Particle kinetics and distribution function inside magnetic mirrors

D. Constantinescu[1,2], K.-H. Glassmeier[1], R. Treumann[3],

1: Institut für Geophysik und Meteorologie, TU Braunschweig

2: Institute for Space Sciences, Bucharest

3: Max-Planck Institut für extraterrestrische Physik, Garching

Contact: d.constantinescu@tu-bs.de

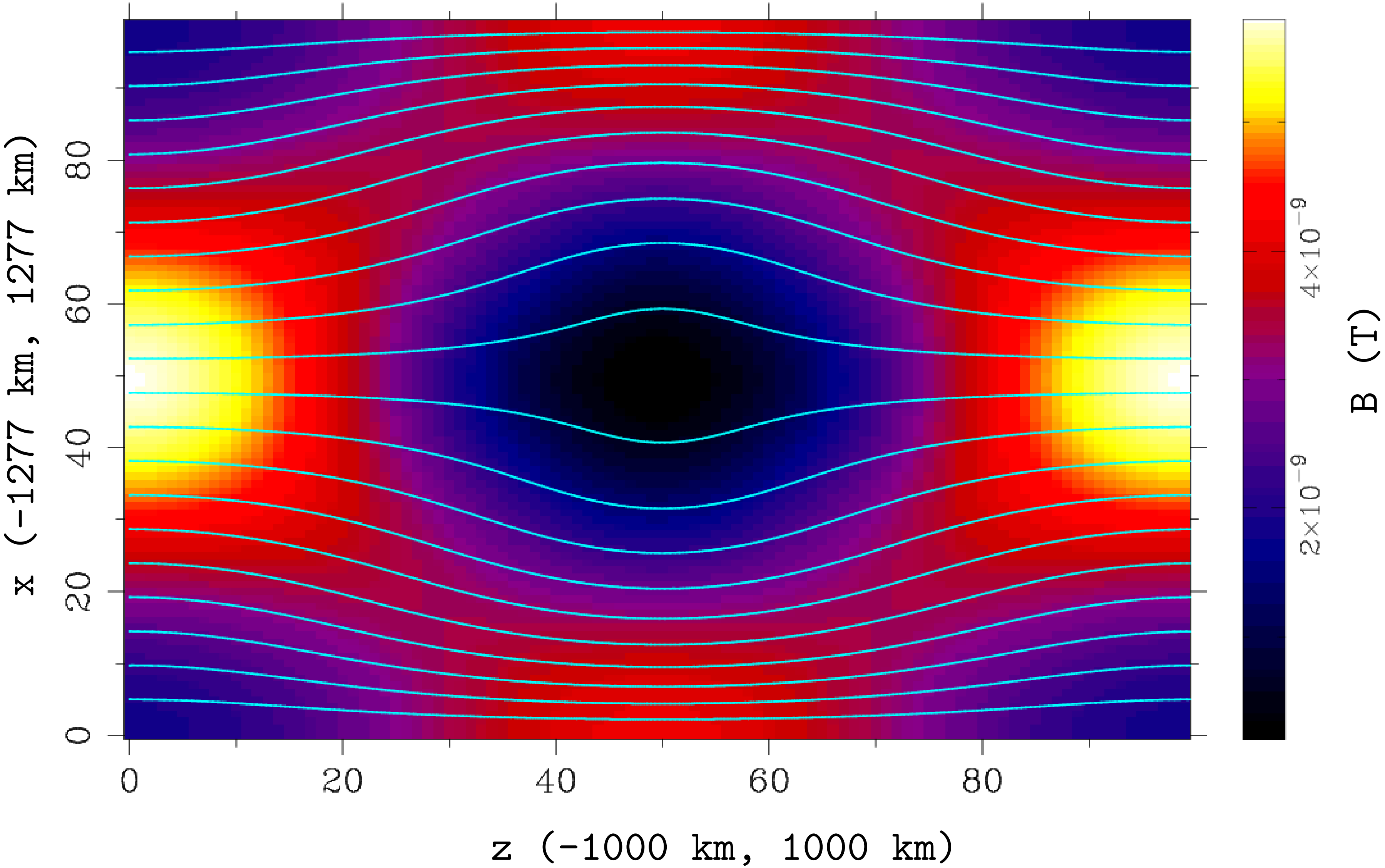
Abstract

We study single particle behavior and derive general properties of the distribution function for magnetic mirrors by means of test particle simulations. For the magnetic field we use a three-dimensional magnetic field model with rotational symmetry and periodicity along symmetry axis.

