Data-driven analysis of breathing and ion-transit modes in 2D hybrid Hall thruster simulations

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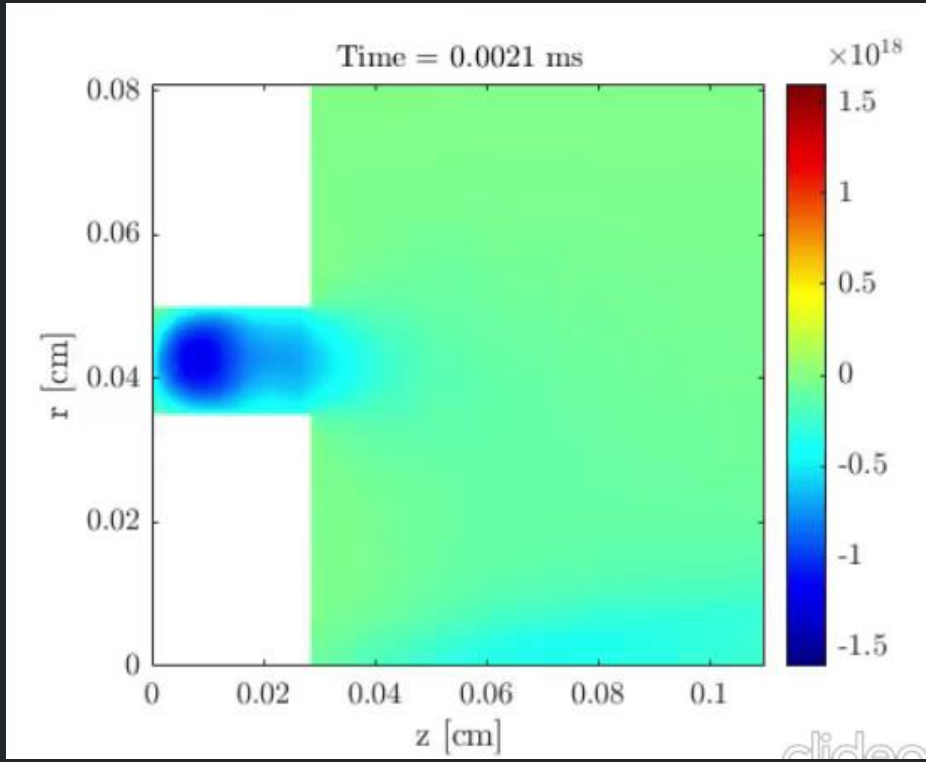
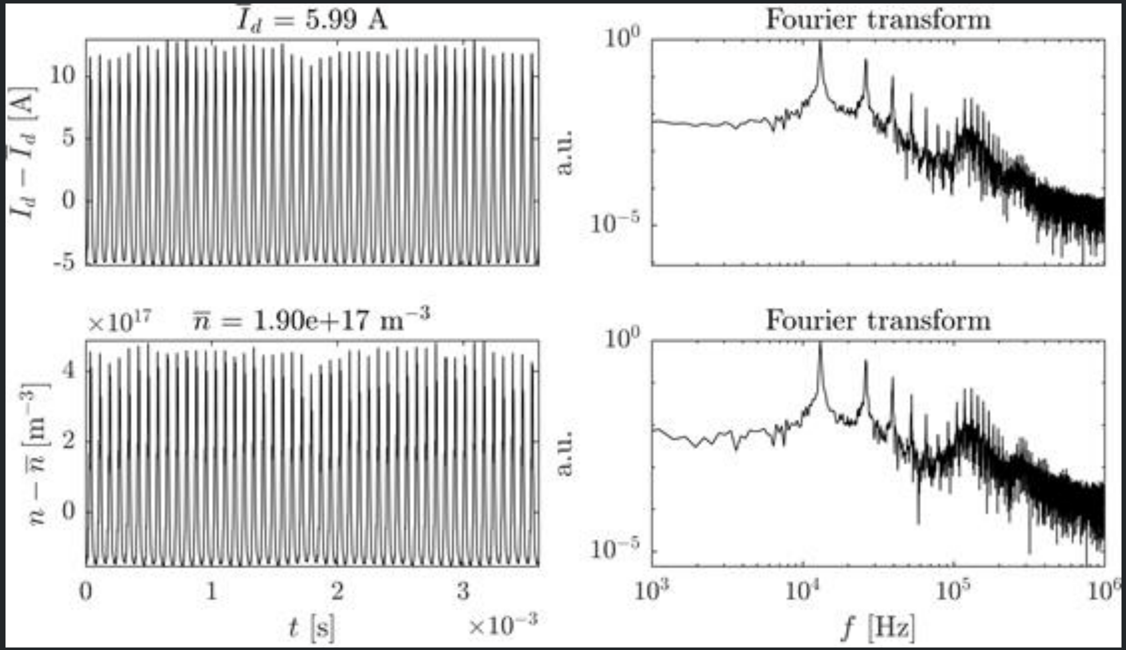
SPT-100 2D hybrid simulations datasets

