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Inflation of dipole field in laboratory experiments for simulation of Hot Jupiter magnetosphere

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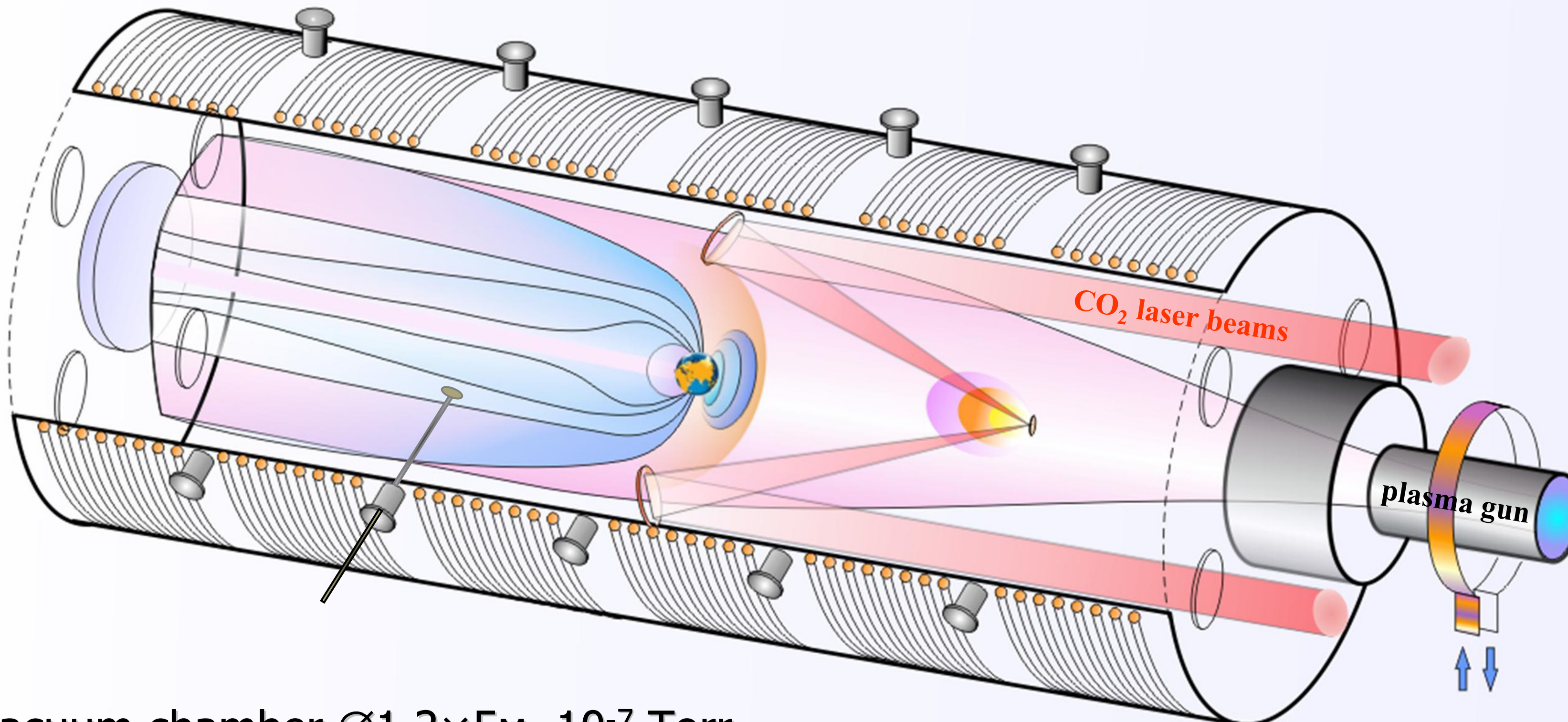
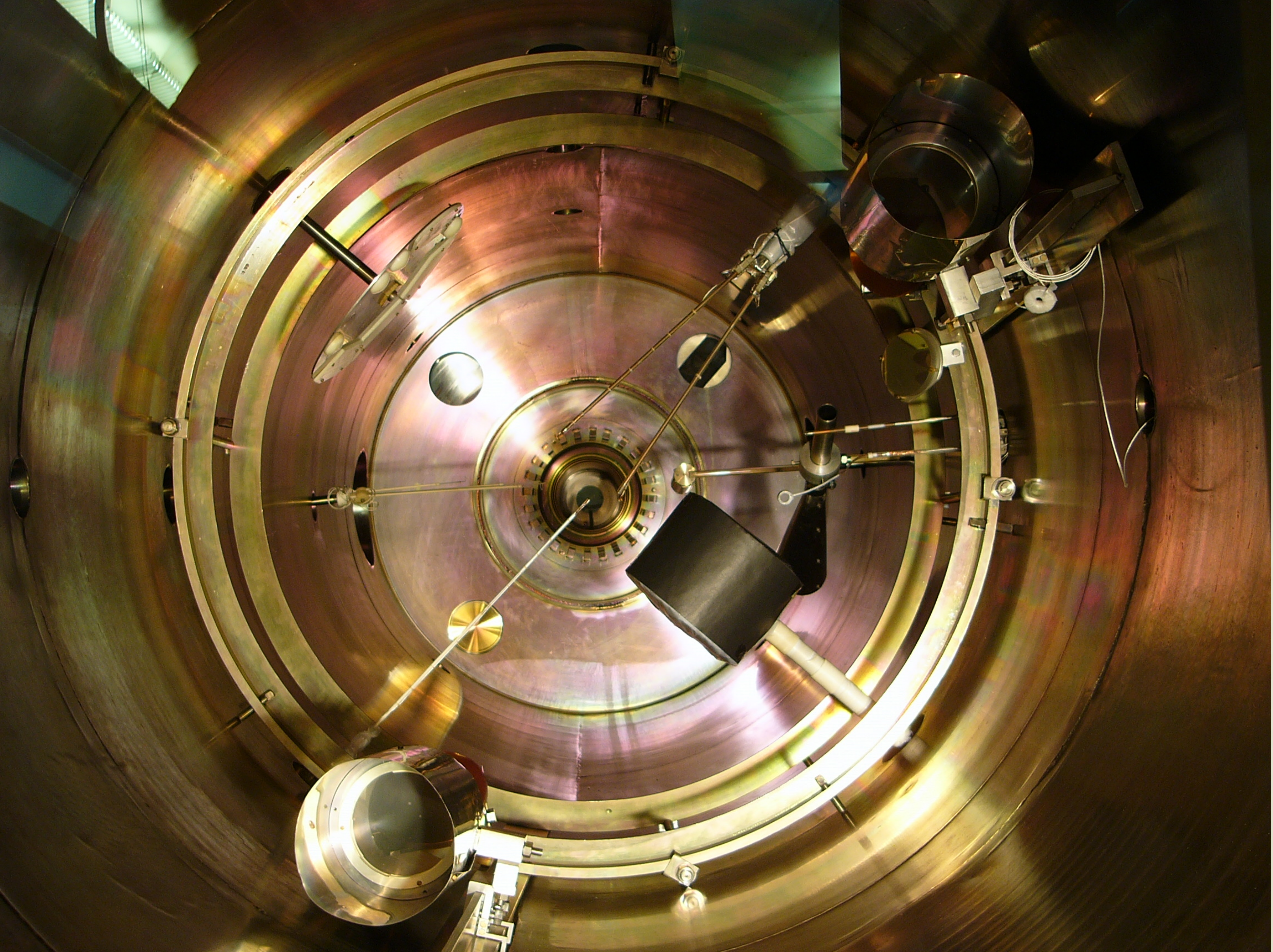
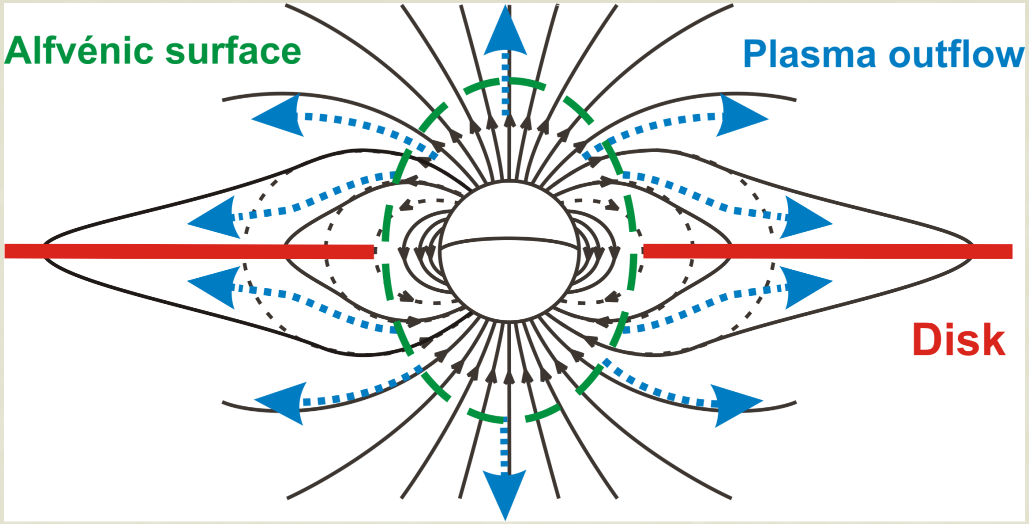
General experimental set up and KI-1 Facility



