Scaling of Spoke Rotation Frequency in a Penning Discharge

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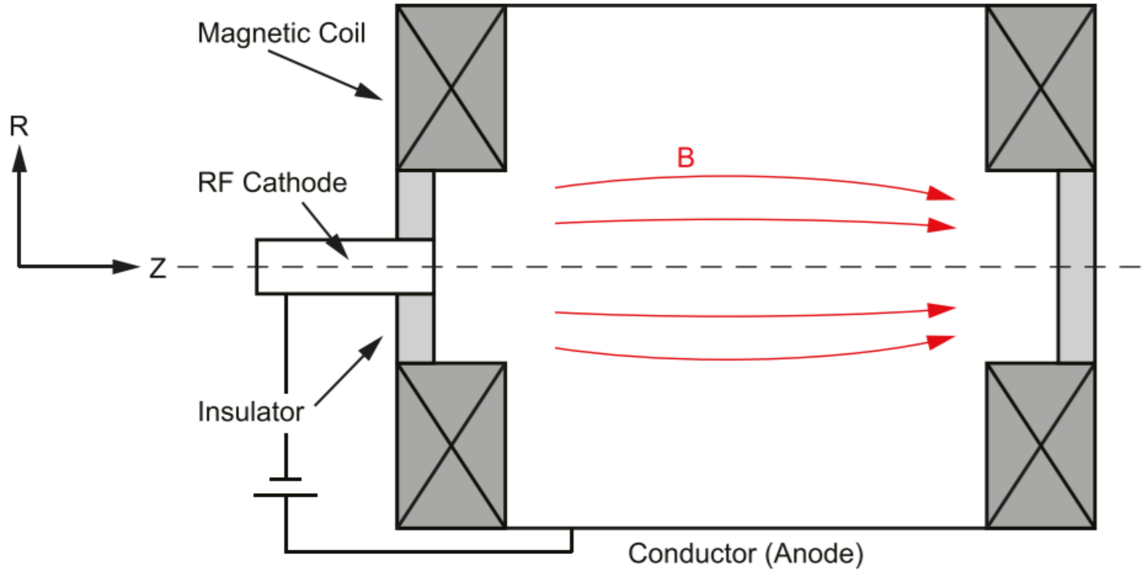
Rotating Spoke in the Penning Discharge

- The Penning discharge is a simplified device for studying E x B phenomenon
  - Improved access for diagnostics
  - Quasi-two-dimensional geometry for simpler theoretical and computational analysis

- Our simulations model the Penning discharge in the PPPL HTX laboratory

R-Z cross section of the Penning discharge experiment



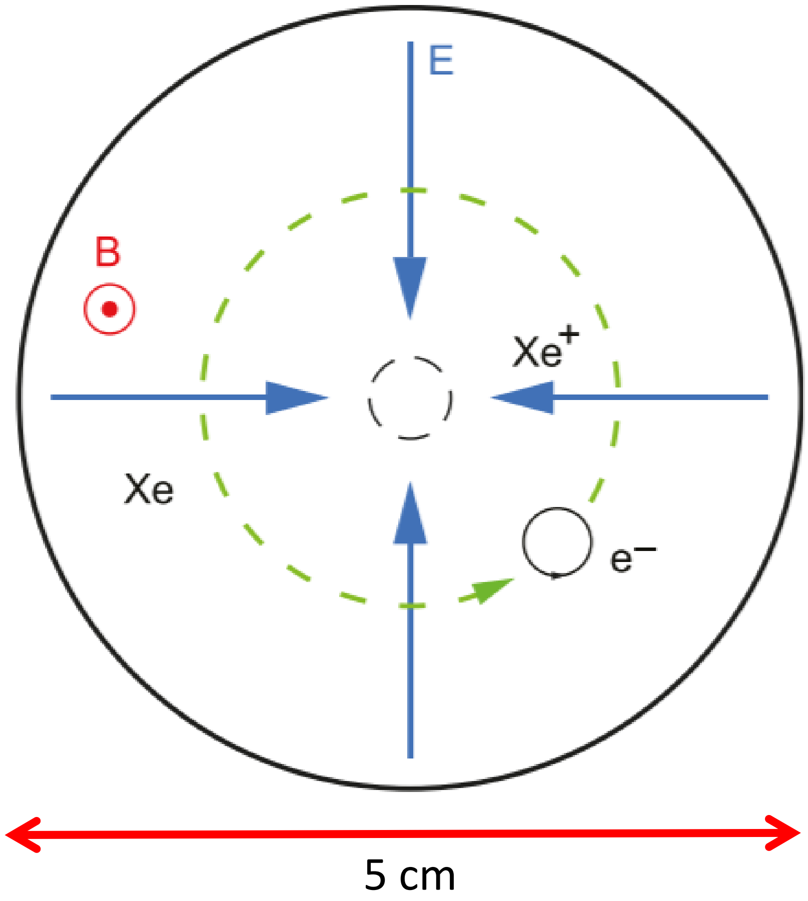
Y. Raitses *et al*, IEPC-2015-307 (2015)

