# Ways of Magnetic Fields in Plasma

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# List of relevant publications


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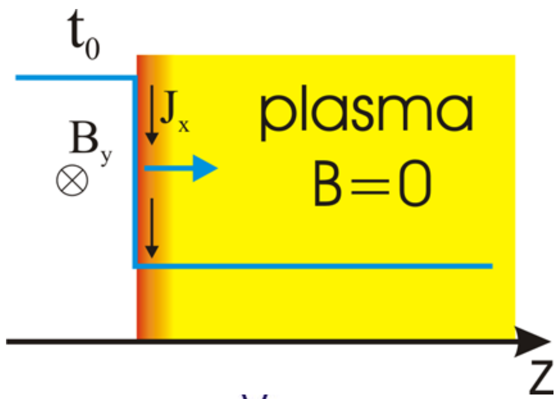
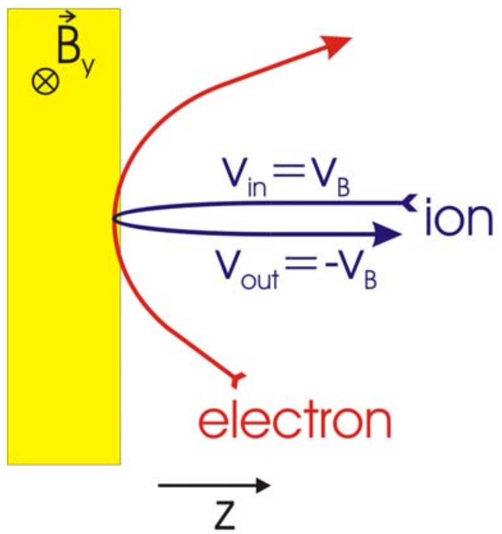
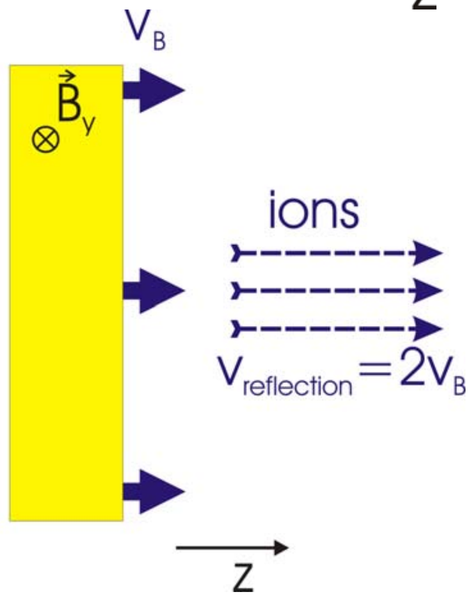
# Collisionless plasma




In the frame
of moving B-field




Laboratory frame

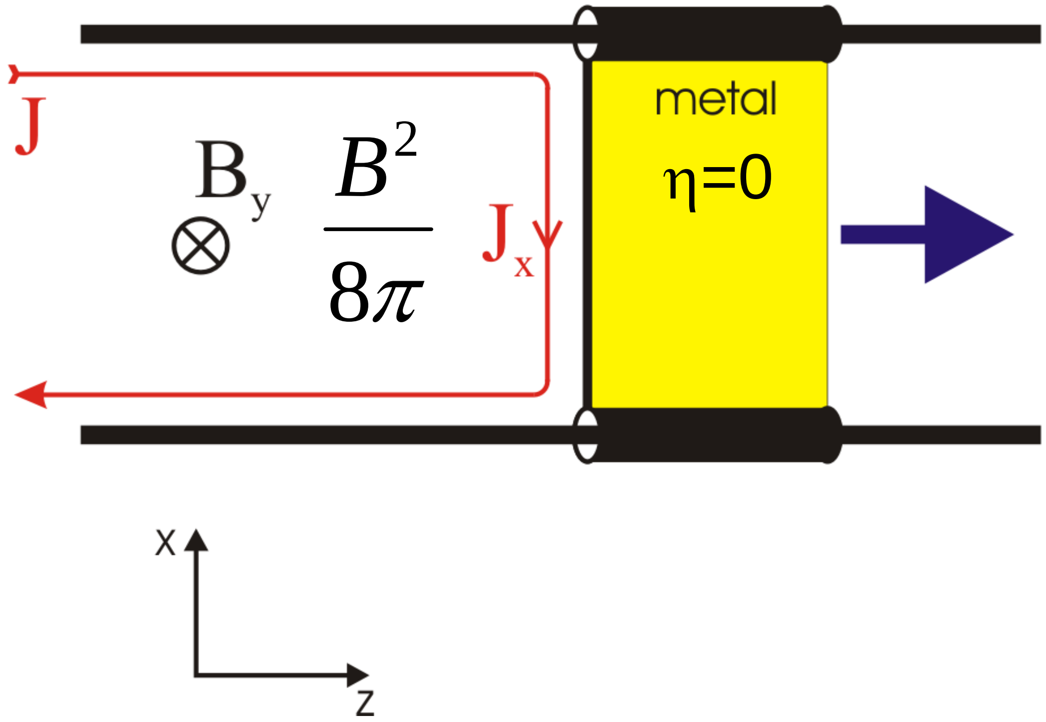
- Plasma Reflection
- Magnetic-Field Energy Dissipation $\cong \dfrac{B^2}{8\pi}$

$$\Rightarrow \frac{M_i V_i^2}{2}$$

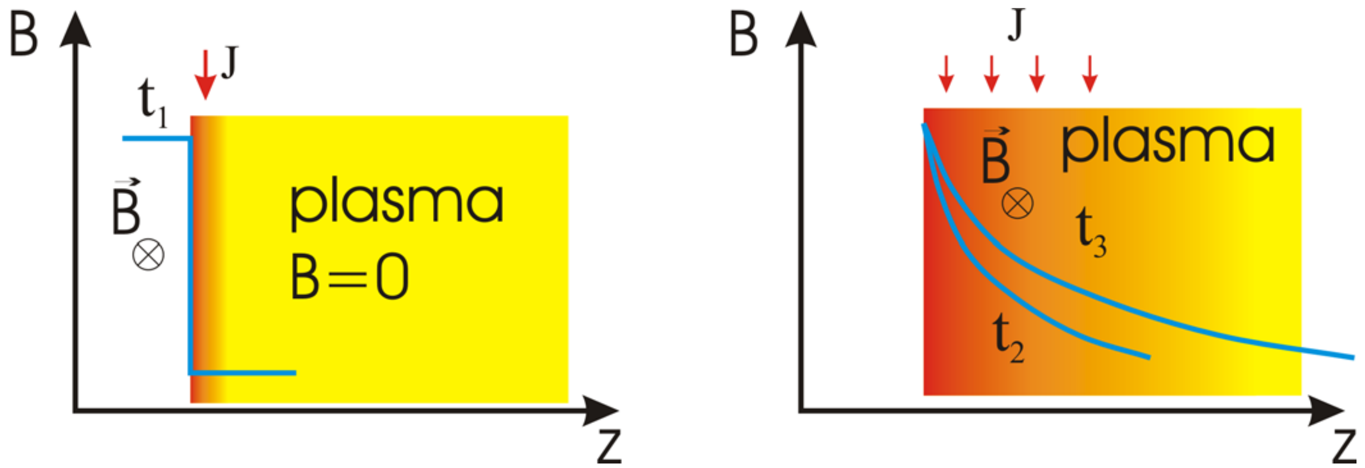
*Ref: M. Rosenbluth (1954)*

Composition plays no role!!!

# Magnetic-Field Pressure



# Highly-collisional plasma




- Field Penetration by Diffusion
- Energy Dissipation ≅ ηj$^2$ (η-resistivity)

$$-\frac{1}{c}\frac{\partial B}{\partial t} = \nabla \times E$$

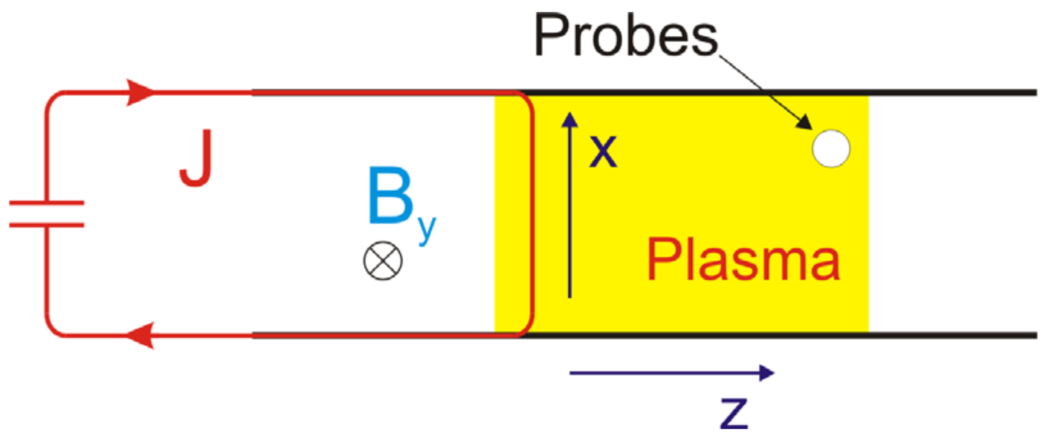
$$E = \eta\, j - \frac{v_e}{c} \times B$$

