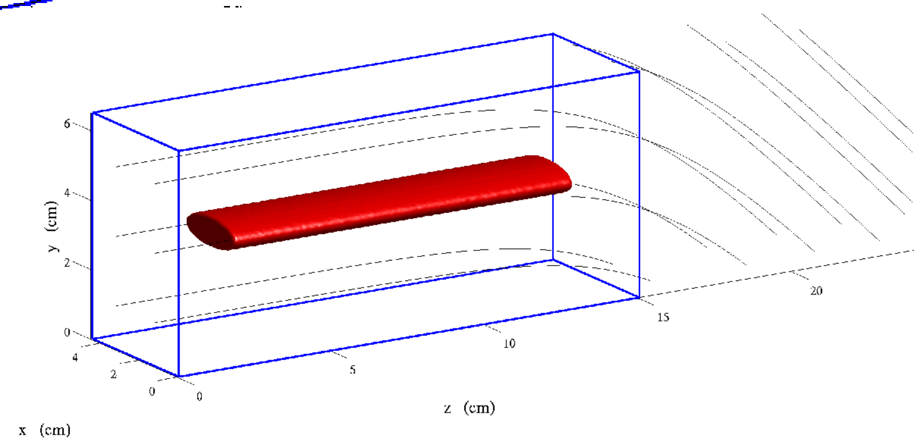
Parameter regions: map

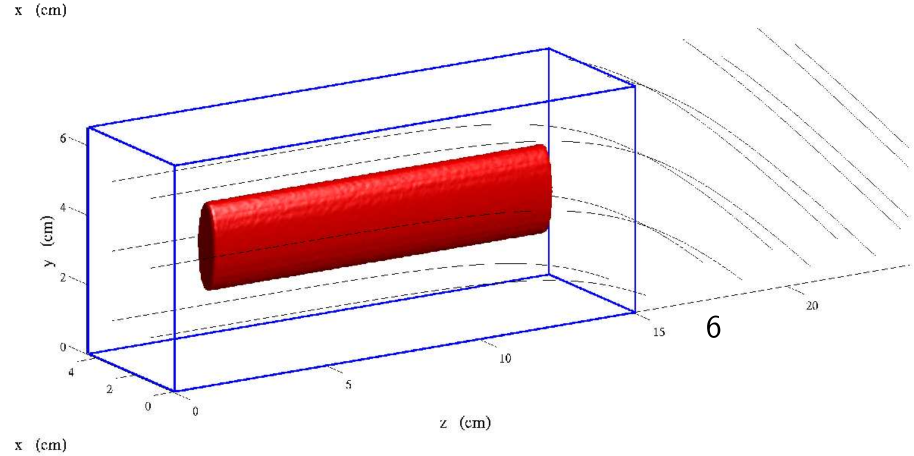


The location of a number of experiments in the $\Pi - \beta_k$ parameter space. The picture is taken from [7] with addition of the experiments by Ripin, et al. [8] and Mostovych, et al. [9] in blue, and the simulations of Gunell, et al. [1] and this study in red.