- 2D axisymmetric hybrid PIC/fluid simulations of a SPT-100 class HET have been produced by Adrián Domínguez-Vázquez (EP2)
  - Total timespan of 3.6 ms, 2400 snapshots
  - Two different operating conditions





Plasma density [m^{-3}]

Time average removed: $X - \bar{X}$

Oscillations on the centreline

Higher Order Dynamic Mode Decomposition

- Classic DMD aims to decompose the snapshots as

Amplitude a_k: dynamical relevance

Growth rate δ_k: mode stability/instability

Frequency ω_k: temporal oscillation characterization

$$\boldsymbol{q}_n \approx \boldsymbol{q}_n^{\text{DMD}} = \sum_{k=1}^{K} a_k \psi_k e^{(\delta_k + i\omega_k)t_n}$$

Mode ψ_k: spatial mode shape (complex)

  - Modes are rather ranked by dynamical importance

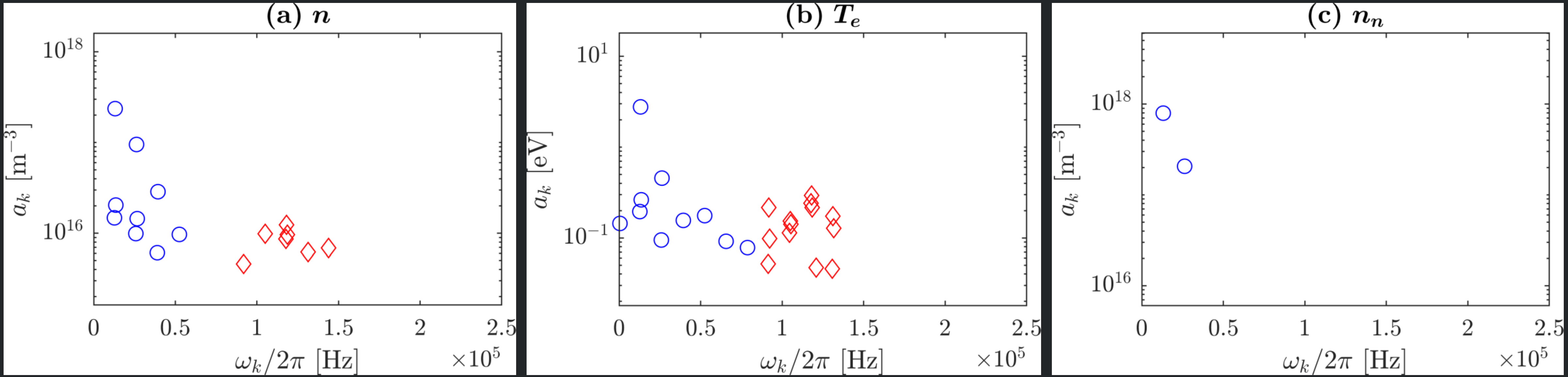
- Standard DMD may produce spurious results for strongly non-linear dynamics with high spectral complexity
  - HODMD allows for improved performances by using time-lagged snapshots

$$\boldsymbol{q}_{n+d} = \boldsymbol{A}_1 \boldsymbol{q}_n + \boldsymbol{A}_2 \boldsymbol{q}_{n+1} + \ldots + \boldsymbol{q}_d \boldsymbol{v}_{n+d-1} \quad \text{for } n = 1, 2, \ldots, N - d$$

