Significance of physical properties in azimuth dimension in Hall thruster ExB plasma:

Toward active control of plasma by artificial azimuthal modulation

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ExB Plasmas Workshop 2022

Madrid, online event

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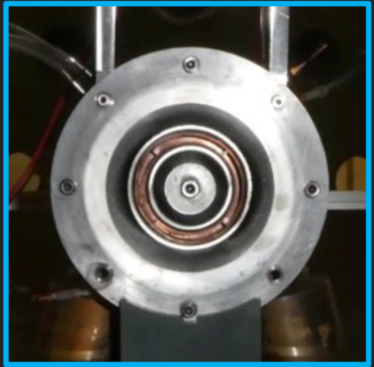
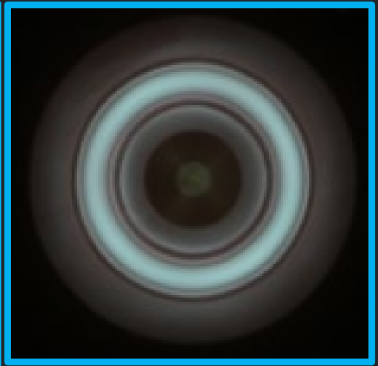
Pitfall of azimuthal mean values of individual physical properties





- Axisymmetric geometry/operation appearance makes us to assume uniform plasma in azimuth
- Are azimuthal distributions of properties really uniform?

  No.. Instabilities, rotating spokes, non-ideal manufactures!
- What is the influence of azimuthal distributions?

Electron axial velocity with azimuthal component becomes…

$$v_z = -\frac{m_e \nu_{en}}{eB^2}\left\{E_z + \frac{1}{n_e}\nabla_z p_e\right\} - \frac{1}{B}\left\{E_\theta + \frac{1}{n_e}\nabla_\theta p_e\right\}$$

$$\Gamma_{e,z} = n_e v_z = -\frac{m_e \nu_{en}}{eB^2}\{n_e E_z + \nabla_z p_e\} - \frac{1}{B}\{n_e E_\theta + \nabla_\theta p_e\}$$

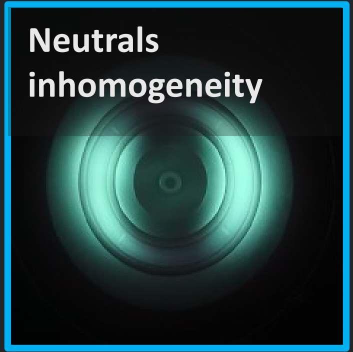
Classical diffusion $\propto 1/B^2$

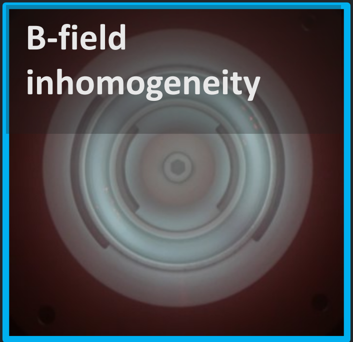
Azimuthal distribution $\propto 1/B$

$1/B$ proportional transport contributions have been ignored!

Q. How significant are these contributions?

Nonuniform operation





Electron cross-field transport in $\mathrm{E} \times \mathrm{B}$ plasma

❑ Electron cross-field (axial-azimuthal) current density

- **Axial:** $j_{ez} = \frac{m_e \nu_{en}}{e B_r^2} e n_e E_z^* + \frac{1}{B_r} e n_e E_\theta^*$
  - $\propto 1/B^2$, $\propto 1/B$
- **Azimuthal:** $j_{e\theta} = \frac{m_e \nu_{en}}{e B_r^2} e n_e E_\theta^* + \frac{1}{B_r} e n_e E_z^*$

