

Electron Drift along a Magnetically Neutral Channel between Gradient Magnetic Fields

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Agenda

- Research background and motivation (NLD plasmas)
- ExB fields configuration
- Simulation results (electron loci & transport parameters)
- Summary

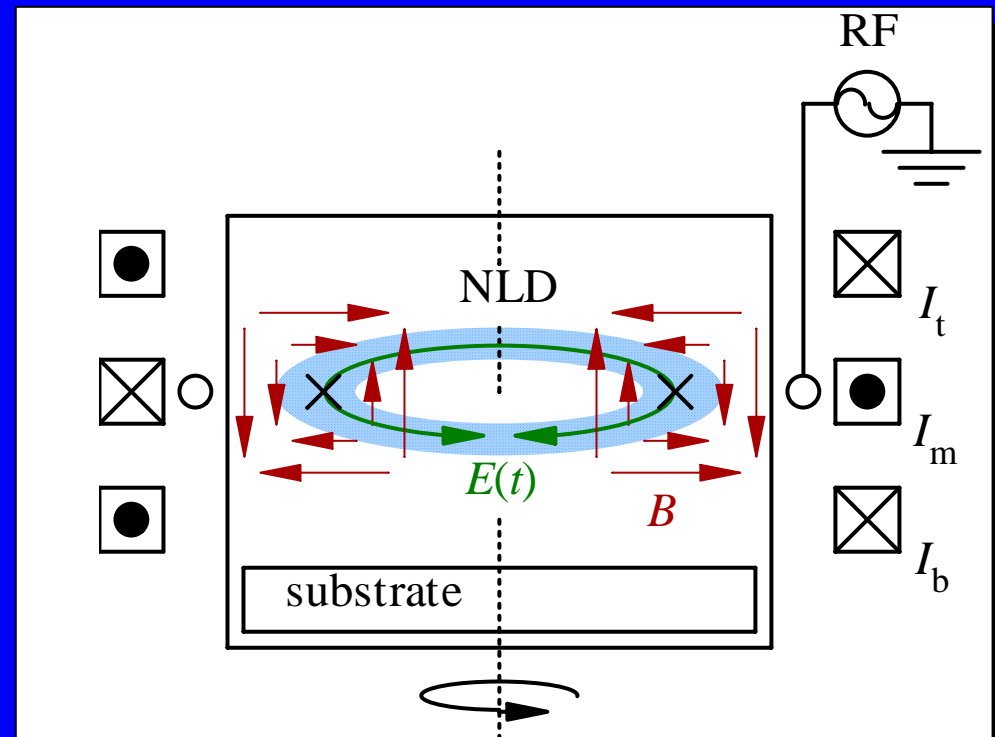
15th Gaseous Electronics Meeting, 3-6/Feb/2008, Murramarang Resort, Australia

Acknowledgements to ULVAC Inc. for photo of NLD plasma and discussions, and to Research Foundation for the Electrotechnology of Chubu for travel expense support.

Background: NLD plasmas for etching

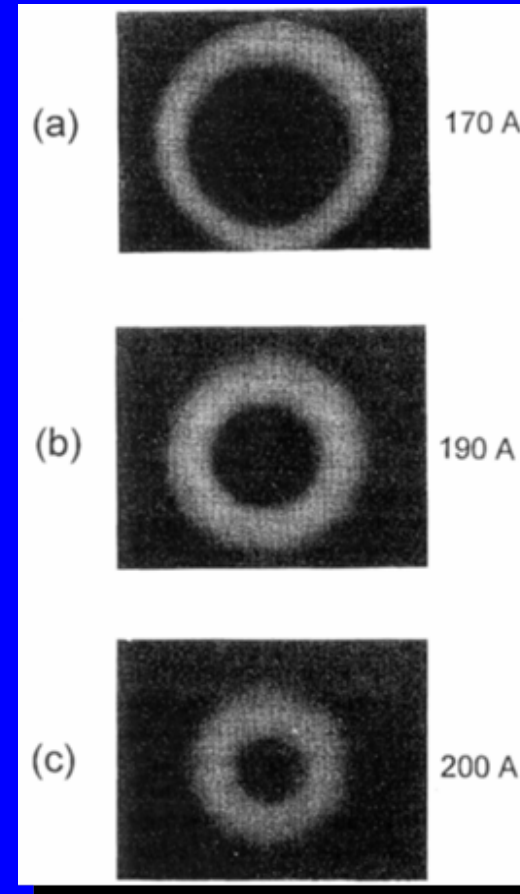
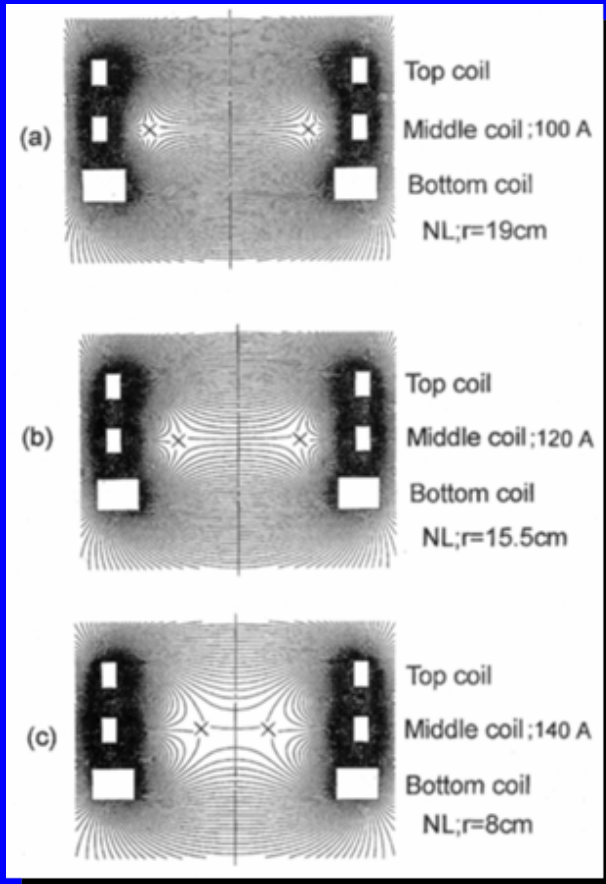
Neutral Loop Discharge (NLD) plasmas

- Plasmas produced along “Neutral Loop” (NL)
 - NL: ring-shaped region of $B=0$ formed by 3 coils
- High density ($\sim 10^{11} \text{ cm}^{-3}$) at low pressures ($\sim 1 \text{ mTorr}$)



Background: NLD plasmas for etching

Controllability of NL radius via coil currents



B fields formed by 3 coils

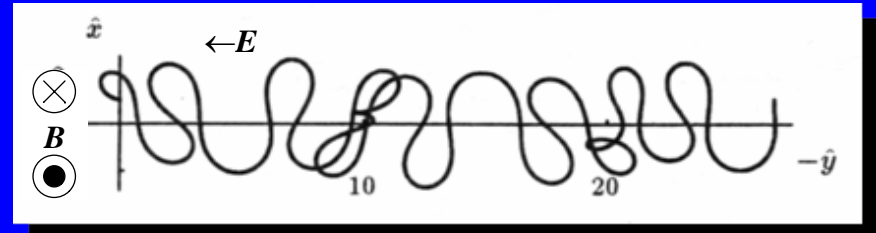
NLD plasmas (top view)