Simulation geometry

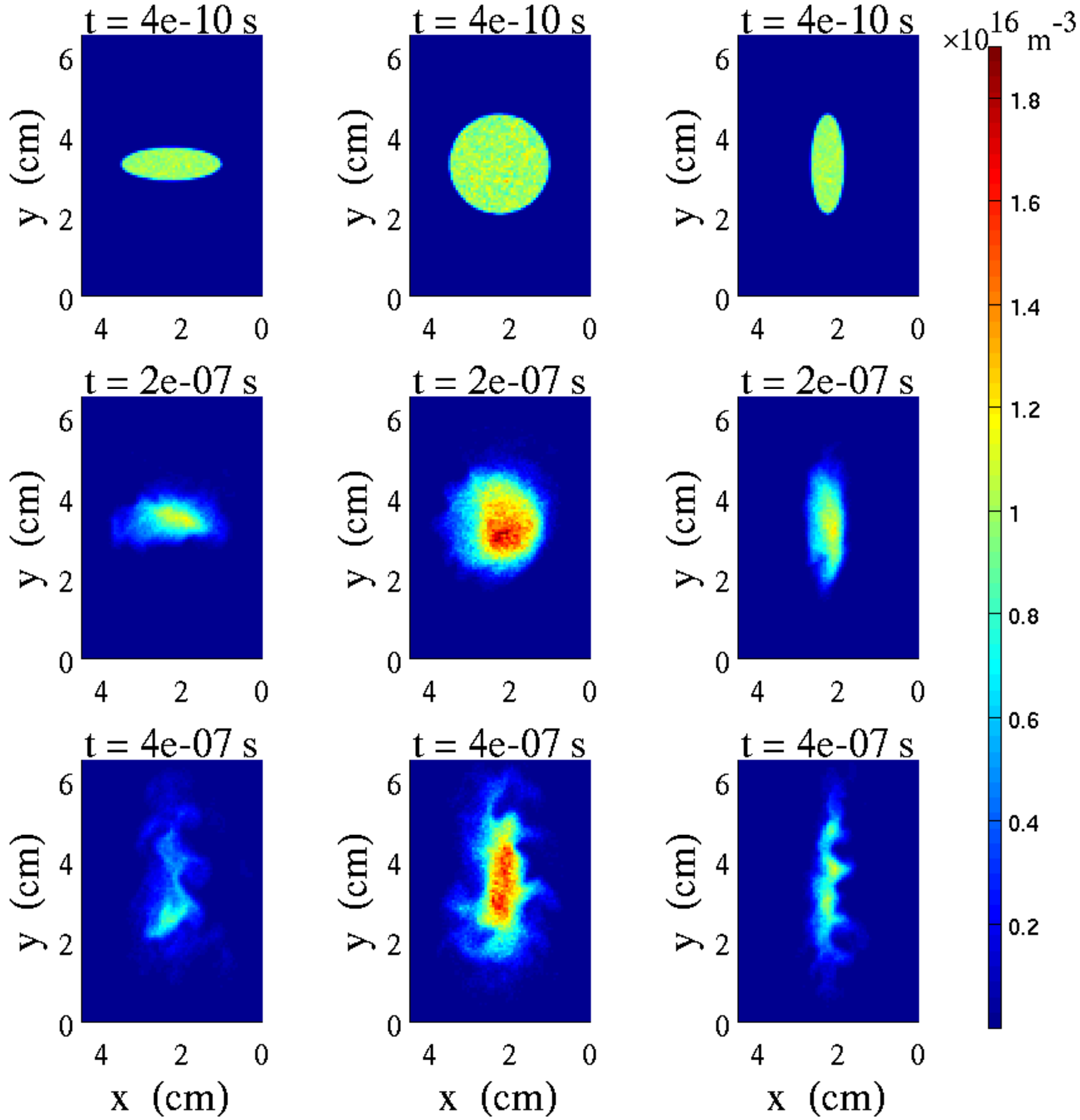






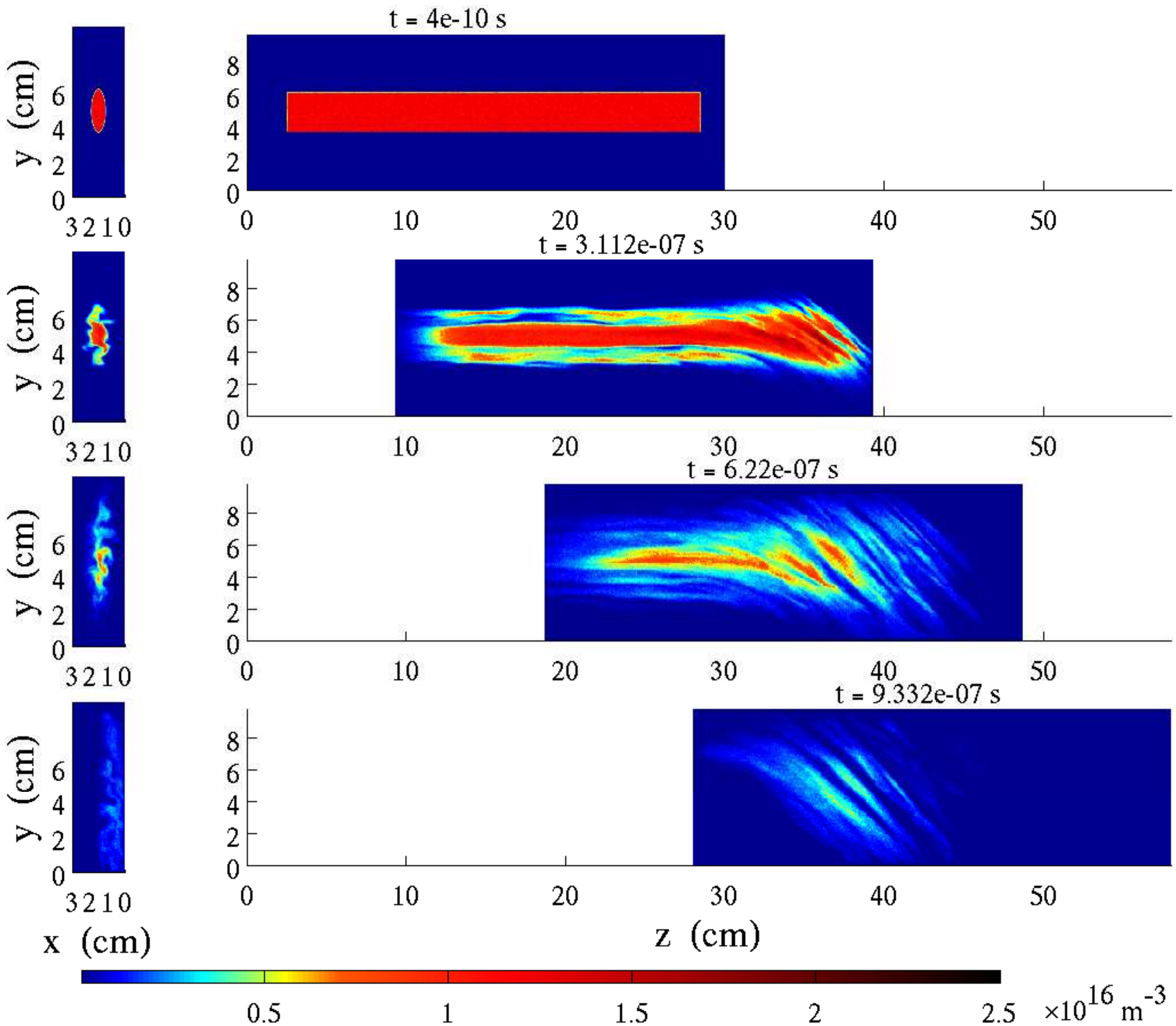
Three different initial plasma geometries: a long plasmoid, whose cross section is a vertical ellipse, a plasmoid with a horizontal elliptic cross section, a plasmoid with a vertical elliptic cross section, section is a vertical ellipse.