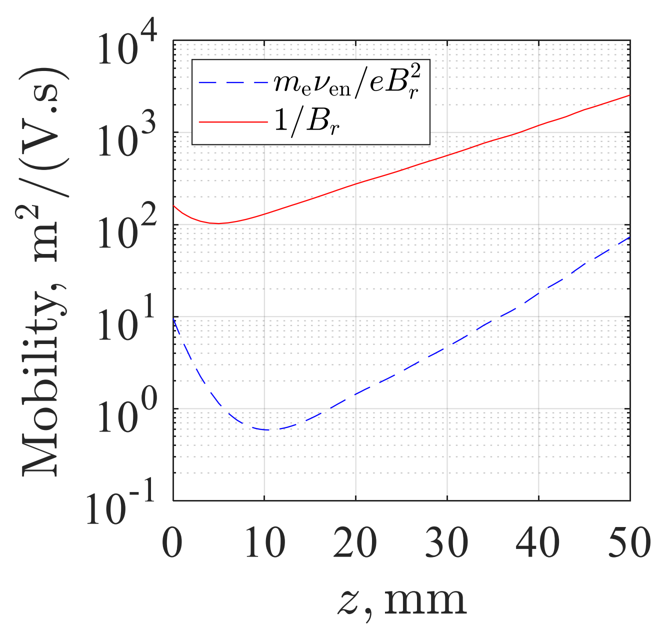
$(E^* \equiv E + \nabla p_e / n_e)$

For **z** direction electrons transport under B-field [1]

	E-field equivalent	Mobility equivalent	Retarded by	Order
$\nabla \parallel$ in z	$\nabla_z V_p (= \mathrm{E}_z)$ $\nabla_z p_e / n_e$	$\frac{m_e \nu_{en}}{e B^2} (= \mu_{cla})$	Cyclotron motion	0.1-10
$\nabla \perp$ in z (=∇ in θ)	$\nabla_\theta V_p (= \mathrm{E}_\theta)$ $\nabla_\theta p_e / n_e$	$\frac{1}{B}$	Collision with neutrals	**10-1000**

- Mobility equivalent, which is *'1/B' itself*, of transport by azimuthal gradient is 2-3 orders higher than the classical one
- This is simply because it is high Hall parameter plasma!

[1]



- Sensitivity of axial transport to azimuthal gradient is much larger
- This is just as the θ direction electron flow is dominated by axial gradient

$$v_{e\theta} \approx \frac{E_z^*}{B_r}$$

(analogous between cross-field dimensions)

[1] J. Bak, R. Kawashima, K. Komurasaki, and H. Koizumi, Phys. Plasmas **26**, 073505 (2019); doi.org/10.1063/1.5090931

Various causes of azimuthal inhomogeneity (E_θ) and our approach

θ propagating Instabilities
(EDI, Spokes, drift waves, etc.)

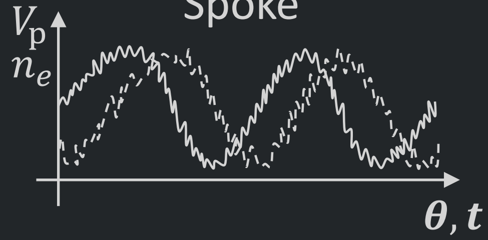
Our work
Neutrals[1,2]/B-field[3] inhomogeneity in θ