**In 1D approximation:**

$$\frac{\partial B}{\partial t} = \frac{c^2 \eta}{4\pi}\nabla^2 B + \nabla \times \left(v_i \times B\right)$$

# The Puzzle

## Low-collisionality plasma ($n_e \cong 10^{14}$ cm$^{-3}$)




Probe measurements show Fast Penetration of B into the Plasma

B. Weber at al. (1984)

R. Kulsrud et al. (1988)
R. Sudan et al. (1988)
$\eta$ must be low
No Diffusion

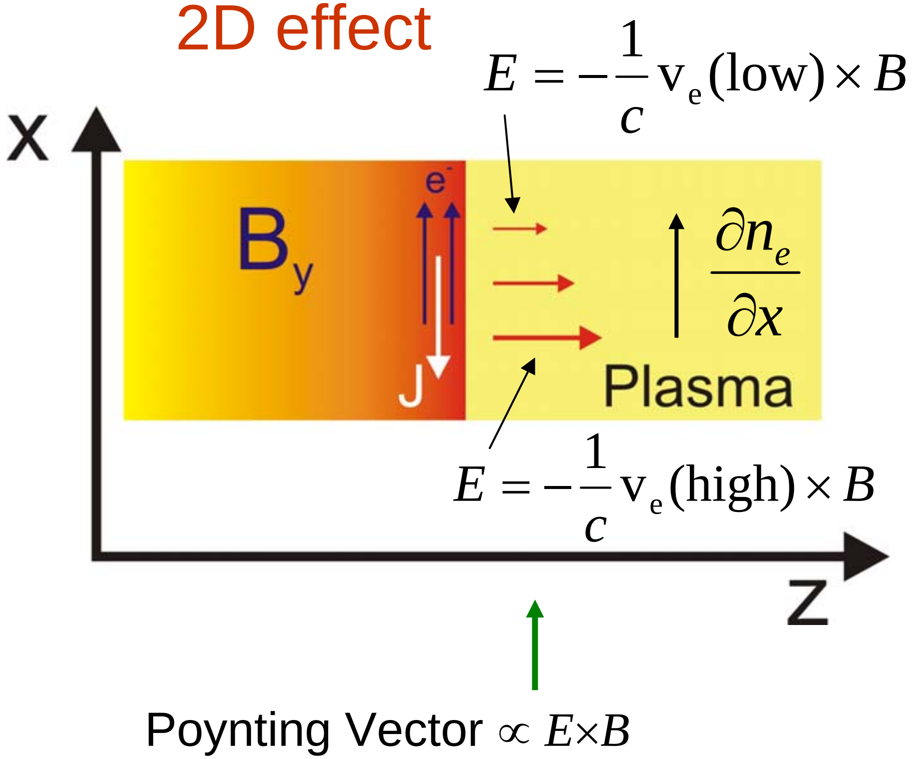
Energy dissipation:

$E_e$ ~ 8 keV/electron

# Penetration due to the Hall-Field effect

Low-collisionality plasma

2D effect




Ion motion was neglected.
EMHD
Energy is dissipated on electrons (~8 keV/electron)

Composition plays no role.

A. Gordeev, A. Fruchtman
L. Rudakov,
A. Kingsep

1990-1994

# Fast penetration due to the Hall-field effect

## 2-D

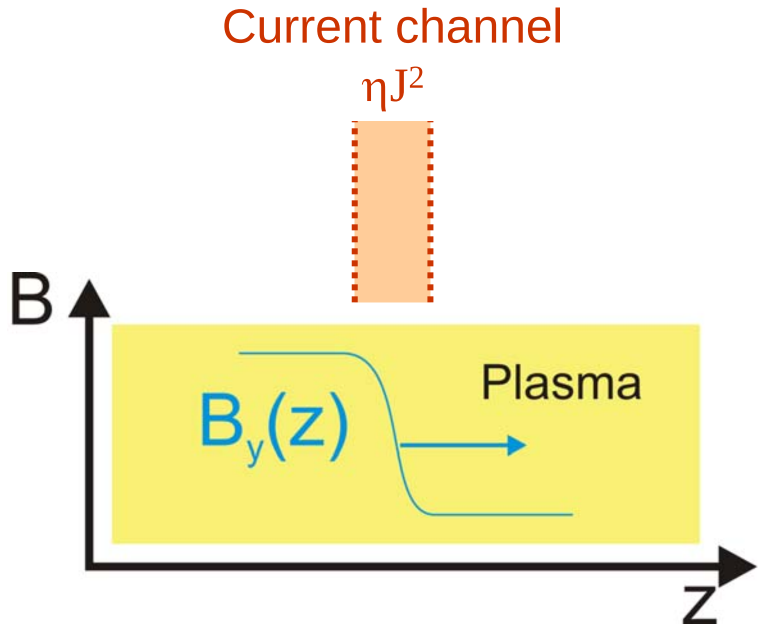
$$\frac{4\pi}{c}J = \nabla \times B$$

$$-\frac{1}{c}\frac{\partial B}{\partial t} = \nabla \times E$$

$$E = \eta J + \frac{J \times B}{enc}; \quad v_i = 0$$

$$J = -nev_e$$

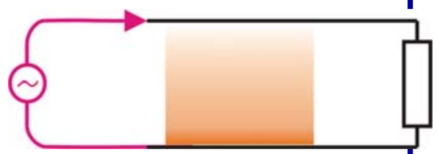
$$\frac{\partial B}{\partial t} = \frac{c^2\eta}{4\pi}\nabla^2 B - \frac{c}{4\pi e}\nabla \times \left[\frac{1}{n}(\nabla \times B)\times B\right]$$



# Plasma Interaction with Pulsed magnetic Fields

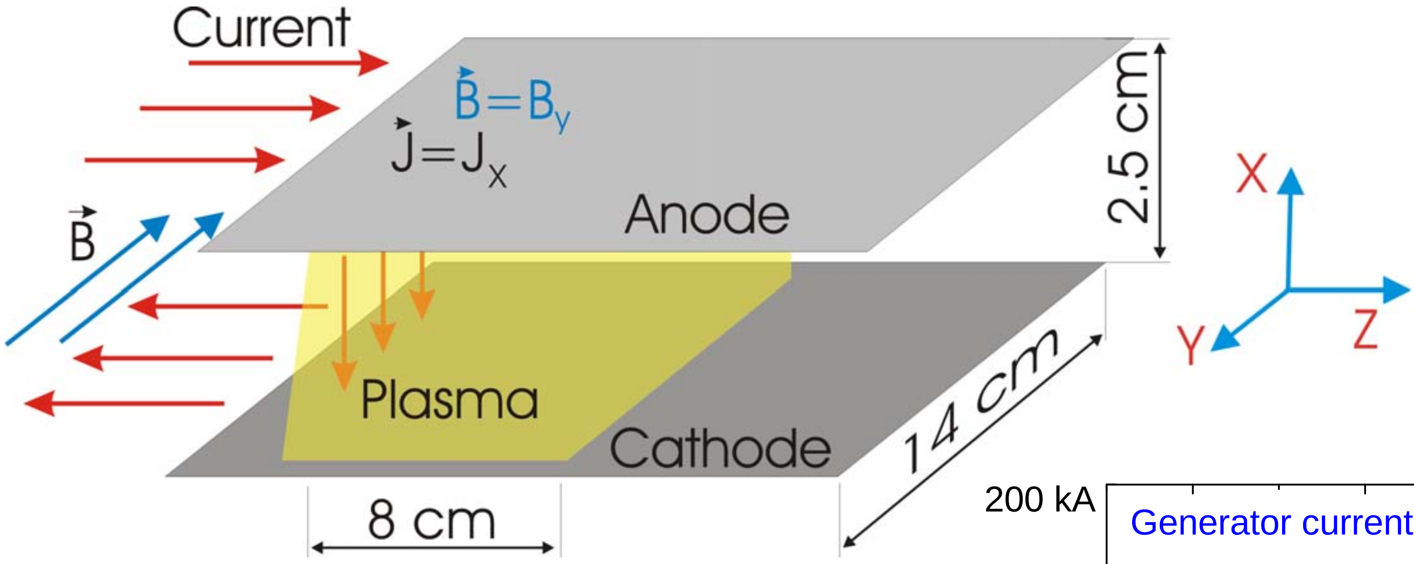
The problem is manifested in:

- Space Physics (Solar flares, Solar wind, Bow shocks, Coronal mass ejection).
- Transmission of high-energy pulses.



- Fusion research (Magnetic Fusion, Plasma Compression)
- Hall-Thrusters for space crafts.