Cross sectional shape

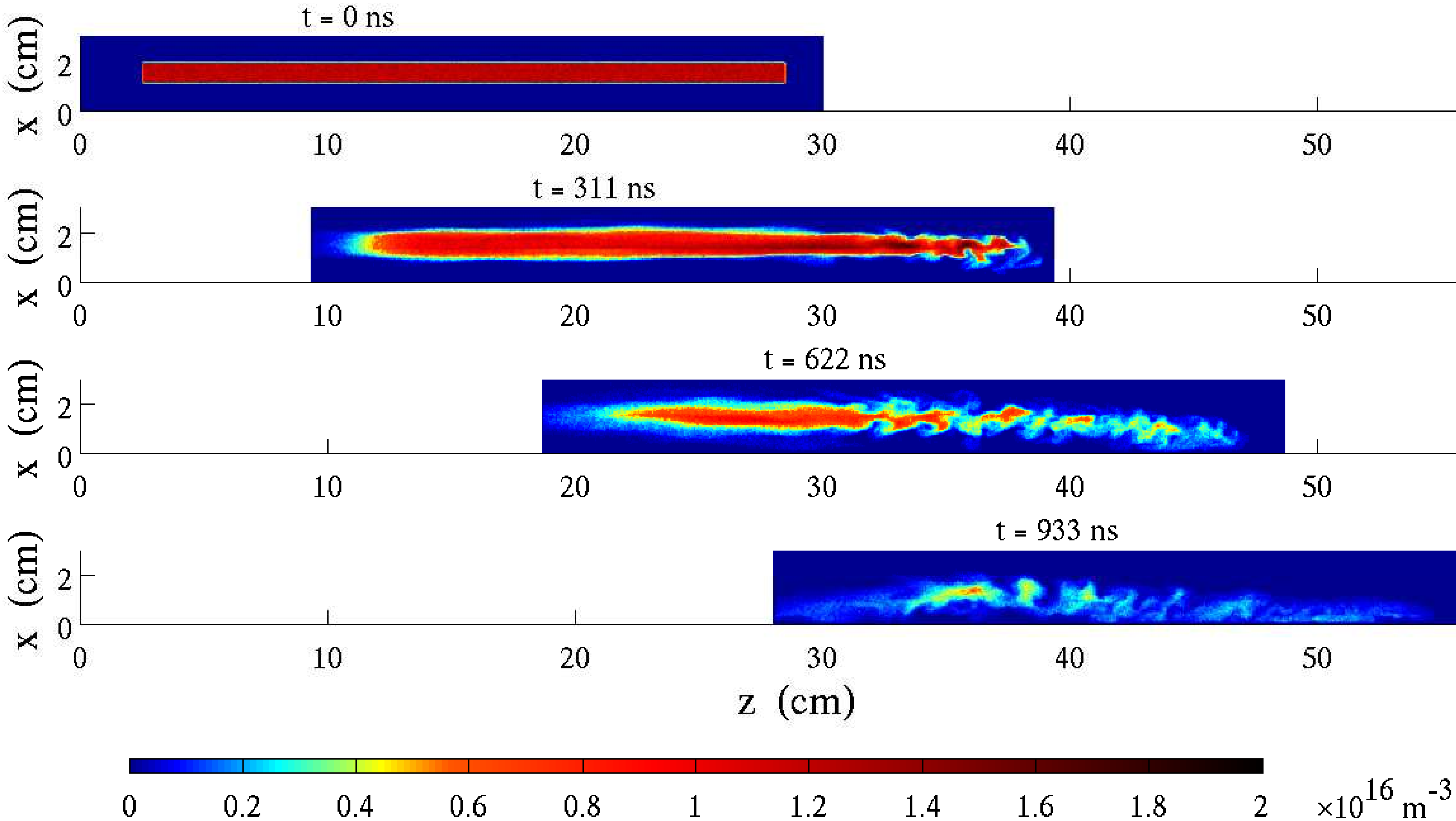


Three simulations with different initial cross sectional shapes at three different simulation times. After 400 ns (bottom row) all plasmoids have been compressed into similar vertical structures.