Single particle motion is analyzed by direct numeric integration of the equation of motion. Particles can be divided into three groups: trapped, escaping and chaotic particles. Each group plays a different role in the stability of the structure.

For the study of the distribution function we start with a bi-Maxwellian ensemble of particles and let it in evolve in time.

Model Magnetic Field



Particles simulation

Equation of motion:

- $$m\frac{\partial^2 \mathbf{r}}{\partial t^2} = q\left(\frac{\partial \mathbf{r}}{\partial t} \times \mathbf{B}\right)$$

Integrator:

- 5th order Runge-Kutta with adaptive step size control

Initial distribution:

- bi-Maxwellian

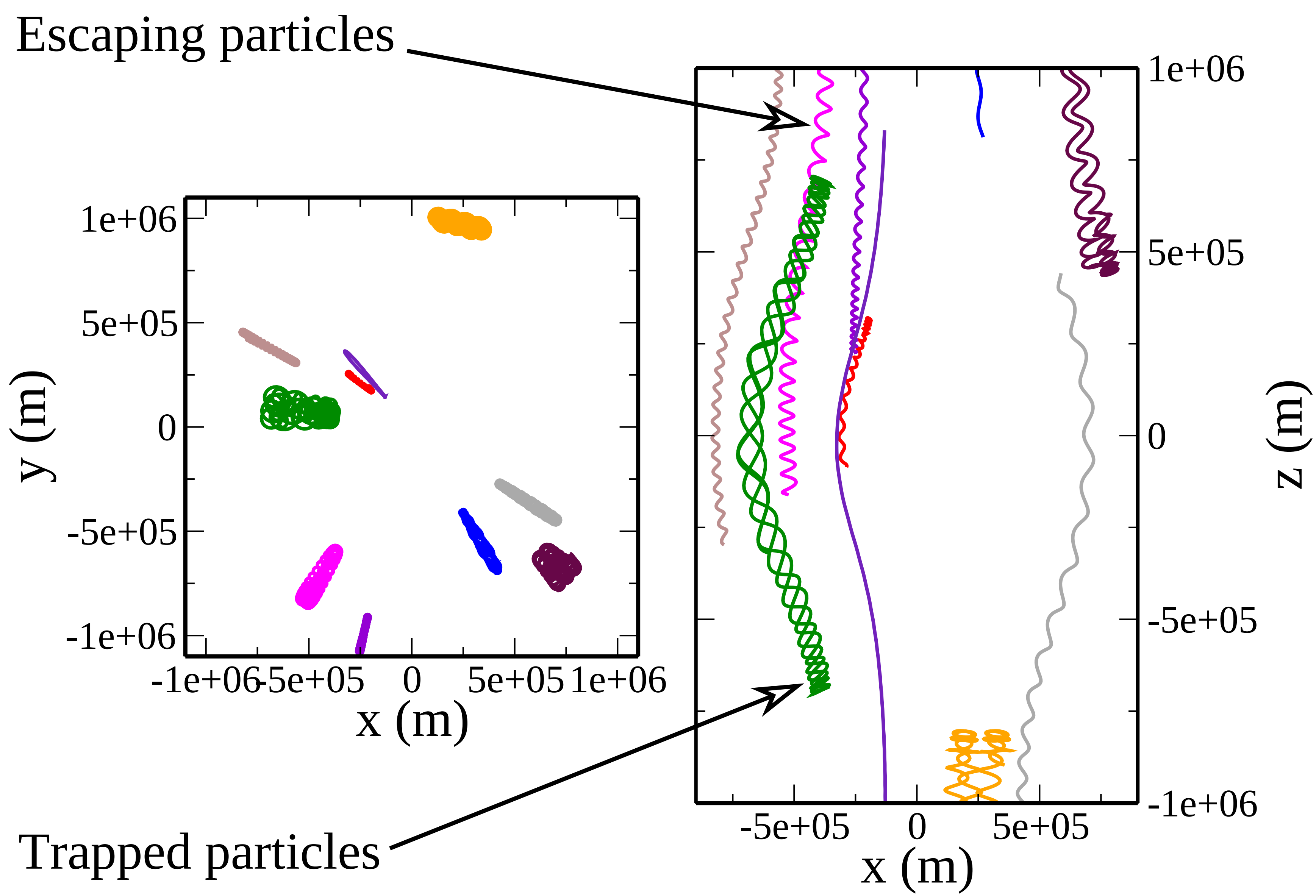
Test particles:

- particles do not influence the magnetic field

Quasi-static magnetic field:

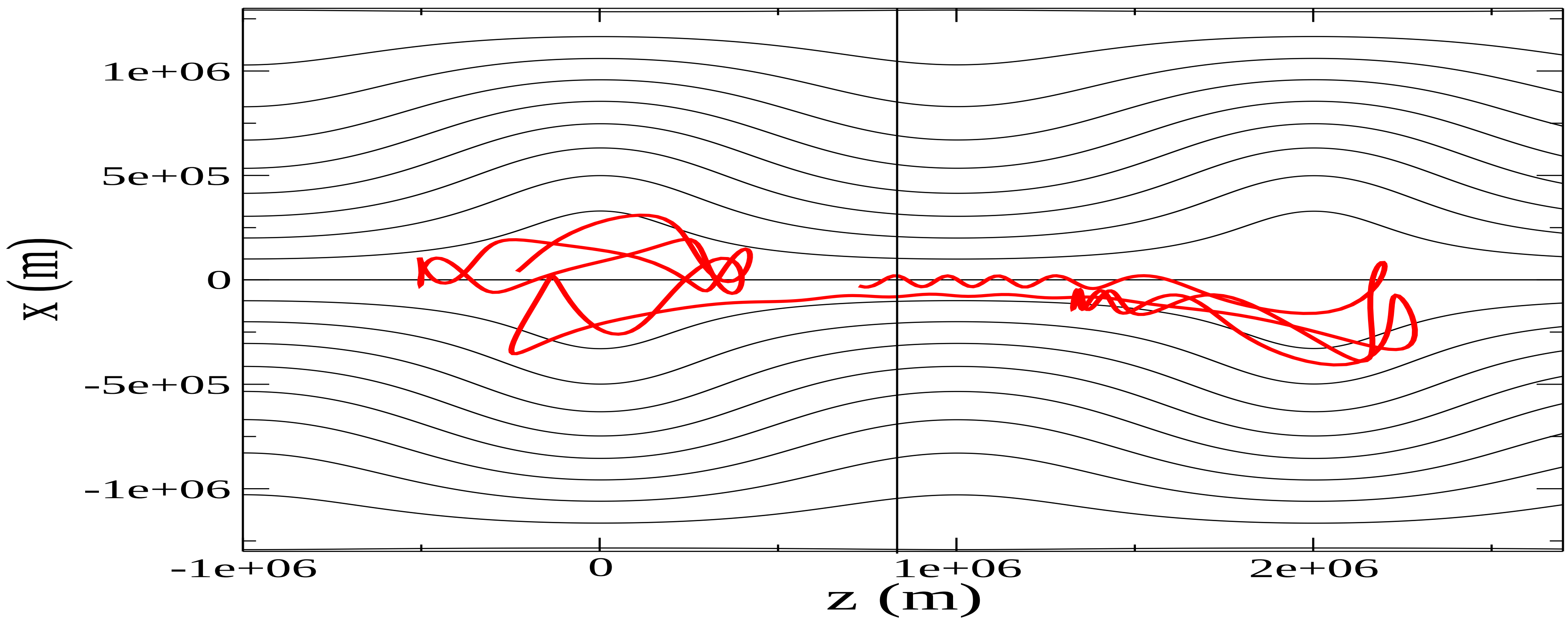
- time scale for the magnetic field variations $\gg$ gyro-period