Code Development

- Modifications to commercial PIC-MCC code LSP* to enable production run **large-size long-time** kinetic simulations
  - Improved collision models
  - Integration with PETSc for faster Poisson solve
  - Scaling of relative permittivity to increase cell size

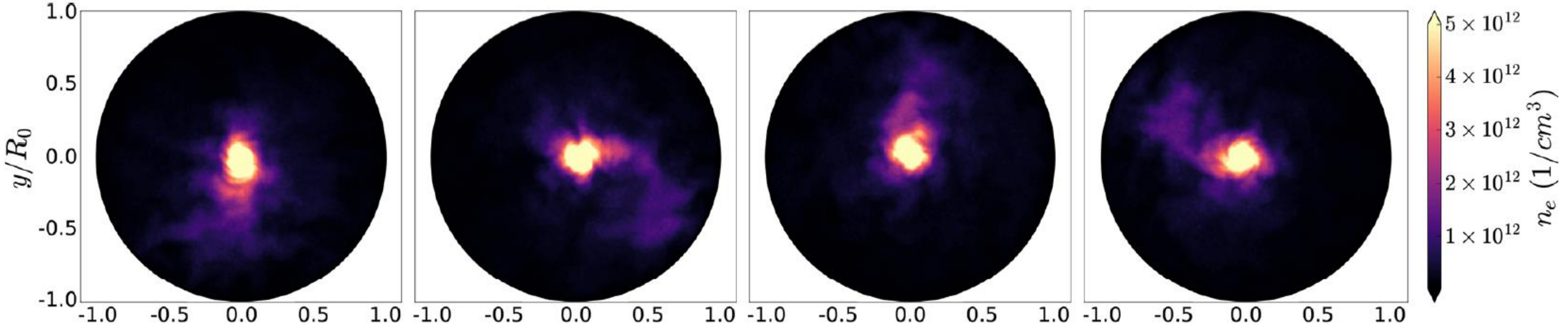
- Penning discharge is modeled in 2D-3V
  - 250 x 250 Cartesian grid with stair-stepping circular conducting boundary
  - Electrons are injected in the center
  - Helium ions are either injected or form via ionization
  - Δx = 200 μm and Δt = 40 ps
  - 2 days to simulate 200 μs (5e6 steps) on 28 cores