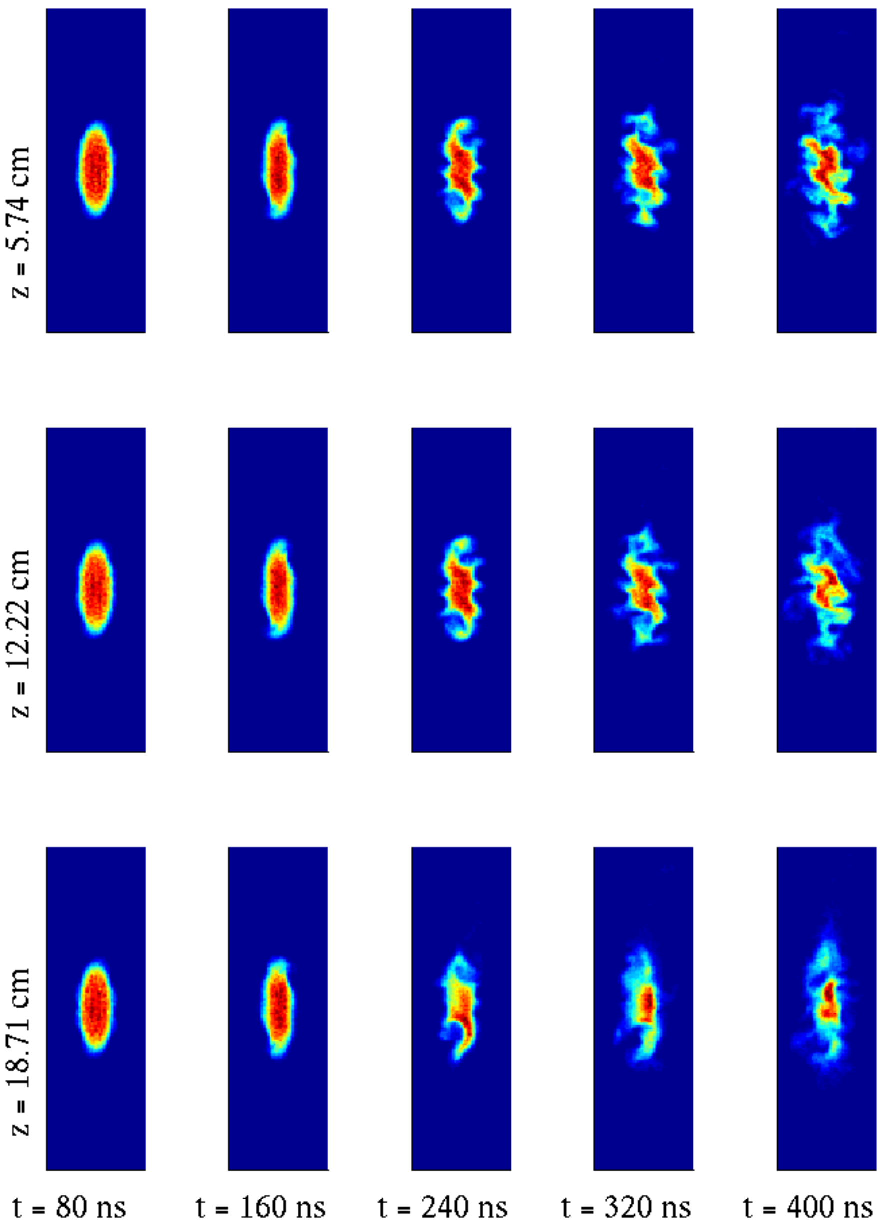
Plasma density at different times



Density in the zx-plane



Non-rigid rotation

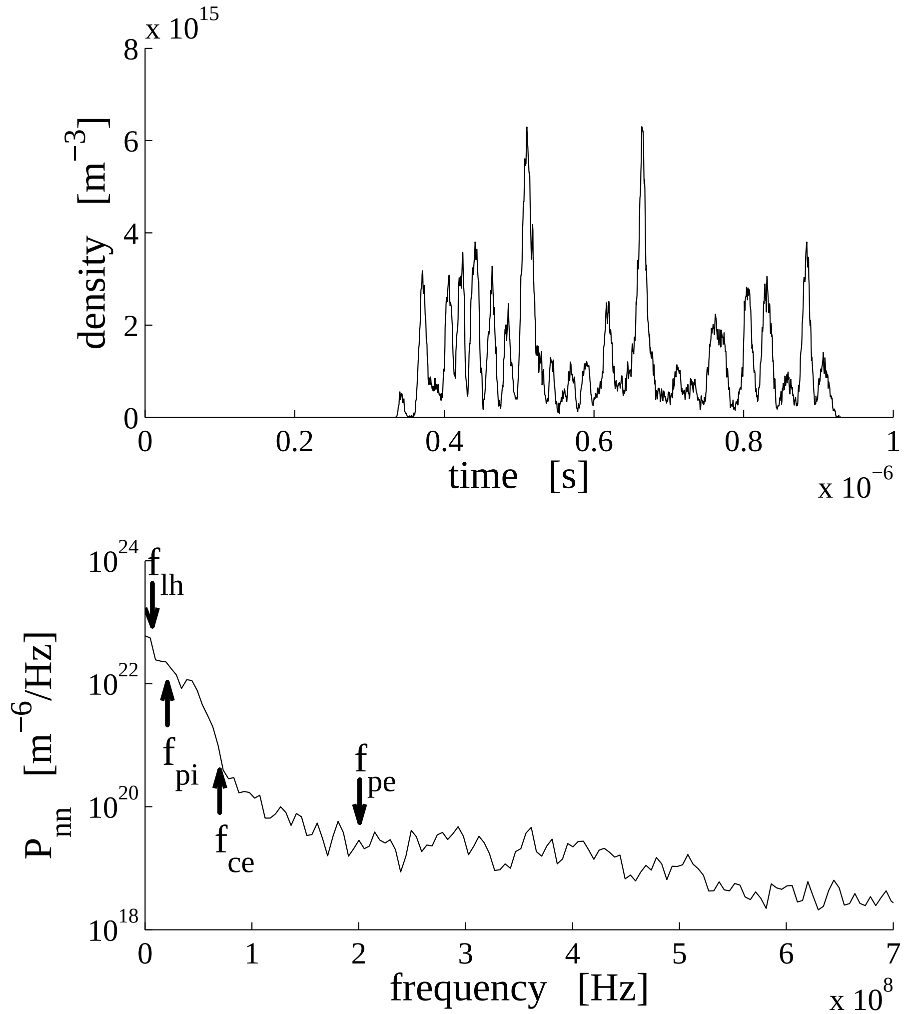


Slices of plasma density in the xy-plane for three different z-positions at five different times.