# Experiment




$N_e$~$10^{14}$ $cm^{-3}$; $T_e$ ~ 6 eV

Plasma Composition:

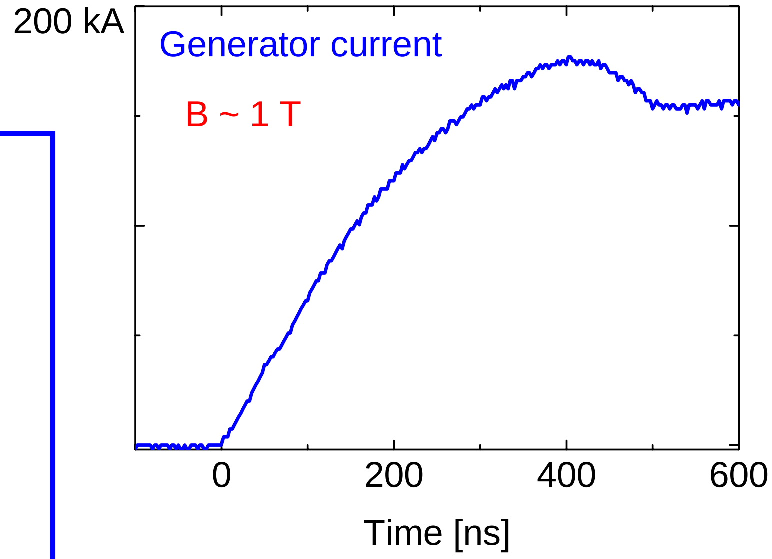
Variable fractions of protons and $C^{3+}$

Proton fraction = 0.08 ÷ 0.3 of total mass

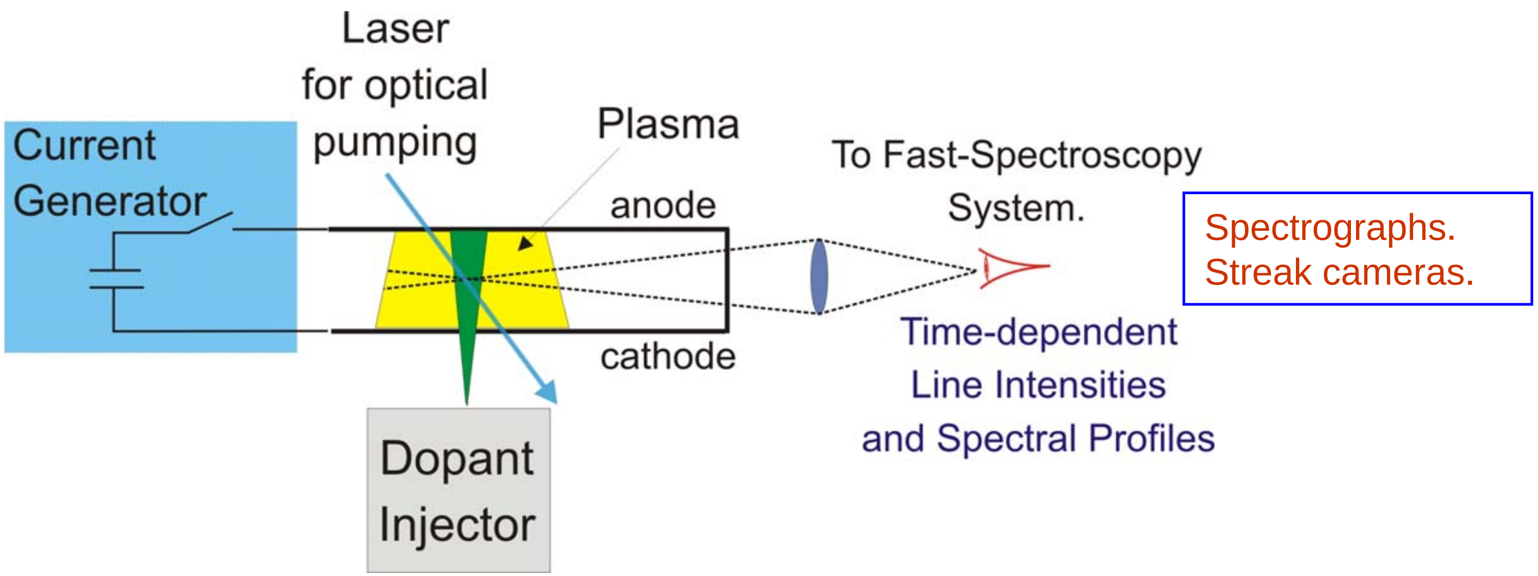
*D. Osin, R. Doron et al. (2003)*

*R. Arad, K. Tsigutkin et al. Phys Plasmas (2000)*

*A. Weingarten, V. Bernshtam et al. Phys Plasmas (1999)*



# Diagnostics




- Doping ⇒
  3D spatially resolved measurements.
- Temporal resolution 5 ns.
- Spectral region:
  2000-7000 Å

*K. Tsigutkin et al. (2003, 2004)*

*E. Stambulchik (2003)*

*Laser spectroscopy,*

*Dipole-forbidden transitions,*

*Stark broadening.*

*R. Arad et al. (2001)*

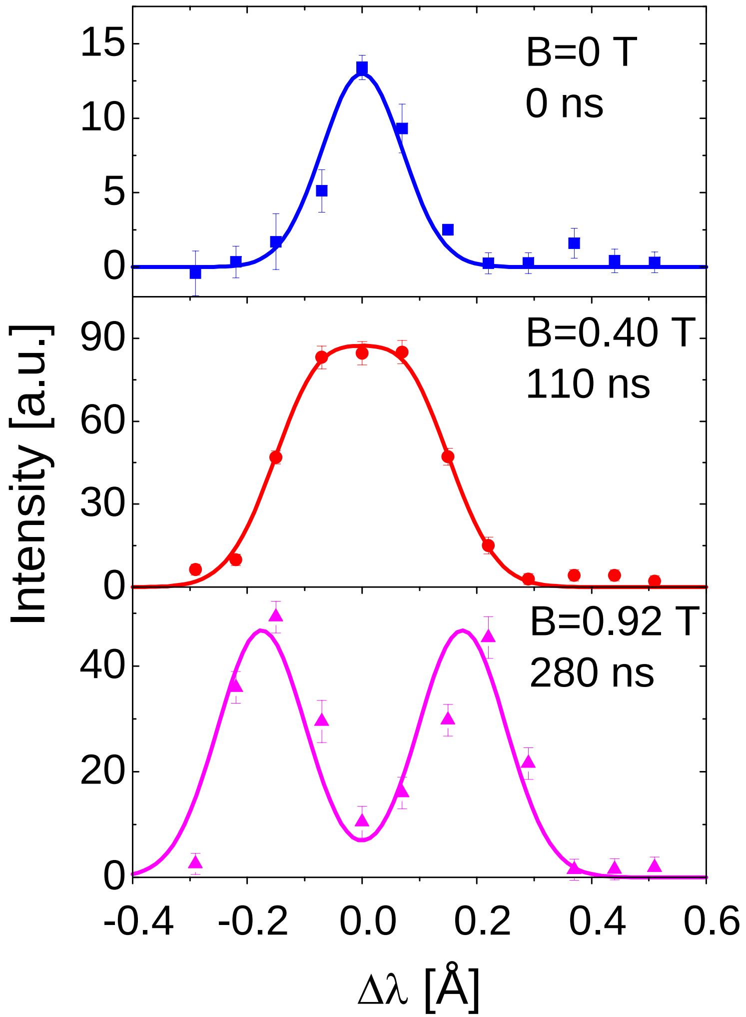
*A. Weingarten et al. (1999)*

*Emission spectroscopy.*

# Magnetic Field Measurements

Zeeman splitting of Doped-HeI line

(2p $^1$P - 3d $^1$D $\lambda$=6678 Å).

