Plasma-Beam Experiment with DC-RF Magnetized Plasma Discharge

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Large Hall Thruster Facility

28 m³, 60,000 l/s for Xe

Hall thrusters and rf-discharges

SEE measurements

2 kW Hall thruster

Thruster kinetic simulations

30 W RF thruster

Basic process in magnetic field
## Comparison of different $E \times B$ plasma devices

<table>
<thead>
<tr>
<th>Device/Parameter</th>
<th>$R$ (cm)</th>
<th>$L$ (cm)</th>
<th>$T$ (eV)</th>
<th>$B$ (Gauss)</th>
<th>$E_{\text{max}}$ (V/cm)</th>
<th>$V_{E/B}/V_{\text{eth}}$</th>
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</thead>
<tbody>
<tr>
<td>LAPD</td>
<td>50</td>
<td>1700</td>
<td>2-5</td>
<td>400</td>
<td>4-18</td>
<td>$&lt; 2 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Compact Auburn Torsatron</td>
<td>17</td>
<td>53</td>
<td>10</td>
<td>1000</td>
<td>5</td>
<td>$&lt; 4 \cdot 10^{-3}$</td>
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<tr>
<td>Blaamann</td>
<td>8</td>
<td>65</td>
<td>9</td>
<td>570</td>
<td>2-6</td>
<td>$&lt; 8 \cdot 10^{-3}$</td>
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<tr>
<td>Continuous Current Tokamak</td>
<td>40</td>
<td>150</td>
<td>150</td>
<td>3000</td>
<td>120</td>
<td>$\leq 8 \cdot 10^{-3}$</td>
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<tr>
<td>ALEXIS</td>
<td>10</td>
<td>170</td>
<td>5</td>
<td>100</td>
<td>2</td>
<td>$\approx 2 \cdot 10^{-2}$</td>
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<tr>
<td>Reflex arc</td>
<td>2.5</td>
<td>300</td>
<td>5</td>
<td>4000</td>
<td>20</td>
<td>$\approx 5 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Mistral</td>
<td>11.5</td>
<td>140</td>
<td>1.4</td>
<td>220</td>
<td></td>
<td>$\approx 4 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Maryland Centrifugal Experiment (MCX)</td>
<td>27</td>
<td>250</td>
<td>3</td>
<td>2000</td>
<td></td>
<td>$\approx 7 \cdot 10^{-2}$</td>
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<tr>
<td>CSDX</td>
<td>10</td>
<td>280</td>
<td>1.5-3</td>
<td>650</td>
<td>3-4</td>
<td>$&lt; 1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>WVU Q-machine</td>
<td>4</td>
<td>300</td>
<td>0.2</td>
<td>1400</td>
<td>14</td>
<td>$5 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>Conventional Hall thruster</td>
<td>2</td>
<td>2</td>
<td>20-60</td>
<td>100-300</td>
<td>700</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>(No SEE) Hall Thruster</td>
<td>2.5</td>
<td>2</td>
<td>100</td>
<td>115</td>
<td>$\geq 1000$</td>
<td>1 - 2</td>
</tr>
</tbody>
</table>
Motivation: **Control of particles distribution functions in low temperature plasma (LTP)**

- For typical low pressure LTP plasmas, the electron energy distribution function (EEDF) can be far from Maxwellian.

- The application of the magnetic field can greatly modify the EEDF:
  - Ionization can be localized affecting plasma uniformity.
  - Separation of plasma regions with hot and cold electrons.
  - Anisotropy in electron motion along and across B.
Motivation cont’d: Control of weakly collisional low temperature plasmas

- We are exploring kinetic effects of the magnetic field and their control for a weakly collisional, partially magnetized plasma in sub-mtorr range of the background gas pressure:

\[
\frac{\lambda}{L} \geq 1, \quad R_{Li} > L >> R_{Le}, \quad \frac{\omega_{ce}}{\nu_e} > 1
\]

- Possible applications to plasma-beam systems and magnetic filters for material processing, ion and neutral beam sources, and magnetized plasma thrusters etc.
Motivation cont’d: Magnetic filter effect in low pressure plasmas

- Application of the magnetic field in a low pressure plasma can cause a spatial separation of cold and hot electron groups.