Particles Orbits. Regular motion

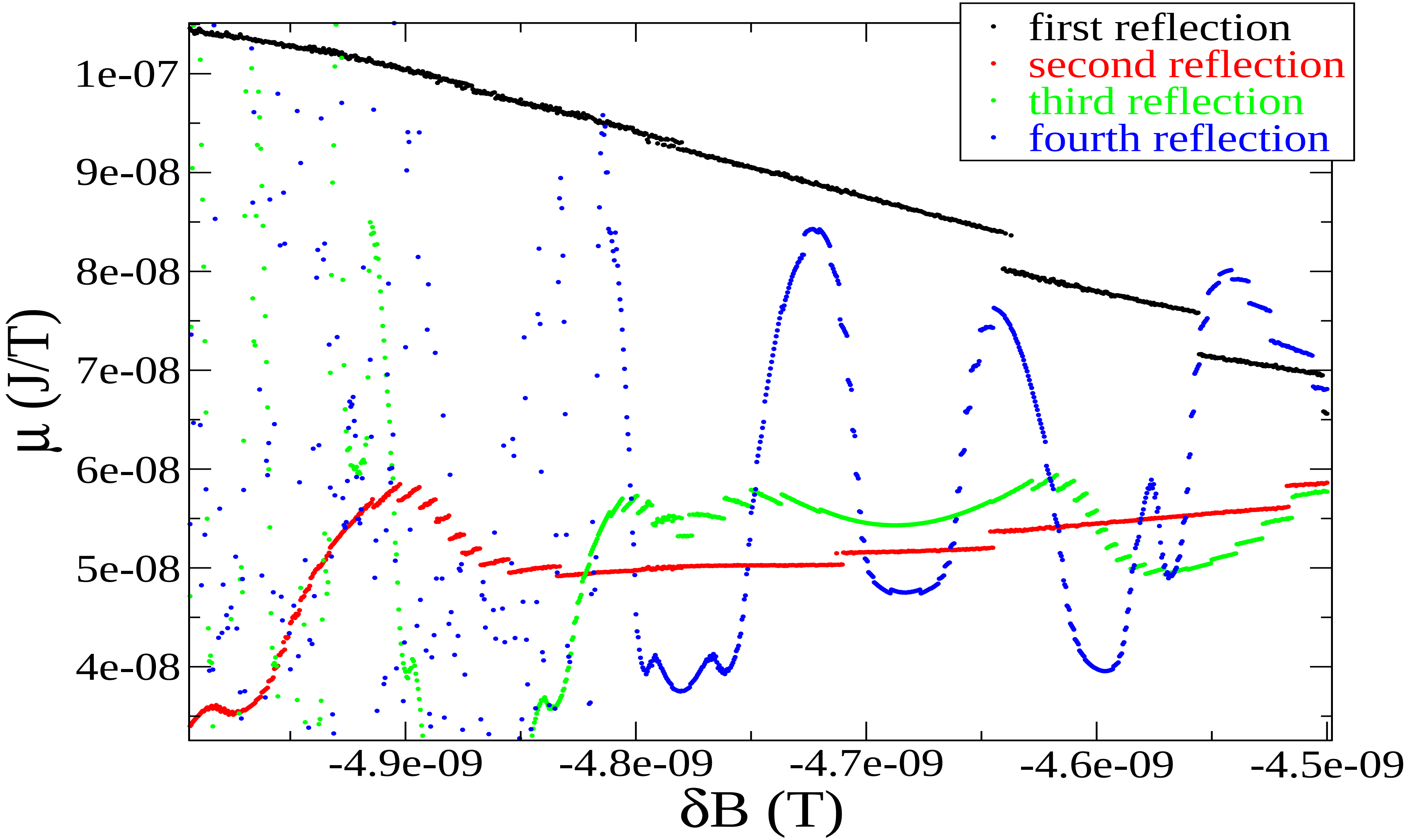


Particles Orbits. Chaotic motion

When the orbit curvature is smaller than the field curvature the motion becomes chaotic. The particle randomly jumps from one structure to other.

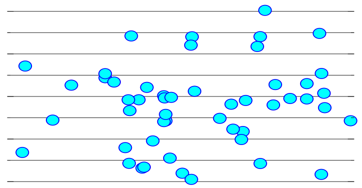


Magnetic moment at mirror point



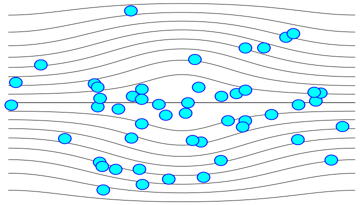
Simulation steps

t_i — distribution function: bi-Maxwellian; magnetic field: uniform



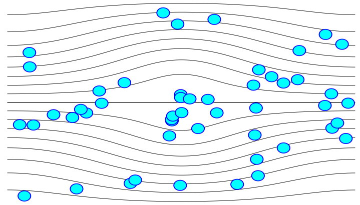
$\int$ equation of motion $\Downarrow$ $\mathbf{B} = \mathbf{B}(t)$

t_1 — mirror magnetic field



$\int$ equation of motion $\Downarrow$ $\mathbf{B} = constant$

t_f — final distribution function



Simulation Input

Magnetic field:

- Mirror length: 2000 km (periodic)
- Mirror radius: 1277 km
- Unperturbed field: 3 nT
- Maximum perturbation: 2.8 nT

Particles:

- Number: 10^5
- Orthogonal temperature: 10×10^6 K
- Parallel temperature: 5×10^6 K

Code:

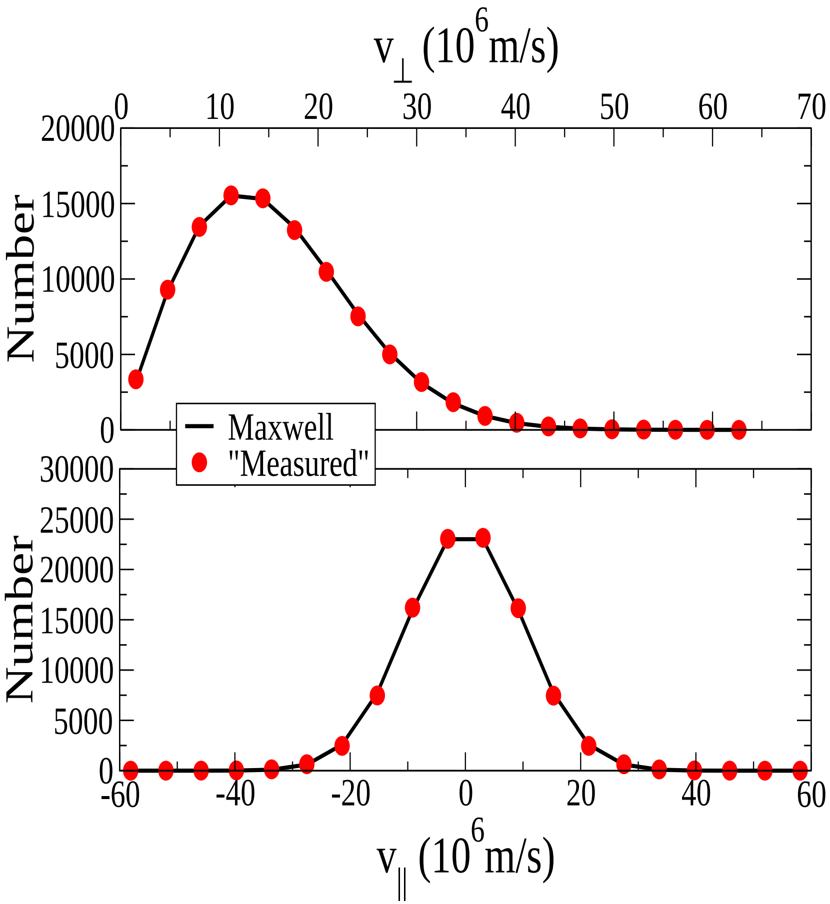
- Simulation time: 30 gyro-periods
- Magnetic field change time: 20 gyro-periods
- Phase space grid: $20\times20\times20\times20$ $(\rho, z, v_\parallel, v_\perp)$