- Preliminary noise filtering and iterations are performed for convergence

HODMD diagrams

Nominal case: $V_d = 300\ \mathrm{V}, \dot{m}_A = 5\ \mathrm{mgs}^{-1}$

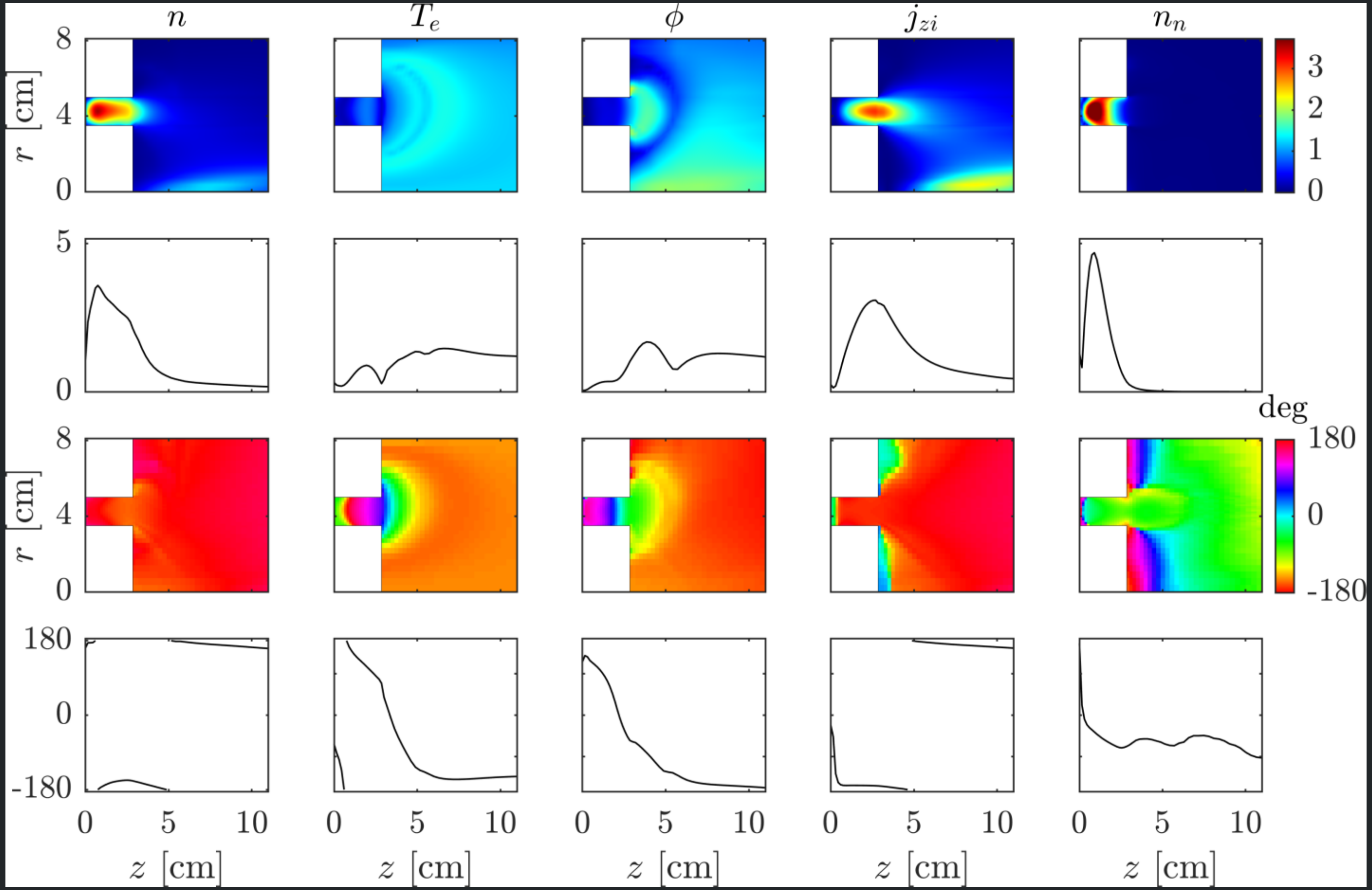


- The two colors represent two different cluster of oscillations : *breathing oscillation* and *ion transit time (ITT) oscillation*
  - Several *replica modes* appear, suggesting highly spectrally complex oscillations

- All variables except neutral density show the same behavior
