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Global Evolution of the Earth's Magnetosphere in Response to a Sudden Ring Current Injection

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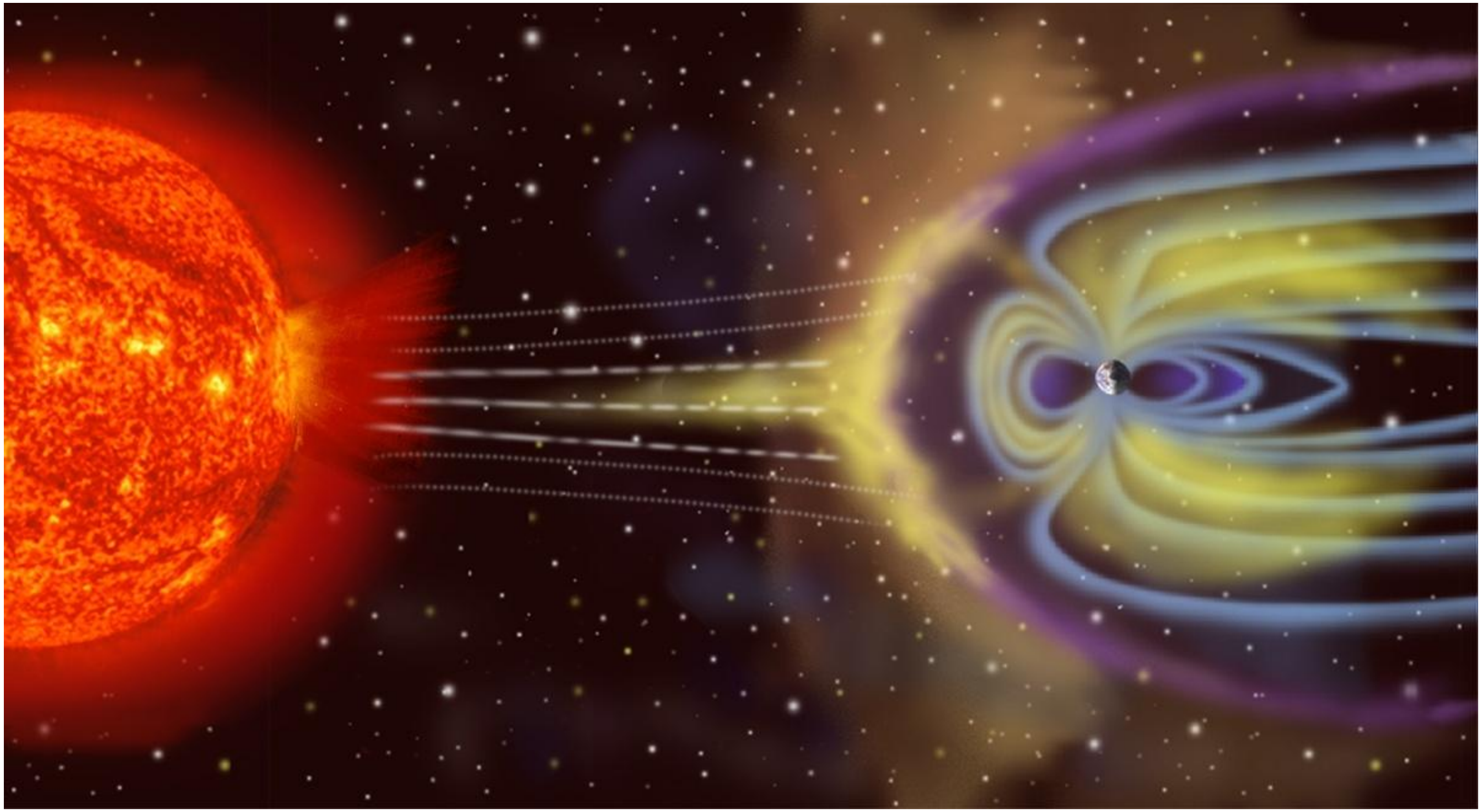
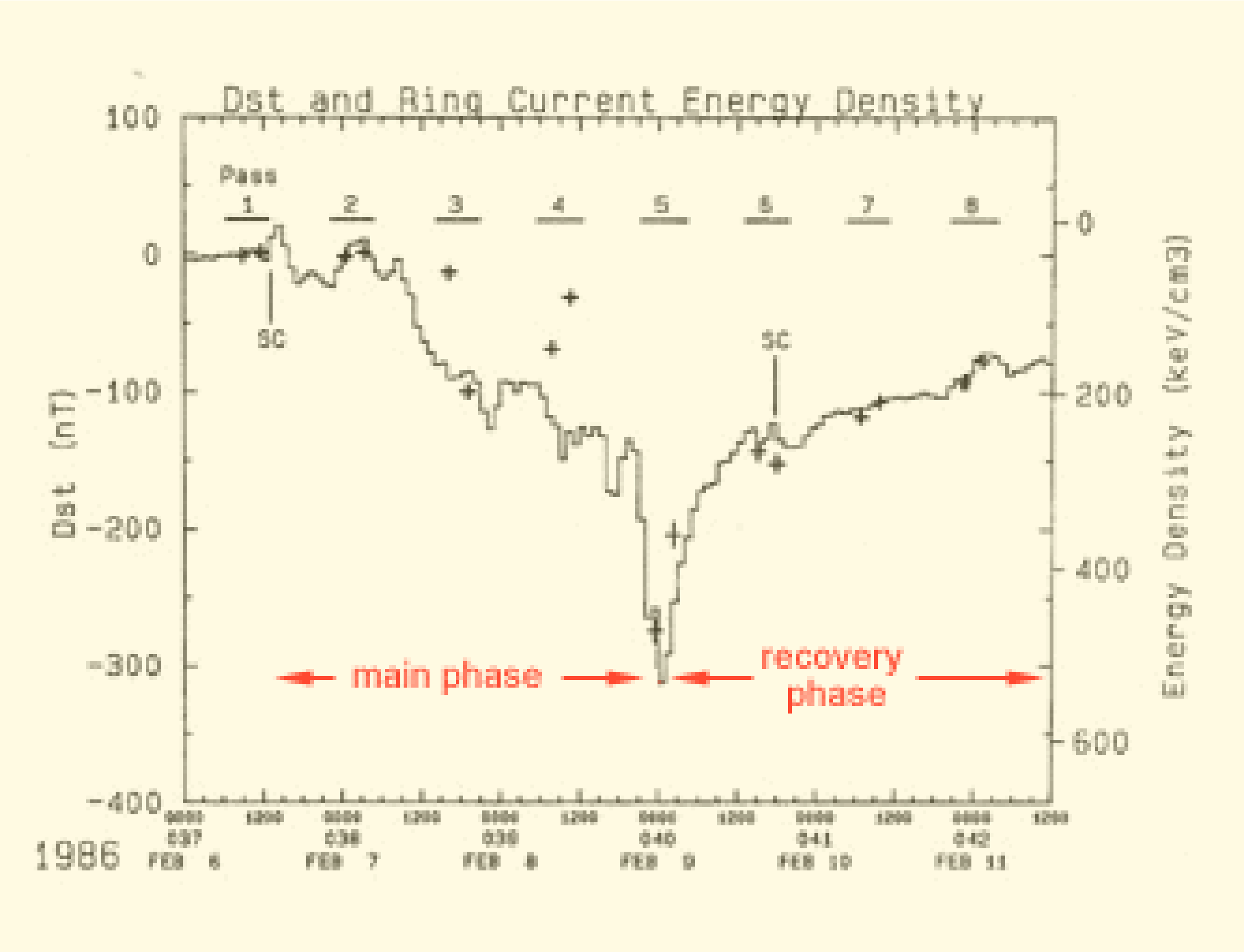
Geomagnetic Storm