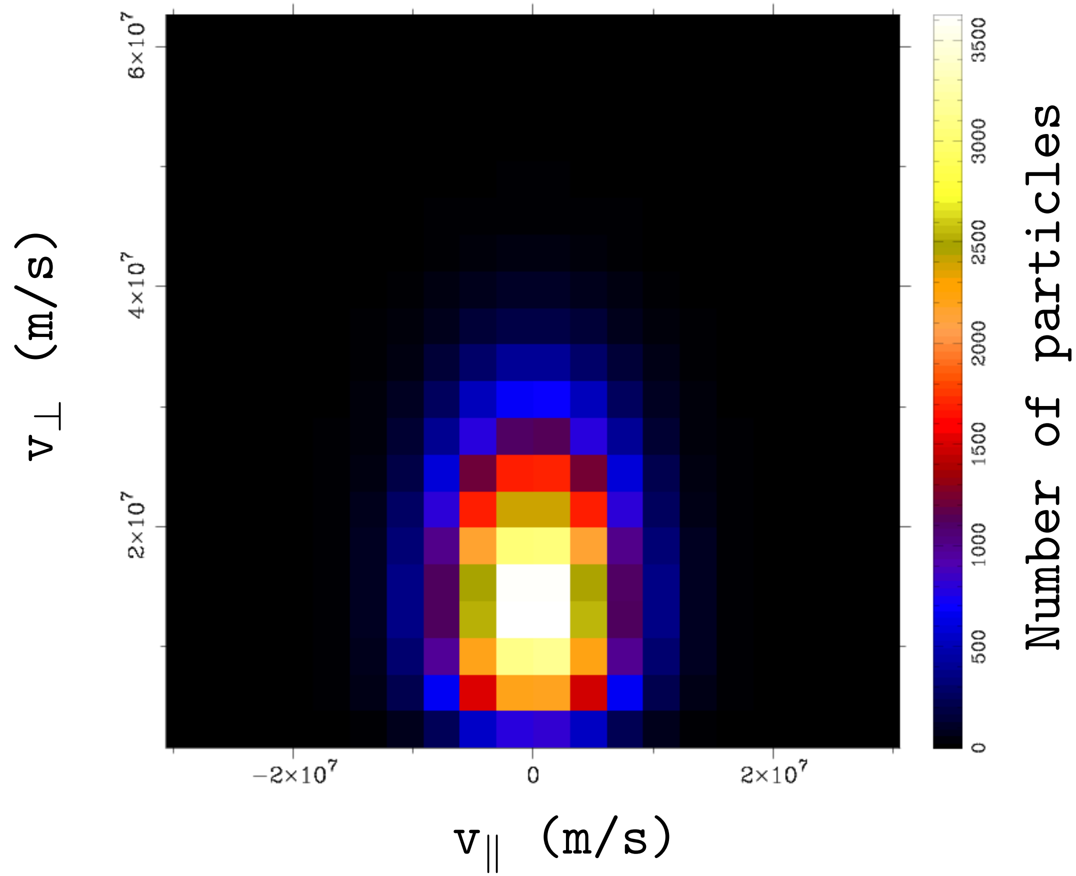
Simulation Output

We can identify four different types of particles

	Initial	Trapped	Escaping	Chaotic	Adiabatic	Total
Number	100000	75966	24033	19742	80257	100000
$T_{\perp} \times 10^6$K	10	11	5.7	11	9.9	10
$T_{\|} \times 10^6$K	5	6.2	8.6	10	5.9	6.8
Anisotropy	2	1.9	0.7	1.1	1.7	1.5