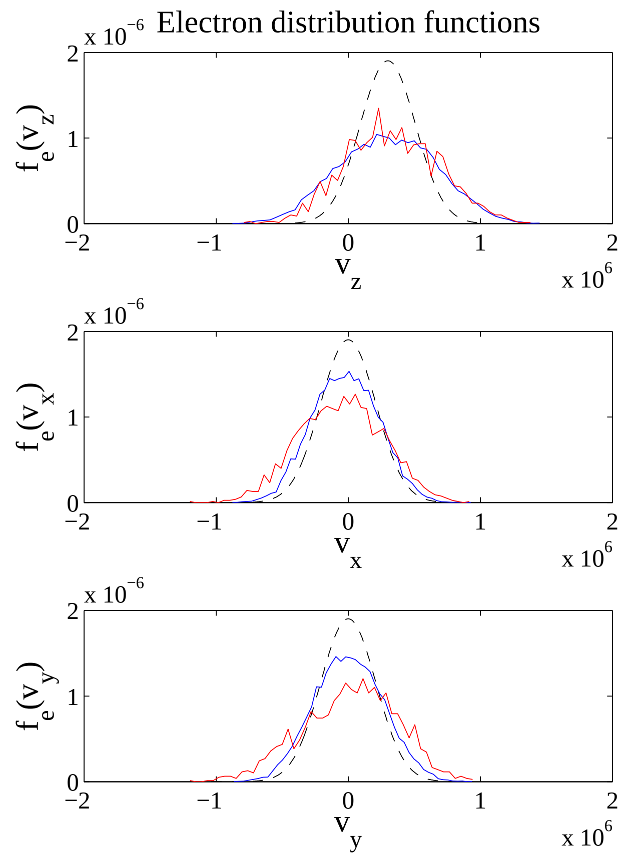
When the front of the plasmoid enters the transverse field, a non-rigid rotation can be seen in the parts of the plasmoid that has not yet reached this region.

A perturbation must be travelling upstream from the curved field region. This is also seen in the figure on page 8, which shows slices of the plasma density in the yz-plane.

Waves in the lower-hybrid frequency range

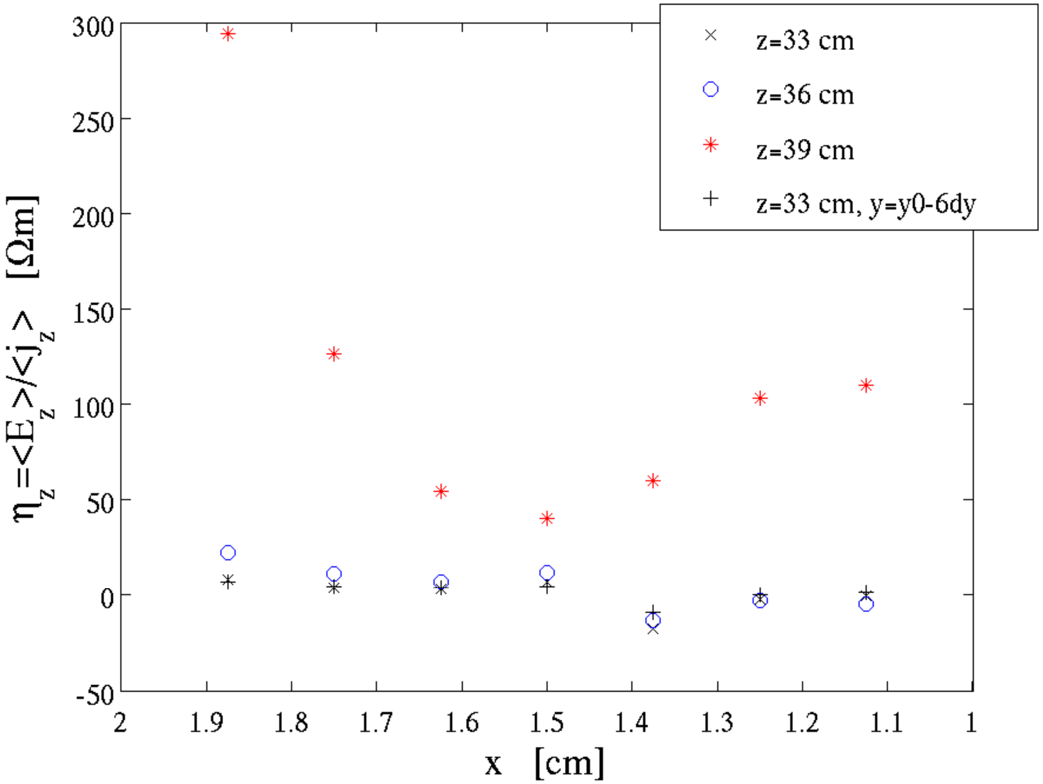


Density probe at $z = 0.39$ m.



Electron distribution functions for $t = 0$ (dashed black line), $t = 480$ ns (blue line), and $t = 920$ ns (red line).

Resistivity



Resistivity $\eta_z = \langle E_z \rangle / \langle j_z \rangle$ as a function of x for different values of z.