- High vacuum chamber ∅1.2×5м, 10^{-7} Torr
- Source of uniform magnetic field B_o ≤1000 G
- Series of compact magnetic dipoles $\mu=10^5 \div 10^7$ G·cm^3
- Electron and ion beams 10-300 keV, 1-10 kA
- CO_2 laser system with output energy up to 1 kJ in up to 4 beams
- Theta-pinch to fill the chamber with plasma ($n \sim 10^{13}$ cm^{-3}, V~100 km/s)
- Diagnostics center based on fast acquisition systems, plasma imaging, spectral analysis, probe measurements



The aim of the study



Schematic view of a magnetodisk formation by outflowing plasma in a dipole magnetic field of Hot Jupiter.

1. **We study the specifics of dynamical interaction of an expanding plasma flow with background dipole magnetic field.**
2. **This leads to formation of a disk-type plasma-magnetic structure with the induced ring current in the vicinity of the dipole equatorial plane and corresponding modification of the self-consistent magnetic field topology.**
3. **As a first step, for a more clear separation of various active factors influencing the formation of magnetodisk, the experimental study was aimed at simulation of only the expansion of plasma, without inclusion of the rotation and gravity effects.**

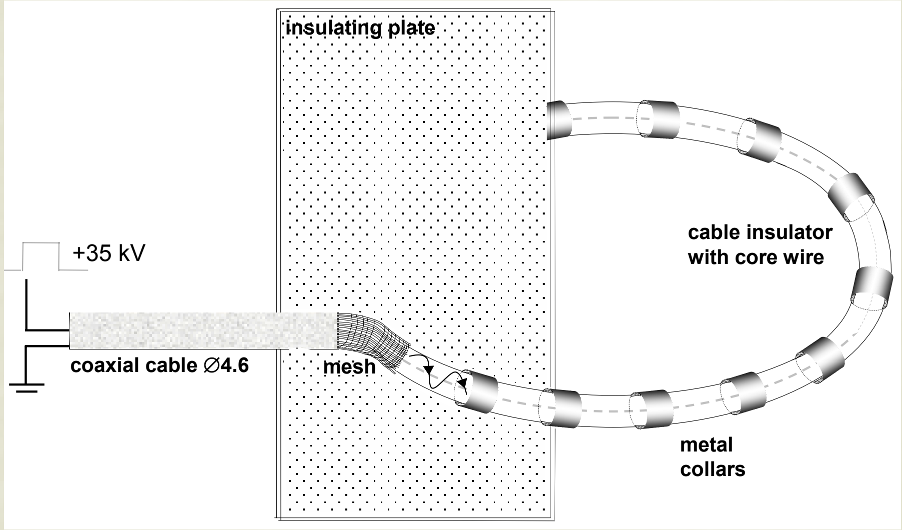
Dimension and dimensionless parameters of the problem

Parameter	Experiment	Hot Jupiter
planet radius R_p, cm	4.5	$\sim 10^{10}$
magnetic moment, $A \cdot m^2$	$3 \cdot 10^3$	10^{26}-10^{27}
temperature T_e, eV	~5	1-10
plasma velocity V, km/s	30-50	≥10
gravitational escape velocity	0	~50
rotation velocity at R_p	0	1-10
Alfvénic radius R_A/R_p	≈3	5-10
Interaction time tV/R_A	≈6	>>1
Reynolds number	~30	>>1
Hall parameter	1.5	>>1
gyroradius R_L/R_A	≈1	<<1

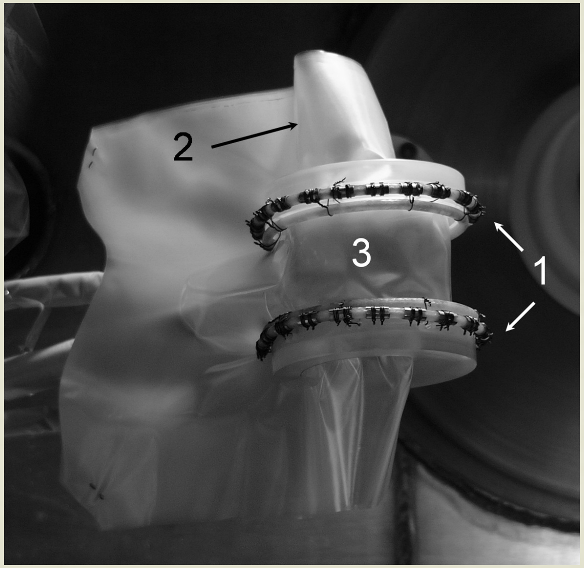
Without gravity and rotation the Alfvenic radius is the main parameter of the problem !