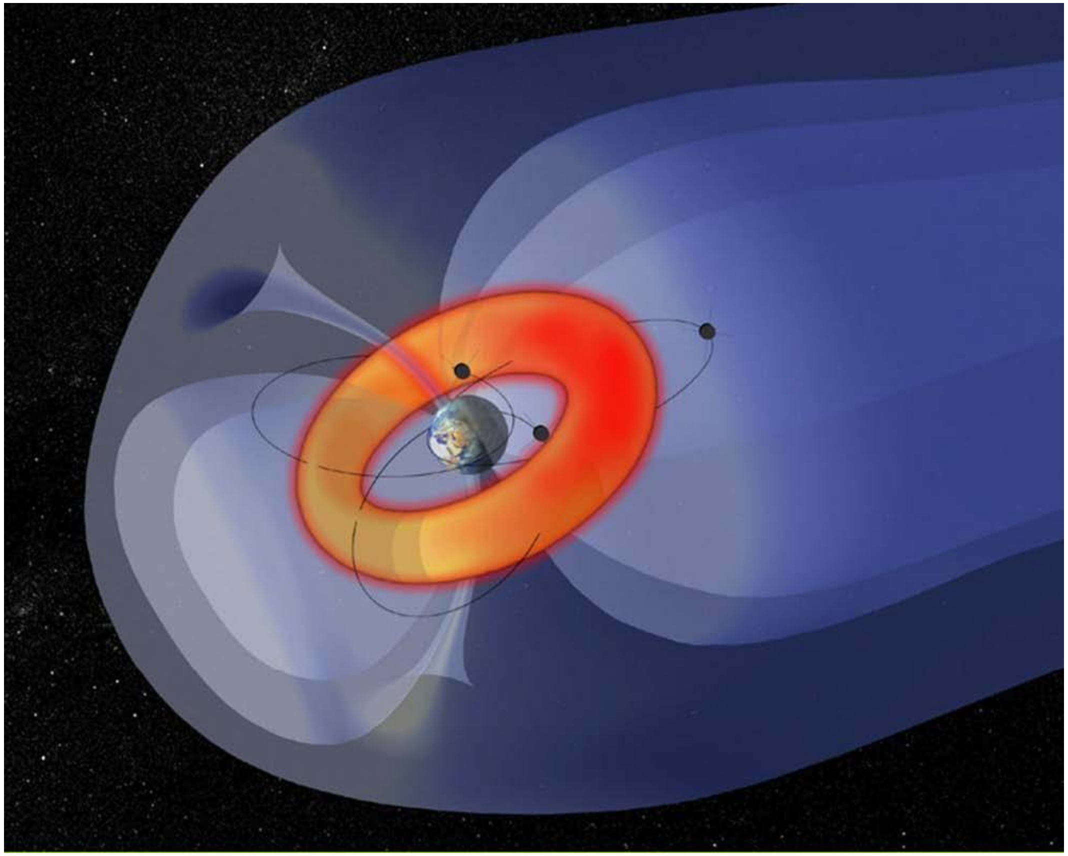
A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock associated with solar coronal mass ejections (CME), coronal holes, or solar flares.

Storm in Terms of Dst Index



The hourly Dst (disturbance storm time) index measures the perturbation in the northward component of magnetic field at magnetometer stations near the equator.

Ring current enhancement causes the Dst index to decrease.



Particle injection into the ring current region during the storm main phase

→ Ring current enhancement

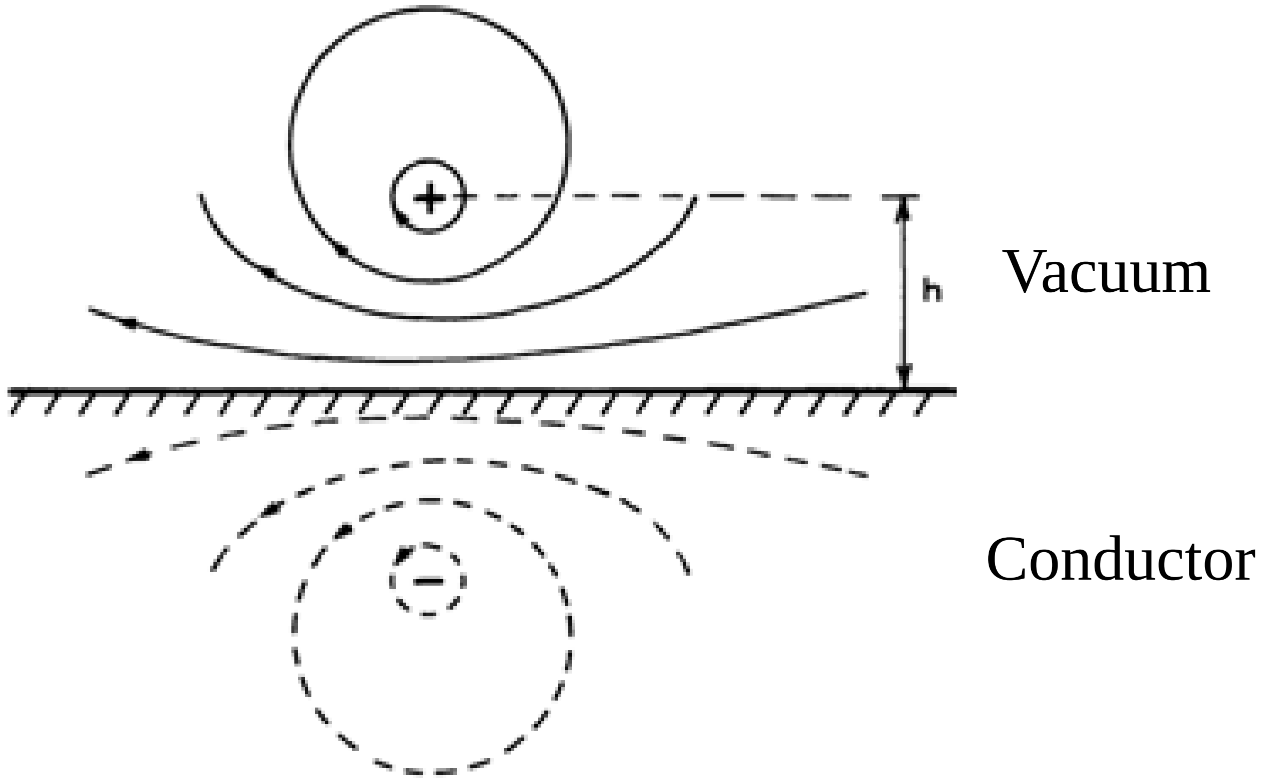
→ Northward magnetic field decreases on the Earth's surface near the equator.

The magnetosphere is not a vacuum, but is filled with a highly conducting plasma.

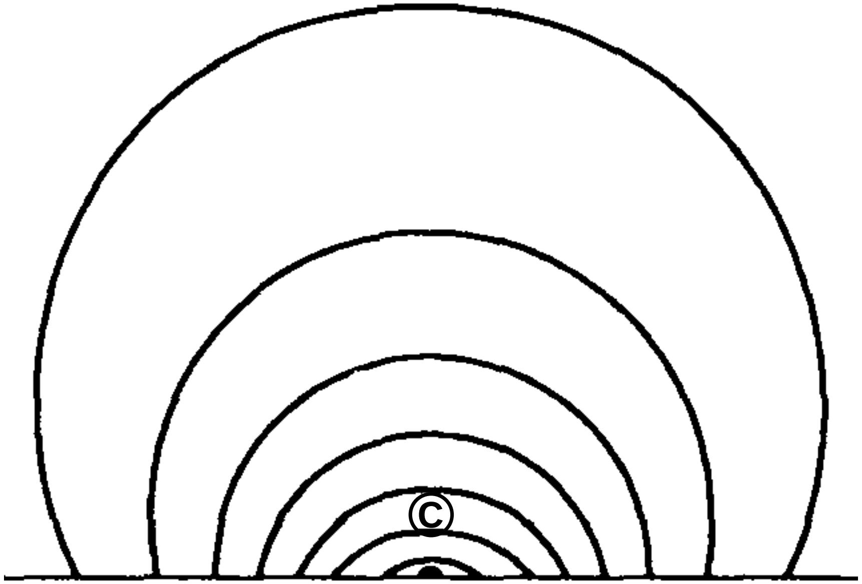
- A perfect conductor is diamagnetic, i.e., a change in the external field can hardly intrude into the conductor.
- Plasma skin depth:

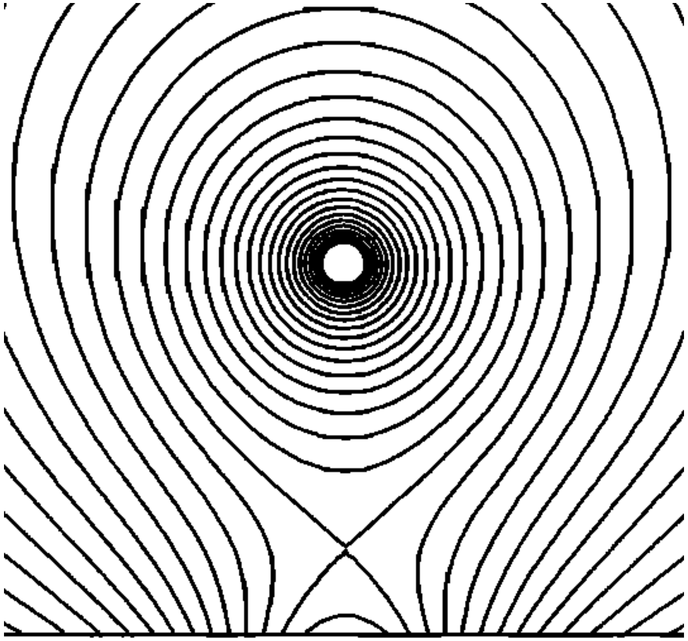
$$c / \omega_{pe} \approx 5 \times 10^5 n_e^{-1/2} \text{ cm} \sim 5 \text{ km} << R_E$$