from H. Tsuboi et al. (1995) Japan. J. Appl. Phys. **34** 2476-81

Motivation: modelling of NLD plasmas

Interest in phenomenology

- Effect of ExB fields



Practical aim

- Control of NLD plasmas

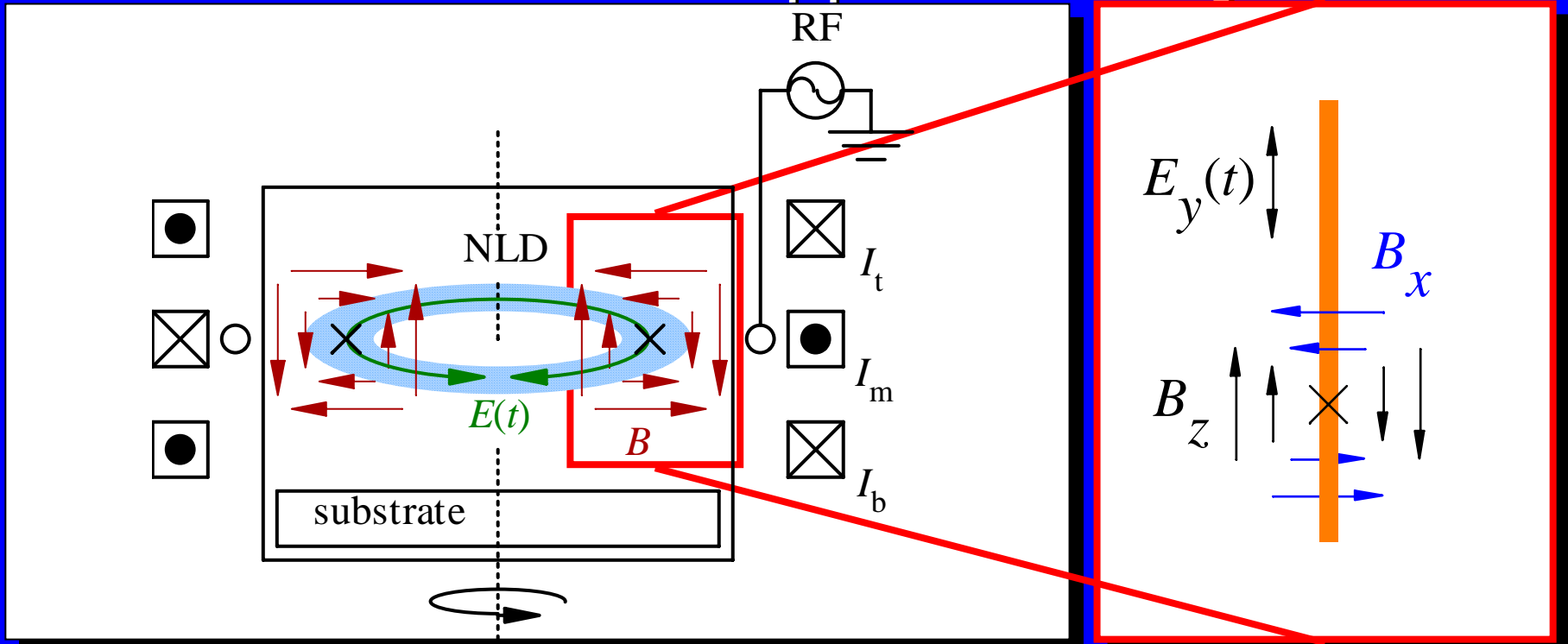
Meandering of electron under RF
E field and static gradient B field
from Z. Yoshida et al. (1998)
Phys. Rev. Lett. **81** 2458-61

This work

- Monte Carlo simulation of electron behaviour in a simplified field model
- Calculation of electron transport parameters under DC E field

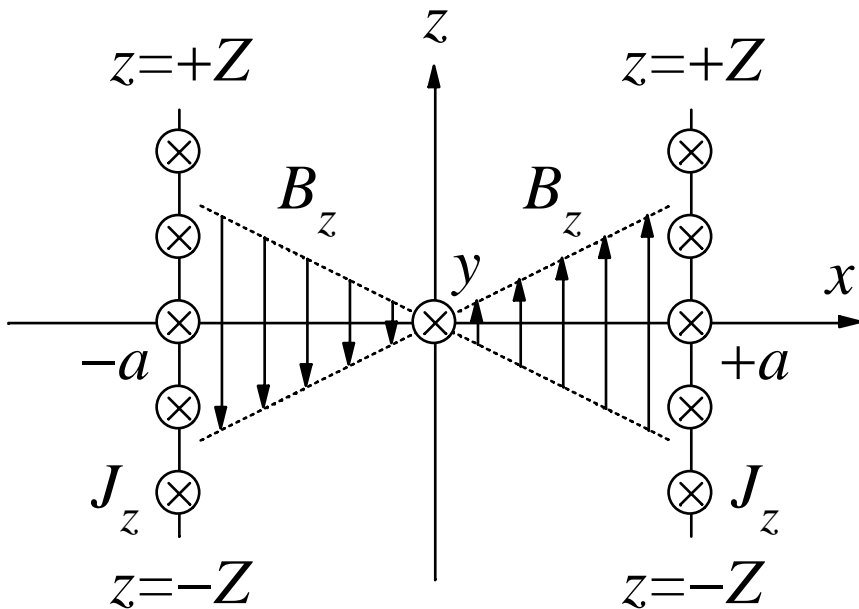
Model: geometry

- NL: expanded into a linear path
- B field: reduced to have B_z component only, linearly gradient in the x direction, static
- E field: uniform, DC, applied in the y direction



Model: linearly gradient B field

B field between parallel equi-current slabs



$$B_z(x) = \frac{\mu_0 J_z}{\pi} \left(\arctan \frac{Z}{a-x} - \arctan \frac{Z}{a+x} \right)$$

$$= \frac{\mu_0 J_z}{\pi} \arctan \frac{2Zx}{Z^2 + a^2 - x^2}$$

$$= \frac{\mu_0 J_z}{\pi} \frac{2Zx}{Z^2 + a^2 - x^2}$$

$$- \frac{1}{3} \frac{\mu_0 J_z}{\pi} \left(\frac{2Zx}{Z^2 + a^2 - x^2} \right)^3$$

$$+ \frac{1}{5} \frac{\mu_0 J_z}{\pi} \left(\frac{2Zx}{Z^2 + a^2 - x^2} \right)^5 - \dots$$

(J_z : current density)

approximated by a linear function when $Z \gg a, x$

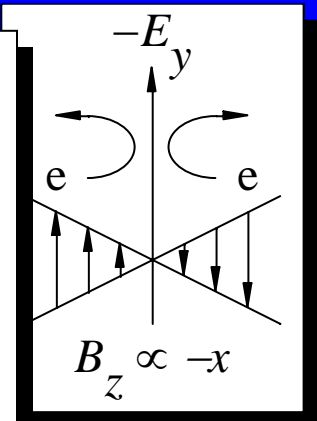
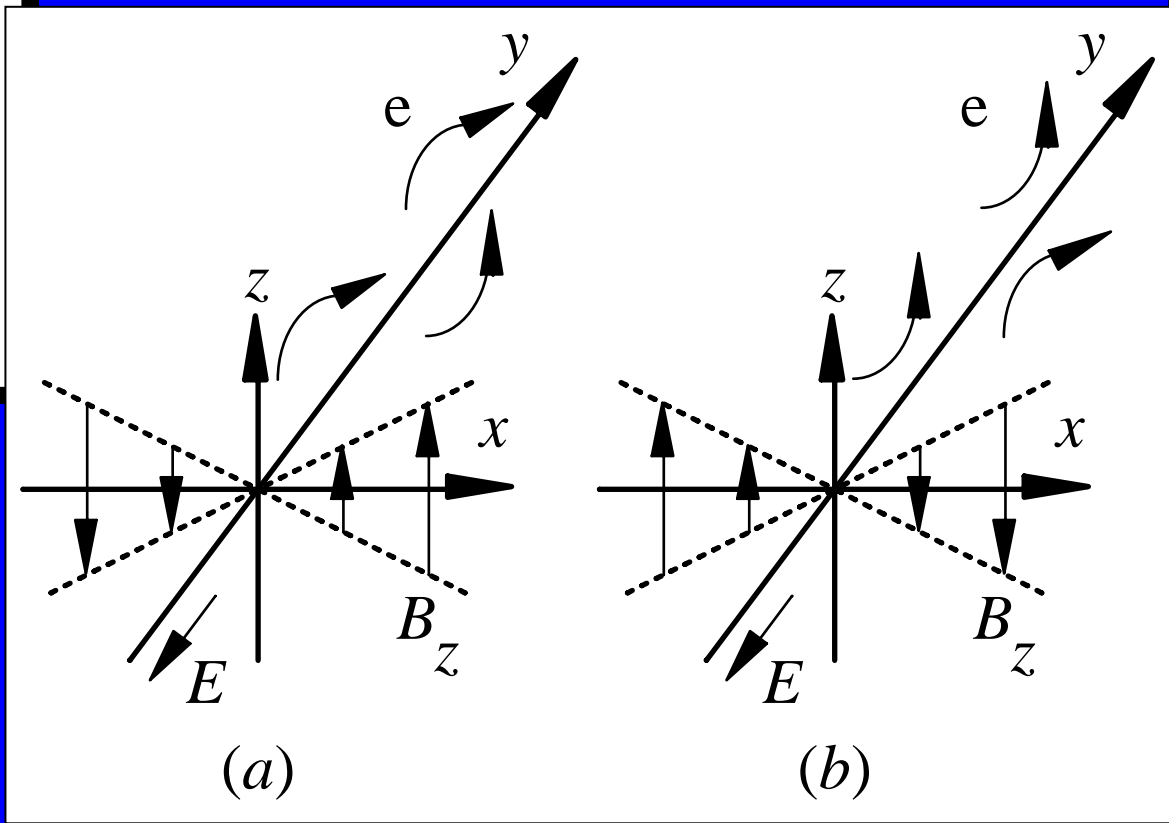
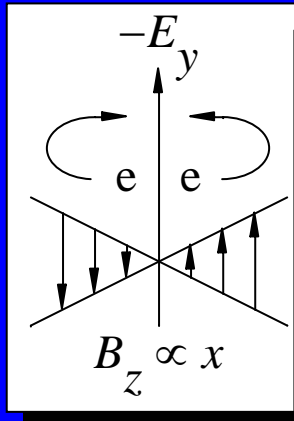
$$B_z(x) \approx \frac{\mu_0 J_z}{\pi} \frac{2x}{Z}$$