Experimental set up

1. For symmetric filling of dipole magnetic field with plasma, discharge injectors made of coaxial cable were used.
2. Two coil injectors are fasten to the cylindrical casing with. Inside the casing pulsed magnetic dipole is placed.
3. Plasma diagnostics consisted of Langmuire probe to measure charge density, Faraday cap to measure ion flux density, Rogovski coil to measure current and magnetic probes.



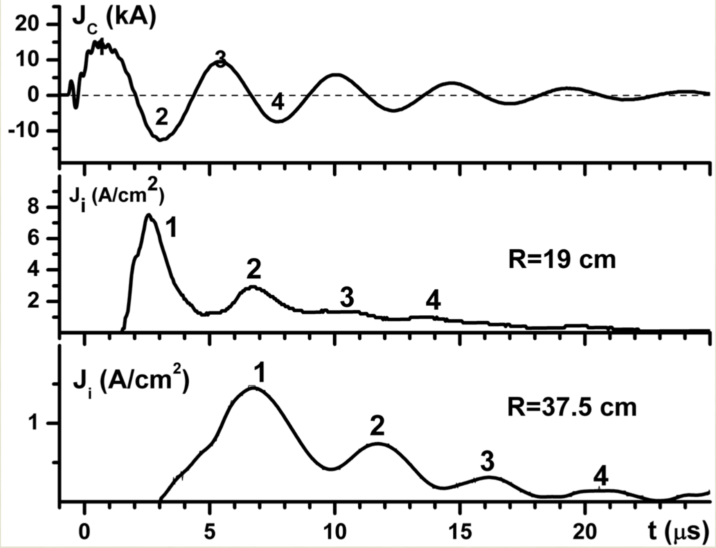
Plasma injector made of a coaxial cable.



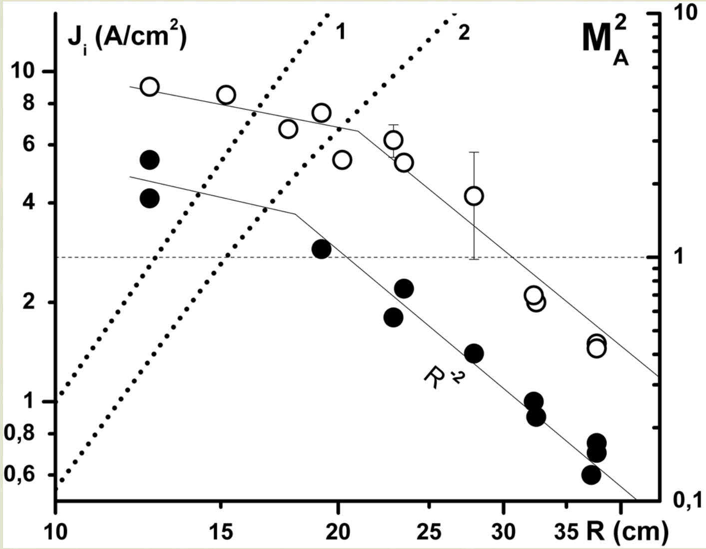
Experimental setup: coil injectors (1) with insulator (2) put over dipole casing (3).

Expanding plasma flow

1. Plasma flow is modulated and is produced by each half-cycle of discharge current. After the second pulse the plasma flow modulations overlap sufficiently well to constitute a continuous flux.
2. Energy and number of produced ions decrease from cycle to cycle as the discharge current falls. The plasma generated by the first, second and third half-cycles of electric current expands with velocity respectively 50, 40, 30 km/s. Amplitude of ion flux density (and density) scales at large distances approximately as $1/R^2$.



Dynamic of discharge current in coil injectors (top panel) and ion flux density measured by Faraday cup at two distances from the dipole center.