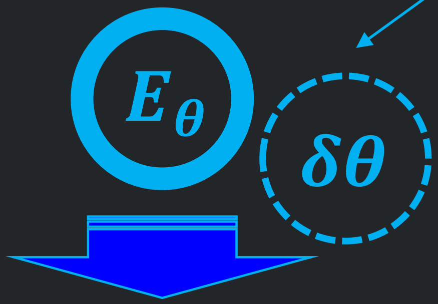
Causes of E_θ

Characteristics of E_θ

Fluctuation of n_e and V_p in θ

$\langle \delta n_e \delta E_\theta \rangle$



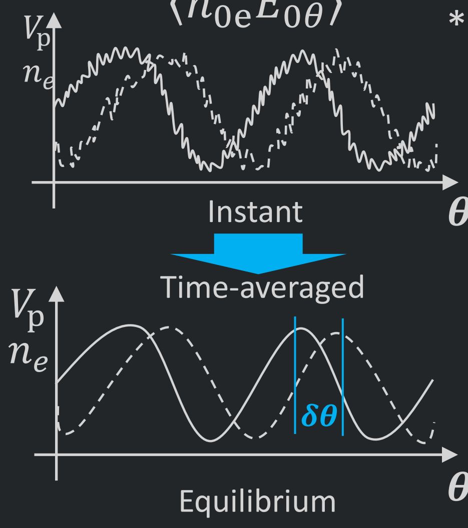


Cross-field transport with $\propto 1/B$ mobility

Static variation of n_e and V_p in θ

$\langle n_{0e} E_{0\theta} \rangle$

$* \langle X \rangle = \frac{1}{2\pi} \int_0^{2\pi} X d\theta$



- Normal operation (Microscopic, or spoke)

$E_\theta(\theta, t) = \overline{E_{0\theta}(\theta)} + \delta E_\theta(\theta, t)$

No-exist

Hard to resolve..

Simultaneously with ne, even harder

- Non-uniform parameter operation

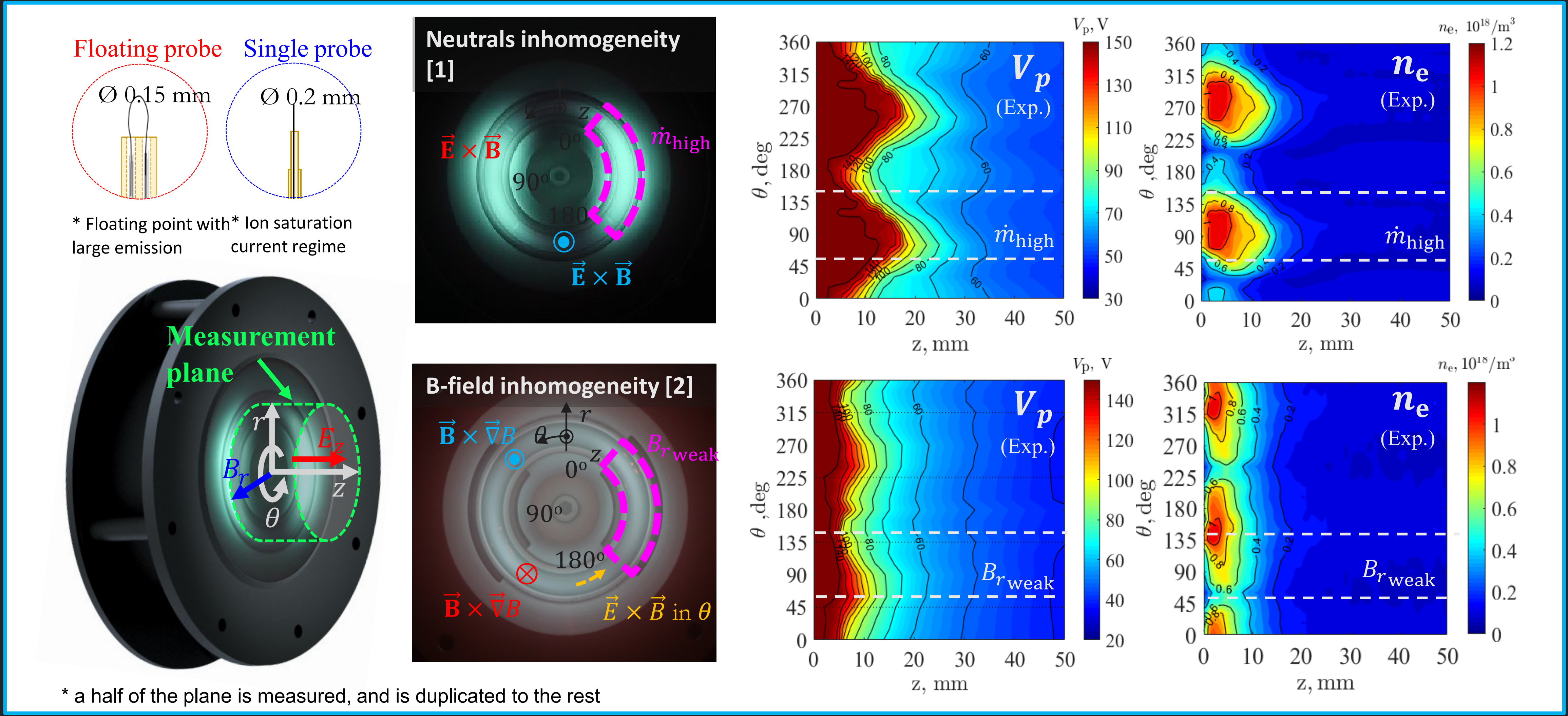
Easy for direct measurement of $\langle n_{0e} E_{0\theta} \rangle$