R-θ cross section of the Penning discharge simulation domain

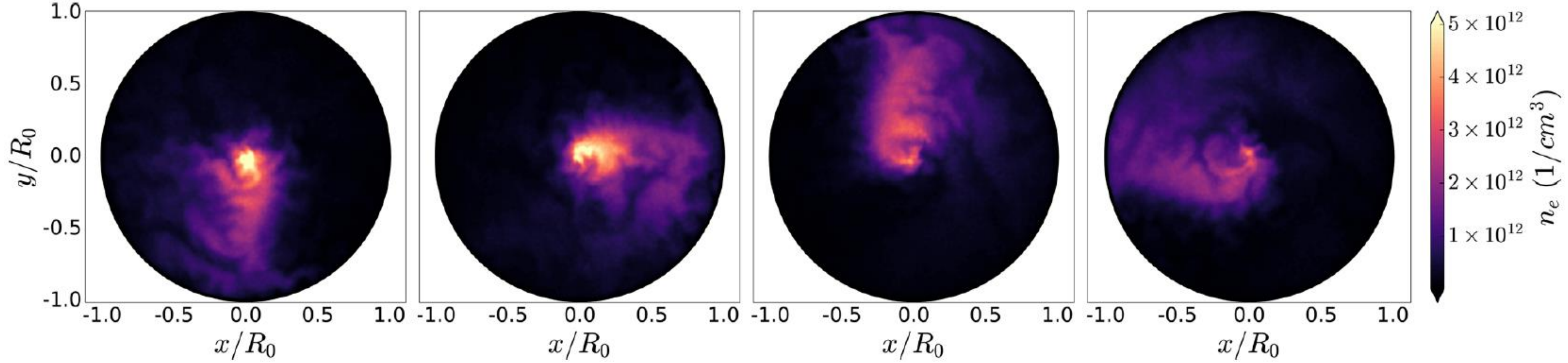


*T. P. Hughes, *et al*, Phys. Rev. Spec. Top.-Accel. Beams **2**, 100401 (1999)

The Spoke Forms With & Without Ionization



*Electron density contours, for spoke forming **without** ionization. Frequency 66.0 kHz*



*Electron density contours, for spoke forming **with** ionization. Frequency 62.4 kHz*

A.T. Powis *et al*, Physics of Plasmas **25**, 072110 (2018)

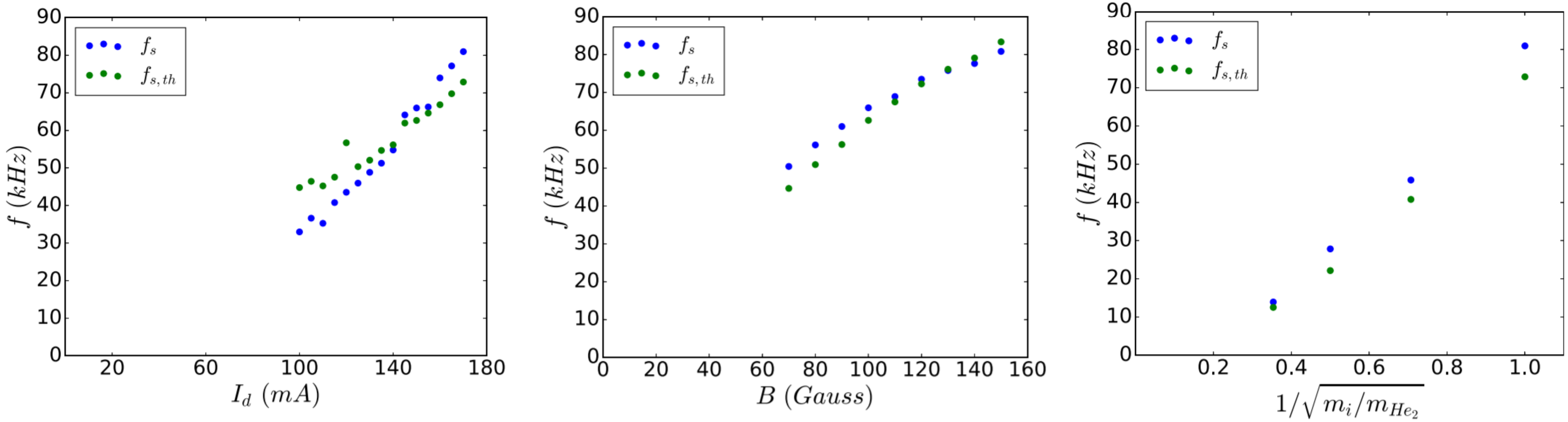
Spoke Frequency Scaling Motivated by Linear Theory for the Collisionless Simon-Hoh Instability