concept from T. Uchida (1998)
J. Vac. Sci. Technol. A **16** 1529-36

Model: field configuration

Two possible arrangements of $E \times B$ fields

– Note: they alternate in case of RF E field



(a) "convergent" configuration (b) "divergent" configuration

Condition: gas and fields

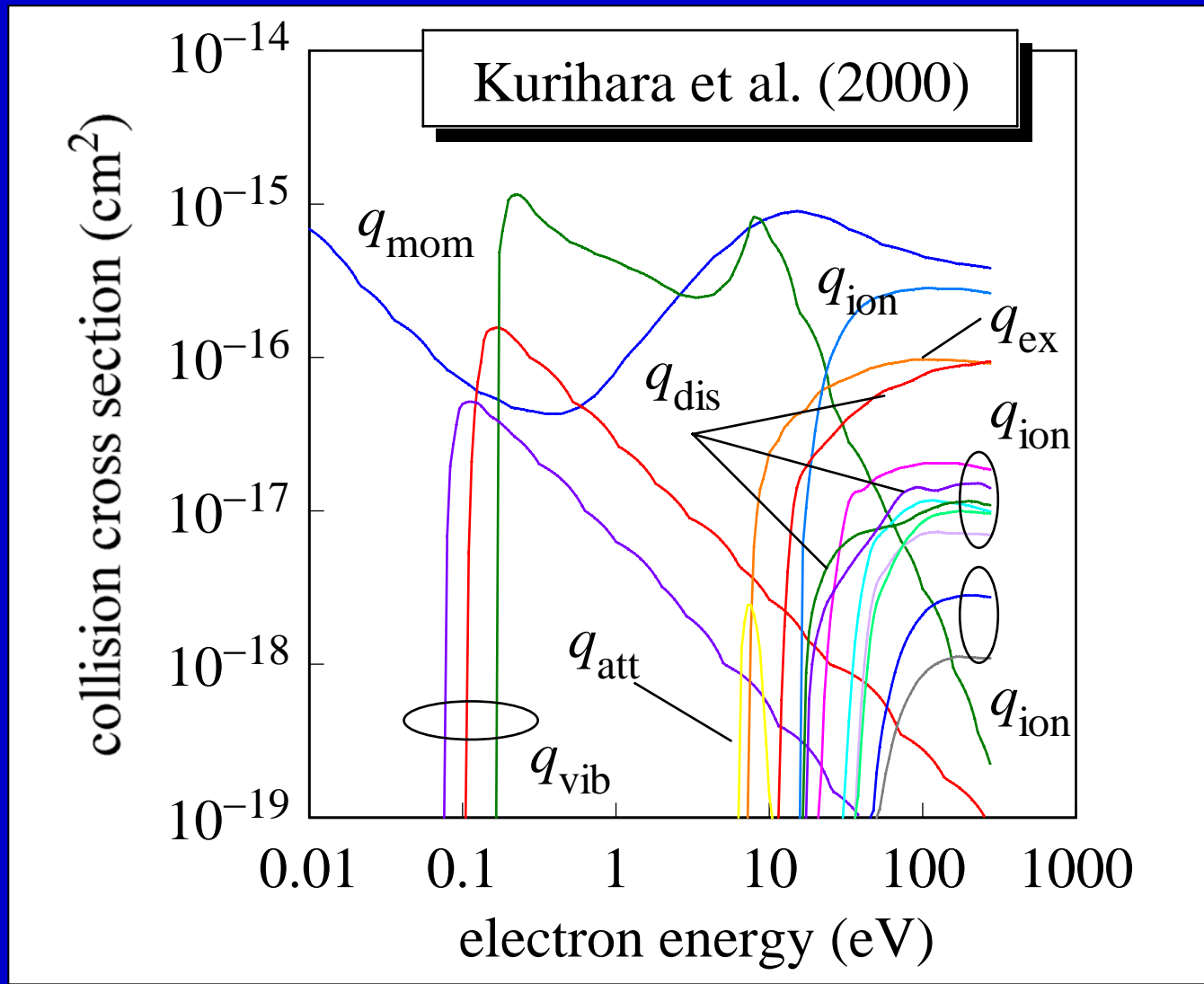
Gas and fields

- Gas: CF_4 , 5 mTorr (0.67 Pa) at 273 K
 - Electron collision cross section set: from M. Kurihara et al., J. Phys. D: Appl. Phys., **33**, 2146-53 (2000)
- B field: B_z gradient = +0.5 or -0.5 mT/cm
- E field: 0.1-3.0 V/cm (E/N of 57-1700 Td)

Monte Carlo simulation (Δt method)

- Velocity distribution of initial electrons: Maxwellian (mean energy = 1 eV)
- Simulation step: $\Delta t = 3.7$ ps
- 10^6 - 10^7 samples

Data: collision cross sections of CF₄



Data: collisional processes of CF₄

momentum transfer: $\text{CF}_4 + e \rightarrow \text{CF}_4 + e$

vibrational excitation (mode 1, 0.108 eV): $\text{CF}_4 + e \rightarrow \text{CF}_4^* + e$

vibrational excitation (mode 3, 0.168 eV) : $\text{CF}_4 + e \rightarrow \text{CF}_4^* + e$

vibrational excitation (mode 4, 0.077 eV) : $\text{CF}_4 + e \rightarrow \text{CF}_4^* + e$

electronic excitation (7.54 eV): $\text{CF}_4 + e \rightarrow \text{CF}_4^* + e$

electron attachment (6.4 eV) : $\text{CF}_4 + e \rightarrow \text{CF}_3 + \text{F}^-$

dissociative ionization (16.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}_3^+ + \text{F} + 2e$

dissociative ionization (21.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}_2^+ + 2\text{F} + 2e$

dissociative ionization (26.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}^+ + 3\text{F} + 2e$

dissociative ionization (34.0 eV): $\text{CF}_4 + e \rightarrow \text{C}^+ + 4\text{F} + 2e$

dissociative ionization (34.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}_3 + \text{F}^+ + 2e$

dissociative double ionization (41.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}_3^{2+} + \text{F} + 3e$

dissociative double ionization (42.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}_2^{2+} + 2\text{F} + 3e$