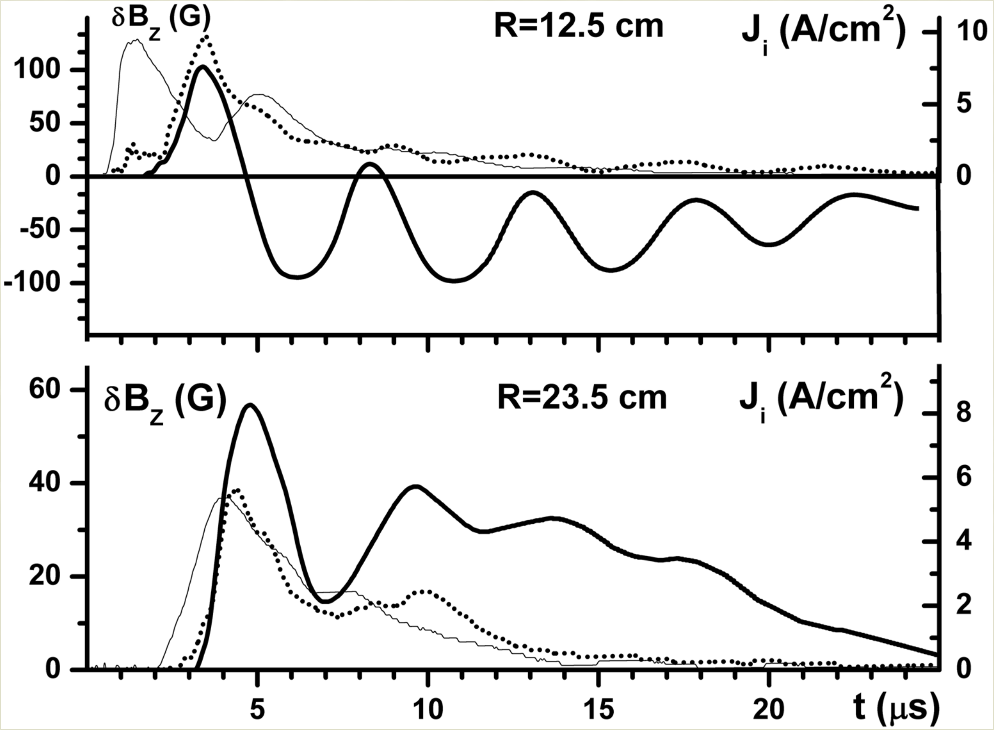


Dependence of ion flux on distance for the first (○) and the second (●) maximum of plasma flow. Dotted curves show calculated Alfvén-Mach number.

Interaction with dipole field

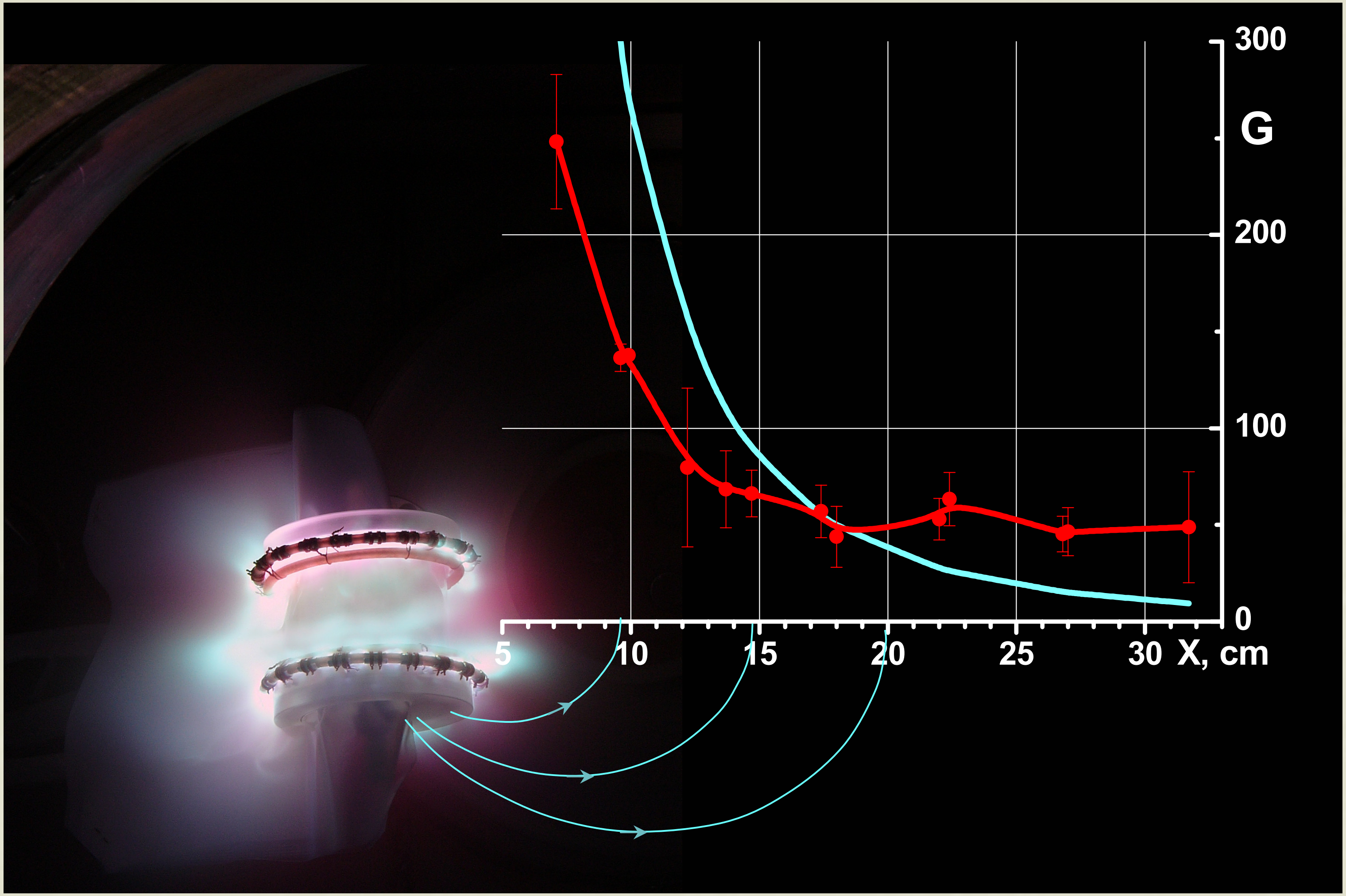
1. **Far from the source (bottom panel) the oscillations are less prominent and the result of interaction of plasma with dipole field is clearly seen. In particular, there is a strong disturbance produced by the first maximum of plasma flow, followed by a sufficiently long main phase of interaction supported by second, third and forth maximums**.
2. **At close distance there is an obvious influence of magnetic field on plasma motion as the first maximum is delayed by when dipole is switched on**.