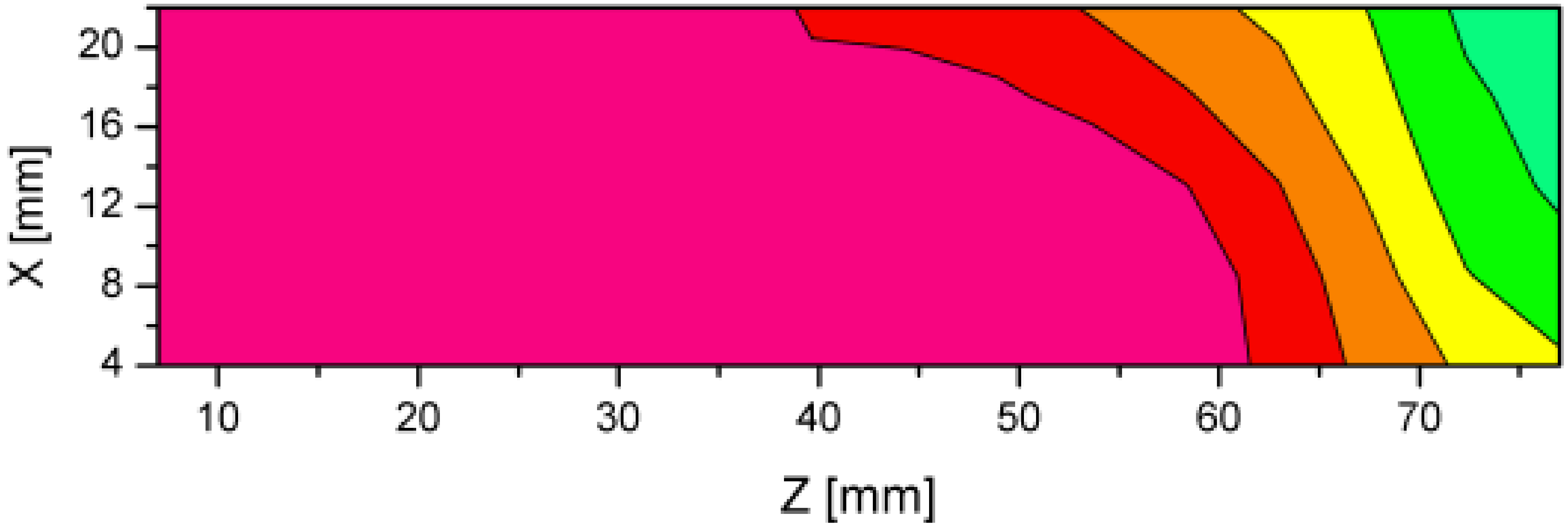



**Only the σ components are seen** since the observations are performed along the magnetic field.

# Techniques for Measuring Electromagnetic Fields and Plasma Properties

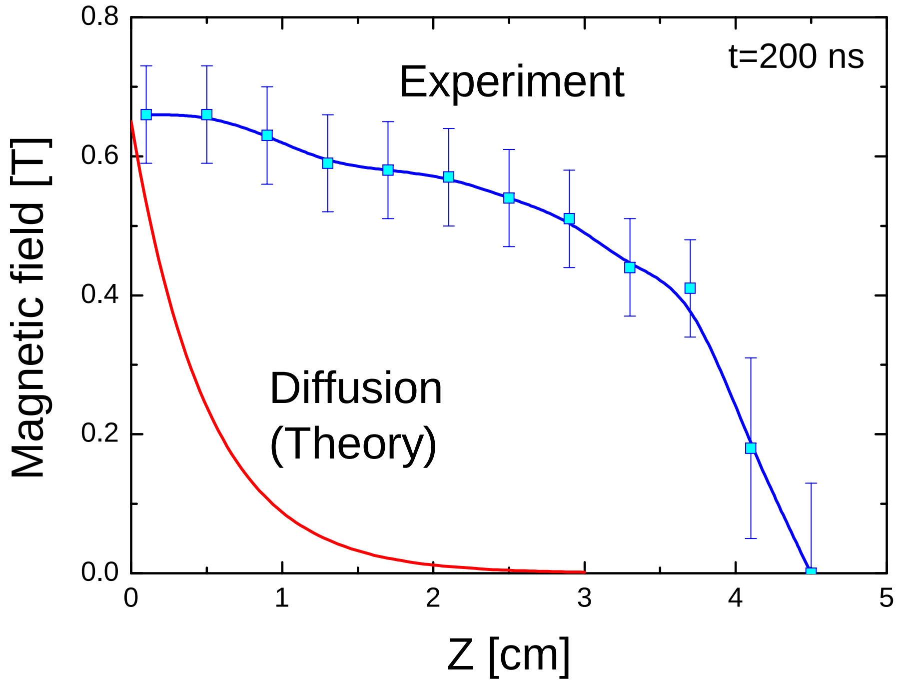
| Parameter | Method |
|---|---|
| **Magnetic field** | Zeeman splitting |
| **Electric fields** | • Stark shift<br>• Spectral line shapes<br>• Anisotropic Stark broadening<br>• Intensity of forbidden lines |
| **Ion velocity distributions** | Doppler line shapes |
| **Electron density** | • Stark broadening<br>• Evolution of line intensities |
| **Electron temperature and Electron Energy Distribution (EED)** | • Line intensities<br>• Ionization times<br>• Atomic-physics modeling<br>• Different-spin transitions |

# Magnetic field evolution




Time: 220 ns

# Magnetic field distribution along z-axis




$\eta \propto \frac{1}{T_e^{3/2}}$ is known.

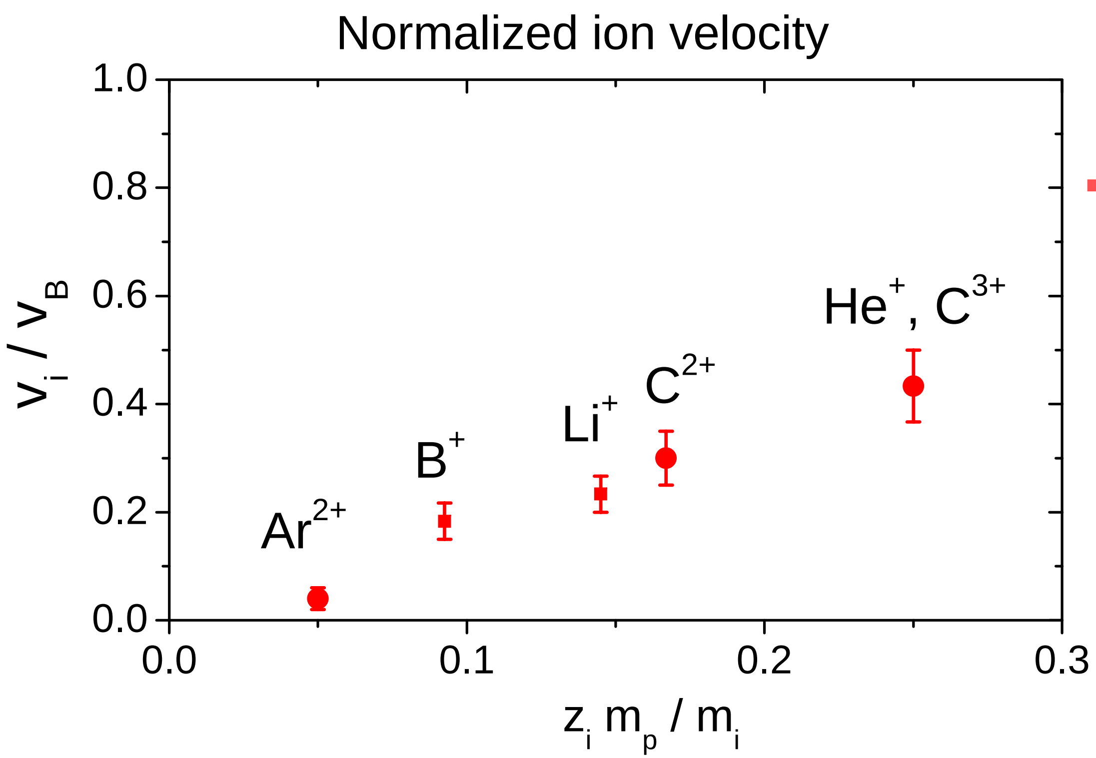
$T_e$ is determined from level-population ratios.

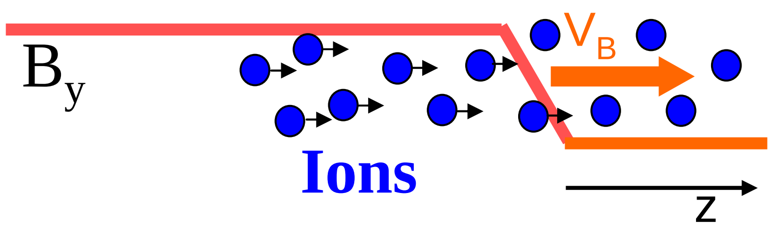
1. The distribution shows fast penetration
2. Magnetic field propagation velocity and profile are **inconsistent** with diffusion.
3. Strongly suggests Hall-field effect