$E_\theta(\theta) = \overline{E_\theta(\theta, t)} = \overline{E_{0\theta}(\theta)} + \overline{\delta E_\theta(\theta, t)}$

Physically exists on operation, but measurement averages out

[1] J. Bak, R. Kawashima, K. Komurasaki, and H. Koizumi, Phys. Plasmas **26**, 073505 (2019); doi.org/10.1063/1.5090931
[2] J. Bak, R. Kawashima, J. Simmonds, and K. Komurasaki, Phys. Plasmas **28**, 102510 (2021); doi.org/10.1063/5.0060377
[3] J. Bak, R. Kawashima, G. Romanelli, and K. Komurasaki, J. Appl. Phys. **131**, 053302 (2022); doi.org/10.1063/5.0067310

Influences of azimuthal inhomogeneity on equilibrium plasma structure

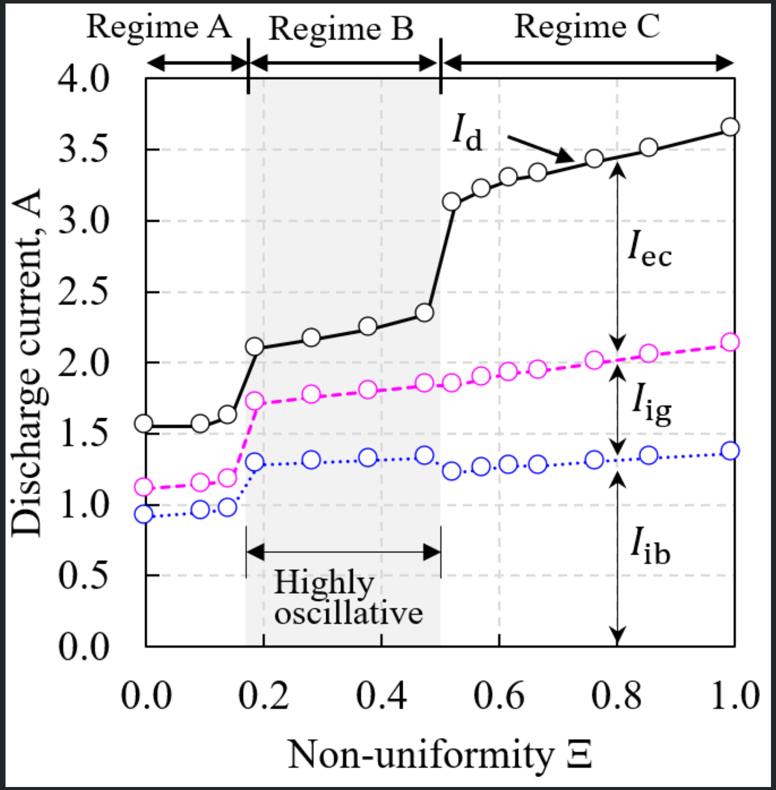


- Plasma structure can be locally controlled. Potential and density correlation differs depending on neutrals/B-field modulation