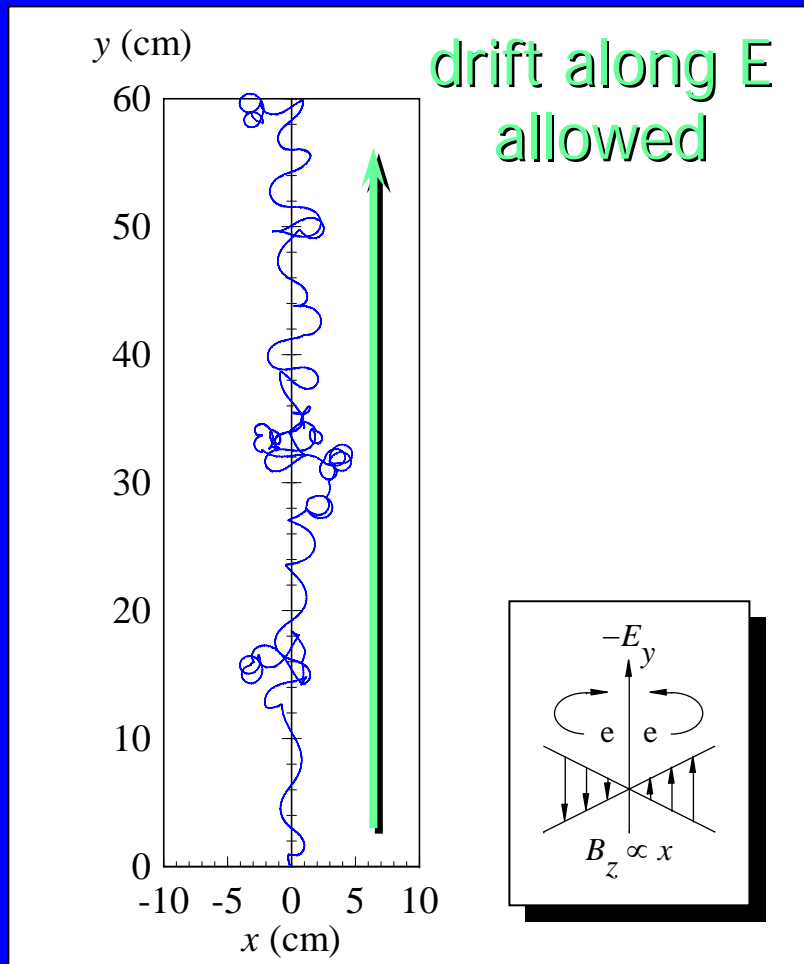
neutral dissociation (12.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}_3 + \text{F} + e$

neutral dissociation (17.0 eV): $\text{CF}_4 + e \rightarrow \text{CF}_2 + 2\text{F} + e$

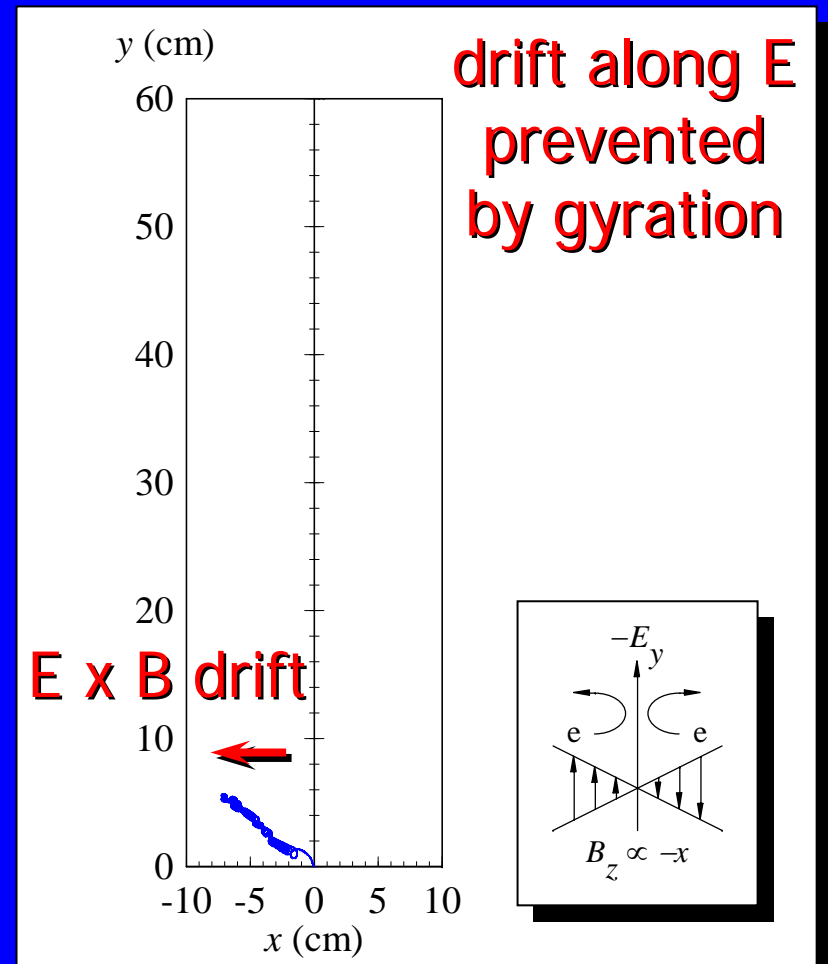
neutral dissociation (18.0 eV): $\text{CF}_4 + e \rightarrow \text{CF} + 3\text{F} + e$

Result: electron loci

Trace of electrons for 1475 ns (20 RF cycles)



