GDR Atelier de recherche
Plasmas magnétisés : Définition d'une source modulable
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The Penning discharge

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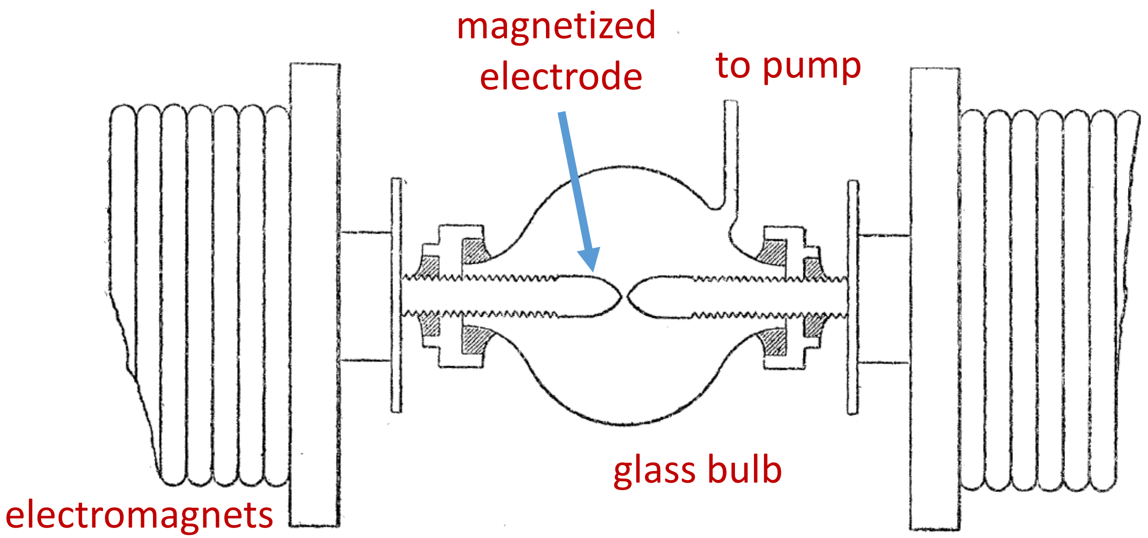
Introduction

- 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)