$$V_{Hall} = \frac{B}{2\mu_o\, e\, n_e\, \Delta L} \approx 3\times10^7\, cm/s$$

*R. Arad, K. Tsigutkin et al., Phys. Plasmas (2003)*

# Ion velocities from Doppler shifts

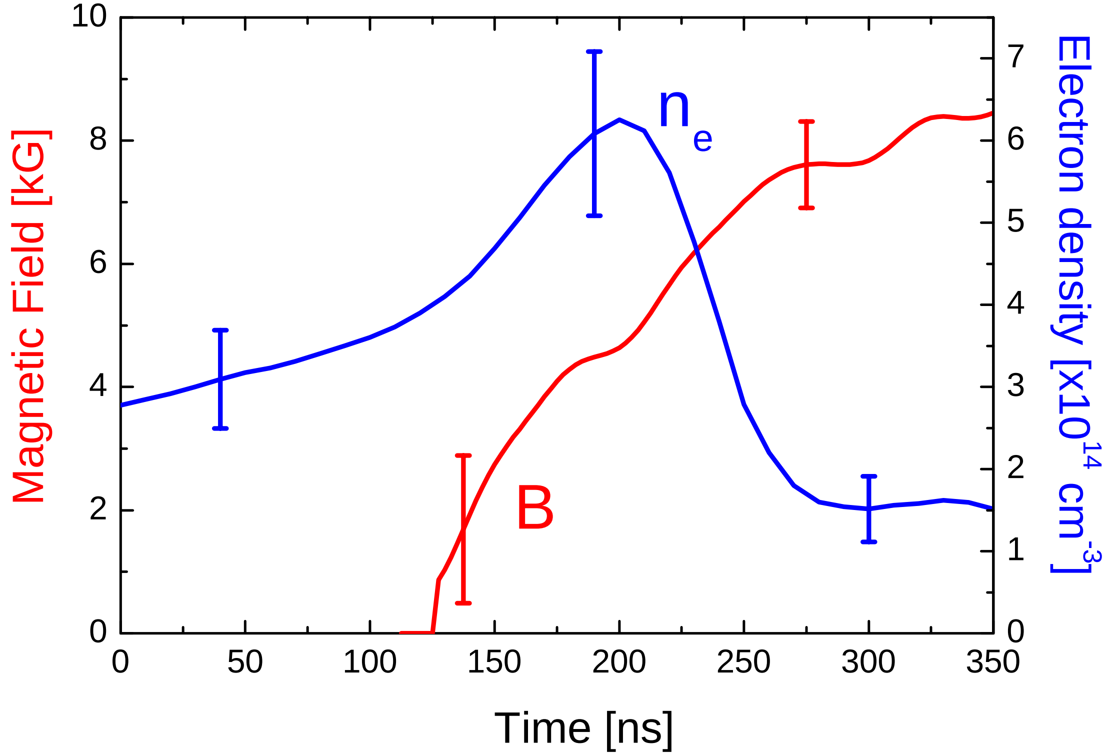



**IONS ARE SLOWER** than the front of B $\Rightarrow$
Consistent with the present theoretical treatments.

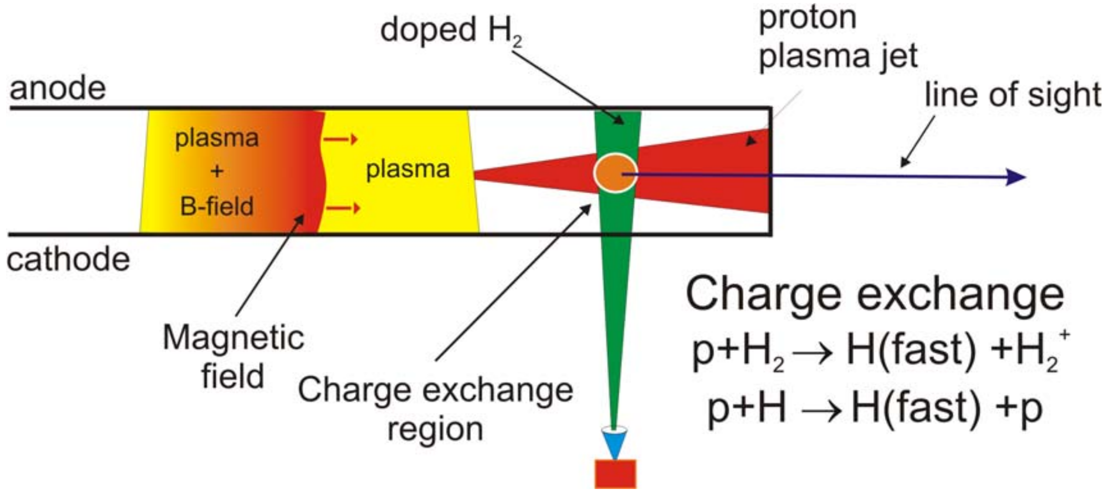
# Field penetration and electron density time dependence

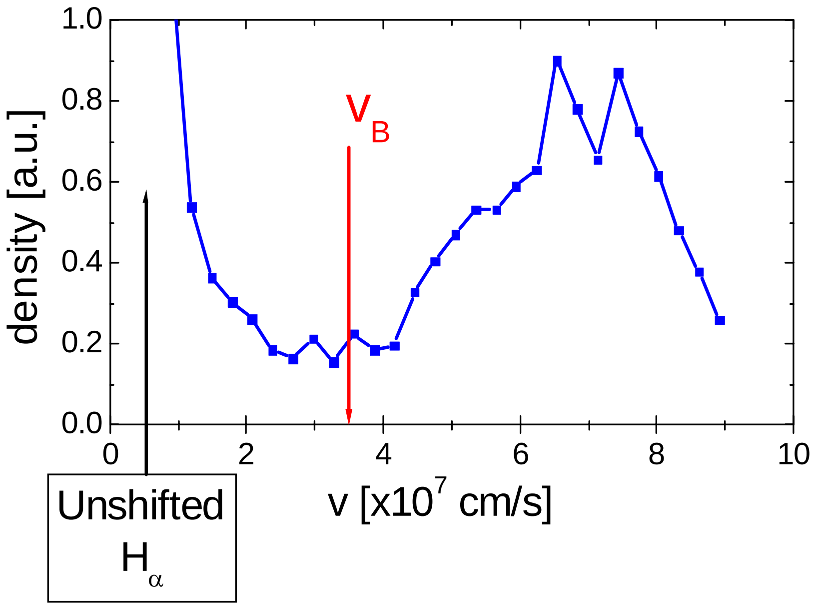
**3D-resolved measurements of B(t) and $n_e$(t)**




**Locally**, $N_e$ drops when B rises ⇒ Ions Move.

# Proton velocity from charge exchange spectroscopy



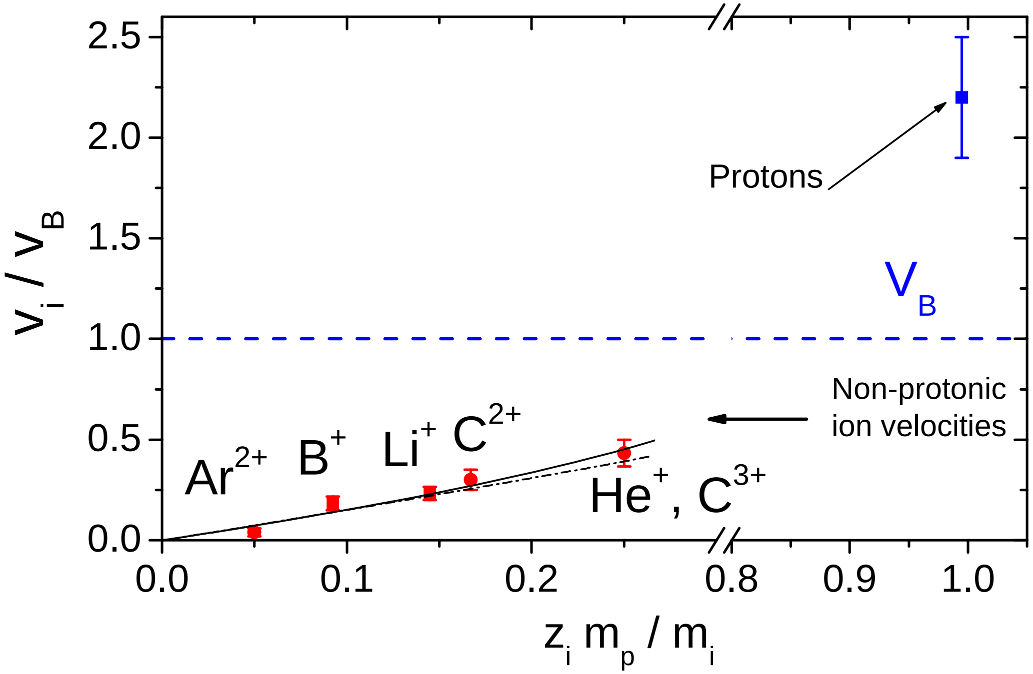




**$V_{protons} \sim 2V_B$.**

The protons are reflected out of the plasma

R. Arad, K. Tsigutkin et al., to appear in Phys. Plasmas

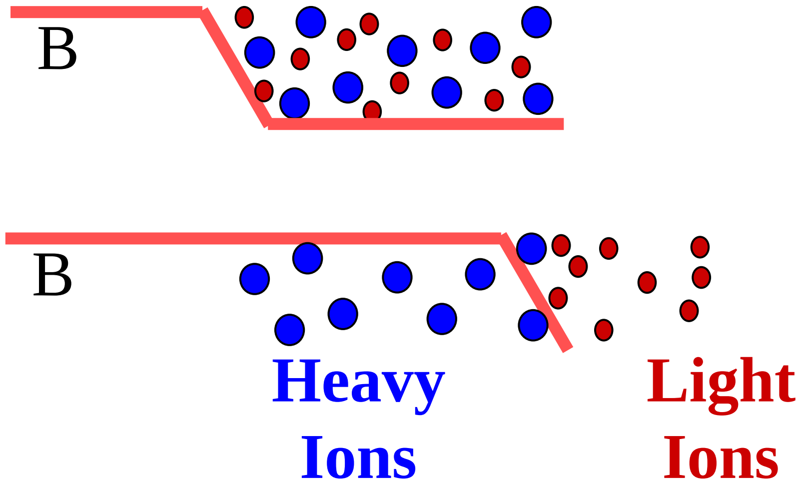
# Ion separation
## (Penetration and Reflection)



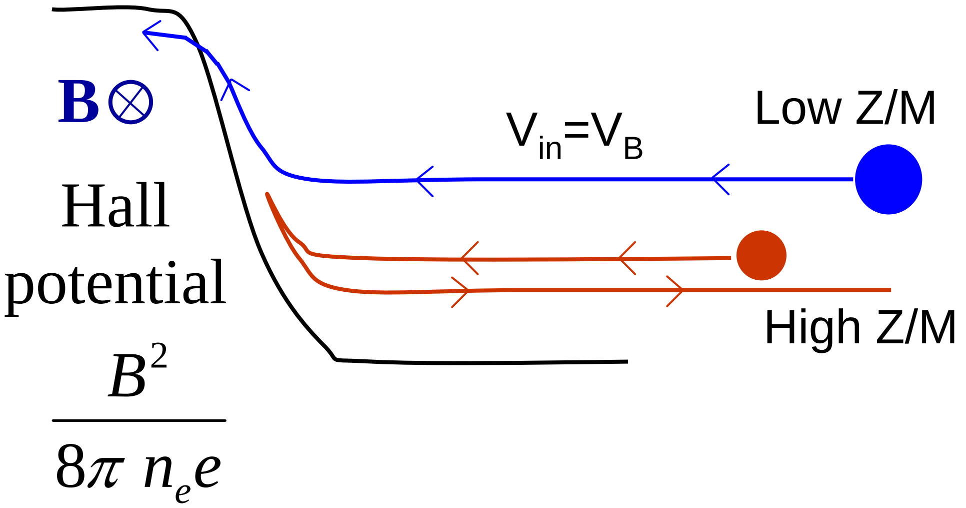

- Protons attain velocities that are about **twice the magnetic Field velocity**.
- Non-Protonic ions have velocities much lower than the Field.