3. **Magnetic variation changes sign between close and far regions of the dipole.**



Dynamic of the main magnetic component perturbation (thick solid lines) measured in equatorial plane close to the dipole (top panel, R=12.5 cm) and far from it (bottom panel, R=23.5 cm). Dotted lines show ion flux density under the same conditions; thin solid lines show ion flux density measured without dipole field.

Plasma stretching dipole field: inflation



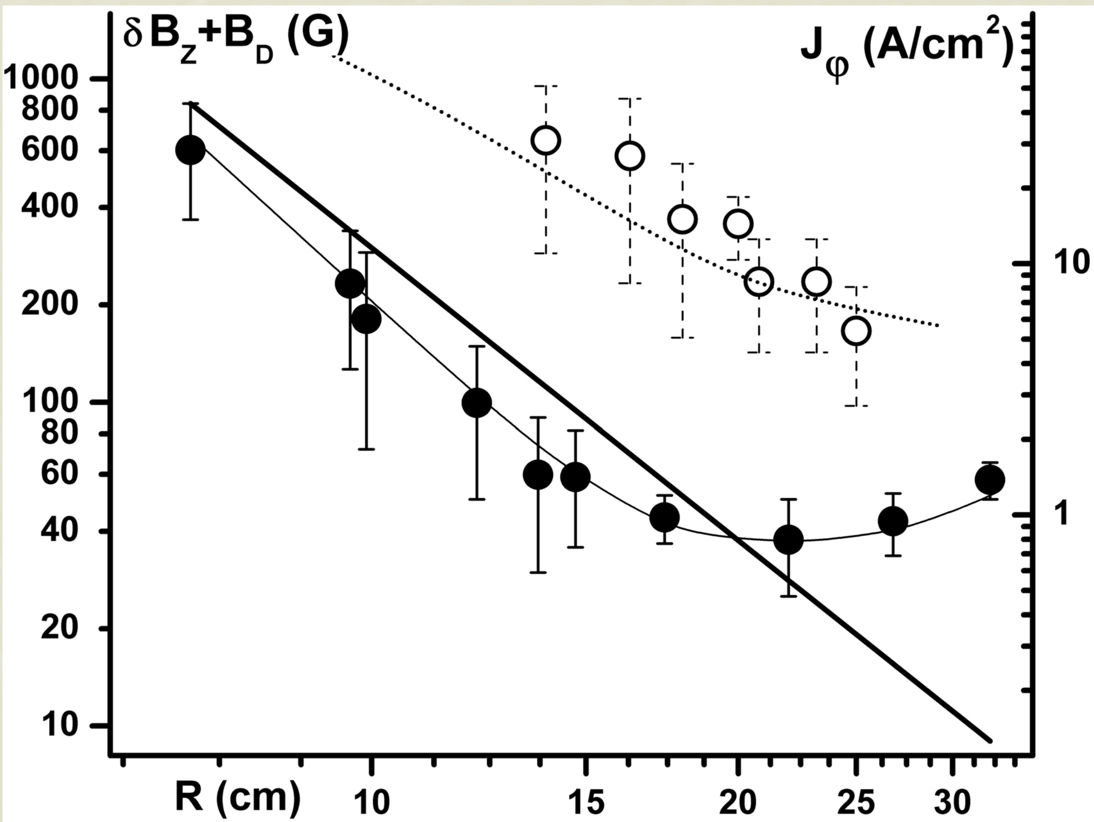
High voltage circular cables generate surface discharge and plasma with parameters

V~40 km/s
$n \sim 4 \cdot 10^{13}$ cm^{-3}
$\tau \sim 30$ μs

It was observed that plasma expansion decelerates. Kinetic energy goes to inflation of magnetic field. Strong increase of magnetic field was measured at distances at least 5 times larger than the source size.