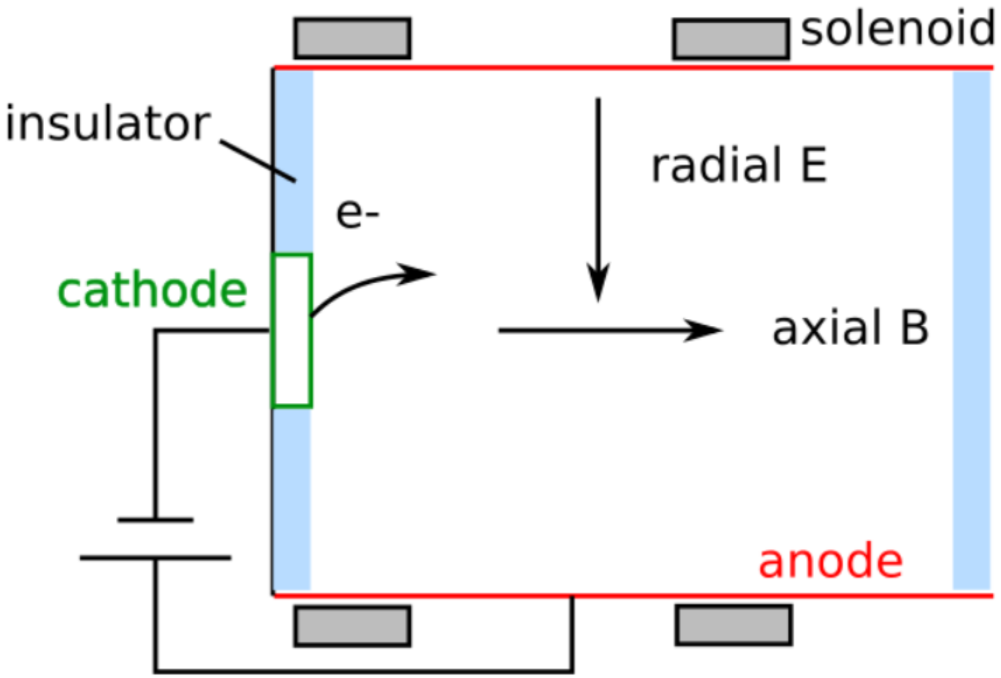
→

emergence of pumping applications – 1950s, Varian

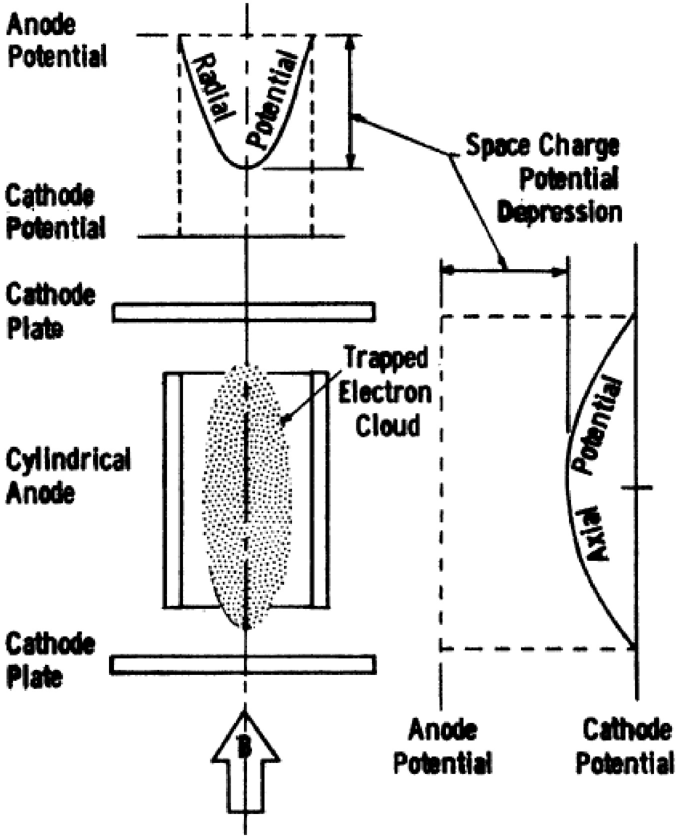
evacuation of ions by cathode material and reduction of pressure

Introduction

- Modern Penning device architecture



general applications:
ion sources, vacuum gauges, and vacuum pumps

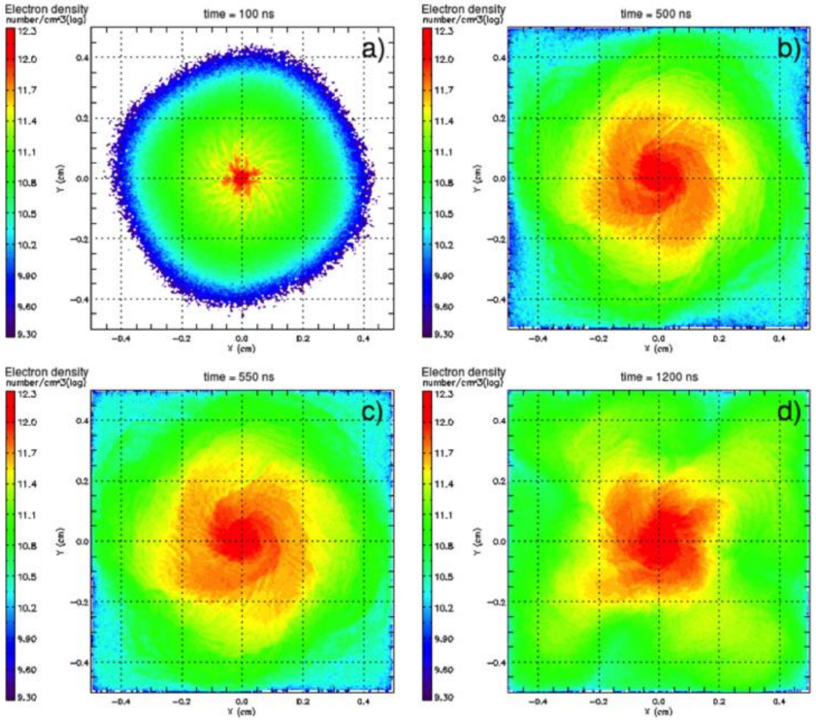


Helmer and Jepsen, Proc. IRE (1961)