# Ion separation in Multi-Species Plasmas

**Field penetration and plasma reflection can occur simultaneously**



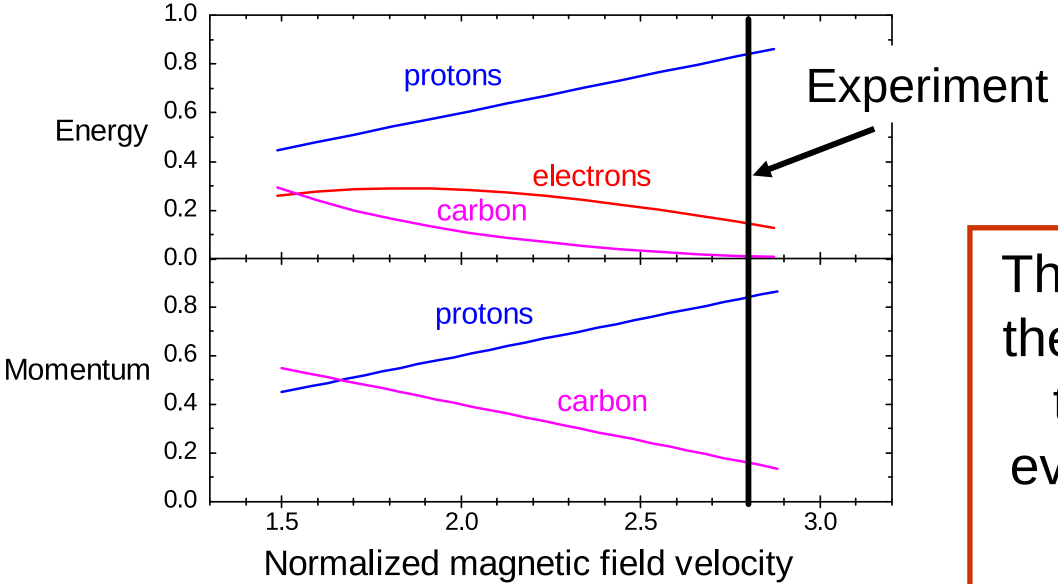

In the frame of the moving Field




*C. Mendel (1983): potential hill in collisionless plasmas, but no field penetration.*

*R. Doron, D. Osin, R. Arad, K. Tsigutkin (2004)*

# Solution based on Energy and Momentum Balance




$$\frac{B^2}{8\pi} = n_l M_l v_l v_B + n_h M_h v_h v_B$$

$$\frac{B^2}{8\pi} = \frac{n_l M_l v_l^2}{2} + \frac{n_h M_h v_h^2}{2} + E_e$$

The reflected ions acquire most of the dissipated energy and most of the magnetic field momentum even though their fractional mass in the plasma is only 20%.

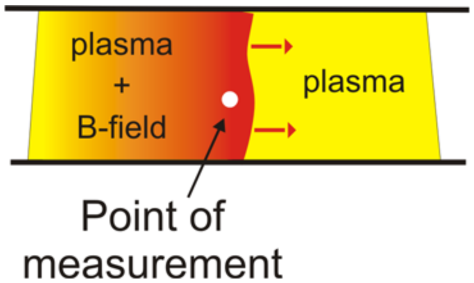
Electrons should only acquire ~1.3 keV/electron.

*A. Weingarten, R. Arad et al.*

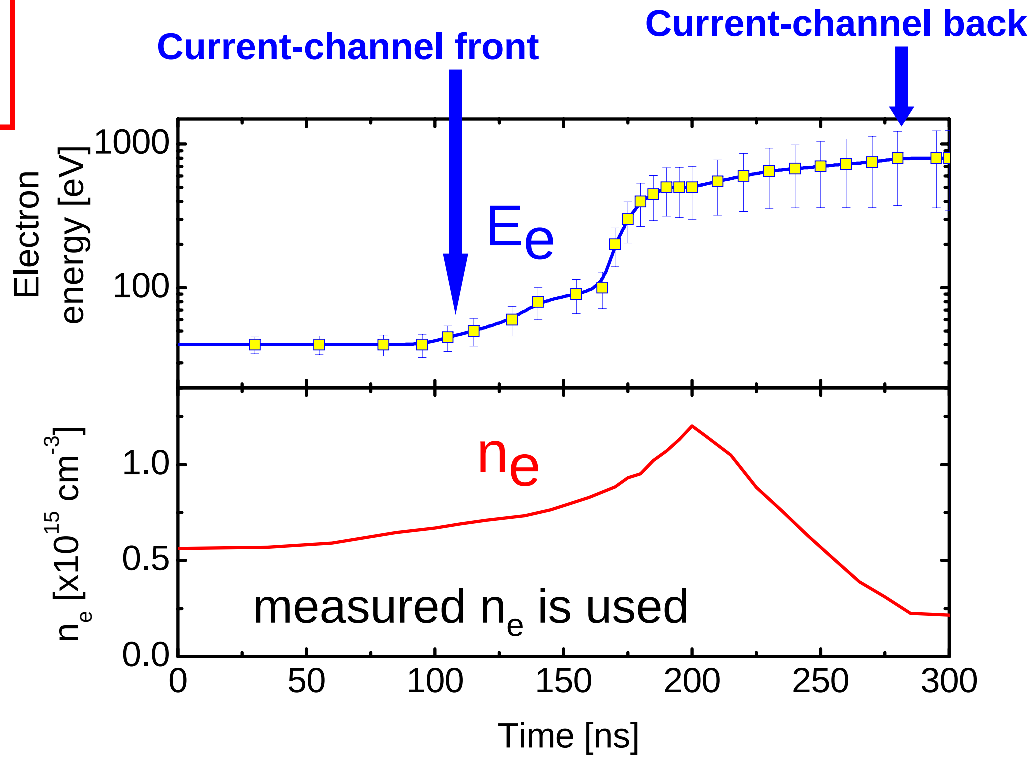
*PRL (2001)*

# Electron Energy Distribution Across the Magnetic-Field Front

High-lying levels are used:
$C^{2+}$ (18 eV), $C^{3+}$ (54 eV), and $C^{4+}$ (304 eV);
Inner-shell Excitations:
$C^{3+}$ 2p $^2P \rightarrow C^{4+}$ 1s2p (400 eV)
$C^{3+}$ $1s^2 \rightarrow C^{4+}$ 1s2s (400 eV)