"convergent" configuration

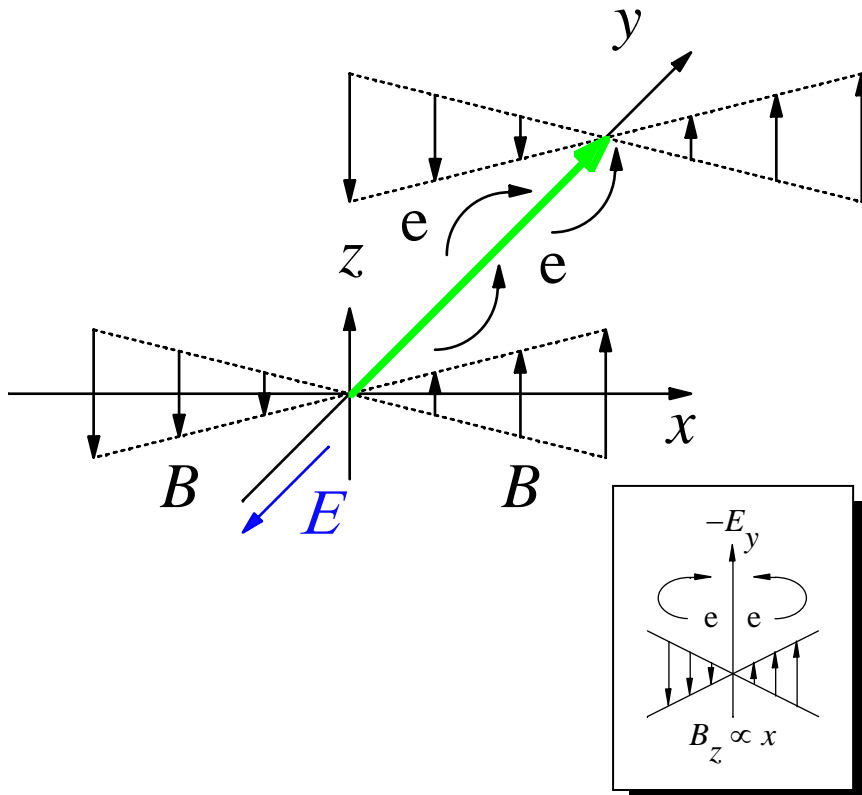


"divergent" configuration

Result: rectification of electron conduction

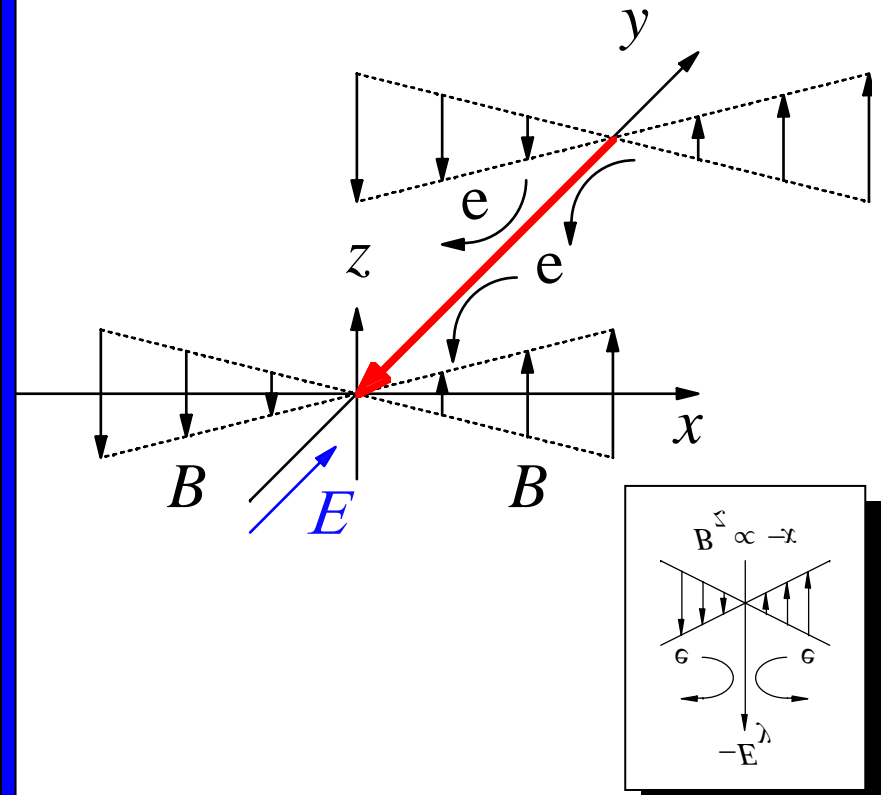
Reverse-blocking effect

drift along E allowed



"convergent" configuration

drift along E prevented

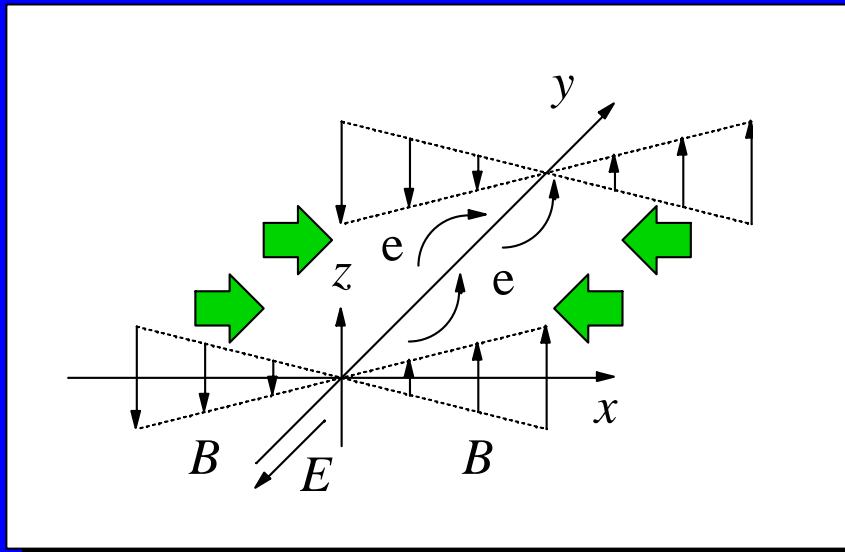


"divergent" configuration

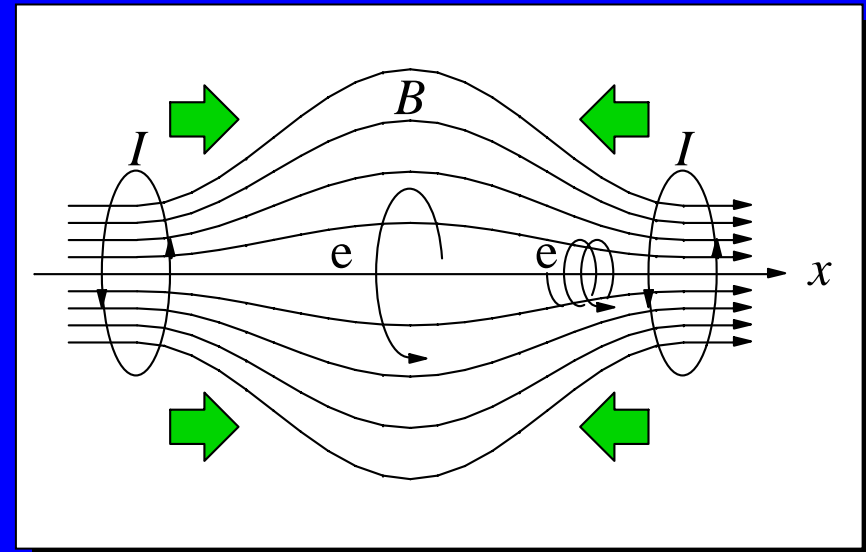
Result: confinement effect

Direction of confinement pressure

- Inward to the neutral channel
 - cf. magnetic mirror effect: along B
- Conduction along E allowed



Confinement by gradient B field
in convergent configuration



Confinement by
magnetic mirror effect

Result: transport parameters

Comparison between parameters under

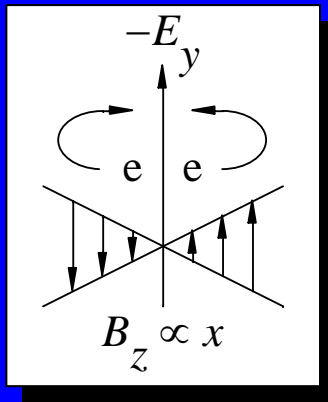
- **ExB fields** (present simulation), and
- **E field only** (without B field)
 - converted from data at 1 Torr by similarity law for dependence of parameters on E/N

Transport parameters compared

- Mean electron energy $\langle \varepsilon \rangle$
- Effective ionisation frequency ν_i (ν_i/N)
- Drift velocity **W**
 - W_v (average velocity) and W_r (centroid velocity)
- Diffusion coefficient **D (ND)**
 - D_{ExB} ($=D_x$), D_E ($=D_y$) and D_B ($=D_z$)