Formation of magnetodisk

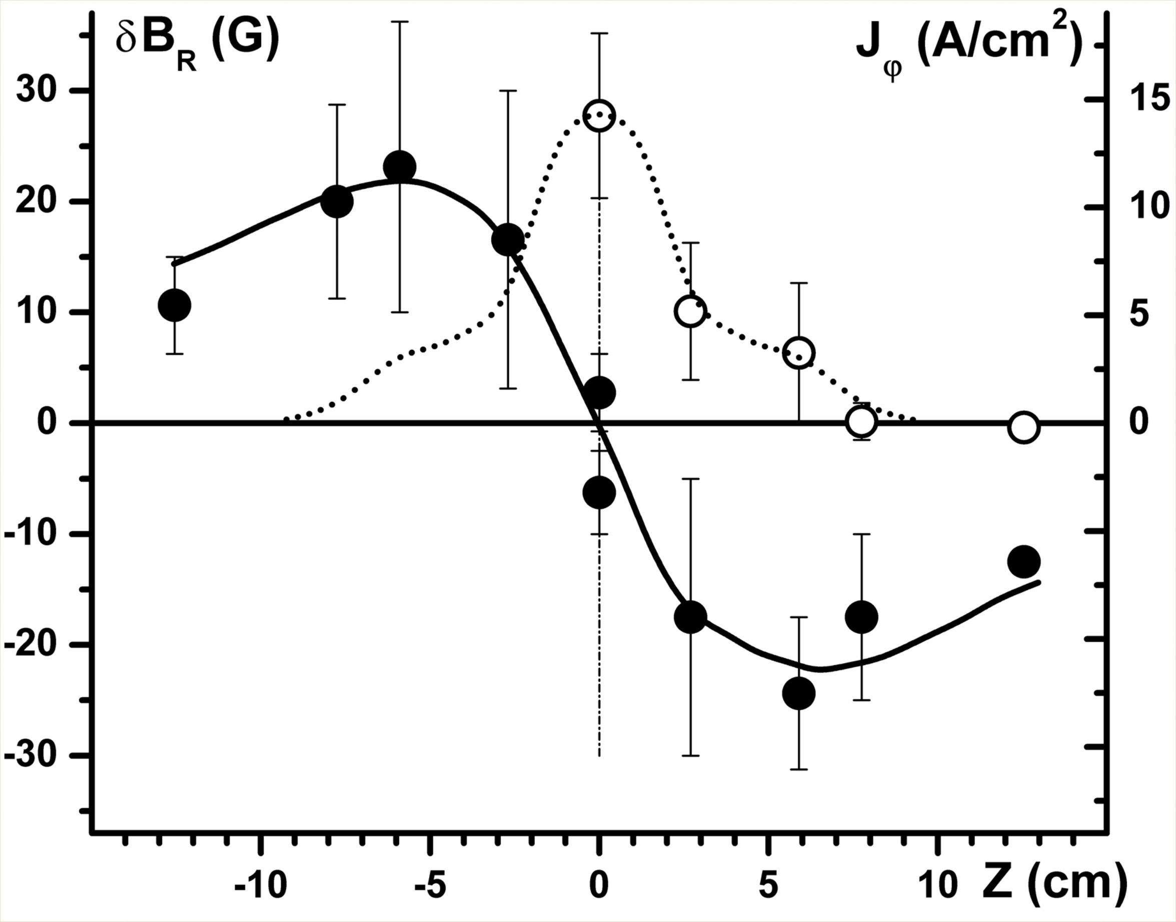
Magnetic probe and Rogovski coil show formation of current sheet in equatorial plane. At distances beyond Alvenic radius additional magnetic field is much larger than initial dipole field.



Left axis: radial profile of total magnetic field (●) in equatorial plane Z=0. Straight line shows initial dipole field . Right axis: current density in plasma obtained by Rogovski coil (○) and calculated using magnetic measurements (dotted line).