[1] J. Bak, R. Kawashima, K. Komurasaki, and H. Koizumi, Phys. Plasmas **26**, 073505 (2019); doi.org/10.1063/1.5090931
[2] J. Bak, R. Kawashima, G. Romanelli, and K. Komurasaki, J. Appl. Phys. **131**, 053302 (2022); doi.org/10.1063/5.0067310

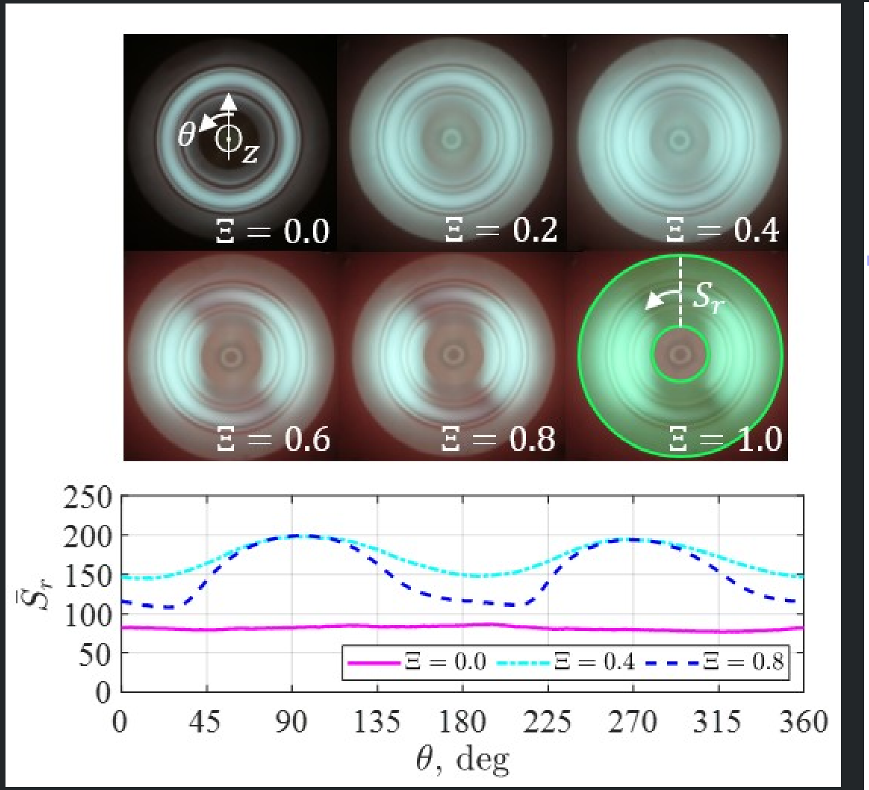
Influences of $\dot{m}$ inhomogeneity strength on Hall thruster operation[1]