If a current is introduced outside a perfect conductor



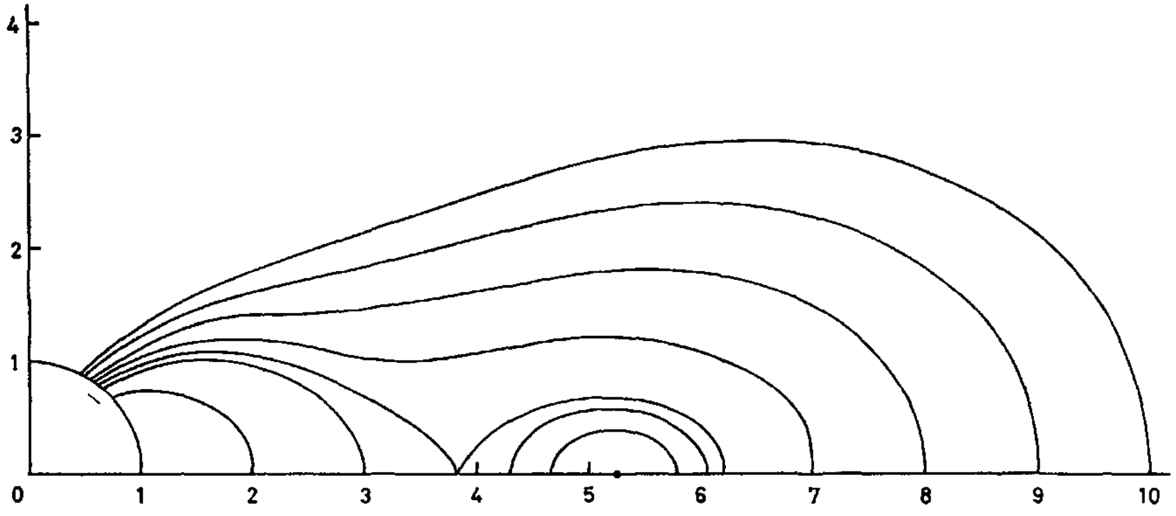
If a current is introduced into a pre-existing field in a plasma





If we have a suddenly enhanced ring current

The magnetic field created by the suddenly enhanced current should be confined in a finite region, e.g., in a **magnetic island**.



Sozou & Windle 1970

Design of the Numerical Experiment – Make it simple!

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) ,$$

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v} \cdot \nabla \mathbf{v} + \frac{1}{\rho} \mathbf{J} \times \mathrm{B} - \frac{1}{\rho} \nabla p + \mathbf{g} + \nu \nabla^2 \mathbf{v} ,$$

$$\frac{\partial p}{\partial t} = -\mathbf{v} \cdot \nabla p - \gamma p \nabla \cdot \mathbf{v} ,$$

$$\frac{\partial \mathrm{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathrm{B}) + \eta \nabla^2 \mathrm{B} ,$$

$$\mathbf{J} = \nabla \times (\mathrm{B} - \mathrm{B}_d) ,$$

Initial Condition

$$\mathbf{B}(t=0) = \mathbf{B}_d + \mathbf{B}_{rc}$$

$$p(t=0) = p_{HS} + p_{rc}$$

For the pressure and magnetic field of the primitive ring current, a Z-pinch profile with a constant current density within 1 R_E of radius centered at 5 R_E is used.

$$p_{rc} = \begin{cases} \frac{1}{4}\mu_0 J_0^2 (r_0^2 - r^2) & \text{if } r \le r_0 \\ 0 & \text{if } r > r_0 \end{cases}$$

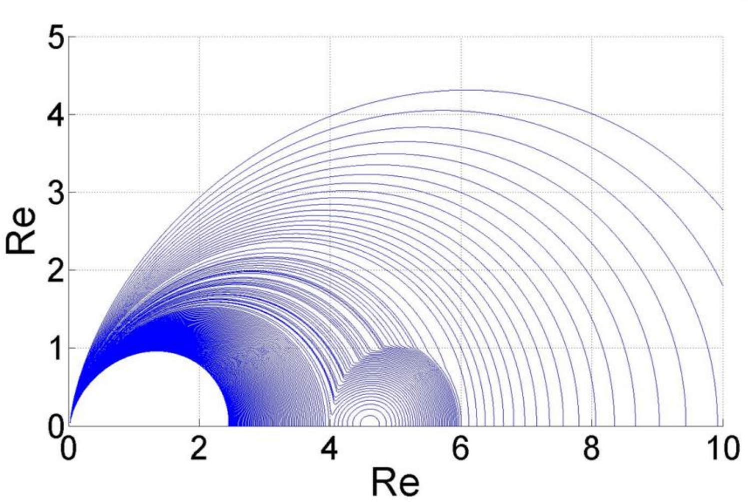
$$B_\theta = \begin{cases} \frac{1}{2}\mu_0 J_0 r & \text{if } r \le r_0 \\ 0 & \text{if } r > r_0 \end{cases}$$

The initial condition is not in equilibrium.

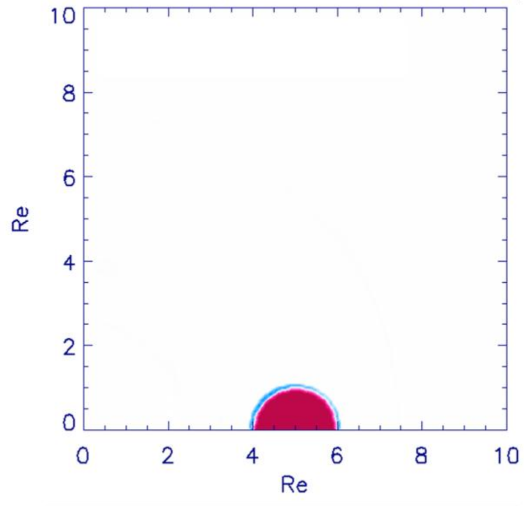
Initial Profiles: Case 1

With $I_0 = \pi r_0^2 J_0 = 2.44\times10^7\,\mathrm{A}$,

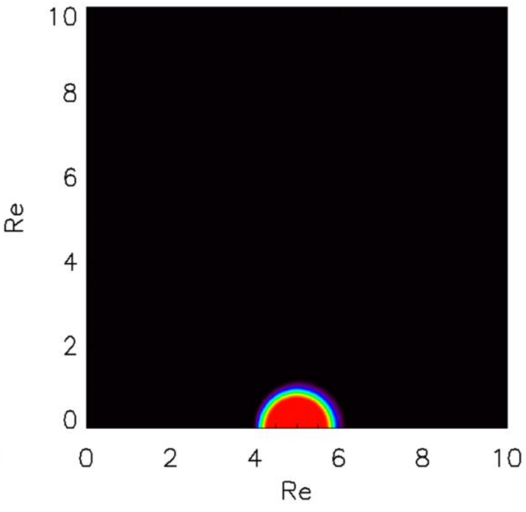
a magnetic island exists initially.



field lines



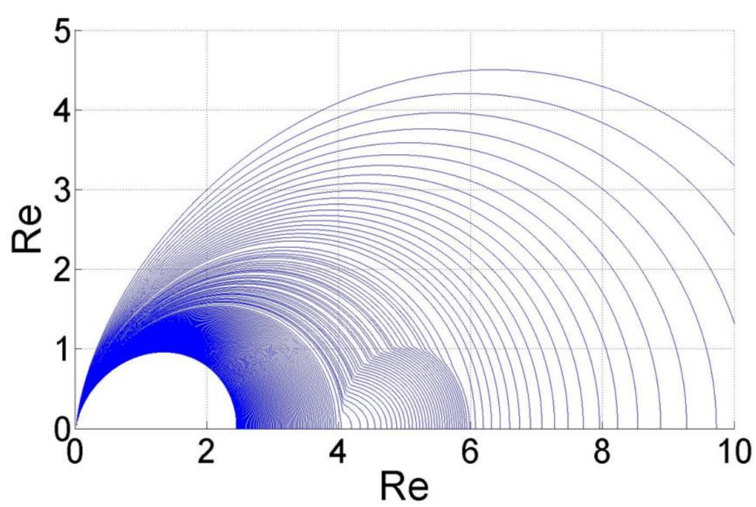
current density



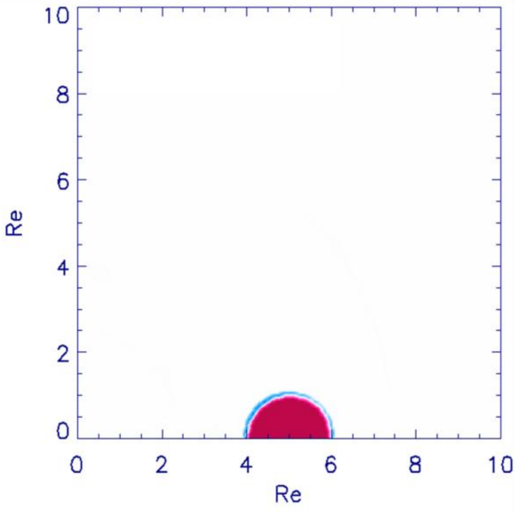
plasma pressure

Initial Profiles: Case 2

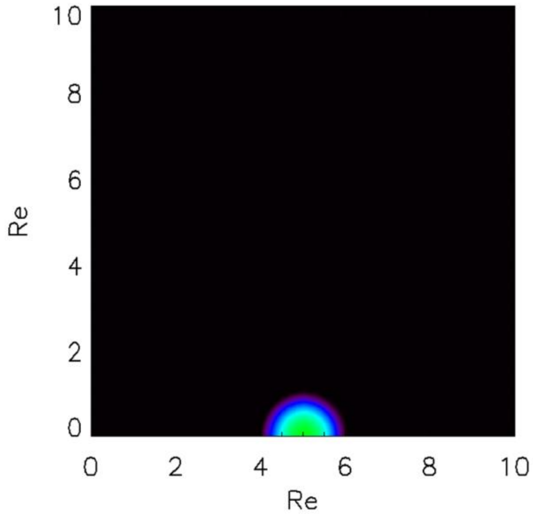
With $I_0 = \pi r_0^2 J_0 = 1.22 \times 10^7$ A, there appears no magnetic island, but a wake of bent field lines.