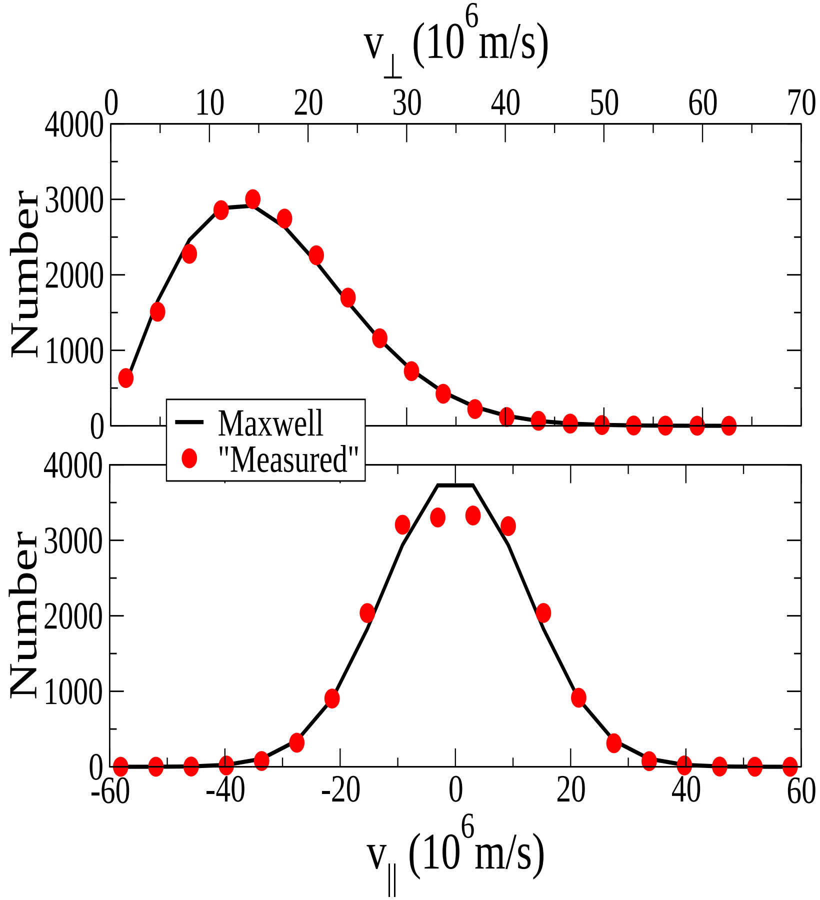
Distribution function: Total

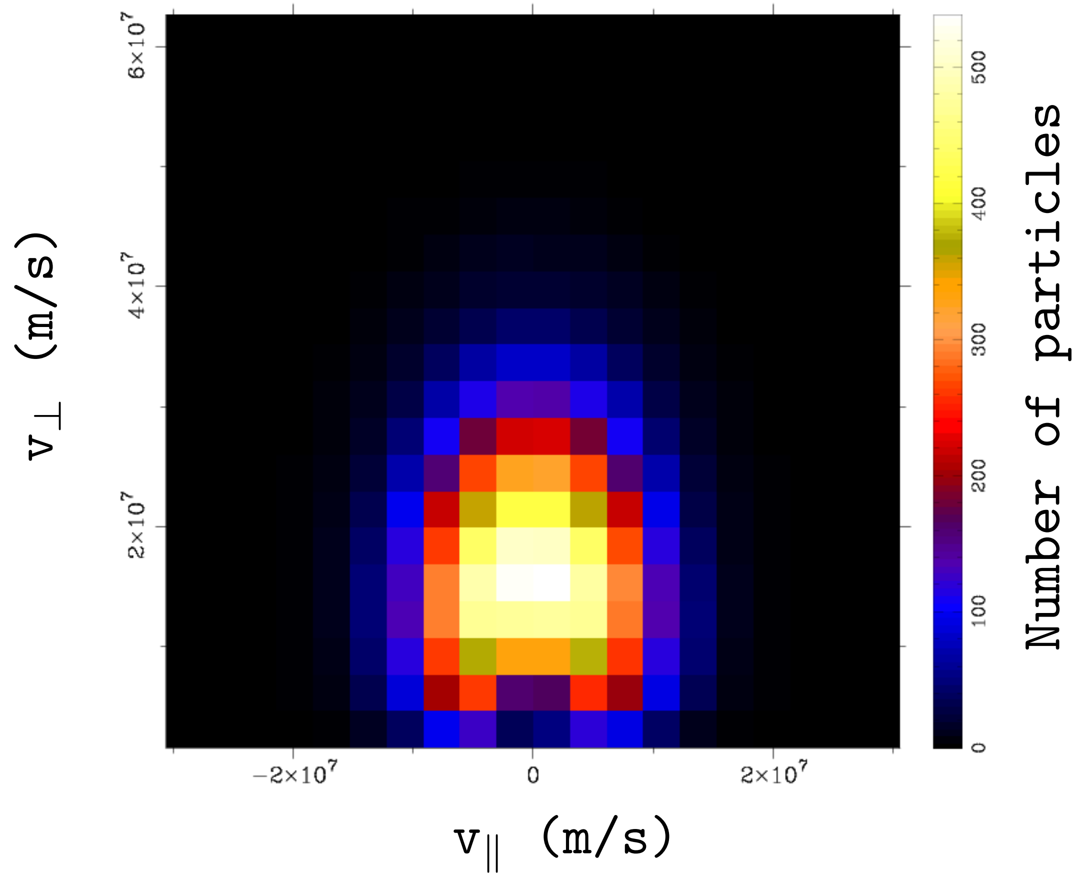




The total distribution function remains close to bi-Maxwellian

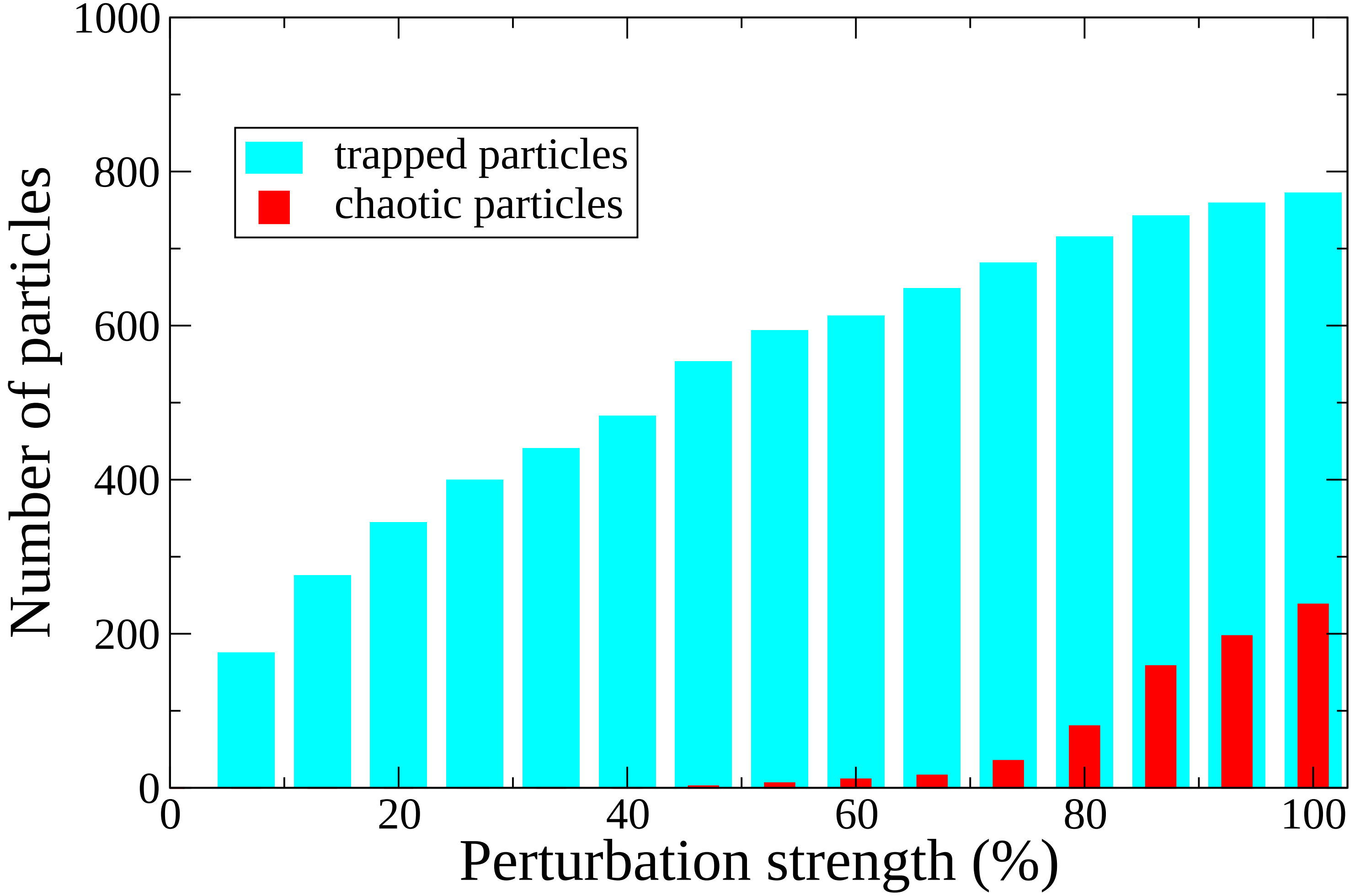
Distribution function: Chaotic part





The distribution function of the chaotic particles deviates from bi-Maxwellian

Effect of perturbation strength



Summary

- The total distribution function remains bi-Maxwellian while the structure builds up
- While total $T_\perp$ remains unchanged, total $T_\parallel$ increases. Therefore the total anisotropy decreases. However, it remains larger than 1 at any point inside the structure
- The total particle density is ruffly anti-correlated with the magnetic field intensity. The deviation is mainly due to the chaotic particles
- The chaotic contribution becomes significant for large magnetic field perturbations
- The chaotic particles are almost isotropic
- The chaotic part of the distribution function deviates from Maxwellian
- The chaotic particles gather in low field regions
- Most of the escaping particles follow those field lines where the variation of |B| is minimum

Conclusions

Of special interest here is the comparison of trapped and chaotic parts. While the chaotic particles diffuse across the field lines, the trapped particles constitute the ring current and therefore they have a stabilizing effect.

The existence of the chaotic part limits the size of the perturbation. This could lead to a relation between the maximum depth of magnetic mirrors and the orthogonal temperature.

Our next step is to relate these theoretical considerations with actual plasma measurements.