❑ Discharge current anatomy



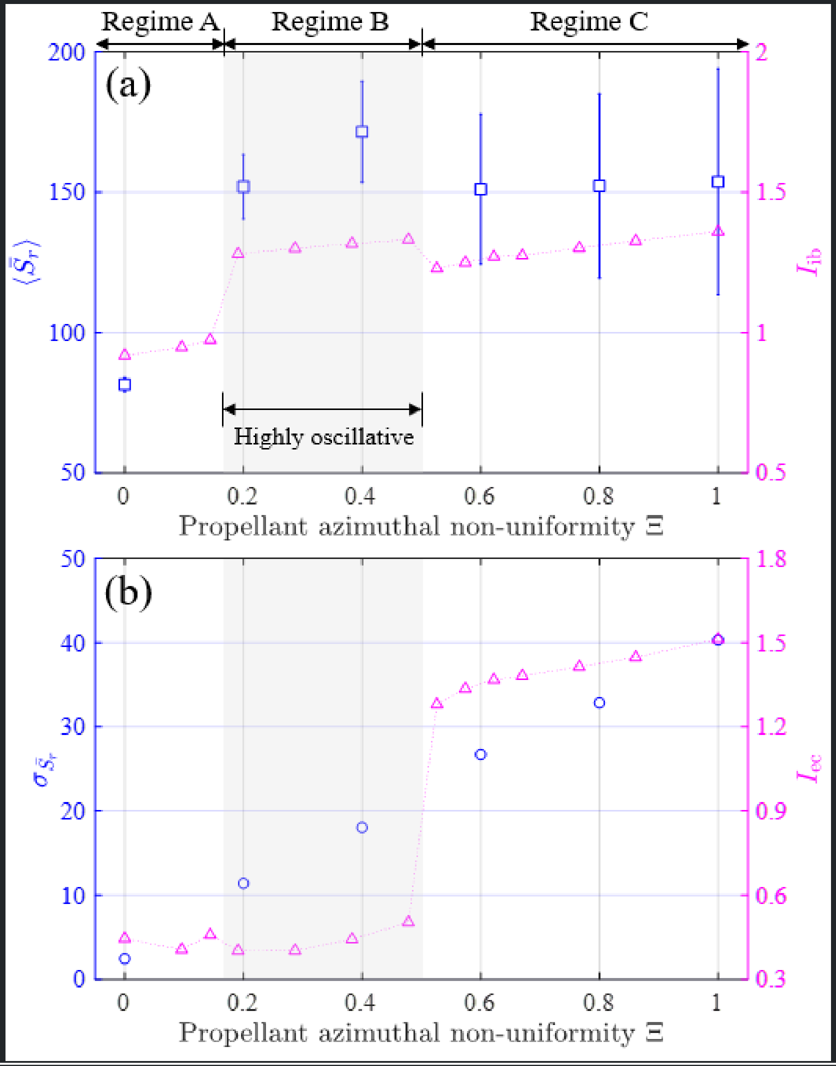
I_{ec}: Electron current
I_{ig}: Guard-ring current (loss to the walls)
I_{ib}: Ion beam current

❑ Induced plasma inhomogeneity



Ξ: neutrals inhomogeneity strengths; closer to 1 = more inhomo.
$\bar{S}_r$: Radial mean of image intensity
$\sigma_{\bar{S}_r}$: Standard deviation of $\bar{S}_r$ in azimuth

❑ Relation to global parameters



- Neutrals inhomogeneity suppresses discharge oscillation and affects discharge current components. Such current behaviors are correlated to plasma azimuthal inhomogeneity

[1] J. Bak, B. Van Loo, R. Kawashima, and K. Komurasaki, J. Appl. Phys. **128**, 023302 (2020); doi.org/10.1063/1.5144851

Spatial correlation of plasma properties and regional characteristics

Azimuth dimension is periodic, so the net transport has to be considered. (not *means of individual properties*)

Ex) For $\Gamma^{-}_{ez,E_\theta} = \frac{1}{B_r} n_e E_\theta$, in the case of uniform magnetic field, the azimuthal correlation n_e and E_θ becomes important

Net axial transport by E_θ at a specific z location: $\Gamma^{-}_{ez,E_\theta} = \frac{1}{B_r}\langle n_e E_\theta\rangle$

With $n_e = n_{e0} + n_{e1}\sin(k\theta)$

$V_p = V_{p0} + V_{p1}\sin(k(\theta + \delta\theta))$

* $\langle X\rangle = \frac{1}{2\pi}\int_0^{2\pi} X d\theta$

Set of affecting parameters[1]

$$\Gamma^{-}_{ez,E_\theta} = 0.5\sin(k\delta\theta)\cdot n_{e1}\cdot E_{\theta 1}\cdot \frac{1}{B_r}$$

- (magenta): Effective weight coefficient from the phase difference
- (blue): Electron density inhomogeneity
- (green): Potential inhomogeneity
- (white): Magnetic flux density