- Electron cross-field displacement between inelastic or wall collisions

\[ X \sim 2R_{Le} \left( \frac{\nu_{\text{scat}}}{2\nu_{\text{loss}}} \right)^{0.5} \]

\( \nu_{\text{scat}} \) electron-atom collision and Coulomb collision \( \propto \frac{1}{T_e^{3/2}} \)

- Electron cooling along magnetic filter in ICP (1-100 mtorr, Ar)

Aanesland et al., Appl. Phys. Lett. 100 (2012)
Examples of magnetic filter applications

• Negative and positive ion sources for fusion injectors and accelerator applications.

• Ion-Ion plasma sources for space propulsion and material processing.

• Cold plasmas, $T_e < 1$ eV, for material processing and nanotechnologies (e.g. functionalization of graphene).

  Elias et al, Science 323 (2009)

• NRL Electron Beam Plasma Source
  US Patent 8,288,950 Walton et al
PPPL experiment: Effect of the magnetic field on EEDF and IEDF at < 1mtorr

- **DC E×B fields** applied in a 20 cm × 50 cm st. steel chamber
- **Plasma cathode**: 2 MHz, 50-200 W Ferromagnetic ICP
- **Operating parameters**: Xenon Bkg. pressure: 0.1-1 mtorr
  DC voltage/current: 0-100 V/0-3 A
  B-field: up to 1 kGauss
- **Plasma**: Plasma density ~ 10^{10} - 10^{12} cm^{-3}
  Electron temperature ~ 0.2-5 eV
- **Diagnostics**: Langmuir probes, emissive probes, OES-TRG, LIF
Diagnostics of PPPL setup

Langmuir probes, moves across B-field
Measure Plasma potential,
EEDF from $I''(V_p)$, $T_{e\text{eff}} \approx 2/3 <\varepsilon>$ and $N_e$

Optical emission Spectroscopy (OES)
Measure $T_e$, EEDF
gas temperature

- Cylindrical probe: $d_p = 0.01$ cm, $L_p = 0.4$ cm, $\Rightarrow d_p/R_{le} \sim 0.07$-0.3
- VGPS probe station with a reference probe
- Emissive probe\(^1\)
- Trace rare gas (TRG) – OES\(^2\)

\(^1\)J. P. Sheehan et al, Phys. Plasmas 18 (2011)
Plasma in \( E \times B \) region: \textit{weakly collisional, non-equilibrium, with magnetized electrons and non-magnetized ions}

Neutral density \( \sim 10^{13} \, \text{cm}^3 \)

Plasma density \( \sim 0.5-3 \times 10^{11} \, \text{cm}^{-3} \)

Electron temperature \( \sim 3-5 \, \text{eV} \)

Magnetic field: 5-1000 Gauss

\[ \lambda_{ea}/L \sim 1-2 \]
\[ \lambda_{ei}/L \sim 10 \]
\[ \lambda_{ee}/L \sim 20-50 \]
\[ \lambda_{ia}/L \sim 0.5-3 \]

Energy relaxation length in inelastic range \( \varepsilon > \varepsilon^* \)

\[ \lambda^*/L \sim 2 \]

For \( B = 35 \, \text{Gauss} \)

\[ \omega_{ce}/\nu_{\text{coll}} \sim 150-200 \]

Electron cross-field displacement during time loss (inelastic or wall collisions)

\[ X/R \sim 2R_{Le} \left( \nu_{\text{scat}}/2\nu_{\text{loss}} \right)^{0.5}/R > 1 \]
DC-RF Discharge Characteristics

Maximum ion current at given $P_{rf}$, Pressure, B-field:

$$I_d^{sat} \propto e n_s (T_e/M_{ion})^{0.5} A_{ch}$$

Plasma measurements for discharge with the minimum ion cost

DC discharge current, A

<table>
<thead>
<tr>
<th>DC Bias Voltage, V</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>0</td>
</tr>
</tbody>
</table>

Total ion cost, W/A

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<tr>
<th>DC Bias voltage, V</th>
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</thead>
<tbody>
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<td>0</td>
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Maximum ion current at given $P_{rf}$, Pressure, B-field:

$$I_d^{sat} \propto e n_s (T_e/M_{ion})^{0.5} A_{ch}$$

Plasma measurements for discharge with the minimum ion cost

Positive electrode or ion flow from the thruster

Negative DC biased metal chamber walls

Positive electrode or ion flow from the thruster

DC biased metal chamber walls

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Spatial variations of EEDF are governed by non-local electron heating and cross-field transport.

