The Penning discharge

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Introduction

• Device development

Penning precursor: cold-cathode discharge in magnetic field by Phillips – 1898

C. E. S Phillips Proc. R. Soc. 64, 172 (1898)

Penning ionization gauge development: Penning and – 1930s and 1940s

F. M. Penning, Physica 3, 873 (1936)
F. M. Penning, Physica 4, 71 (1937)
F. M. Penning and K. Nienhius, Philips Tech. Rev. 11, 116 (1949)

Emergence of pumping applications – 1950s, Varian

Evacuation of ions by cathode material and reduction of pressure
Introduction

- Modern Penning device architecture

Helmer and Jepsen, Proc. IRE (1961)

general applications:
ion sources, vacuum gauges, and vacuum pumps
Penning discharge physics

2D PIC modelling

- evidence of large-scale plasma rotation


edge density and radial current show similar time-scale variations

transport mechanism in simulations:
- rotating spoke channels
- radial current in short bursts
- spoke “arc” of connects discharge edge with center
- electron motion along equipotentials

mass effect
Penning discharge physics

2D PIC modelling


electron density

spoke rotation velocity $<\ll$ critical ionization velocity (Alfvén)

spoke angular frequency scaling from collisionless Simon-Hoh

good agreement between theoretical and measured rotation frequencies

- numerical studies of spoke scaling
  - frequency with $B$, current, ion mass

- current flow dominated by spoke
Penning discharge physics

2D PIC modelling


<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity</td>
<td>( \varepsilon_r )</td>
<td>400</td>
<td>...</td>
</tr>
<tr>
<td>Discharge radius</td>
<td>( R_0 )</td>
<td>2.5</td>
<td>cm</td>
</tr>
<tr>
<td>Injection radius</td>
<td>( R_i )</td>
<td>0.1</td>
<td>cm</td>
</tr>
<tr>
<td>Applied magnetic field</td>
<td>( B_0 )</td>
<td>100</td>
<td>G</td>
</tr>
<tr>
<td>Electron current</td>
<td>( I_e )</td>
<td>250</td>
<td>mA</td>
</tr>
<tr>
<td>Ion current</td>
<td>( I_i )</td>
<td>100</td>
<td>mA</td>
</tr>
<tr>
<td>Discharge current</td>
<td>( I_d )</td>
<td>-150</td>
<td>mA</td>
</tr>
<tr>
<td>Electron injection temperature</td>
<td>( T_{e,\text{inj}} )</td>
<td>5</td>
<td>eV</td>
</tr>
<tr>
<td>Ion injection temperature</td>
<td>( T_{i,\text{inj}} )</td>
<td>293</td>
<td>K</td>
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<tr>
<td>Electron beam energy</td>
<td>( V_B )</td>
<td>15</td>
<td>eV</td>
</tr>
<tr>
<td>Neutral pressure</td>
<td>( P_n )</td>
<td>1</td>
<td>mTorr</td>
</tr>
<tr>
<td>Neutral temperature</td>
<td>( T_n )</td>
<td>293</td>
<td>K</td>
</tr>
<tr>
<td>Electron-neutral cross-section</td>
<td>( \sigma_{en} )</td>
<td>( 2.88 \times 10^{-19} )</td>
<td>m(^2)</td>
</tr>
</tbody>
</table>
Penning discharge physics

Theory

- accounting for formation of large-scale structures, "spokes"
  - ionization wave
  - modes driven by density gradient

collisionless Simon-Hoh instability (CSHI), often termed modified Simon-Hoh instability (MSHI)

F. C. Hoh, Phys. Fluids 6, 1184 (1963)

- for mode to be present: radial E and density gradient must be collinear
Theory

- collisionless Simon-Hoh instability (CSHI)

\[
\frac{\omega_x}{\omega - \omega_0} = \frac{k_B^2 c_s^2}{\omega^2}
\]

- density gradient length scale
- electron diamagnetic drift frequency
- E x B drift frequency

\[
\omega_x = -k_0 k_B T_e / e B L_n
\]

\[
\omega_0 = k_0 E_r / B
\]

\[
\gamma = \frac{k_0 c_s}{\omega_*} \sqrt{\omega_0 \omega_* - \frac{k_0^2 c_s^2}{4}}
\]

- growth rate

- potential

- density
Penning discharge physics

Experimental characterization

applied $B = 30 - 150$ G
radial $E = 200$ V/m
maximum $I_d = 1.2$ A
pressure $\sim 3 \times 10^{-4}$ mbar

$Te = 1 - 5$ eV
$ne = 10^{16} - 10^{17}$/m$^3$

Rodriguez et al., Plasmas 26, 053503 (2019)
Possible interest as flexible discharge

• operation with multiple gas types possible
  - He, Ar, Xe

• relatively open geometry for diagnostics access

• large range of operating regimes possible
  - pressure
  - magnetic field: 100s of gauss to 1 kG

• potentially relevant to simulation benchmark efforts

• controlled study of material interactions possible