Hurtig, et al. [6], estimated the wave-induced resistivity

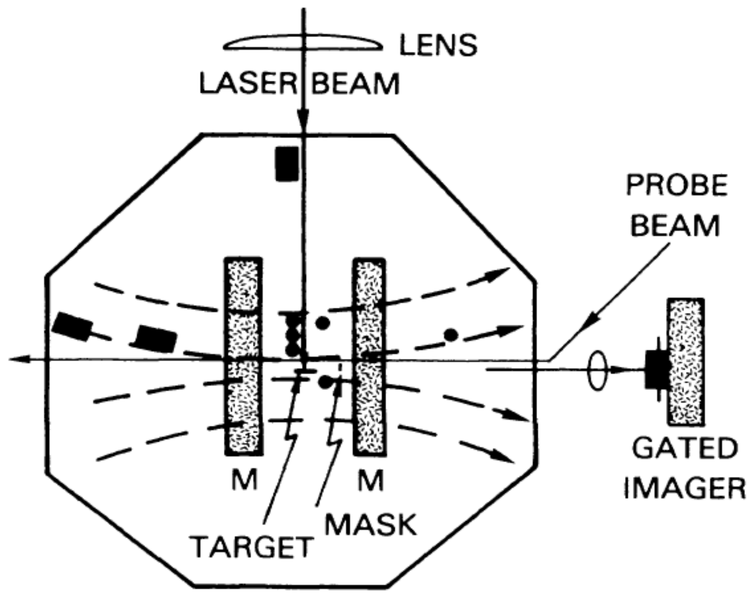
$$\eta_{wave} = \frac{\langle n_e E_z \rangle}{e\,(v_i - v_e)\,\langle n_e \rangle^2}$$

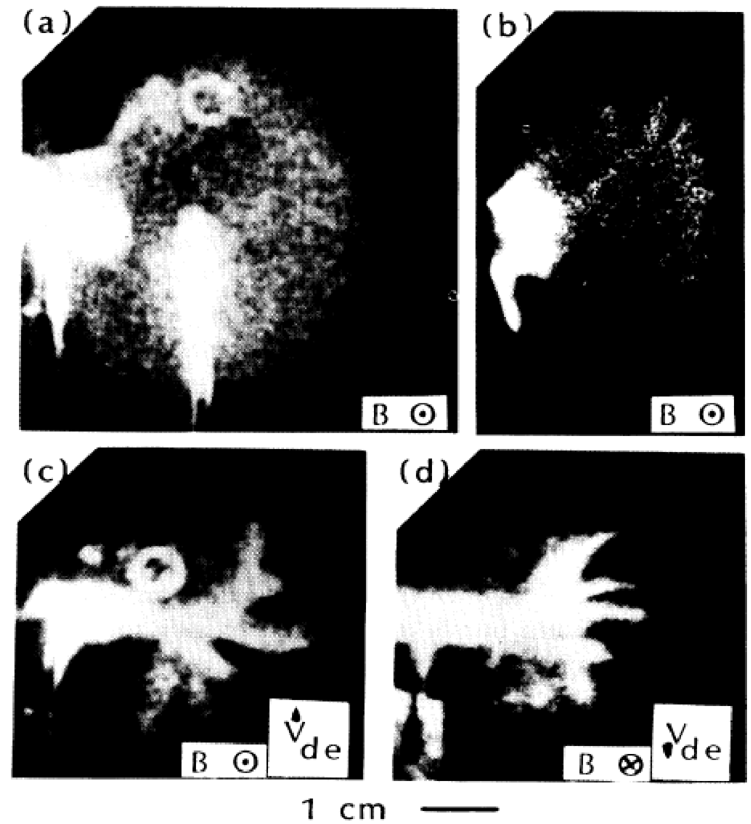
from measured densities and fields in their $n_e = 3.2 \cdot 10^{18}$ m^{-3} plasma and arrived at

$$\eta_{wave} \approx 0.0068\ \Omega\text{m}.$$

Assuming that η_{wave} scales proportionally with $1/n_e$ we should expect $\eta_{wave} \approx 2\ \Omega$m in the simulated $n_e = 10^{16}$ m^{-3} plasma, which is close to what we obtain at $z = 0.33$ m.

Plasmoid breakup





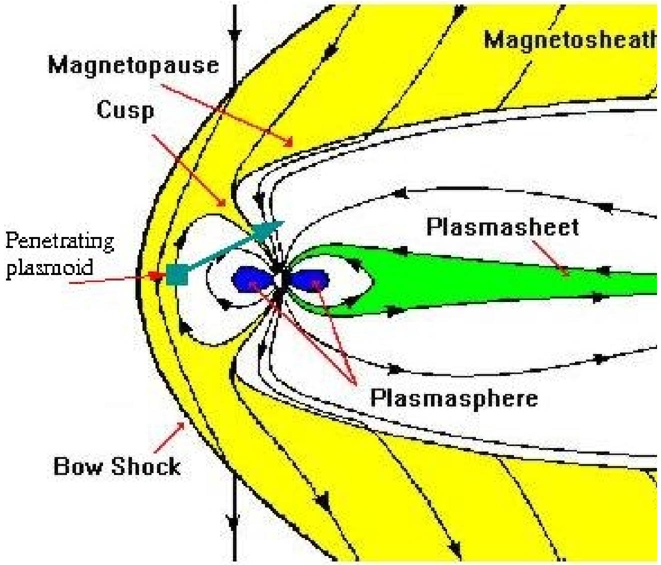
Ripin et al. [8] performed experiments where a large plasmoid was broken up into smaller "fingers" by an interchange Rayleigh-Taylor instability. Figures from [8].