  - Neutral density does not participate to the ITT oscillation

HODMD dominant breathing mode

- Are the two mentioned cluster of modes really belonging to two different oscillations?



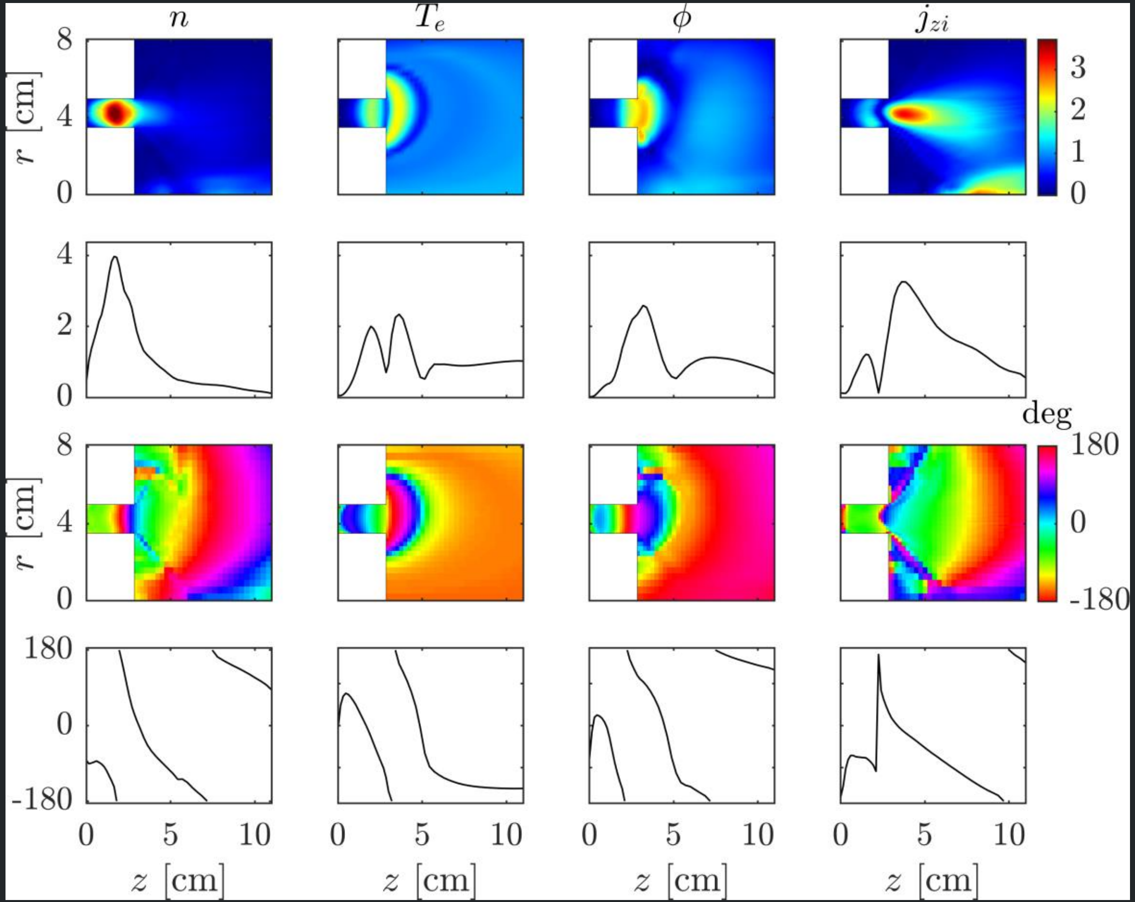
$f_{br} = 13.1$ kHz

- n, j_{zi} and n_n show a global oscillation behavior
  - n_n shows a 90 deg phase shift, in agreement with the predator-prey model
  - Grossly located within the chamber, where the ionization takes place