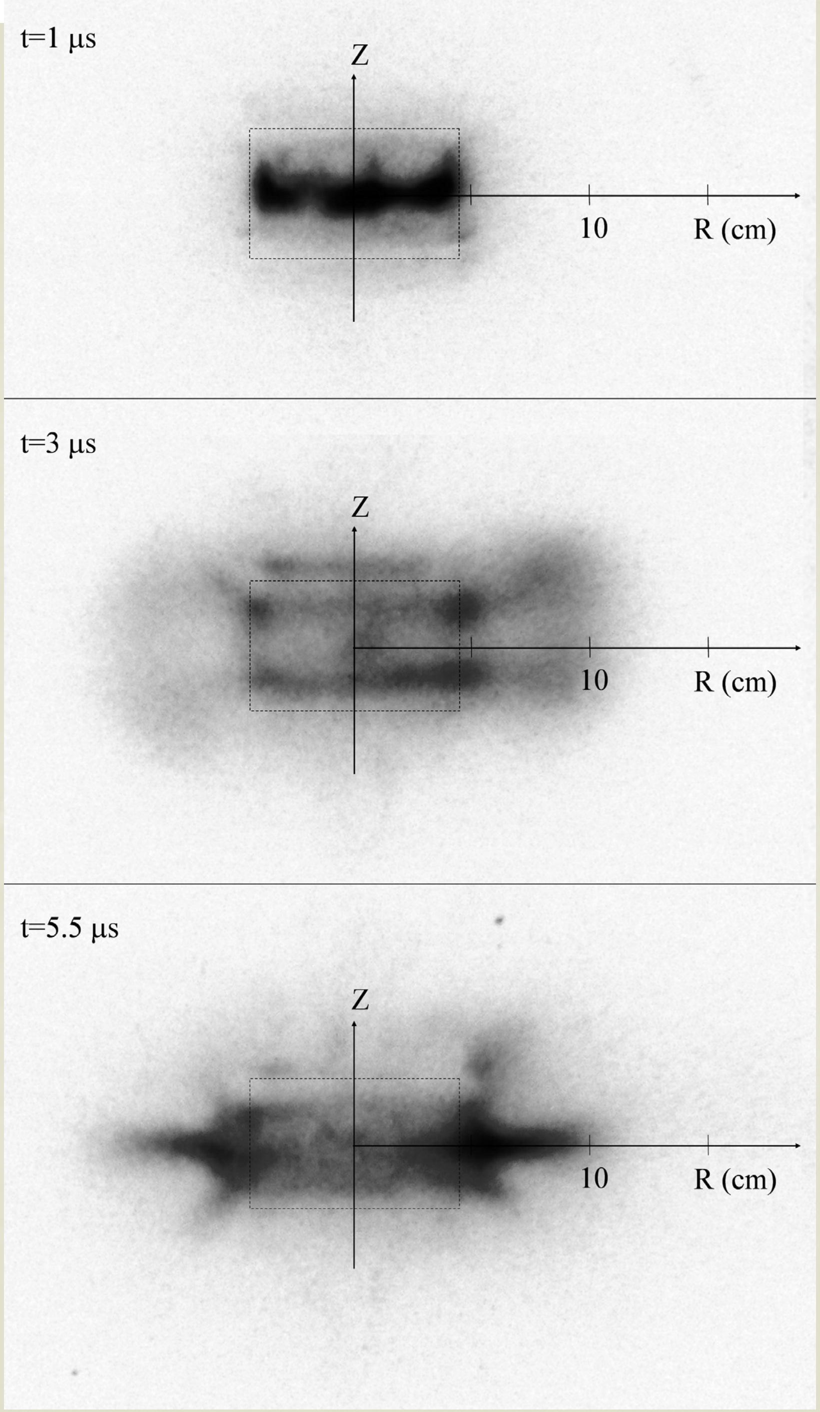
Magnetodisk structure

The width of current sheet is much smaller than its length and of the order of ion gyroradius.



Profiles of radial component (●, left axis) and current in plasma (○, right axis) across the equatorial plane at a distance of $R \approx 20$ cm.

Snap-short images



Short-time images of plasma expanding in a dipole magnetic field. Rectangle marks the dipole casing. The first image is taken just after the discharge initiation. In the second image one can see a wide halo formed by plasma generated by the first half-cycle of discharge. Bottom image corresponds to the quasi-continuous phase of interaction when plasma generated by the second and third half-cycles of discharge span distances up to 20 cm from the dipole. At this stage a thin equatorial disk appears.

Conclusions

- **The major purpose of the present laboratory study was <u>to demonstrate experimentally the expected formation of magnetodisk around a Hot Jupiter, and the effect of inflation of the initial planetary dipole magnetic field.</u>**

- **These effects, in the case of expanding plasma envelopes of a Hot Jupiter may lead to significant increase of the planetary magnetosphere size and contribute to better magnetospheric protection of the planet against of stellar wind and energetic particle impacts.**

- **The conducted experiment gives evidence, supported by measurements of magnetic field and current in plasma and shot-time images, of magnetodisk formation. The inflated field, or the field generated by induced currents, sufficiently far from the dipole center is much larger than the initial dipole one.**

- **Laboratory experiment provided really new and unavailable information and insight !!!**