Hot electrons near the axis, \( R \leq 2 \text{ cm} \), could be due to interaction of electron beam from the RF cathode with plasma.
Effect of the magnetic field on radial profiles of the plasma parameters: $T_e$, $N_e$, and $\phi$

**Note:**
- Electric potential is related to the cathode.
- For a dense plasma region ($R < 6$ cm), $\Delta V$ across $B = 35$ and 160 Gauss is very small.
- Density profile $\propto R^{-1}$
- Electron temperature distribution is affected by B-field.
Potential distribution in cross-field region: “weak” magnetic field case, 35 Gauss

Discharge voltage = 35 V
Xenon
P ≈ 0.3 mtorr

\[ \phi \approx \phi_r \approx \phi_r^0 \]

\[ \phi \approx \phi_{r2} \]

\[ \phi \approx \phi_{r0} \]

Anode

Cathode electrons

B

Ceramic

Ceramic

r

z

Radial distance from the axis, cm

Potential wrt cathode, V

Local potential wrt wall, V

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Potential distribution in cross-field region:
Strong magnetic field case, 160 Gauss

Discharge voltage = 53 V
Xenon
P ≈ 0.3 mtorr

Anode
Cathode electrons

Potential wrt cathode, V

Local potential wrt wall, V

Radial distance from the axis, cm

\[ \phi_r < \phi_r^2 \]
Classical collisional electron cross-field transport can not explain measured results

\[ J_r = \frac{\sigma}{1 + \left( \omega_{ce} / \nu_{eff} \right)^2} \left( - \frac{\partial \phi}{\partial r} + \frac{\partial T_e}{\partial r} + T_e \frac{\partial \ln n}{dr} \right) \]

\[ \frac{\partial J_r}{\partial r} + \frac{\partial J_z}{\partial z} + \frac{J_r}{r} = 0, \quad \sigma = eB_r / m_e \nu_{eff} \]

From the experiment: \( l_{er} \approx l_d = 1.6-2.5 \text{ A} \)

Penning stage: \( R \approx 10 \text{ cm}, L \approx 38 \text{ cm}, P_{xe} = 0.3 \text{ mtorr} \)

- Electron–neutral collision frequency: \( \nu_{en} \approx \sigma_{en} N \nu_{et} \sim 4 \times 10^6 \text{ s}^{-1} \)
- Electron-ion collision frequency \( \nu_e \sim 5 \times 10^5 \text{ s}^{-1} \)
- In order to match the observed electron current to the anode, the effective electron scattering \( \nu_{eff} \sim 10^8 \text{ s}^{-1} \)
Main result: Surprising effect of B-field on the electron temperature profile in $E \times B$ region

- The increase of the magnetic field leads to a more uniform profile of the electron temperature across the magnetic field.
  - Magnetic filter does not work -?
- Analysis of experimental results points to non-classical, anomalously high electron transport that causes mixing of hot and cold electrons at larger magnetic fields.
  - Estimated cross-field displacement is larger than system radius

$$ \frac{X}{R} \sim 2R_{Le} \sqrt{v_{sc} / v_{loss}} / R \sim 1 - 5 $$

- Electron temperature deduced from EEDF measurements across B-field.
Anomalous electron cross-field transport in DC-RF magnetized discharge

- High-speed imaging and probe measurements revealed a few kHz coherent rotating structure, so-called *spoke*.

- Spoke rotates in $E \times B$ direction with the speed of much smaller than $E/B$.

- Spoke conducts the largest fraction of the current across B-field.

- Possible mechanisms – ionization and gradient-driven instabilities.$^{1,2}$

- Kinetic simulations predict that spoke can affect both electron and ion VDF’s.$^{1}$

- Rotating plasma structure responsible for anomalous cross-field transport.