- ϕ and T_e show a progressive wave behavior (i.e. traveling wave)
  - The progressive structure stops at the cathode, where the phase becomes essentially constant
  - Located in the proximity of the chamber exit, in the acceleration zone

HODMD dominant ITT mode

- Are the two mentioned modes really belonging to two different oscillations?



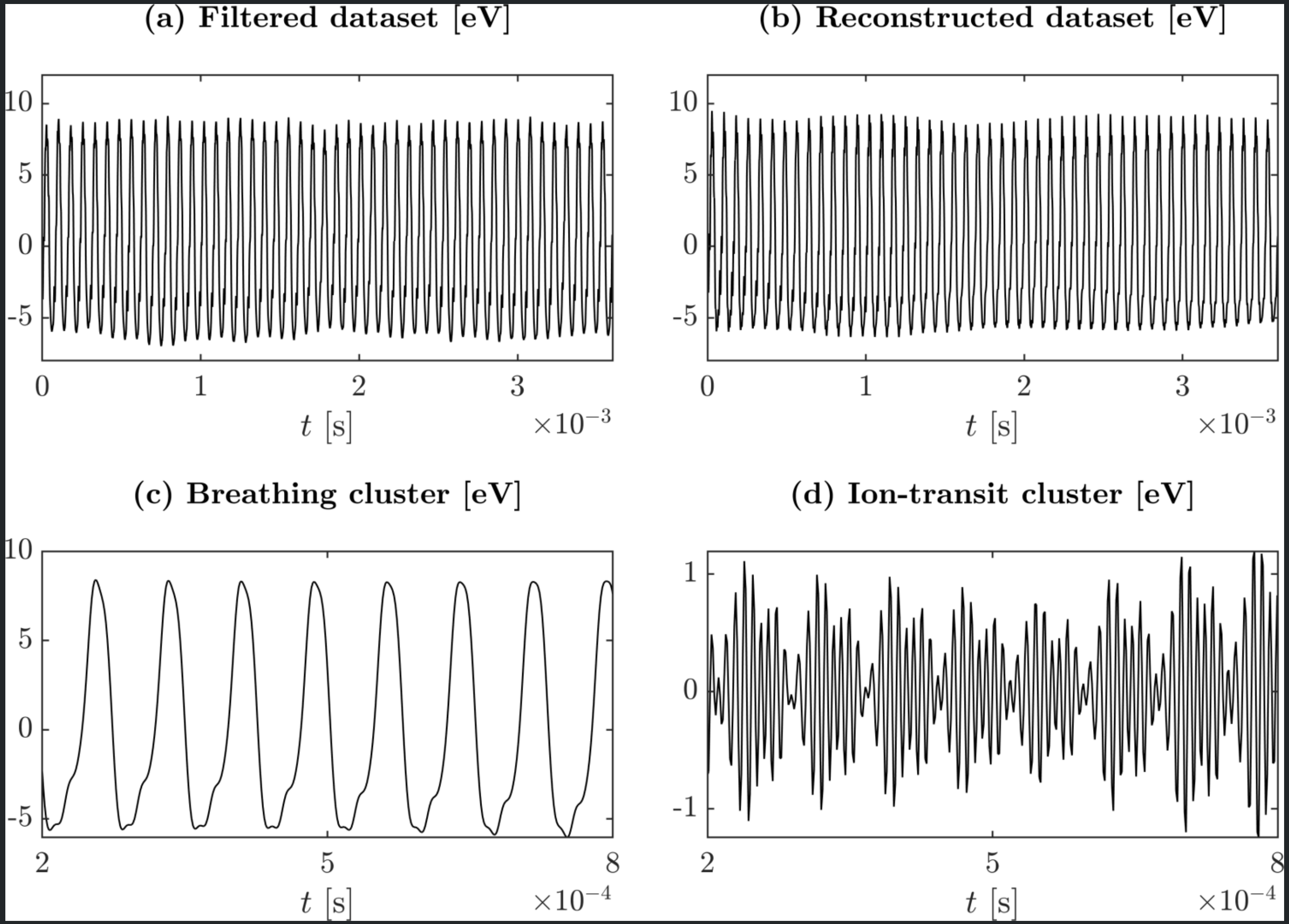
$$f_{itt} = 118 \text{ kHz}$$

- All wave structures are now progressive
  - n and j_{zi} switched from global to progressive
- Ion current density shows two magnitude peaks
  - The first one is linked to the plasma density oscillations in the chamber
  - The second one is linked to the ion velocity oscillations induced by the plasma potential