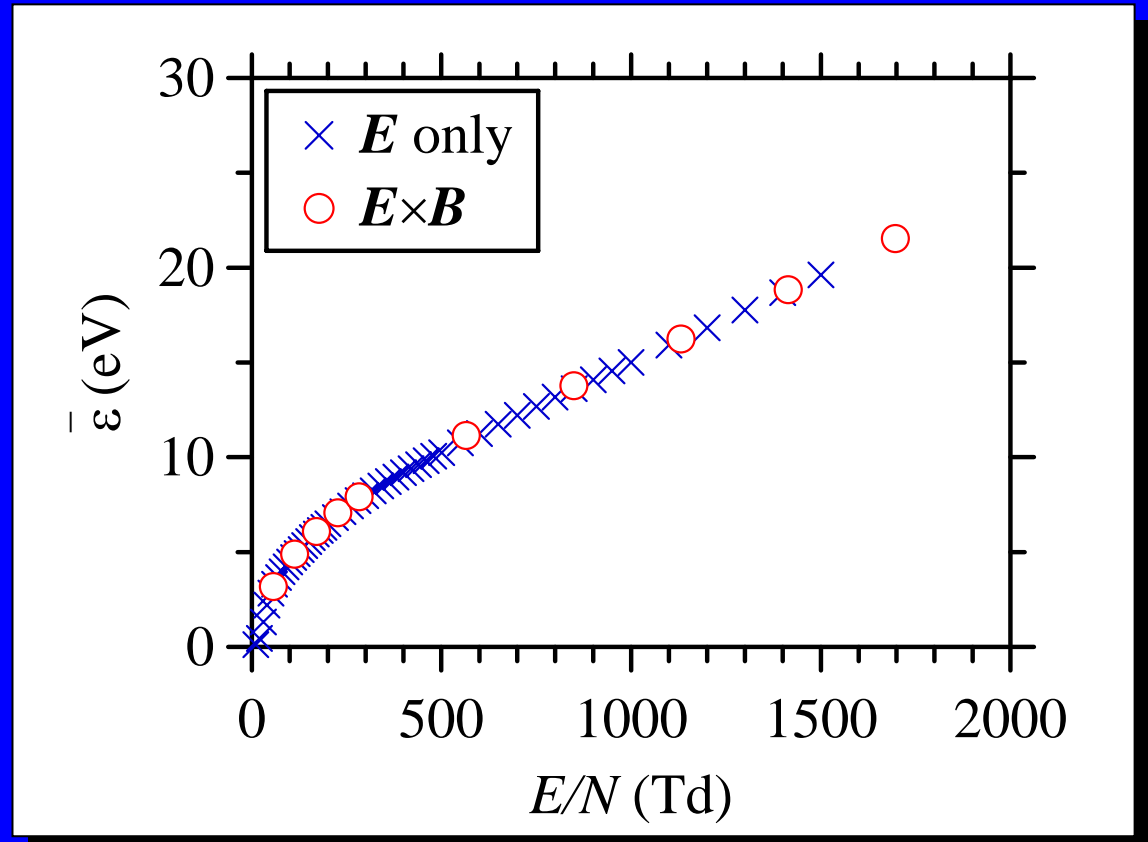
Result: transport parameters ($\langle \varepsilon_i \rangle$)

Comparison between parameters under $E \times B$ fields (convergent configuration) and E field only



convergent configuration

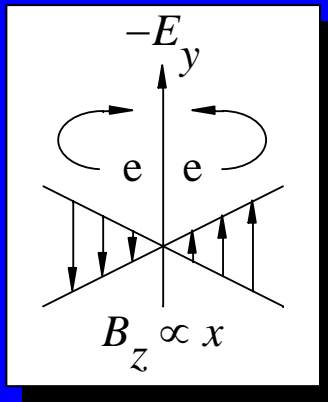
good agreement with little deviation



Mean electron energy

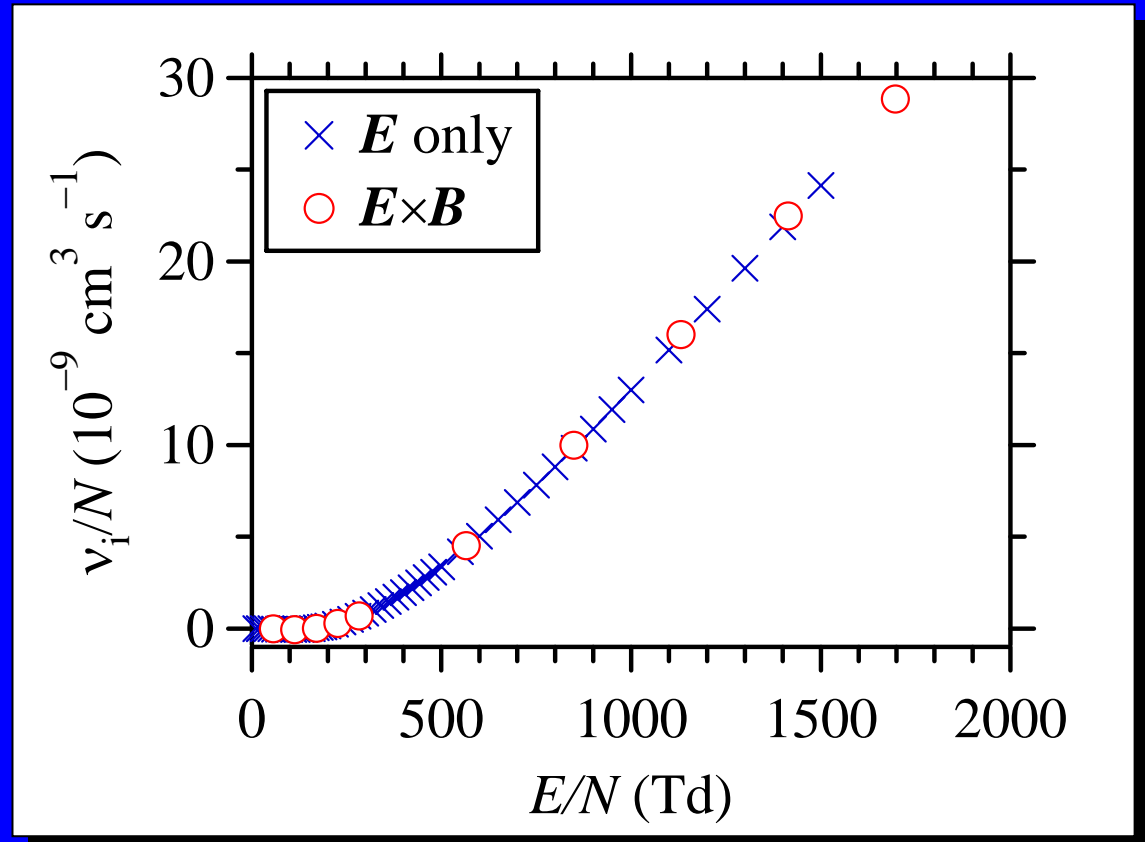
Result: transport parameters (ν_i)

Comparison between parameters under ExB fields (convergent configuration) and E field only