$^{1}$Matyash et al., IEPC 2011
Anomalous cross-field transport through coherent structures in different magnetized plasmas

- Non-diffusive transport - particles are not moving by a random walk (drift wave fluctuations), but rather form coherent structures (or blobs) that convect towards the walls.

Evolution of turbulent structures at the edge of the NSTX tokamak

- UCLA Lapd

- Hall thrusters
Anomalous cross-field transport through coherent structures in different magnetized plasmas (Cont’d)

MISTRAL, Aix-Marseille Univ. (E×B linear device)

E×B rotating oscillations


High Power Magnetrons (HIPIMS)
100’s kHz E×B rotating oscillations
LBNL, Illinois, UR Bochum.
Possible instability mechanism responsible for $E \times B$ rotating structure in DC-RF discharge*

- **Simon-Hoh instability (SHI)**

  Fig. 1. Instability mechanism. The lower figure shows the steady state, axisymmetric distribution of density and potential. No axial electric field is present. The upper figure shows the consequence of an $m = 1$ density perturbation. Because the ions drift more slowly than the electrons in the $\phi$ direction, a charge separation is formed. The electric field so produced drives the plasma outwards and amplifies the perturbation.

- **Conditions for SHI**

  $\nabla n_{eo} \neq 0$

  $\nabla n_{eo} \cdot E_{r0} > 0$

  Hoh, Phys. Fluids 6, 1963

- **Modified Simon-Hoh instability (MSHI)**

  Electrostatic instability in a plasma with magnetized electrons and non-magnetized ions due to finite ion gyro radius effect on azimuthal velocity difference between electrons and ions.

  Sakawa at al., Phys. Fluids B 5, 1993

* For MISTRAL, Th. Pierre, 2010
Coherent structures in Hall thruster (HT)

- Records 400,000 fps
- Unfiltered emission
- ~ 7.5 m away

PPPL Hall Thruster: 12 cm diameter, 2 kW, Xenon

Phantom camera V7.3

Slow movable radial probe on X-Y table positioner
X-Y movable table
Fast movable axial probe
Rotating spoke

Azimuthal non-uniformity of visible light emission and plasma density rotating in $E \times B$ direction ($\sim 10$ kHz) observed using fast cameras and electrostatic probes for different types of HTs.

- Spoke rotates $\sim 10$ times slower than local $E \times B$ velocity!
- Azimuthal spoke oscillations of the current are detected only with segmented anode:
- Electric potential and density fluctuations
- Cross-field current estimation

\[ E = -\frac{dV}{dx} = -\frac{dV}{dt} \left( \frac{dx}{dt} \right)^{-1} = -\frac{1}{\nu_{spoke}} \frac{dV}{dt} \]

• The density oscillates in-phase with the spoke current
• The potential is \(~45^\circ\) out of phase
• The azimuthal electric field

\[ I_{drift} = e\nu_d n_e A. \]

• The current to the anode: where \(\nu_d = E/B\)
• The drift current is \(~\frac{1}{4}\) the discharge current, explaining a large fraction of the electron cross-field current to the anode

Can MSHI be excited in CHT plasma?

From the dispersion relation for MSHI, the instability is excited when

$$\nu_{\theta}^{\text{ion}} < \frac{E_{z0}}{B_{r0}}, \quad \nu_{d}^{e} < \frac{E_{z0}}{B_{r0}}$$

Azimuthal ion velocity at the location of instability

$$\nu_{\theta}^{\text{ion}} \approx \frac{E_{z0}}{B_{r0}\sqrt{2\pi b}}, \quad b = \frac{R_{\text{Lion}}^{2}}{2L_{0}^{2}} \ll 1$$

Y. Sakawa et al Phys. Fluids B 5, 1993

From probe measurements of plasma properties and spoke in near-anode region of the Xenon CHT thruster:

$$B_{r} \approx 900 \text{ Gauss, } E_{z} \approx 10-20 \text{ V/cm, } k_{\theta} \approx 1 \text{ cm}^{-1}, \text{ and } b \approx 30$$

$$f \approx k_{\theta}\nu_{\theta}^{\text{ion}} / 2\pi \approx 10 - 20 \text{ kHz}$$

Not far from our observations
Ionization and neutral depletion processes in spoke oscillations

- A linear stability analysis of the ionization region in HT

An extension of Morozov’s linear analysis for collisionless instability $\nabla (B/n) < 0$

Spoke appears when the ionization and E-field make it possible to have positive gradients of plasma density and ion velocity

*Escobar and Ahedo, IEPC 2011*

- 3-D Full PIC with MC collisions relate the spoke to neutral depletion

*Matyash et al., IEPC 2011*
Feedback circuitry to suppress the spoke in HTs

- Resistors, $R_f \sim 1\Omega - 300\,\Omega$, attached between each anode segment and the discharge power supply.