- The ion velocity in the acceleration region divided by the length of such region provides good agreement

$$f_{itt,2} = 127 \text{ kHz}$$

- The phase velocity of n and j_{zi} corresponds with the ion axial velocity

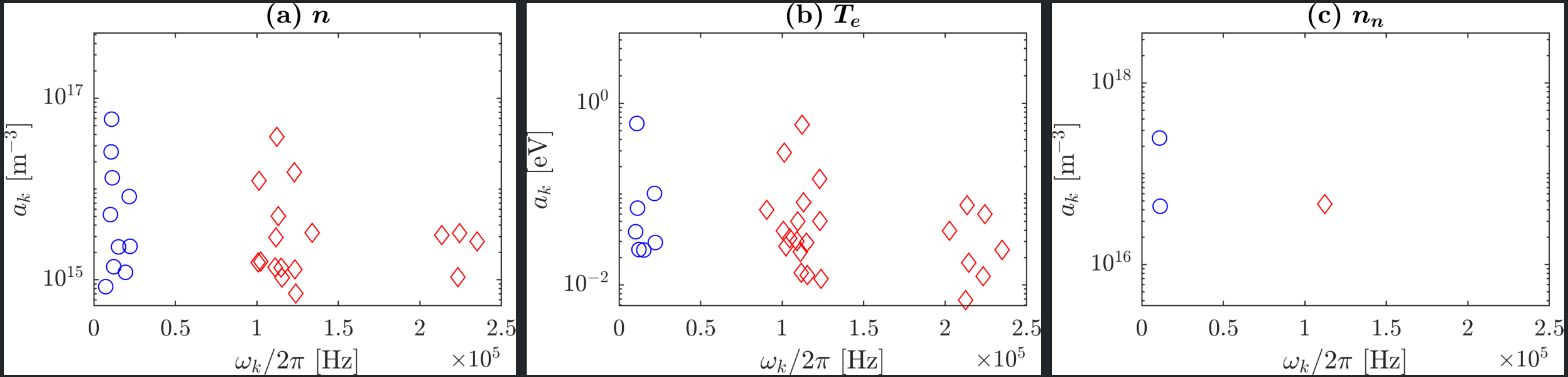
HODMD reconstructions



- The two different clusters can be reconstructed singularly
  - Growth rates are forced to zero due to the reconstruction being asymptotic
- ITT is fully modulated by the breathing dynamics
  - The ITT frequency is an exact multiple of the breathing one
  - The ITT peaks are in phase with the breathing peaks
    - This does not happen for all the cases analyzed