convergent configuration

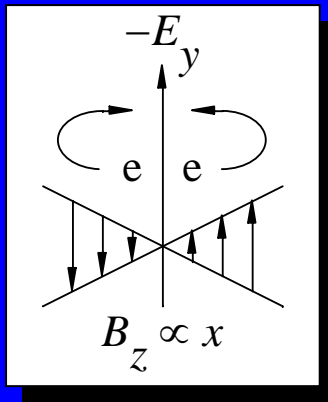
good agreement with little deviation



Effective ionisation frequency

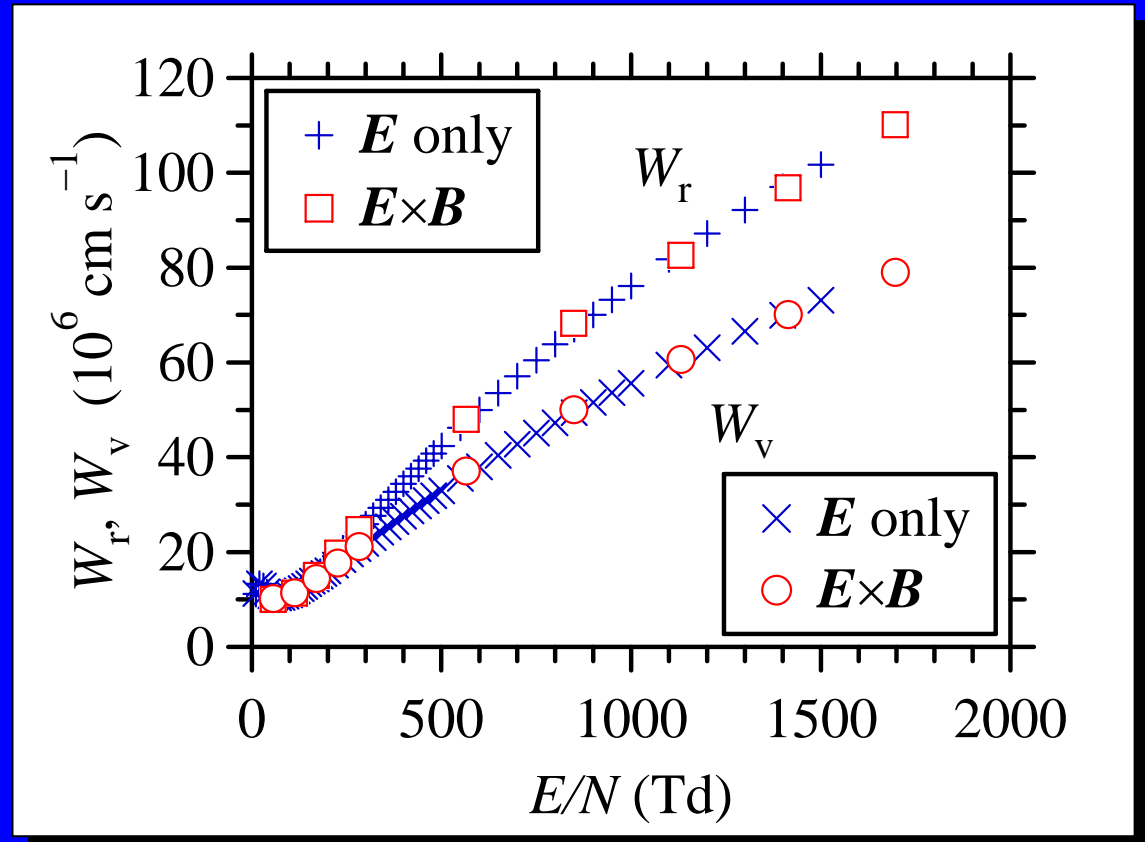
Result: transport parameters (W_v , W_r)

Comparison between parameters under $E \times B$ fields (convergent configuration) and E field only



convergent configuration

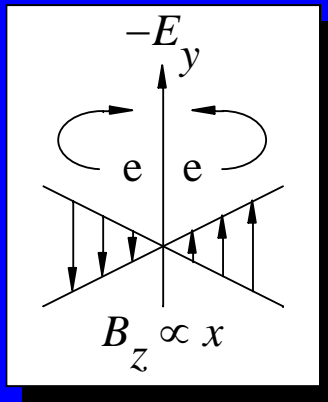
good agreement with little deviation



Drift velocities

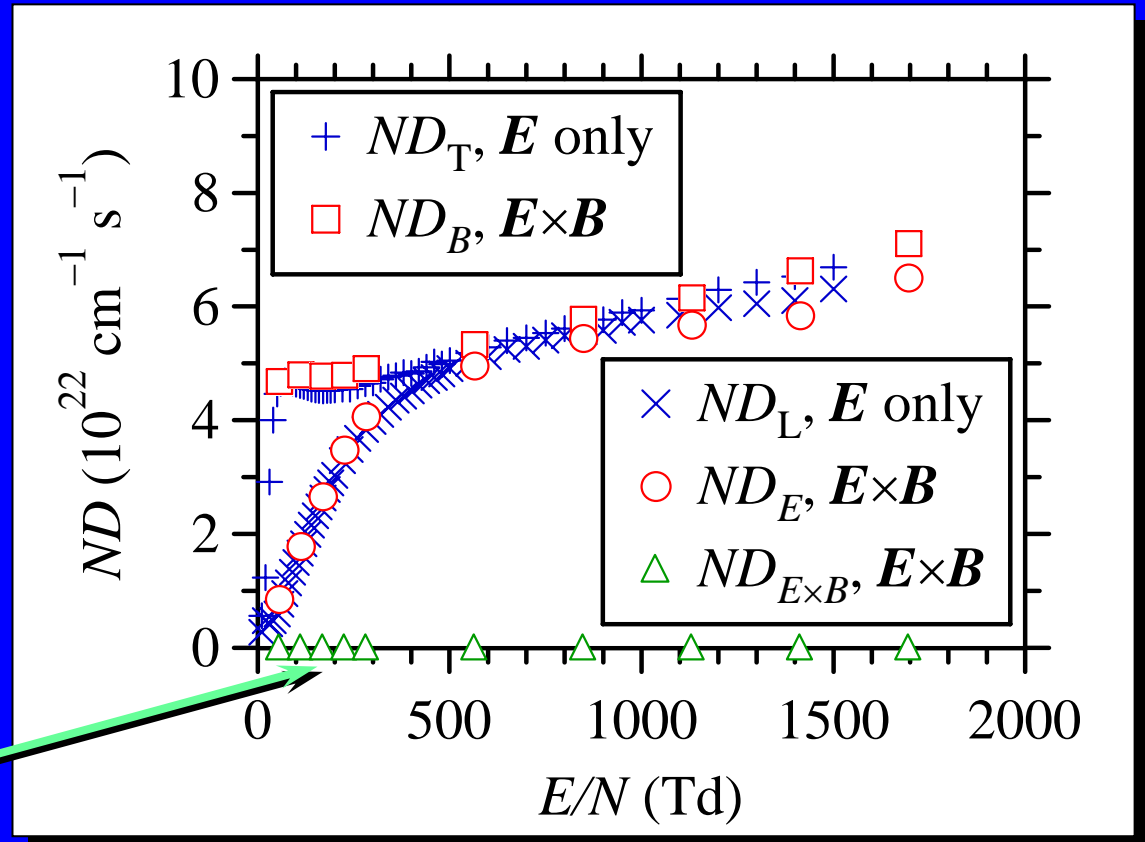
Result: transport parameters (D_{ExB} , D_E , D_B)

Comparison between parameters under ExB fields (convergent configuration) and E field only



convergent configuration

diffusion in the x direction suppressed (confinement)

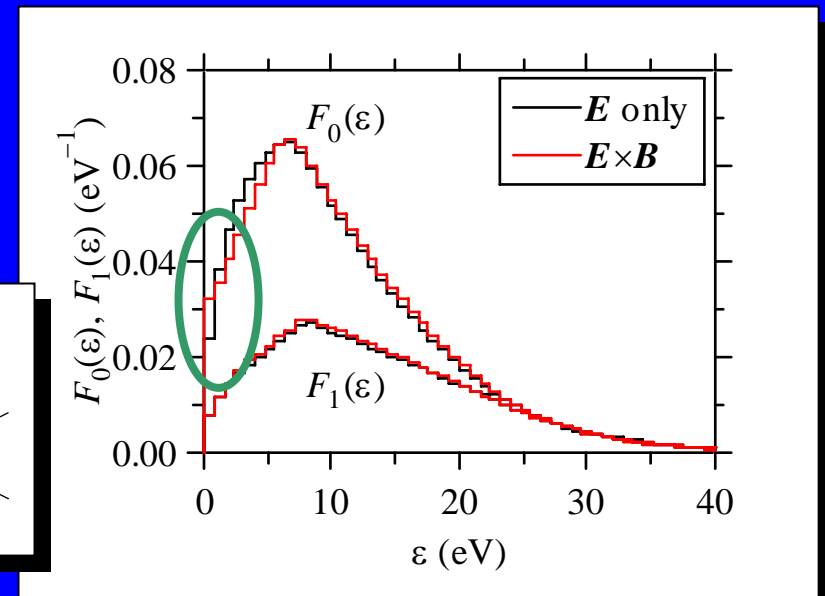
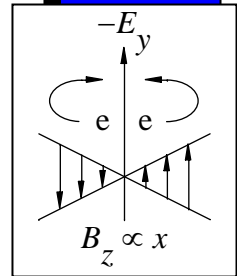
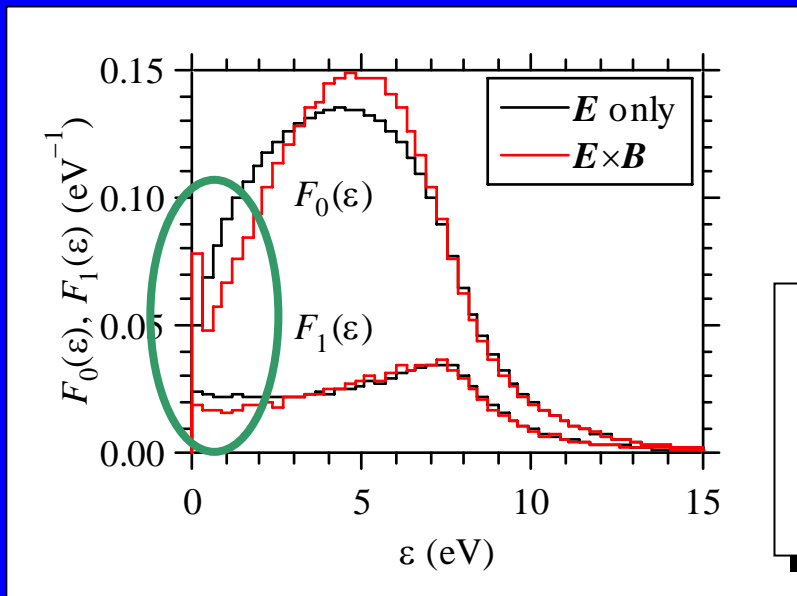