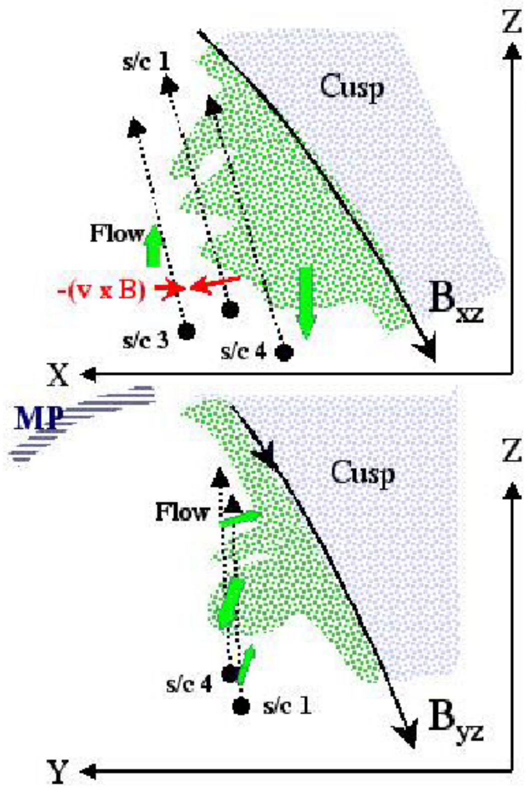
Interchange Rayleigh-Taylor instability?

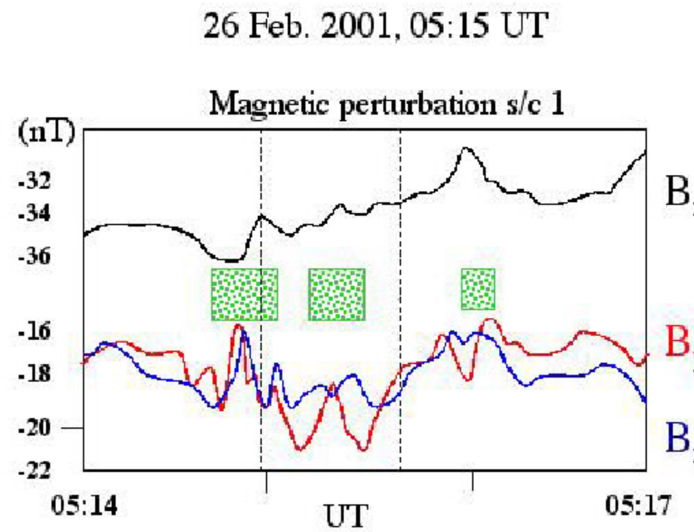
We estimate the growth rates for the parameters of our simulation and for the magnetopause, following [8] and [10], assuming $g = \omega_{ci} v_0$, and $\lambda = w$.

Simulation: $v_0 = 300$ km/s, $B = 0.05$ T, $L_n = 0.01$ m, $w = 0.01$ m.
Rayleigh-Taylor: $\gamma = \sqrt{\frac{g}{L_n}} = 1.2 \cdot 10^7$ s^{-1}
Large r_L approximation [10]: $\gamma = \frac{2\pi}{\lambda}\sqrt{g L_n} = 7.5 \cdot 10^7$ s^{-1}

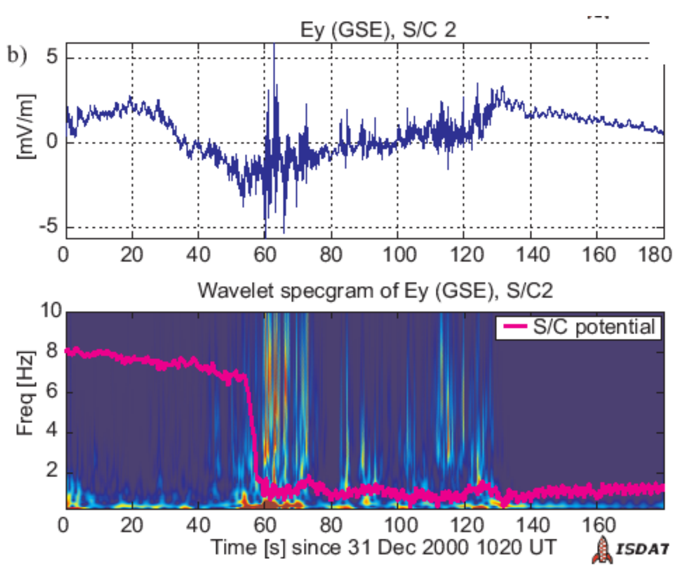
Magnetopause: $v_0 = 100$ km/s, $B = 30$ nT, $L_n = 50$ km, $w = 8$ km.
Rayleigh-Taylor: $\gamma = \sqrt{\frac{g}{L_n}} = 2.4$ s^{-1}
Large r_L approximation [10]: $\gamma = \frac{2\pi}{\lambda}\sqrt{g L_n} = 94$ s^{-1}







GSE	X (Re)	Y (Re)	Z (Re)
s/c 1	2.83	3.46	8.19
s/c 3	2.89	3.46	8.14
s/c 4	2.78	3.44	8.10



Above left: Schematic of the magnetosphere showing where penetration and convection take place. (Original picture from NASA)

Above right: Schematic by Lundin, et al., [11] showing penetrating plasmoids as observed by Cluster.

Left: Observation by the Cluster spacecraft of oscillations in the lower hybrid range on the inside of the magnetopause. (Picture from [12]).