* Note that this can be applied to different wavenumber/frequency components

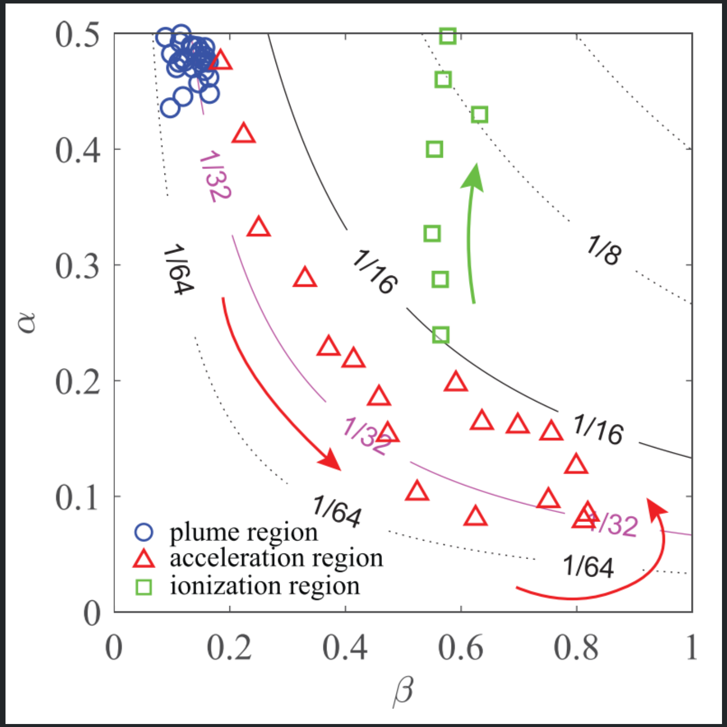
Evolution of effective mobility coefficient κ of Γ^{-}_{ez,E_θ}

$$\Gamma^{-}_{ez,E_\theta} = \frac{\alpha\beta\gamma}{B_r} n_{e0}\langle E_z\rangle = \frac{\kappa}{B_r} n_{e0}\langle E_z\rangle$$

$\alpha \equiv 0.5\sin(k\delta\theta)$; weight coefficient
$\beta \equiv n_{e1}/n_{e0}$; density inhomogeneity
$\gamma \equiv E_{\theta 1}/\langle E_z\rangle$; E-field ratio

- Contour map of κ[1]

(by a static equilibrium E_θ under azimuthal $\dot{m}$ inhomogeneity; the result is limited to this specific case)



At acceleration/plume region, effective mobility coefficient seems to maintain a certain value, in this case, ~ 1/32

[1] J. Bak, R. Kawashima, J. Simmonds, and K. Komurasaki, Phys. Plasmas **28**, 102510 (2021); doi.org/10.1063/5.0060377

Conclusion and open questions

- ❑ **Physical properties in azimuth dimension significantly affect electron cross-field transport in Hall thrusters**
  - Transport by azimuthal gradient of potential/pressure can easily become dominant transport mechanism
- ❑ **Artificial azimuthal modulation of operation parameters induces characteristic equilibrium plasma structures**
  - Can a localized plasma control be useful for some applications? How good controllability can we achieve?
  - How would such artificial modulation influence time-varying phenomena (instabilities, spokes, etc.)?
  - Does the equilibrium structure from artificial modulation have similarity to the instant structure?
- ❑ **Strength of azimuthal inhomogeneity affects thruster performance**
  - Enhanced electron transport is bad for efficiency-critical-applications, but can it be useful for other applications? (ex, enhance electron flow near anode inside thrusters)
  - What would be an acceptable inhomogeneity level for efficiency-critical-applications?
- ❑ **Spatial correlation of azimuthal plasma properties is critical on net cross-field transport**
  - How the affecting parameters in different wavenumber/frequency components (by different causes of inhomogeneity) are related to each other and evolve spatially?

* Acknowledgments - This work was supported by the JSPS KAKENHI (Grant Nos. JP18J14592 and JP20H02346)