field lines

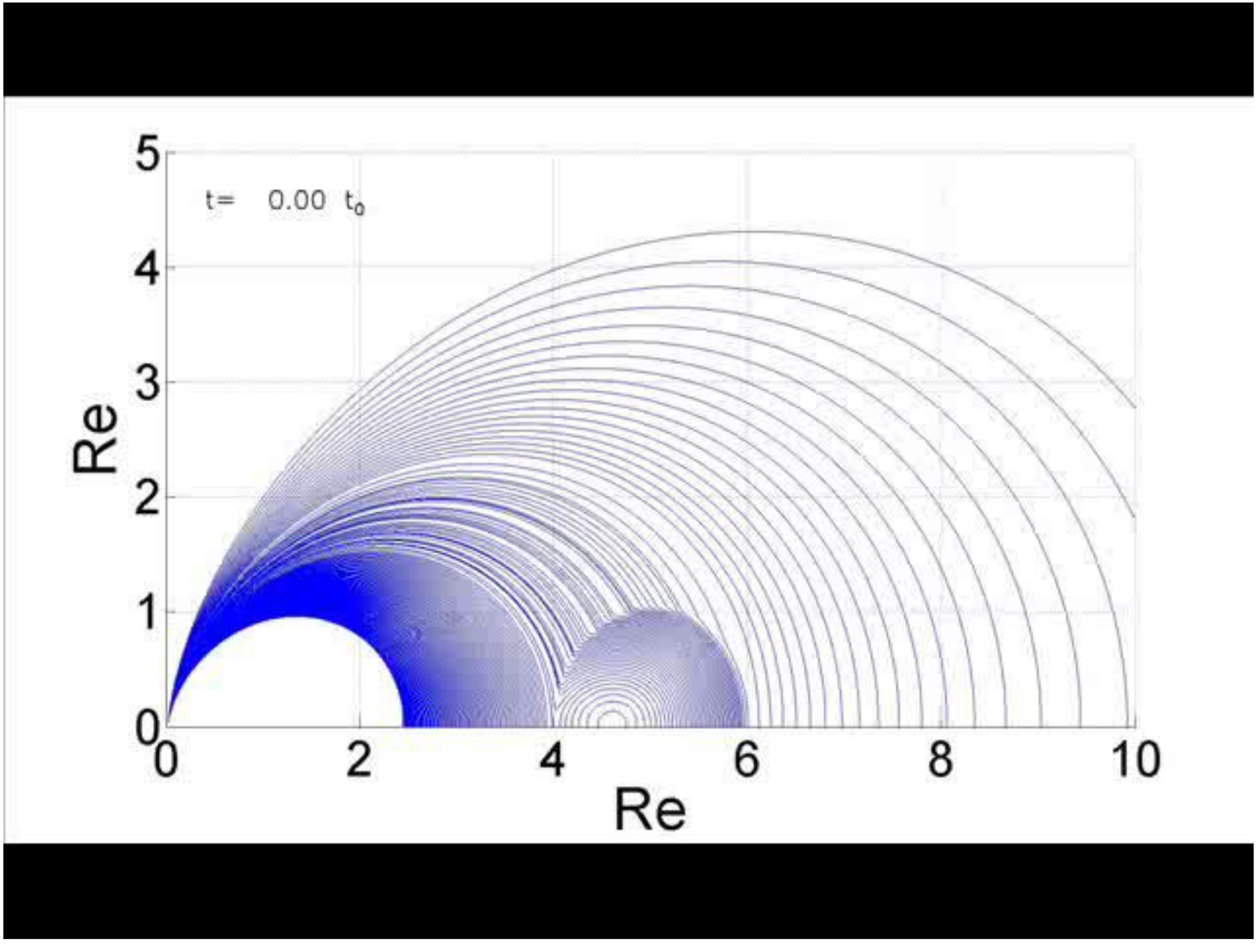


current density

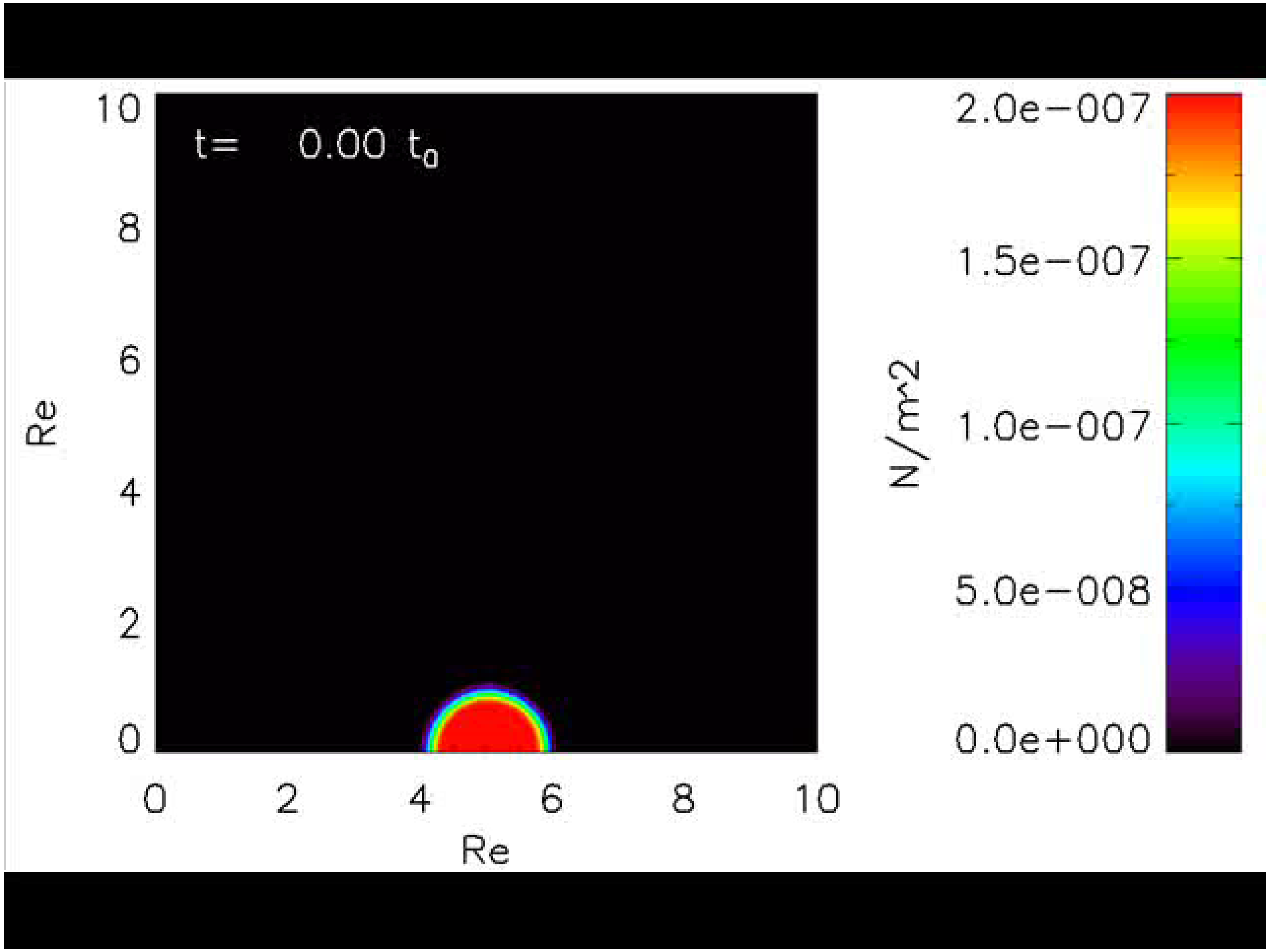


plasma pressure

Case 1: Field Evolution