$$f_{s,th} = \frac{1}{\pi R_0}\sqrt{\frac{eE_r L_n}{m_i}}$$

E_r- Time averaged radial electric field

L_n- Time averaged gradient length scale

R_0 – Penning discharge radius

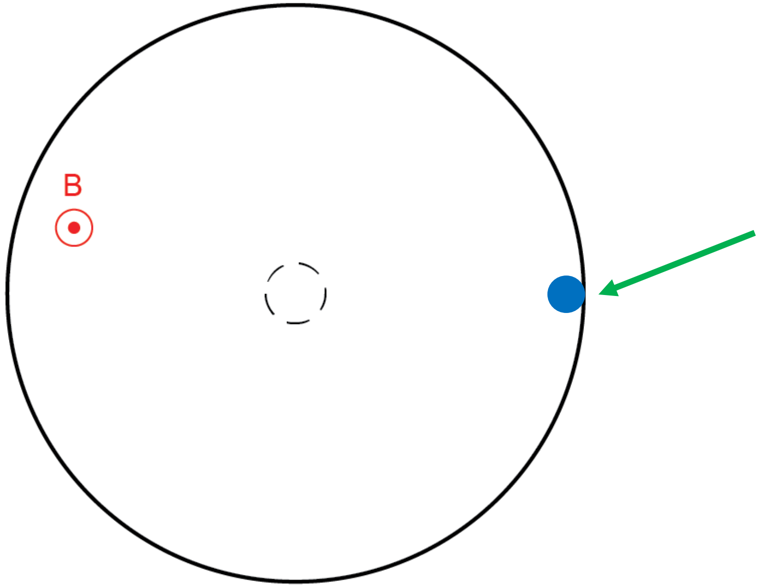


Measured spoke frequency f_s (blue) and theoretical frequency $f_{s,th}$ (green) against discharge current I_d (left), applied field strength B (middle) and inverse square-root of mass ratio (right)

A.I. Smolyakov *et al*, Plasma Phys. Control Fusion **59**, 014041 (2017)