HODMD diagrams

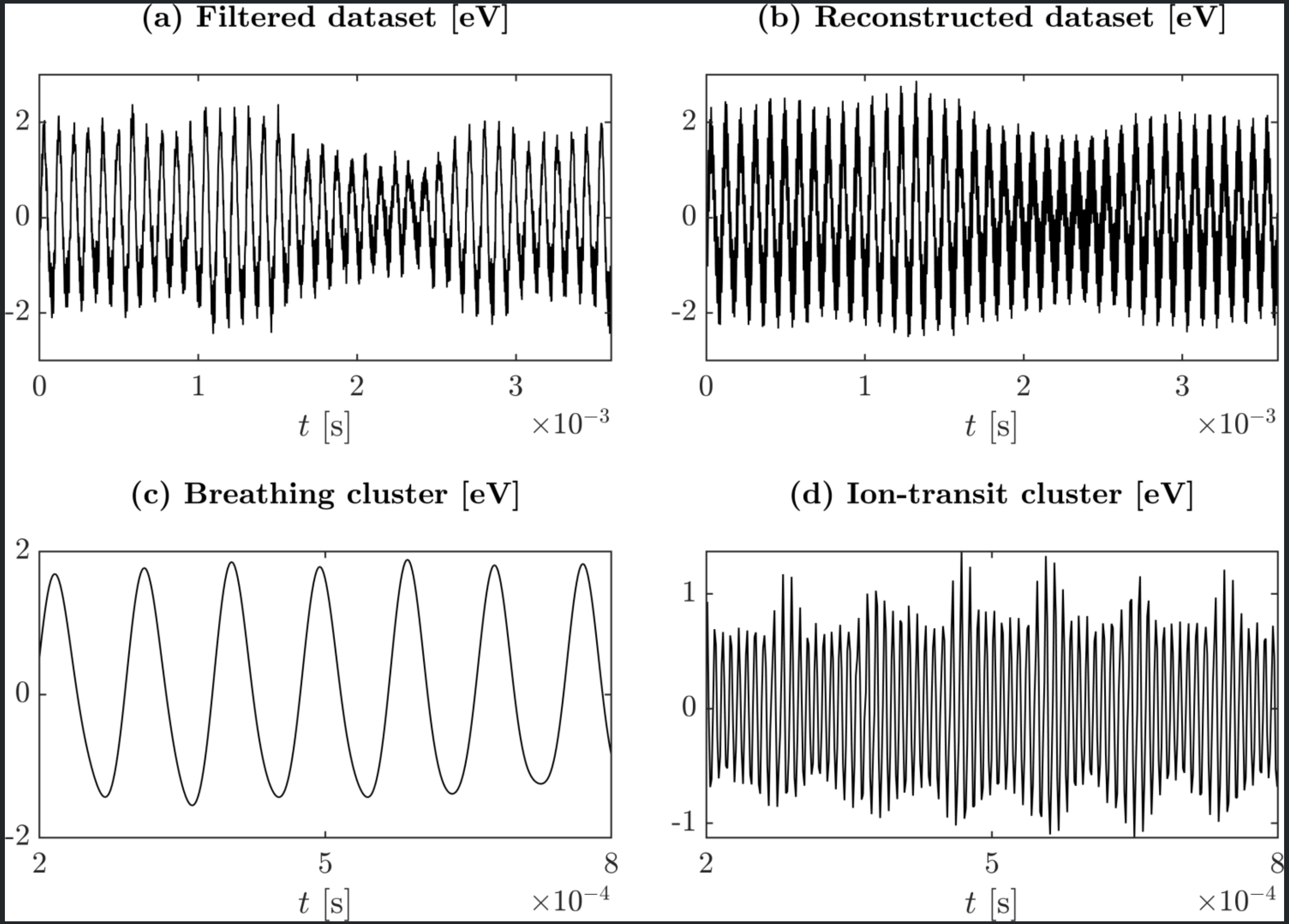
Low voltage case: $V_d = 200$ V, $\dot{m}_A = 5$ mgs^{-1}



- The dynamic importance of breathing and ITT clusters is now comparable
  - The neutral density now shows one mode in the ITT cluster, but with significant lower amplitude

- The number of replica modes is again significant---and has increased
- One new cluster centered around the first harmonic of the ITT dominant mode is now recovered

HODMD reconstructions



- The breathing cluster has a magnitude which is comparable with the one of the ITT
- The modulation of the ITT by means of the breathing dynamic gets weaker
  - The ITT frequency (112 kHz) is no longer an exact multiple of the breathing one (10.1 kHz)
  - The ITT peaks are now out of phase with respect to the breathing ones

Acknowledgments

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