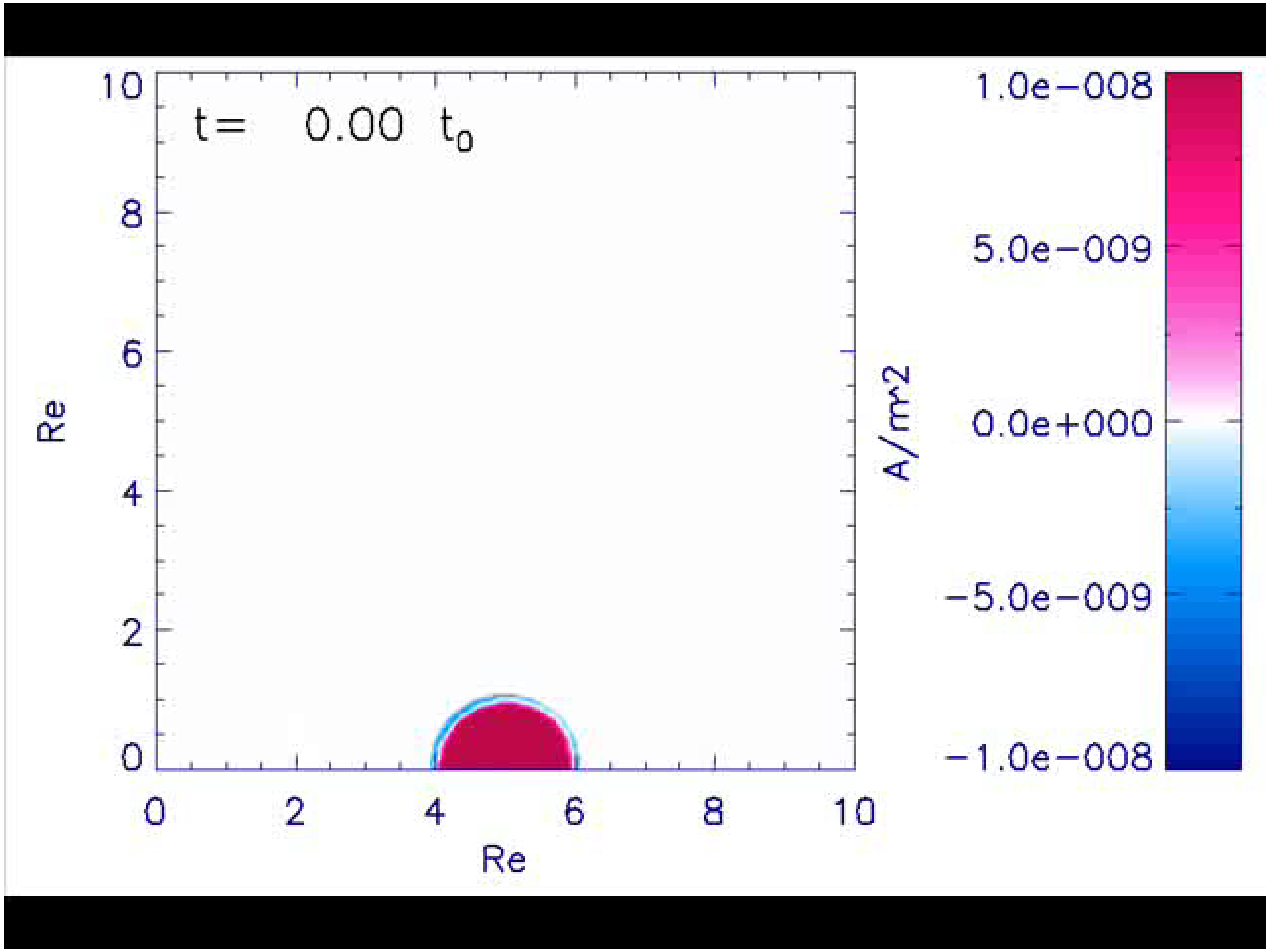


Case 1: Pressure Evolution



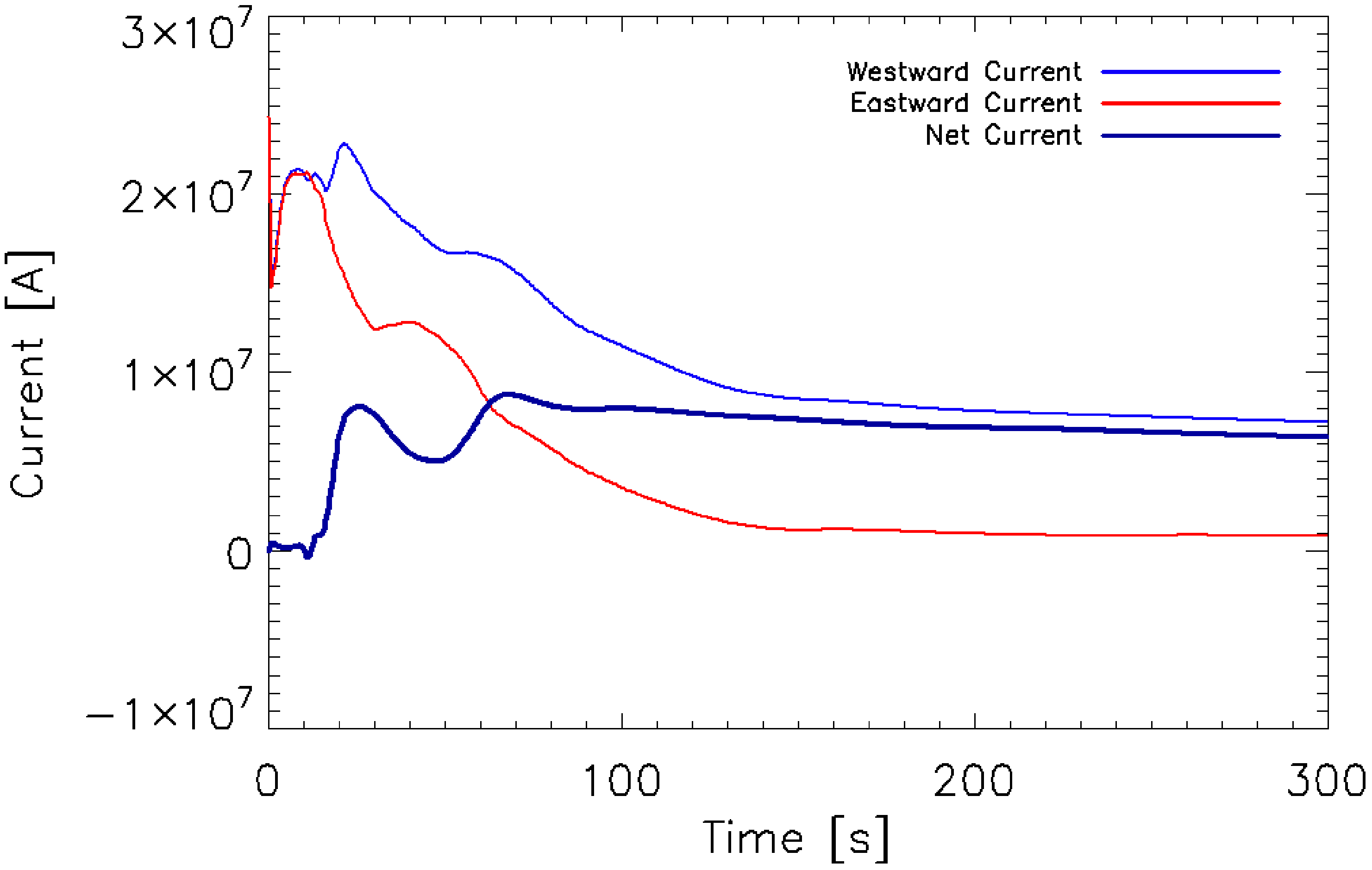
$\mathbf{B} \bullet \nabla p = 0$ in equilibrium