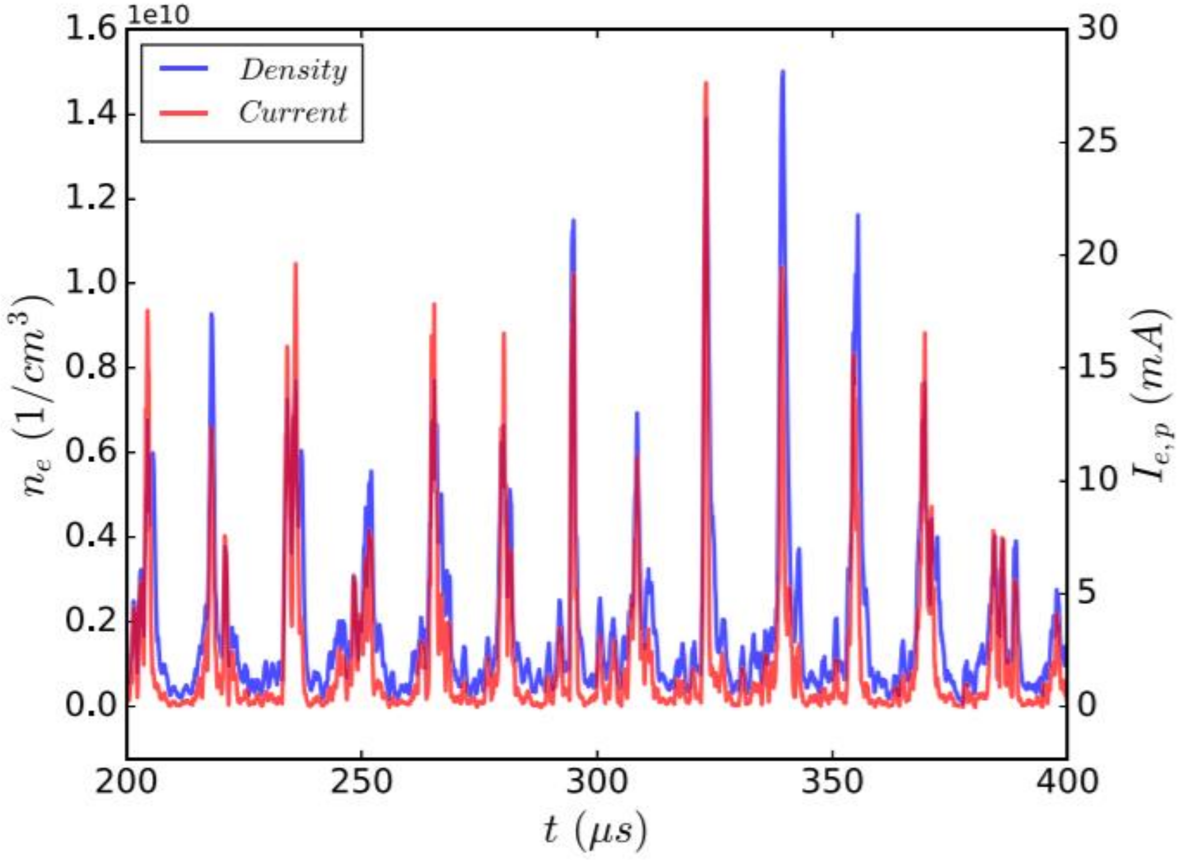
Anomalous Transport through the Spoke

Radial cross-field electron transport is enhanced within the spoke structure



Density and current probe location

Plot of instantaneous electron density (blue) and radial electron current (red) against time



A.T. Powis *et al*, Physics of Plasmas **25**, 072110 (2018)

Open Questions

- What is the fundamental mechanism for the formation of the spoke?
  - Is it the saturation of one single type of mode?
  - Is it the interaction of many modes (inverse cascade)?
  - What role does ionization play in higher pressure discharges (such as a HiPIMS magnetron)?

- Why does the simple collisionless Simon-Hoh linear theory do a good job of describing the spoke frequency scaling?

- What role does the spoke play in anomalous transport?
  - Which wavenumbers are responsible for enhancing transport?

Backup

Collisionless Simon Hoh Instability

- Driven by charge separation between ions and electrons due to different rates of $E \times B$ and diamagnetic drifts.

- Ions are weakly magnetized, therefore electrons drift faster.

- If $\boldsymbol{E}_0 \cdot \nabla n_0 > 0$ the resulting charge separation will enhance the density perturbation.

Collisionless Simon Hoh Instability

$$\omega = \omega_{0i} + \frac{k^2 c_s^2}{2\omega_*} + \sqrt{\frac{k^4 c_s^4}{4\omega_*^2} + \frac{k^2 c_s^2}{\omega_*}(\omega_{0i} - \omega_0)}$$

- From measures values of diamagnetic velocity, ExB velocity and ion sound speed and assuming no ion rotation $\omega_{0i} = 0$ we obtain,

$$\omega \approx \sqrt{\frac{v_s^2 v_0}{v_*} k^2} = \sqrt{\frac{eE_r L_n}{m_i} k^2}$$