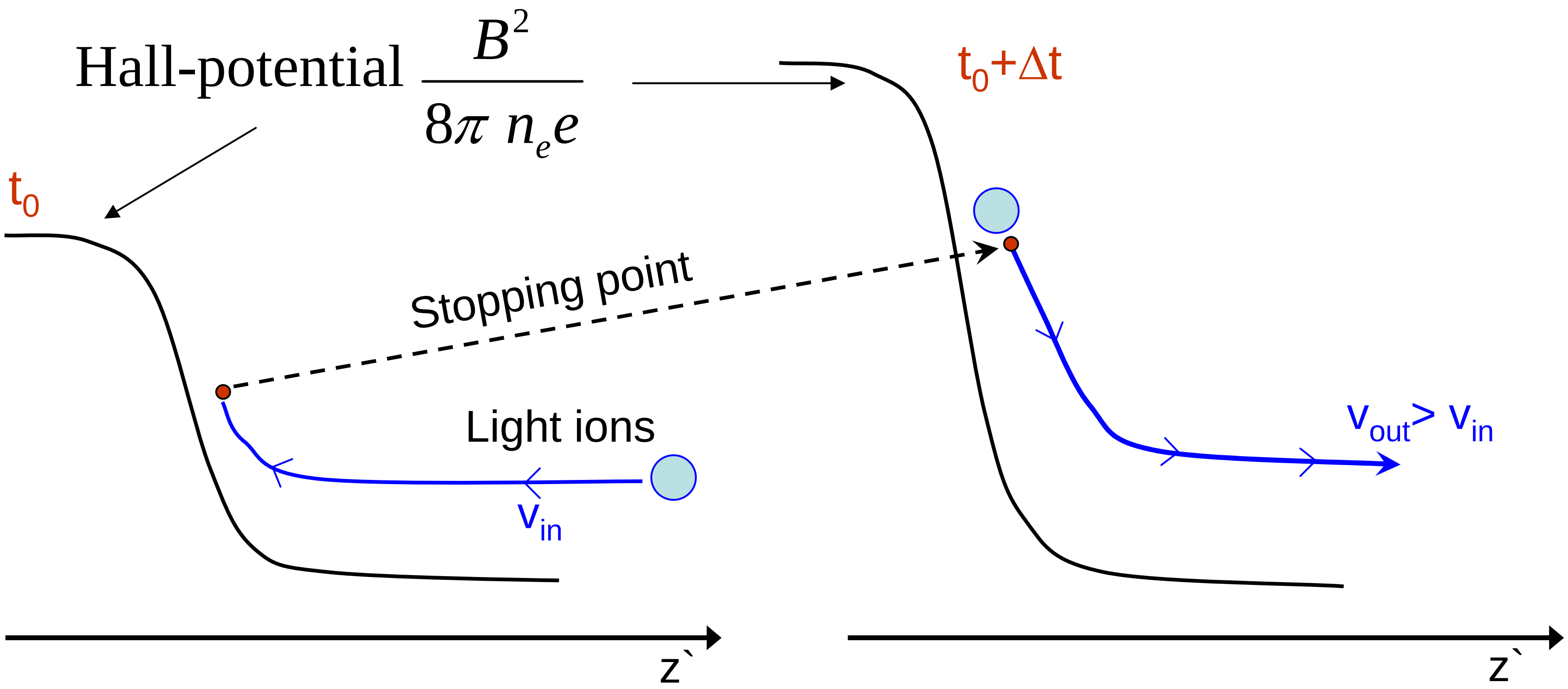



Electron energy rises across the current-channel.



# Light-Ion reflection at $V > 2V_B$ due to time-dependent potential hill

In the frame of the moving Field




**In the Lab frame $V_{ion} > 2V_B$**

# Relevance to Space Physics

NASA Report, September 2003

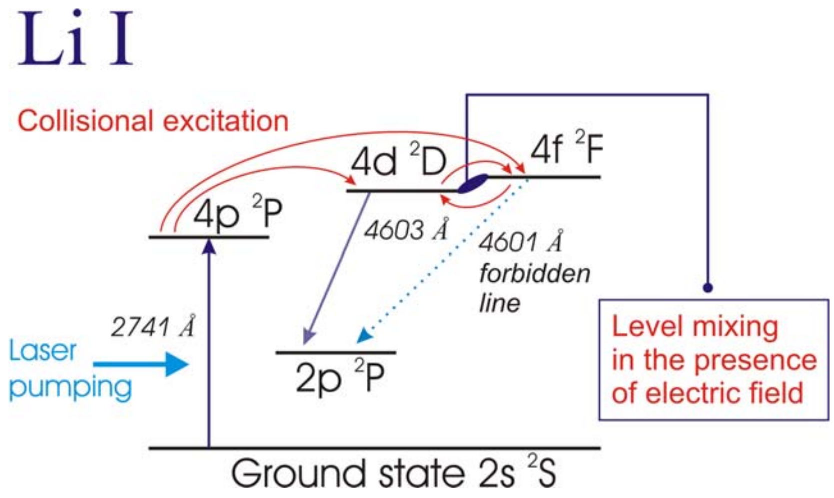
**NASA RHESSI satellite**: "New observations revealed that solar flares somehow sort particles, either by their masses or their electric charge"

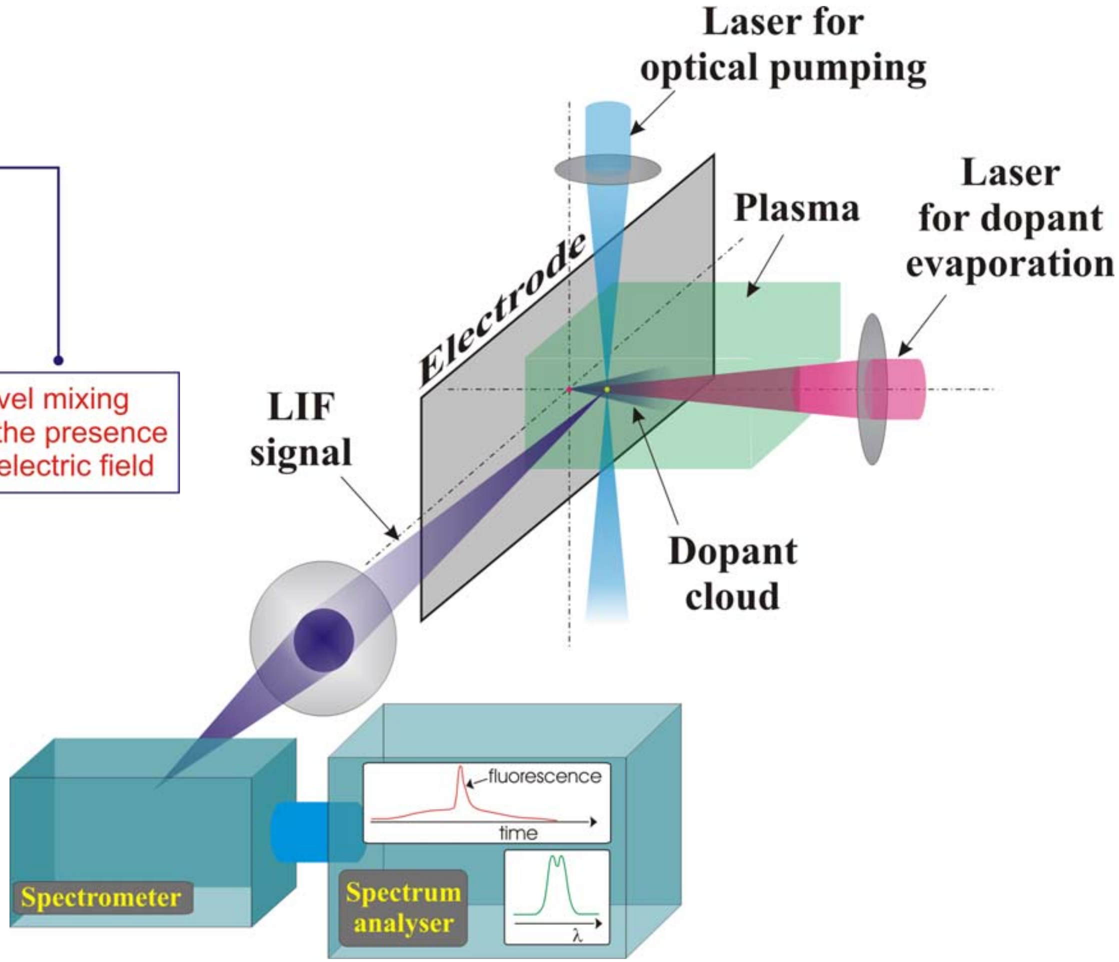
**NASA ACE satellite**: A reflected cool proton beam observed upstream of an interplanetary shock as well as scattered diffuse ions. (Tokar et al., April 2000)

**ESA Cluster satellites**: Observation of Ion reflection and transmission at the quasi-perpendicular earth bow shock (Kucharek et al., April 2003)

**R. Doron, et al., and J. Huba, Phys. Plasmas (2004)**
**H. Strauss, R. Doron, Y. Maron, APS meeting, Nov. 2004**
**J. Drake (University of Maryland)**

# High-resolution spectroscopy



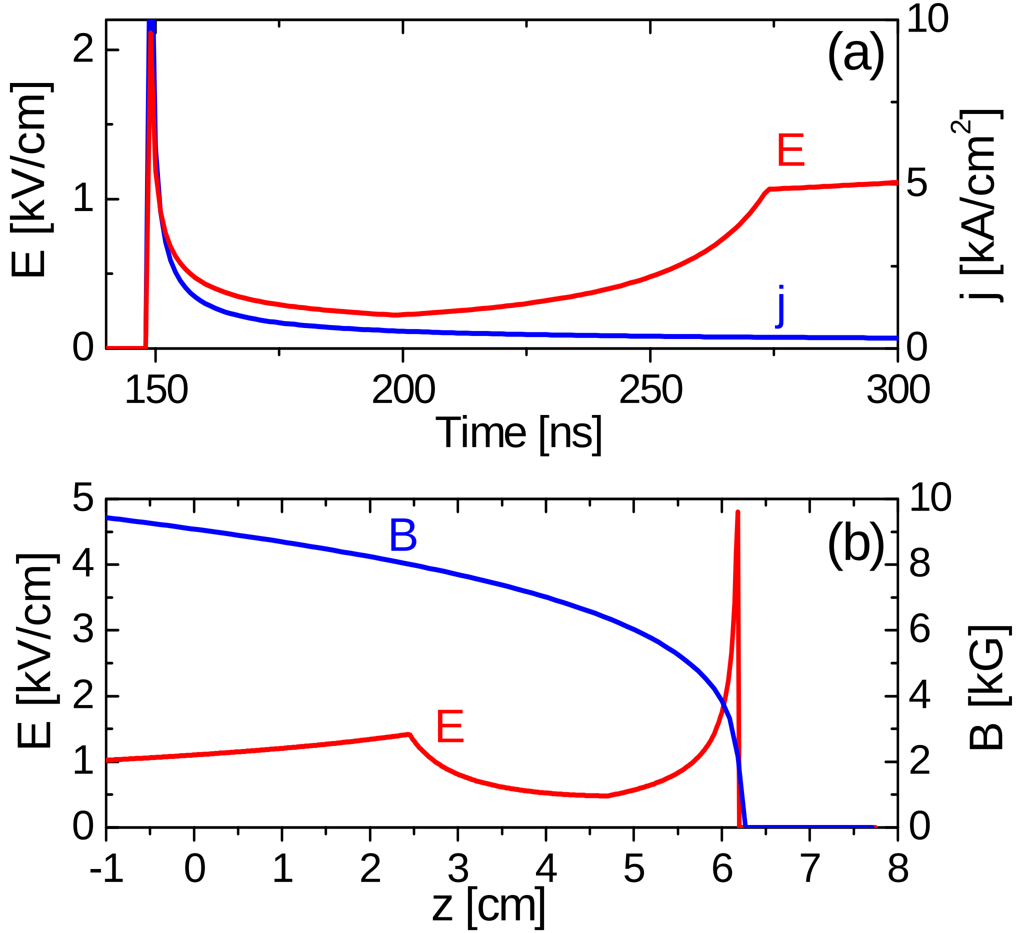

The intensity of forbidden transitions is a precise tool for determination of electric fields.