- Spoke increases the current through the segment leading to the increase of the voltage drop across the segment resistor.

- This results in the reduction of the voltage between the segment voltage and the cathode.

- Segmented anode with a passive feedback to suppress the spoke

Spoke dumping mechanism

Local plasma density $\uparrow \Rightarrow$ Segment current $\uparrow \Rightarrow$ Segment voltage $\downarrow \Rightarrow$
$\Rightarrow$ Local electron temperature $T_e$ $\downarrow$ Local ionization $\downarrow \Rightarrow$
$\Rightarrow$ Local plasma density $\downarrow \Rightarrow$ Segment current $\downarrow$

- Traces of the currents through 4 anode segments

Driving rotating spoke-type mode in a E×B discharge of Hall thruster

- Motivation:
  - Investigate the nature of spoke by inducing artificial perturbation.
  - Determine the dispersion relation of spoke instability.
- Driving azimuthal modes with segmented anode.
  - First experiments in a Hall thruster with 4 anode segments.
- Segmented anode and square wave voltage with successive 90° phase shift applied to each anode segment.
Preliminary results of spoke-driving experiments in HT

- Azimuthal modes can be driven in both ExB and –ExB directions.
- Frequency of azimuthal modes exactly follow driving frequency in the range 10 KHz-50 KHz.
- Coherence of the azimuthal modes depends on driving frequency.

- ExB direction, 15 kHz
- - ExB direction, 15 kHz

High speed camera images of an artificial spoke driven oscillations in a cylindrical Hall thruster plasma.
Concluding remarks

• Formation of EEDF and its spatial variations in $E \times B$ DC-RF discharge are governed by a non-local electron heating (possibly due to beam-plasma instability) and anomalous electron transport across the magnetic field.

• Plasma measurements revealed that the magnetic filter effect (spatial separation of cold and hot electron groups) does not work at pressures below 1 mtorr.

• Anomalous electron cross-field transport causes mixing of hot and cold electrons.

• High-speed imaging and probe measurements revealed a few kHz rotating structure, so called spoke, responsible for the anomalous electron transport.

• Theoretical studies point to possible mechanisms of the spoke, including ionization and electrostatic gradient instabilities.

• Spoke can be controlled and suppressed with a feedback circuitry.
Some open questions

✓ What determines plasma production and losses in the E×B discharge?
  • Why the increase of the discharge voltage does not increase optical emission from neutral atoms at the axis, but ions?

✓ Why electron temperature peaks at the axis of the magnetized discharge?
  • If there an electron beam from the cathode, how it is formed and interacts with plasma electrons?
  • What determines beam relaxation in such a weakly collisional plasma?
  • Is there electron anisotropy in the system? What are its spatial variations across and along B-field?

✓ How electrons are transported across the magnetic field?
  • What is the spoke mechanism and how electrons get across B-field inside the spoke?

✓ Does spoke affect ions and neutral atoms?

✓ Do plasma boundaries have affect on all of the above processes?
Future works

- 3-D PIC simulations and theoretical studies of the DC-RF discharge, including plasma-beam interaction and spoke mechanisms.

- More detail spatial measurements of EEDF (probes), IEDF (RPA), anisotropic properties of the plasma (probes), neutral depletion (OES-TRG).

- Investigate the nature of coherent rotating structures by inducing artificial spoke-type perturbations.

- To validate predictions of PIC simulations that spoke affects IVDF
  - Time-Resolving LIF (TR-LIF) diagnostic has been developed and applied for time-resolving measurements of ion velocity and electric field.
Relevant recent publications

Y. Raitses, Rotating spoke in E × B discharges, Invited talk at 2012 GEC Conf. Austin, TX.