Case 1: Current Density Evolution

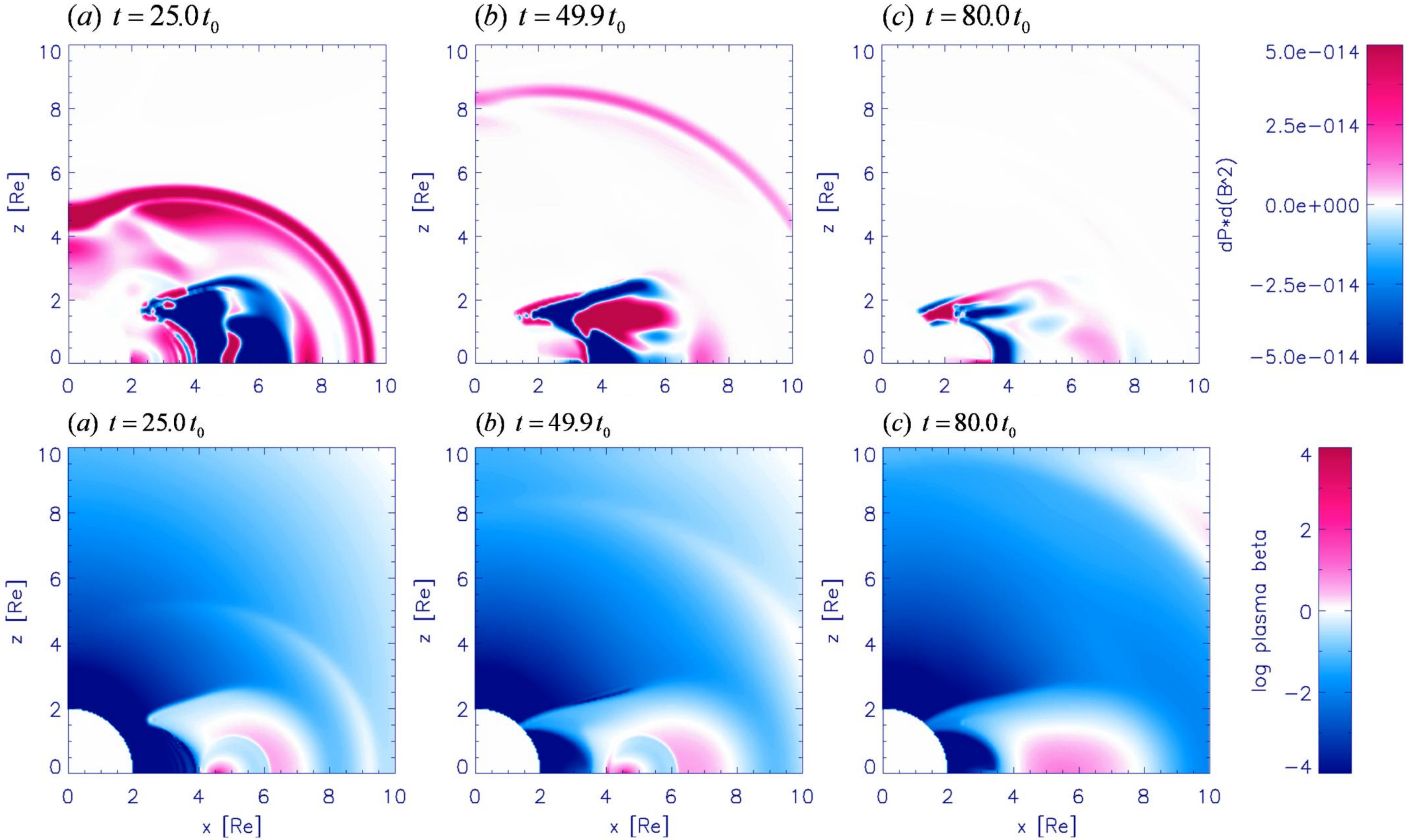


$$\mathbf{B} \bullet \nabla J_{\varphi} = 0 \text{ in equilibrium}$$

Case 1: Total Current Evolution

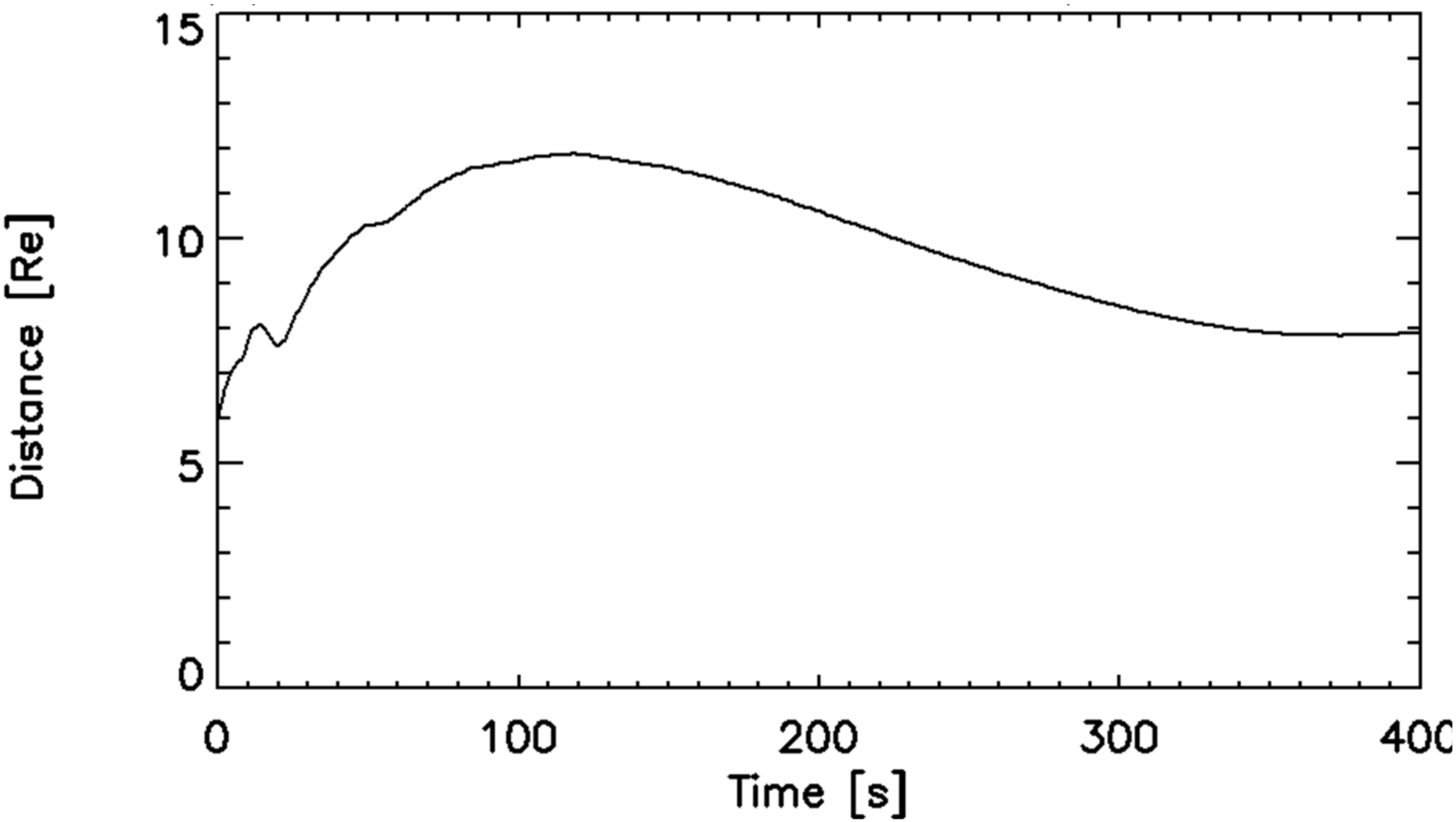


MHD Waves



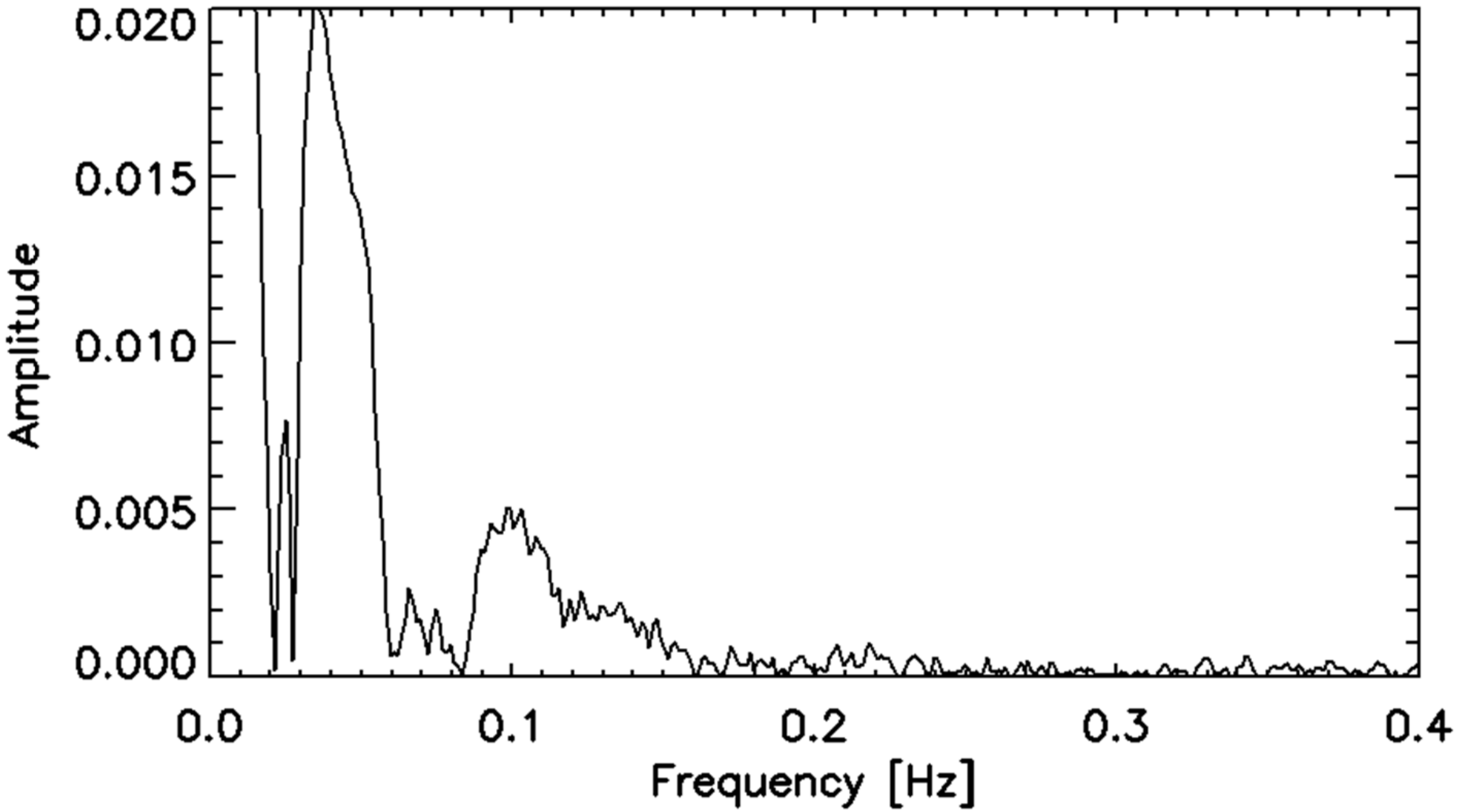
(a) t = 25.0 t0
(b) t = 49.9 t0
(c) t = 80.0 t0
z [Re]
x [Re]
dP*d(B^2)
5.0e-014
2.5e-014
0.0e+000
−2.5e-014
−5.0e-014
log plasma beta
4
2
0
−2
−4