Penning discharge physics

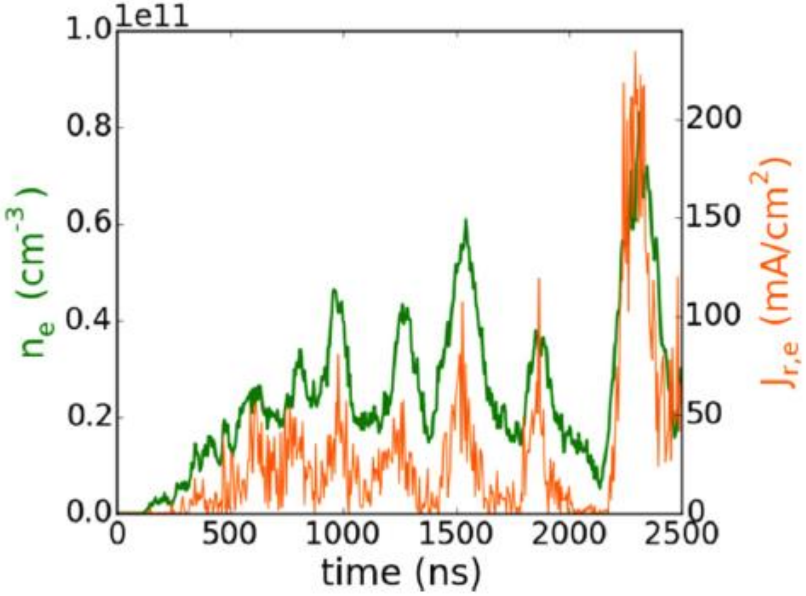
2D PIC modelling

electron density



Carlsson et al., Phys. Plasmas 25, 061201 (2018)

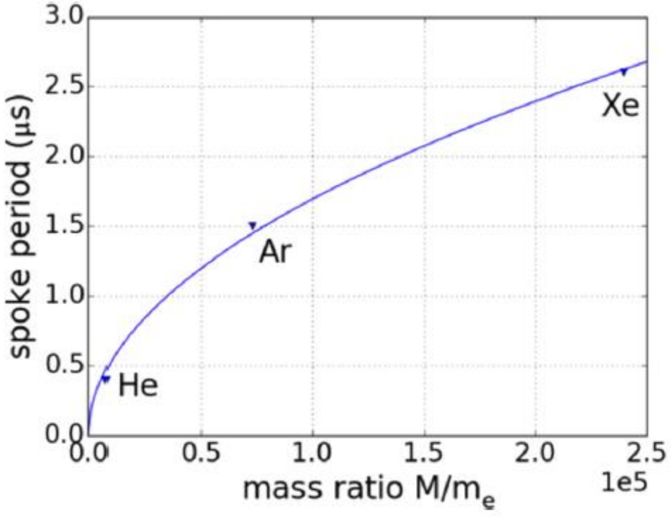
- evidence of large-scale plasma rotation