Diffusion coefficients

Result: energy distribution ($F_0(\varepsilon)$, $F_1(\varepsilon)$)

$F(\varepsilon)$ under $E \times B$ fields and DC E field only

- Increase of low-energy electrons
- Distortion is significant at low E/N
- **Question:** why some parameters unchanged?



$E/N = 113 \text{ Td}$

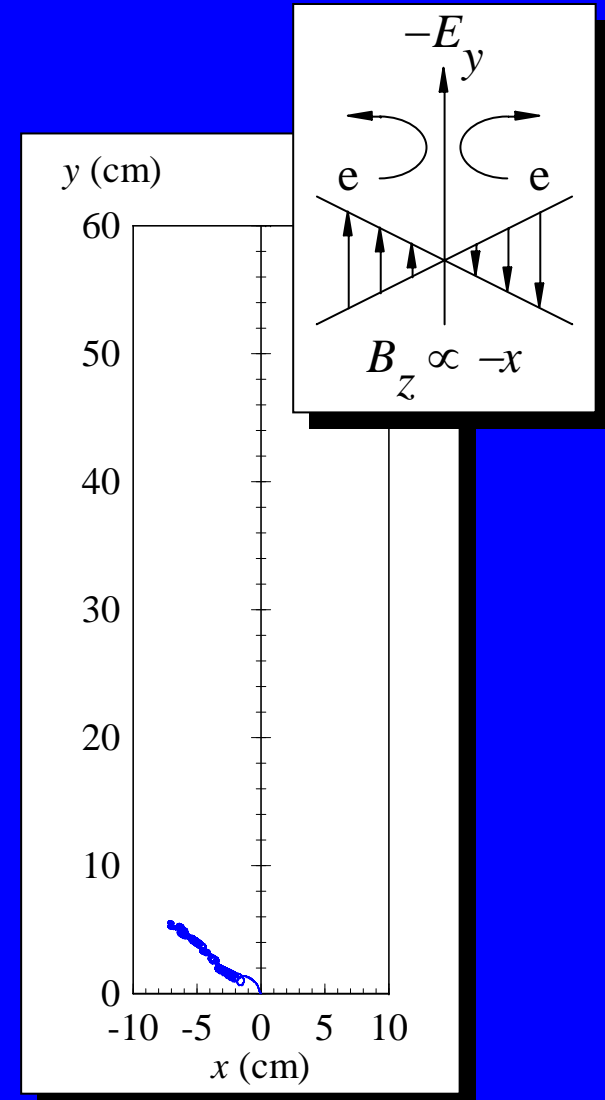
convergent
configuration

$E/N = 566 \text{ Td}$

Result: transport parameters

Parameters under ExB fields in divergent configuration

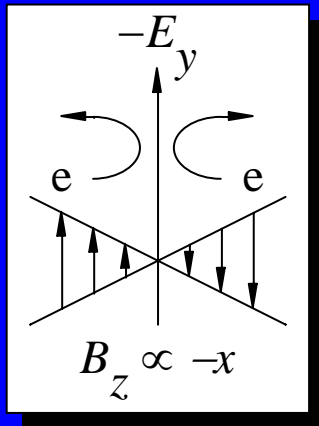
- Little energy gain
- $\langle \varepsilon \rangle$, v_i , W_v , W_r , D_E and D_B decayed slowly
- Their equilibrium values **not available** by $t=100$ RF cycles
- Exception: $D_{\text{ExB}} (=D_x)$



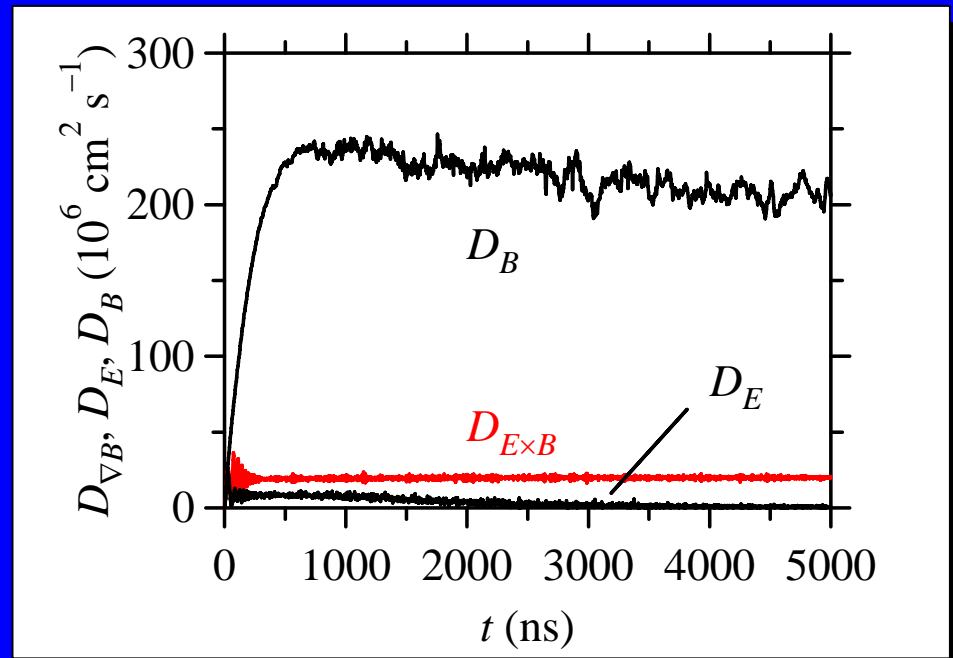
Result: transport parameters

Equilibrium value of D_{ExB} : $D_{ExB} = E / (dB_z/dx)$

- Analytically derivable at low pressures such that mean free time \gg cyclotron period
- Effectively collisionless



divergent
configuration



Relaxation of diffusion coefficients

Result: transport parameters

Equilibrium value of D_{ExB} : $D_{\text{ExB}} = E / (dB_z/dx)$

- Analytically derivable at low pressures such that mean free time \gg cyclotron period
- Effectively collisionless
- Constant independent of N
- Similarity law does not apply to D_{ExB}
cf. ND is unique for given E/N under DC E field only
- ExB drift-based diffusion
- ExB drift velocity = $E / (-B_z(x))$
position-dependent, proportional to $|1/x|$

Summary

Electron behaviour along the neutral channel between linearly gradient antiparallel B field was simulated. Rectification of electron drift by the gradient B field was observed.

Electron transport

- **Convergent configuration:** DC like
 - $\langle \varepsilon \rangle$, v_i , W , D_E and D_B : close to DC values
 - D_{EXB} : negligibly small (confinement)
- **Divergent configuration:** reverse blocked
 - equilibrium parameters not available except D_{EXB}
 - D_{EXB} : constant value $E/(dB_z/dx)$

Future tasks

Extension of simulation model

- RF E field, quadrupole B field
- Cylindrical 3D geometry

Simulation flow