Pulsation of the Magnetosphere by a Sudden Ring Current Injection



The L=6 field line distance in the equatorial plane.

Pulsation of the Magnetosphere: Fourier Amplitude

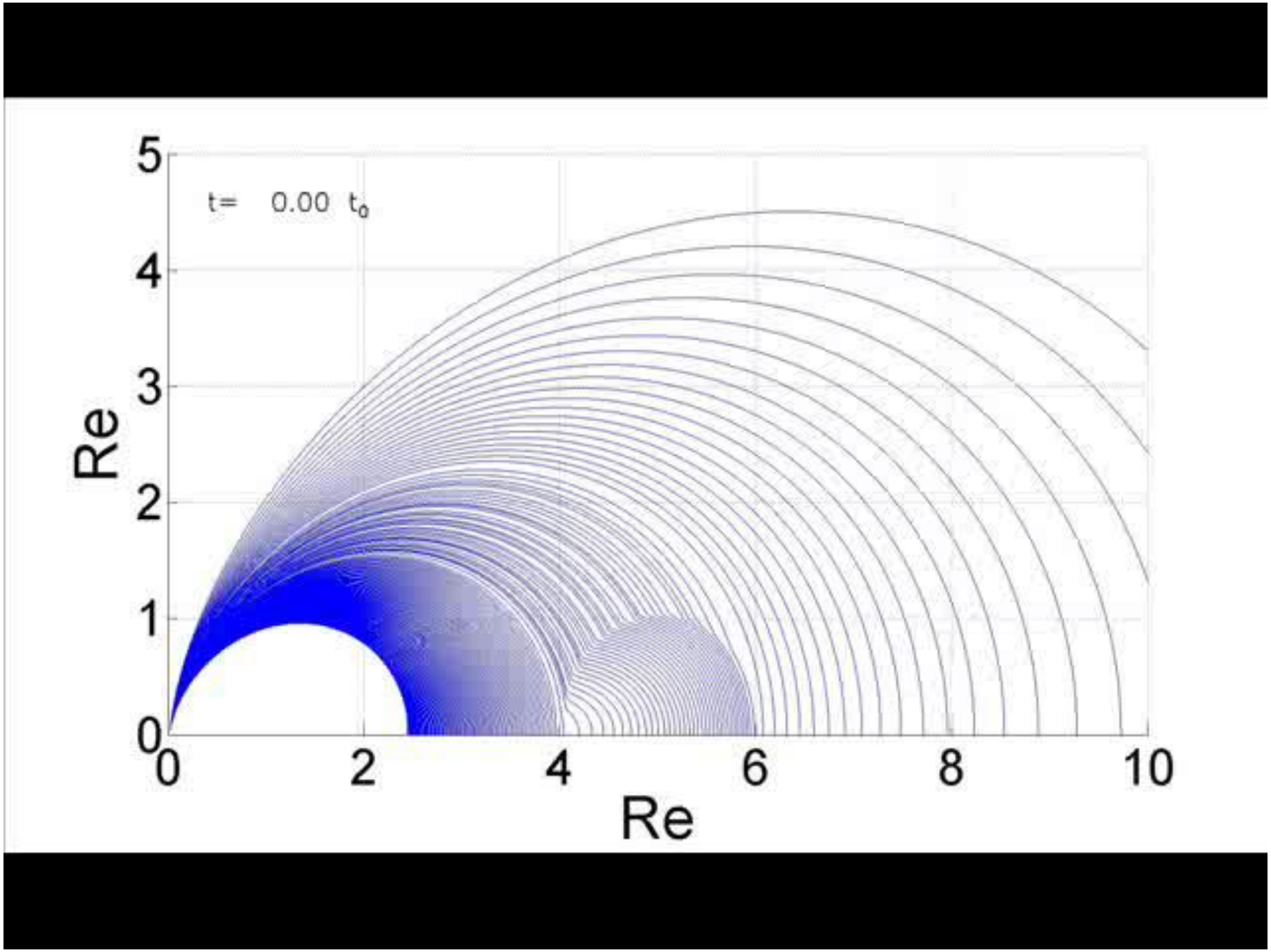


1st peak: <0.005 Hz (global pulsation)

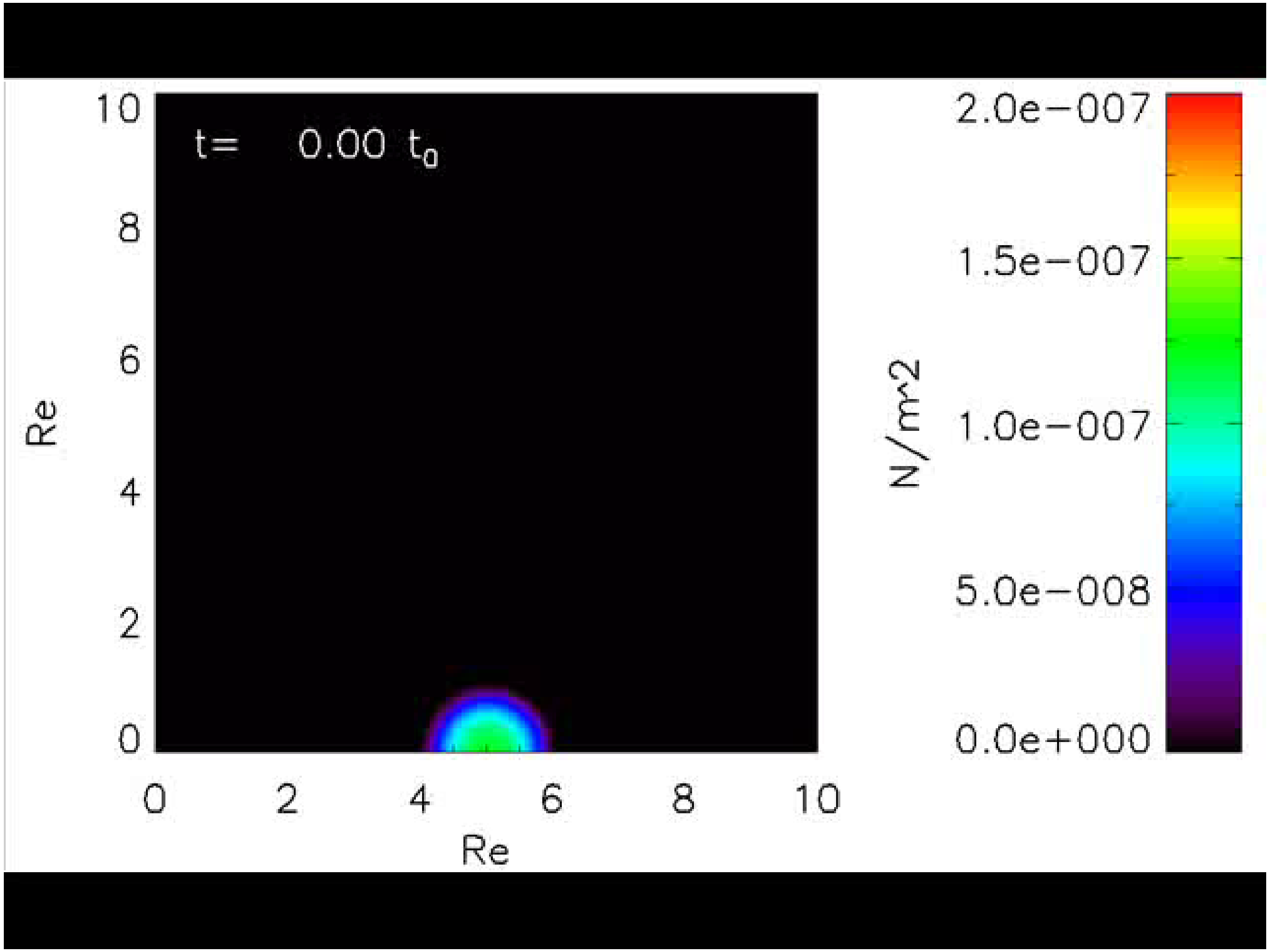
2nd peak: 0.034 Hz (island destruction)