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



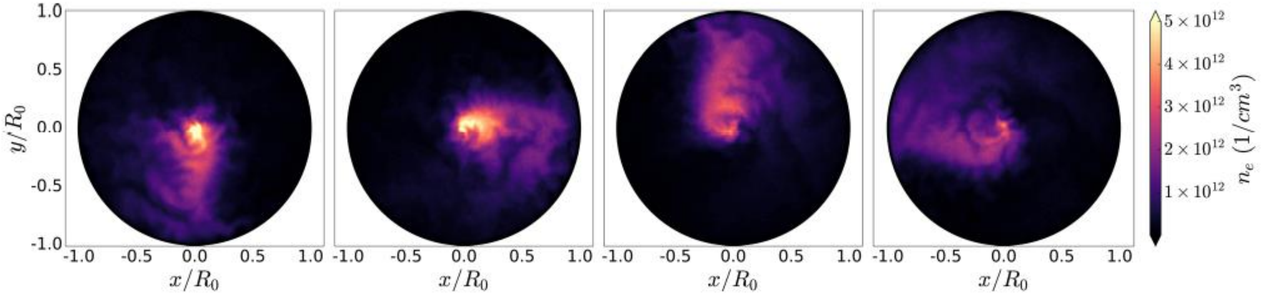
mass effect

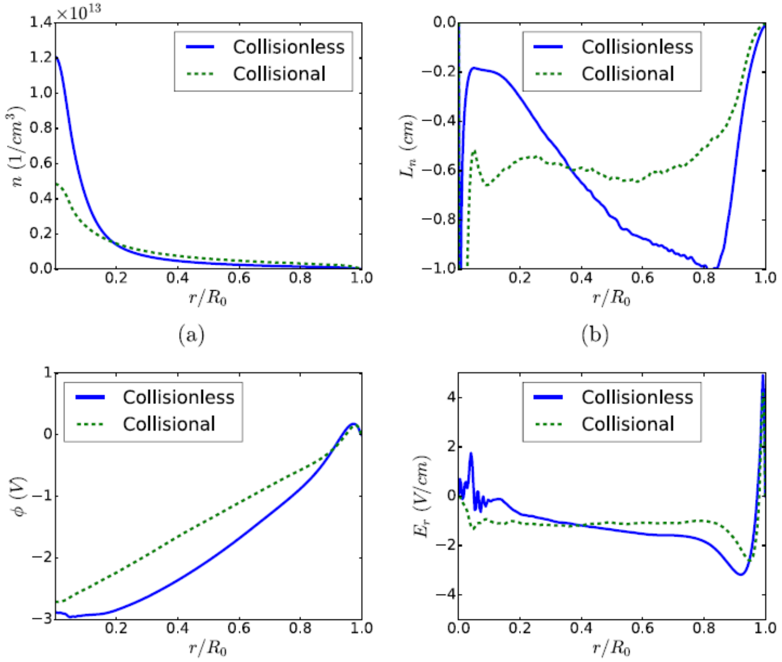
Penning discharge physics

2D PIC modelling

Powis et al., Phys. Plasmas 25, 072110 (2018)

electron density

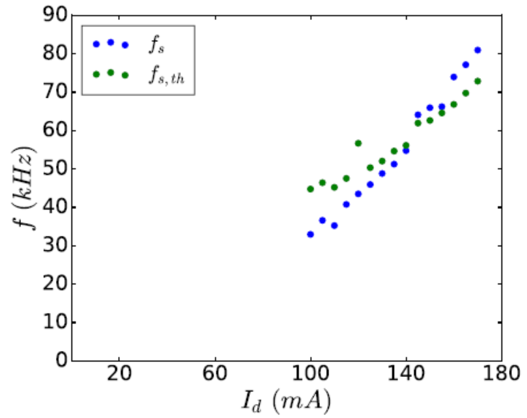




spoke rotation velocity << critical ionization velocity (Alfvén)

$$\omega_{s,th} = \sqrt{\frac{v_s^2 v_0}{v_*}k^2} = \sqrt{\frac{eE_r L_n}{m_i}k^2}$$

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

Powis et al., Phys. Plasmas 25, 072110 (2018)