- Assume a single azimuthal mode propagating at $r = R_0/2$ leads to the assumed scaling of,

$$f_{s,th} \approx \frac{1}{\pi R_0} \sqrt{\frac{eE_r L_n}{m_i}}$$

Averaged Spoke Radial Profiles

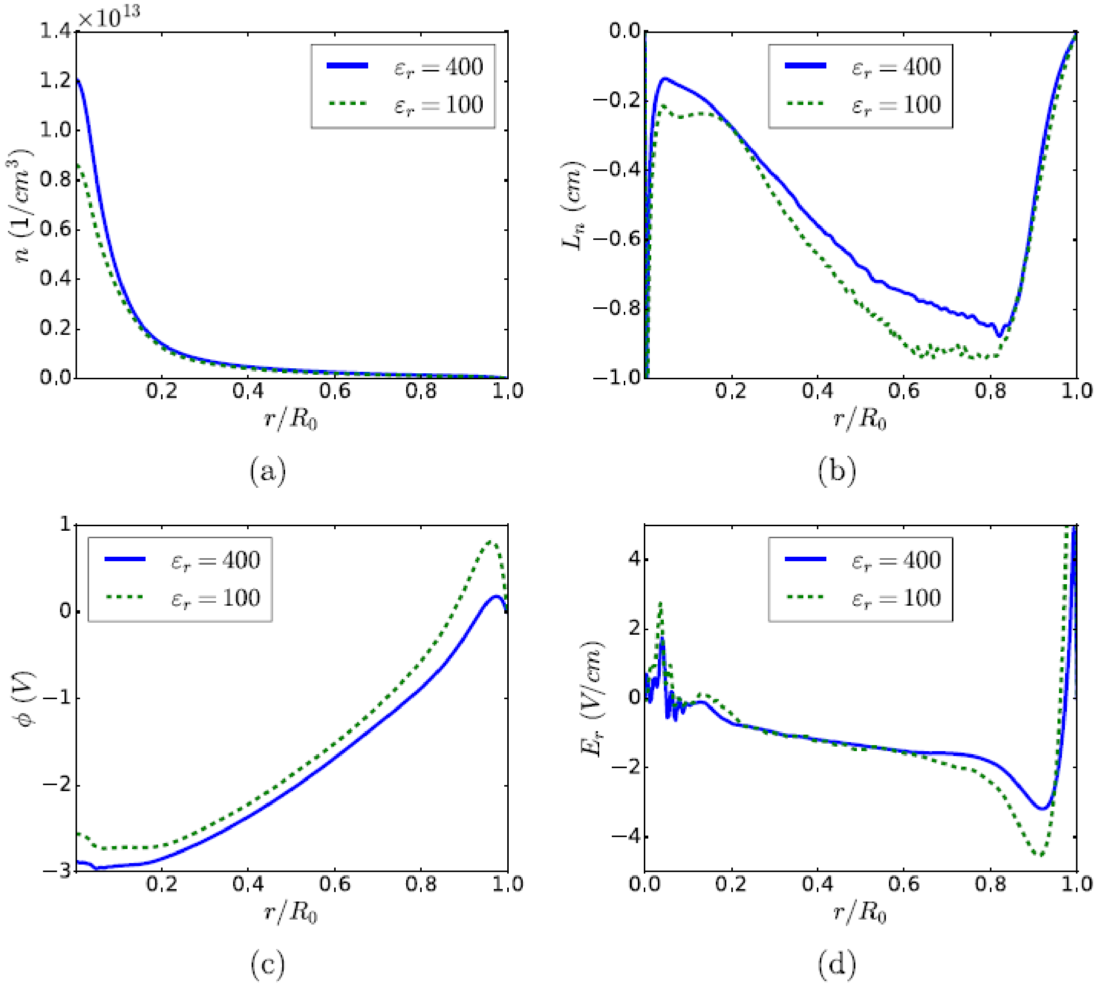


FIG. 3. (a) Azimuthally and temporally averaged radial profiles of (a) electron density $n_e(r)$, (b) gradient-length-scale $L_n(r) = n_e(r)/(dn_e(r)/dr)$, (c) electric potential $\phi(r)$, (d) radial electric field $E_r(r)$, for $\varepsilon_r = \{100, 400\}$.