3rd peak: 0.1 Hz (fast mode frequency)

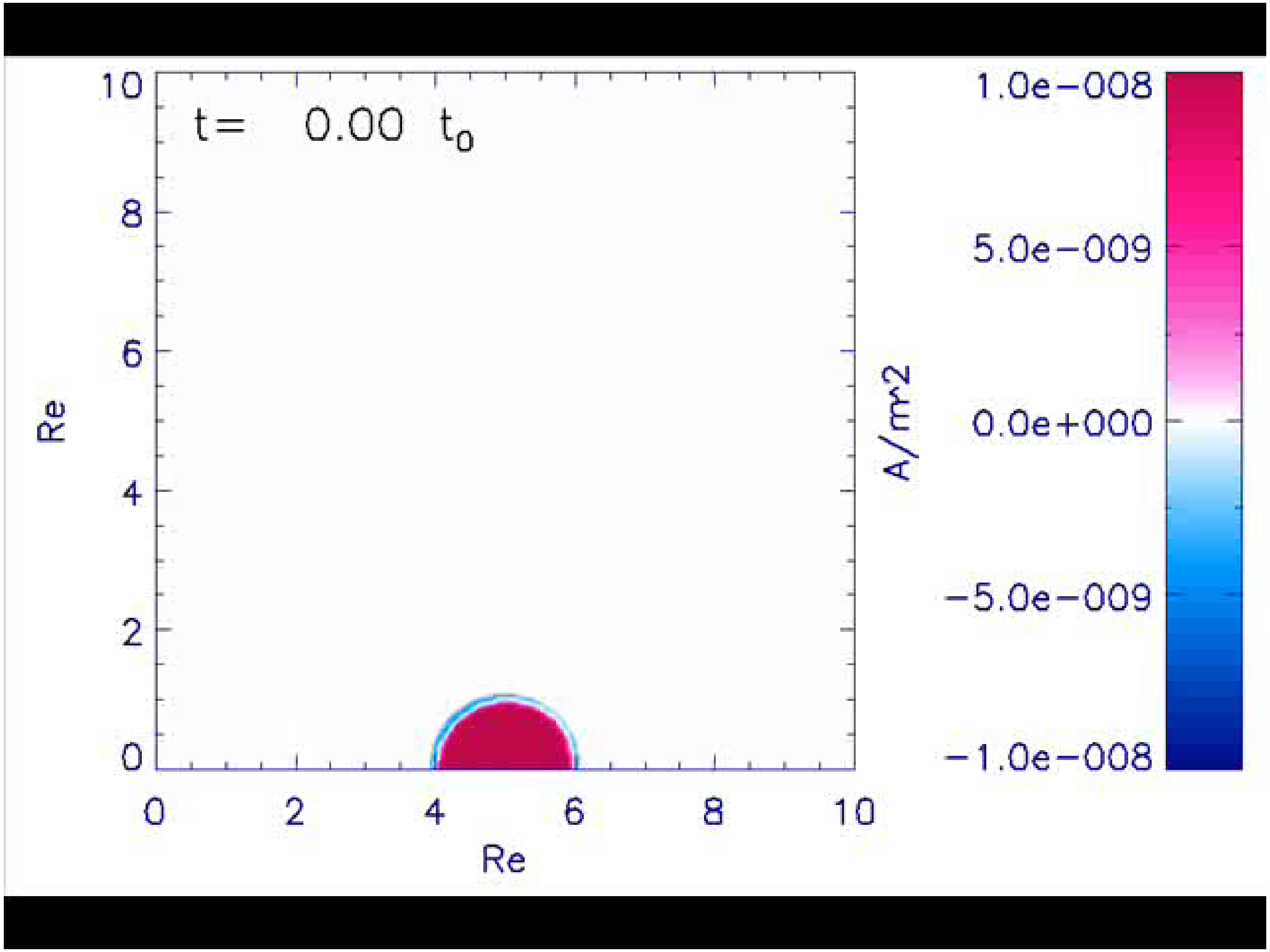
Case 2: Field Evolution



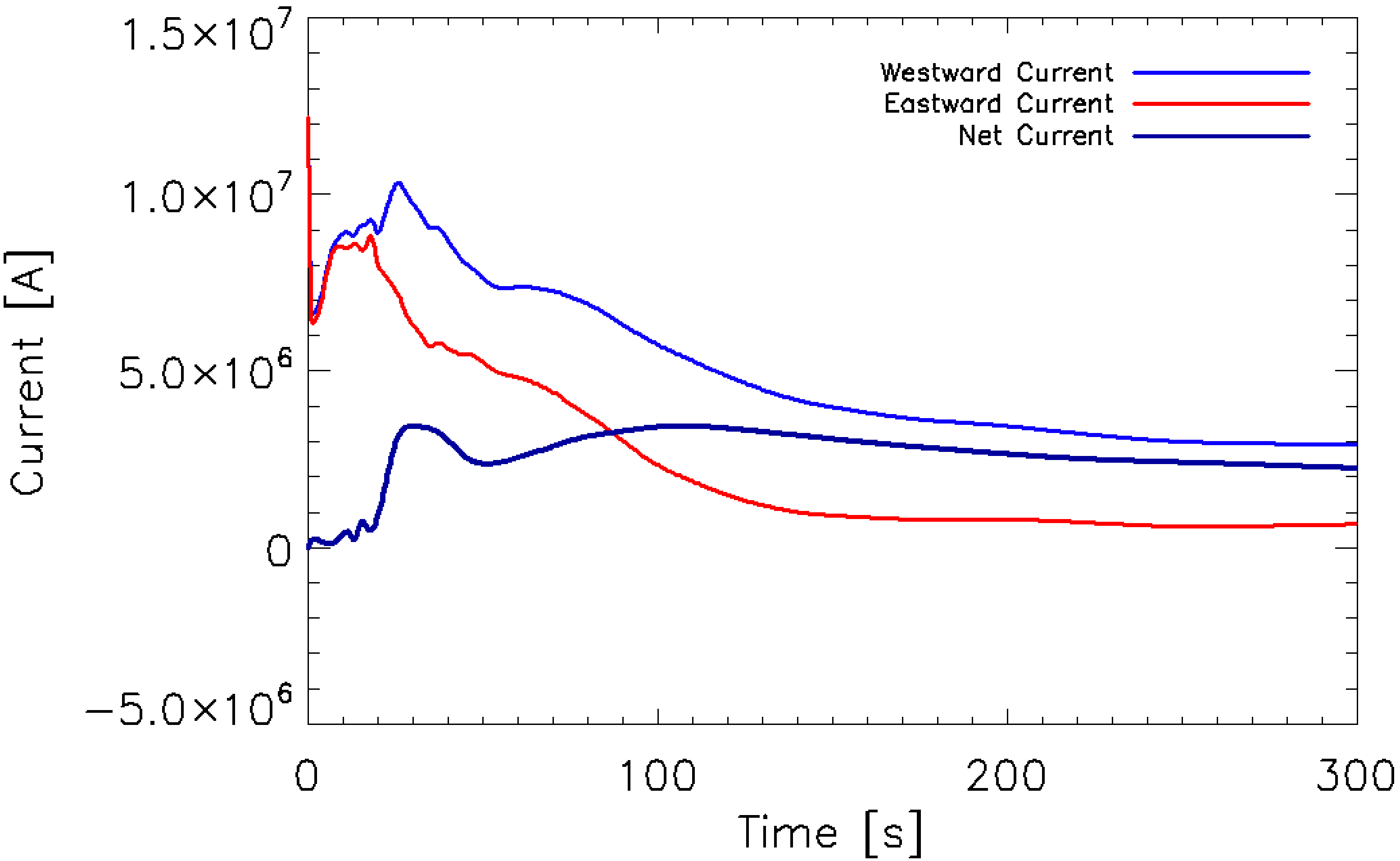
Case 2: Pressure Evolution



Case 2: Current Density Evolution



Case 2: Total Current Evolution



Summary

- It is argued that the magnetic field generated by a suddenly enhanced ring current be initially confined in a finite region.
- The evolution of the magnetosphere toward equilibrium involves
  - magnetic reconnection (if there is a magnetic island),
  - expansion and contraction in the direction perpendicular to the geomagnetic field, and
  - pressure-balancing motion in the field direction.
- The relaxation time of the magnetosphere is found to be about 5 minutes, over which the westward ring current is reduced to about 1/4 of its initial value whereas the eastward current is reduced to about 1/30 of its initial value.
- A sudden ring current injection can generate appreciable global pulsations.