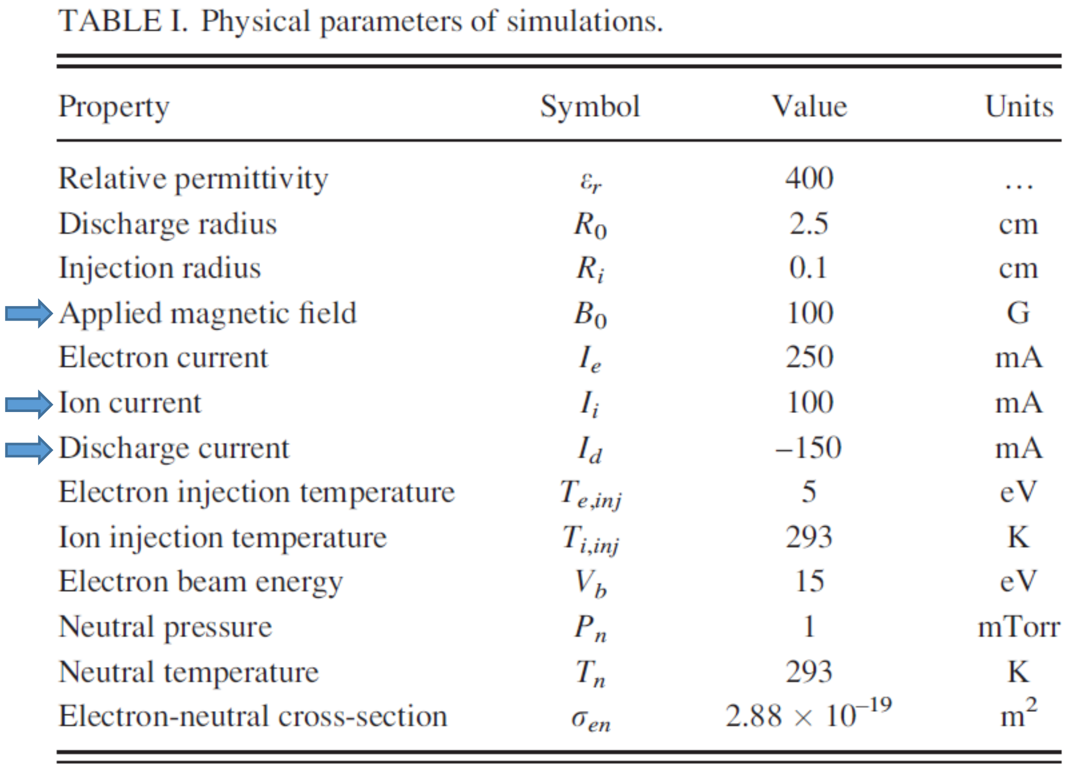


TABLE I. Physical parameters of simulations.

Property	Symbol	Value	Units
Relative permittivity	ε_r	400	…
Discharge radius	R_0	2.5	cm
Injection radius	R_i	0.1	cm
➡ Applied magnetic field	B_0	100	G
Electron current	I_e	250	mA
➡ Ion current	I_i	100	mA
➡ Discharge current	I_d	-150	mA
Electron injection temperature	$T_{e,inj}$	5	eV
Ion injection temperature	$T_{i,inj}$	293	K
Electron beam energy	V_b	15	eV
Neutral pressure	P_n	1	mTorr
Neutral temperature	T_n	293	K
Electron-neutral cross-section	σ_{en}	2.88×10^{-19}	m^2

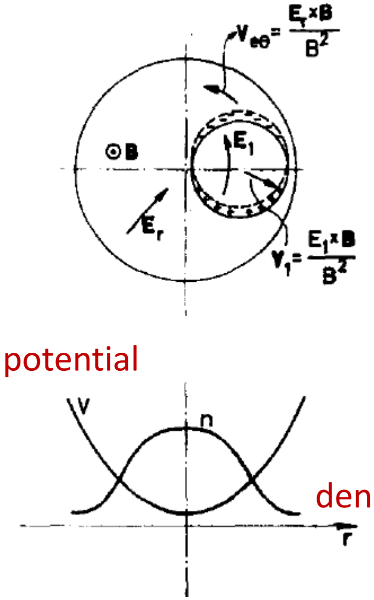
Penning discharge physics

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)



potential

density

Hoh described:

- azimuthal charge separation
- electric field pushing plasma outwards
- amplification of instability

- for mode to be present:

  radial E and density gradient must be collinear

Penning discharge physics

Theory

- collisionless Simon-Hoh instability (CSHI)

$$L_n^{-1} \equiv |\nabla n|/n$$

density gradient length scale

dispersion relation

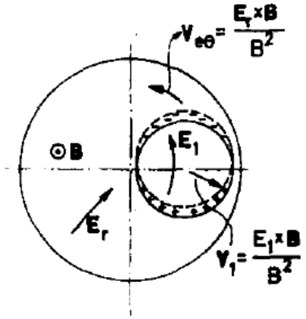
$$\frac{\omega_*}{\omega - \omega_0} = \frac{k_\theta^2 c_s^2}{\omega^2}$$

$$\omega_* = -k_\theta k_B T_e/eBL_n$$

electron diamagnetic drift frequency

$$\omega_0 = k_\theta E_r/B$$

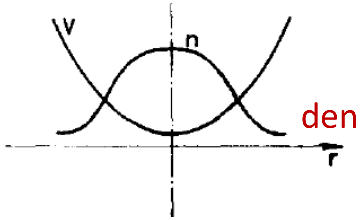
E x B drift frequency



growth rate

$$\gamma = \frac{k_\theta c_s}{\omega_*}\sqrt{\omega_0\omega_* - \frac{k_\theta^2 c_s^2}{4}}$$

potential



density

Penning discharge physics

Experimental characterization

Rodriguez et al., Plasmas 26, 053503 (2019)

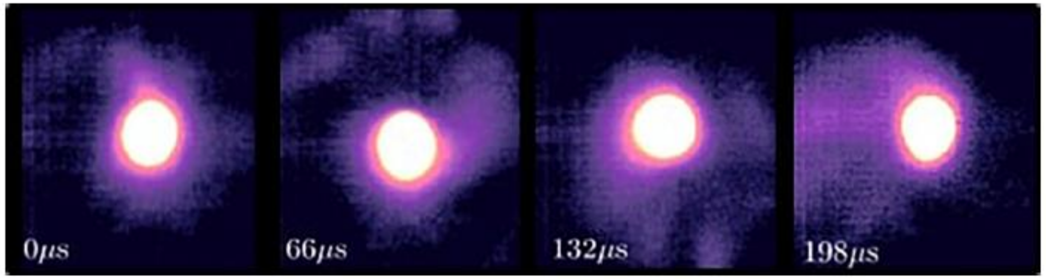


FIG. 1. Rotating spoke seen along the axis of the Penning device with a fast-frame camera. $B = 80$ G is out of the page and E is radially inward (Xenon at 0.2 mTorr pressure).