Space

parameter	Magnetopause [12, 13]	sim.	exp.[2]
v_0/(km/s)	100–200	300	300
$B_\perp$/T	(10–30)$\cdot 10^{-9}$	0.05	0.015
n_0/m^{-3}	$\approx 2 \cdot 10^7$	10^{16}	10^{18}
W_K/W_E	(0.4–4)$\cdot 10^7$	756	$8 \cdot 10^5$
$\frac{1}{10}\frac{W_K}{W_E}\sqrt{\frac{m_e}{m_i}}$	(1–9)$\cdot 10^4$	7.9	$2 \cdot 10^3$
$\beta_k = W_K/W_B$	0.5–17	$8 \cdot 10^{-4}$	0.8
$\Pi = \frac{w}{r_{\mathrm{gi}}} K \sqrt{\beta_{\mathrm{ith}}}$	?	$4.2 \cdot 10^{-3}$	0.1
f_{pe}	40 kHz	200 MHz	9 GHz
f_{ce}	(0.3–1.1) kHz	70 MHz	0.4 GHz
f_{pi}	0.9 kHz	20 MHz	0.2 GHz
f_{lh}	(7–26) Hz	7 MHz	10 MHz

Parameters at the magnetopause region [12, 13], the simulation presented here, and the experiments [2].

Conclusions

- We have presented three-dimensional electrostatic particle in cell simulations of plasma penetration of a magnetic barrier. Waves in the lower-hybrid frequency range are observed.

- A non-rigid rotation of the plasmoid is observed upstream of the transition to the transverse field.

- Different cross sectional shapes are compressed into something that approximates the vertical ellipse when the plasmoid enters the transverse field region.

- The plasmoid moves in the $-\vec{v} \times \vec{B}$ direction after entering the transverse field region, in agreement with [8] and [10].

- Resistivity can be seen in the simulations, in agreement with experiments [6].

- For penetration of the magnetopause w must be small compared to the ion gyro radius. One possibility is that an interchange Rayleigh-Taylor instability could break up large plasmoids into small plasmoids that are able to penetrate.

References

[1] H. Gunell, T. Hurtig, M. Koepke, and N. Brenning, "Simulations of a plasmoid penetrating a magnetic barrier," *Plasma Physics and Controlled Fusion*, vol. 50, 2008.

[2] T. Hurtig, N. Brenning, and M. A. Raadu, "Three-dimensional electrostatic particle-in-cell simulation with open boundaries applied to a plasma beam entering a curved magnetic field," *Physics of Plasmas*, vol. 10, pp. 4291–4305, 2003.

[3] G. Schmidt, "Plasma motion across magnetic fields," *Physics of Fluids*, vol. 3, no. 6, pp. 961–965, 1960.

[4] W. Peter and N. Rostoker, "Theory of plasma injection into a magnetic field," *Physics of Fluids*, vol. 25, no. 4, pp. 730–735, 1982.

[5] H. Ishizuka and S. Robertson, "Propagation of an intense charge-neutralized ion beam transverse to a magnetic field," *Physics of Fluids*, vol. 25, no. 12, pp. 2353–2358, 1982.

[6] T. Hurtig, N. Brenning, and M. A. Raadu, "The role of high frequency oscillations in the penetration of plasma clouds across magnetic boundaries," *Physics of Plasmas*, vol. 12, p. 012308, 2005.

[7] N. Brenning, T. Hurtig, and M. A. Raadu, "Conditions for plasmoid penetration across abrupt magnetic barriers," *Physics of Plasmas*, vol. 12, 2005.

[8] B. H. Ripin, E. A. McLean, C. K. Manka, C. Pawley, J. A. Stamper, T. A. Peyser, A. N. Mostovych, J. Grun, and J. Huba, "Large-Larmor-radius interchange instability," *Phys. Rev. Lett.*, vol. 59, no. 20, pp. 2299–2302, 1987.

[9] A. N. Mostovych, B. H. Ripin, and J. A. Stamper, "Laser-produced plasma jets - collimation and instability in strong transverse magnetic fields," *Phys. Rev. Lett.*, vol. 62, pp. 2837–2840, June 1987.

[10] A. B. Hassam and J. D. Huba, "Structuring of the AMPTE magnetotail barium releases," *Geophys. Res. Lett.*, vol. 14, no. 1, pp. 60–63, 1987.

[11] R. Lundin, J.-A. Sauvaud, H. Rème, A. Balogh, I. Dandouras, J. M. Bosqued, C. Carlson, G. K. Parks, E. Möbius, L. M. Kistler, B. Klecker, E. Amata, V. Formisano, M. Dunlop, L. Eliasson, A. Korth, B. Lavraud, and M. McCarthy, "Evidence for impulsive solar wind plasma penetration through the dayside magnetopause," *Annales Geophysicae*, vol. 21, pp. 457–472, Feb. 2003.

[12] M. André, R. Behlke, J.-E. Wahlund, A. Vaivads, A.-I. Eriksson, A. Tjulin, T. D. Carozzi, C. Cully, G. Gustafsson, D. Sundkvist, Y. Khotyaintsev, N. Cornilleau-Wehrlin, L. Rezeau, M. Maksimovic, E. Lucek, A. Balogh, M. Dunlop, P.-A. Lindqvist, F. Mozer, A. Pedersen, and A. Fazakerley, "Multi-spacecraft observations of broadband waves near the lower hybrid frequency at the earthward edge of the magnetopause," *Annales Geophysicae*, vol. 19, pp. 1471–1481, 2001.

[13] D. Sundkvist, A. Retinò, A. Vaivads, and S. D. Bale, "Dissipation in turbulent plasma due to reconnection in thin current sheets," *Phys. Rev. Lett.*, vol. 99, p. 025004, 2007.