$$E_{Hall} = \frac{1}{8\pi\, en_e}\frac{\partial B^2}{\partial z} \approx 15\ \text{kV/cm}$$

Measured E-field: 16±3 kV/cm

Tsigutkin et al., IEEJ (2004)
Tsigutkin, Stambulchik, EPS Conf on Plasma Sci. 2003

# Knowledge of B(z,t) & $n_e$(z,t) allows for determining the Hall E(z,t) $= \nabla\left(\frac{B^2}{8\pi\, n\, e}\right)$

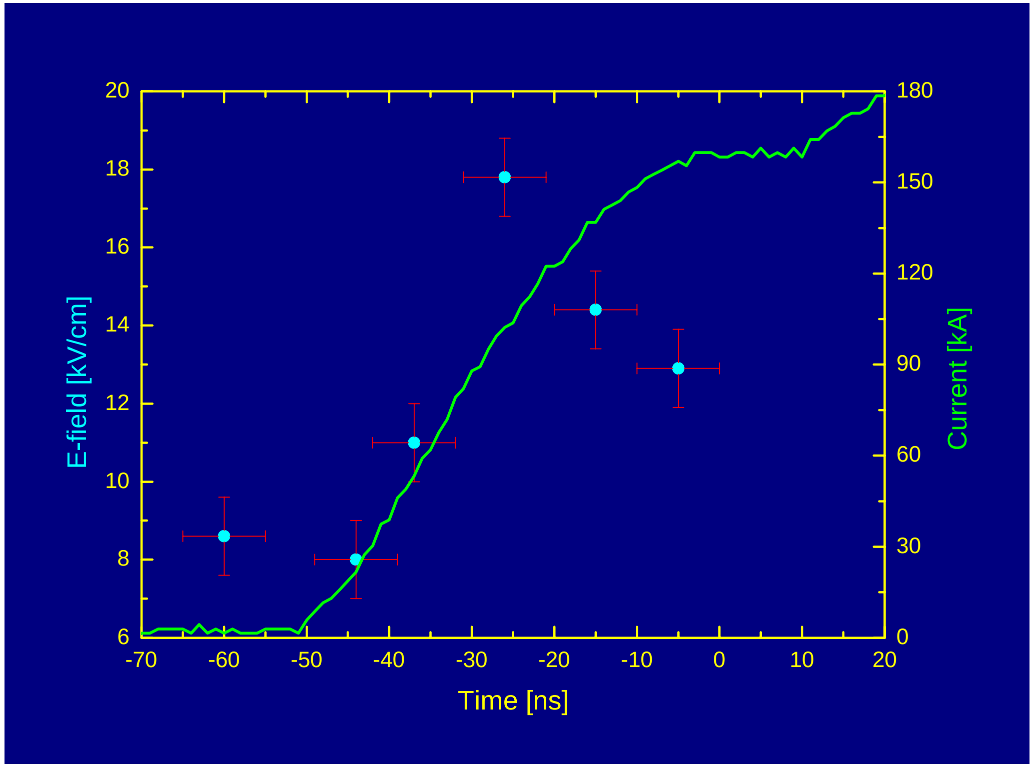



Z=2.2 cm

t= 280 ns

E is high even though $\frac{\partial B}{\partial z}$ is low.

# E-field measurements in the current-carrying plasma

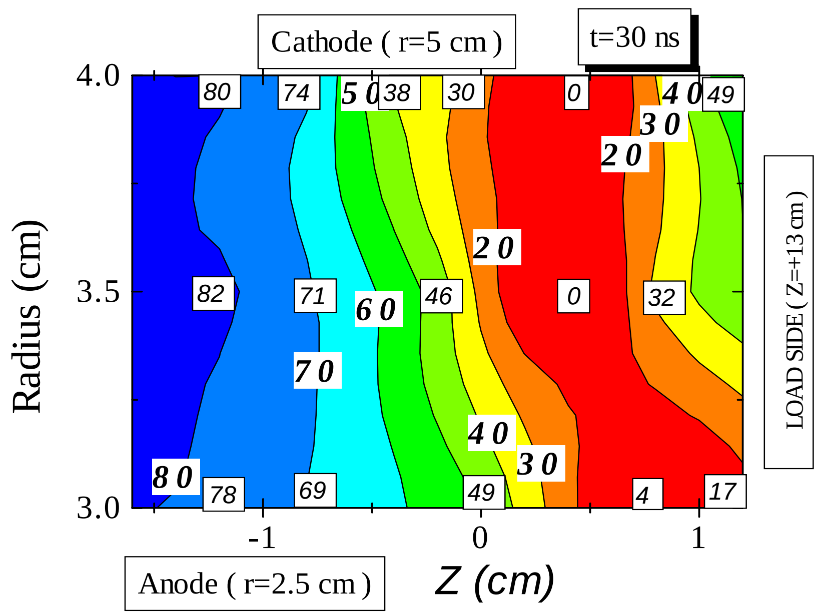



$$E_{Hall} = \frac{1}{8\pi \, en_e} \frac{\partial B^2}{\partial z}$$

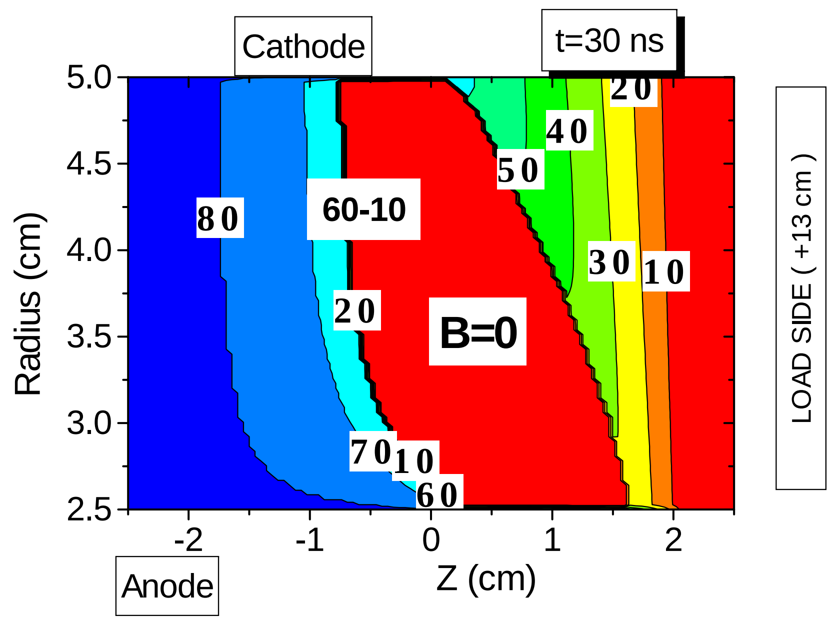
A nature of the observed E-field reveals mechanism of the B-field-plasma interaction. In the case of the enhanced turbulence, anomalous collisions lead to B-field diffusion. Alternatively, the Hall E-field indicates MHD mechanism.

# Magnetic vortex

**Experimental current lines : I=B/5r**




**Simulation based on the EMHD theory**




K. Gomberoff and A. Fruchtman Physics of Fluids B, 1993

# Summary

- Observed fast field-penetration strongly suggests a role of the Hall-term.
- Field penetration and plasma reflection can occur simultaneously accompanied by ion separation.
- Composition plays an important role.
- This helps to understand the energy dissipation.
- Ions can be reflected with a velocity > $2 \times v_B$ (B-field)
- Theoretical modeling is required.
  The data are now used to examine simulations, including those used in space-physics research.
- Important for basic Plasma Physics, Applications, and Space-Physics.

THERE ARE 3-4 THINGS THAT ARE MIRACLES FOR ME:

THE WAY OF A SNAKE ON STONES.
THE WAY OF AN EAGLE IN THE SKY.
THE WAY OF A MAN AND A WOMAN,

-------------------

AND THE WAY OF MAGNETIC FIELDS IN PLASMAS.

*MISHLEY*