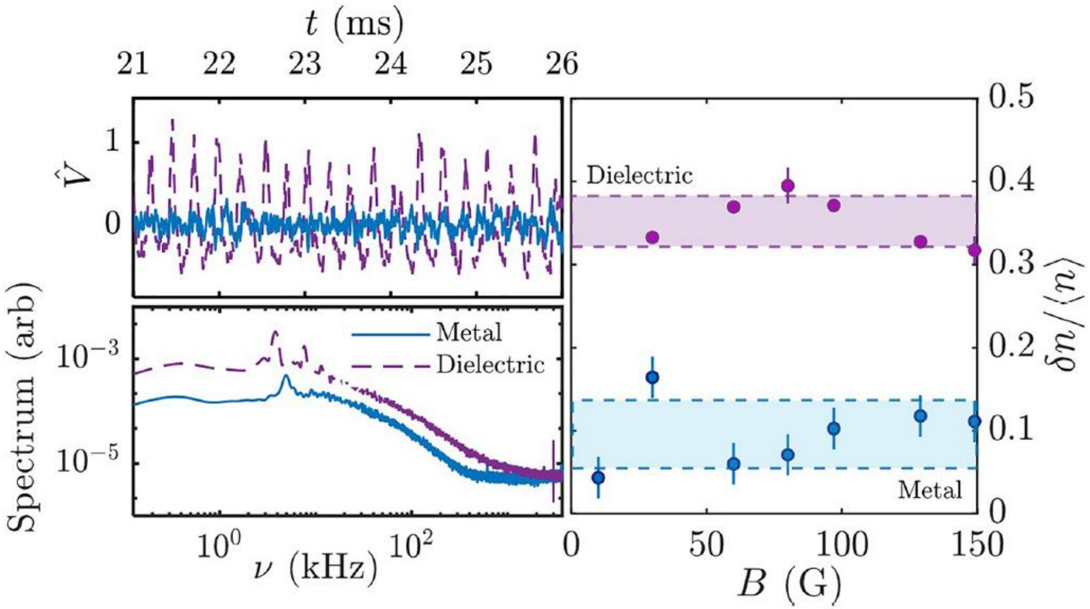
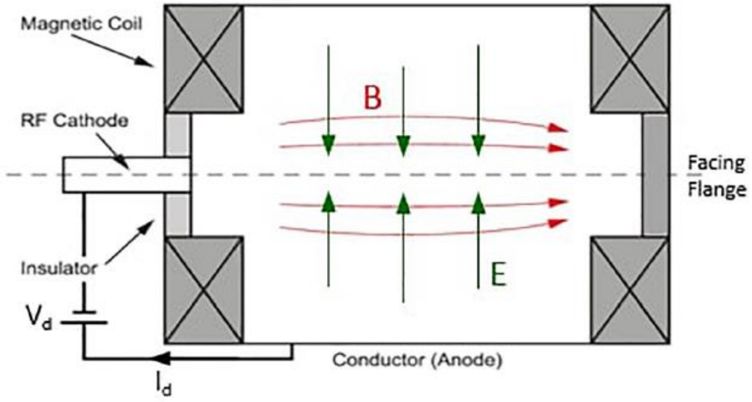


FIG. 3. Change in oscillatory behavior of the plasma when changing the boundary. (Left) Plots of normalized ion probe signal $\hat{V} = \frac{n-\langle n\rangle}{\langle n\rangle}$ for metal and glass boundaries, and their corresponding spectrum, for $B = 30$ G. (Right) Magnitude of variations, representative of instability, defined as $\delta n/\langle n\rangle$ as a function of B; δn is the standard deviation of the time signal of the main spectral component of the perturbation.



applied B = 30 – 150 G
radial E = 200 V/m
maximum Id = 1.2 A
pressure ~ 3 x 10^{-4} mbar

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

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