# Report from MEGAEDGE Project

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# List of communications/publications of MEGAEDGE

1. J. Dominguez-Palacios et al., “Simulations predict key role of energetic ion kinetic effects on Edge Localized Modes in tokamak plasmas”, Submitted to Nat. Phys. (2022)

2. J. Dominguez-Palacios et al., “Hybrid kinetic MHD multi-n simulations of ELMs in the ASDEX Upgrade tokamak with MEGA”, 3rd Spanish HPC Fusion Workshop (Online), Invited talk, 2022. This talk was selected as one of the outstanding presentations by early career scientists

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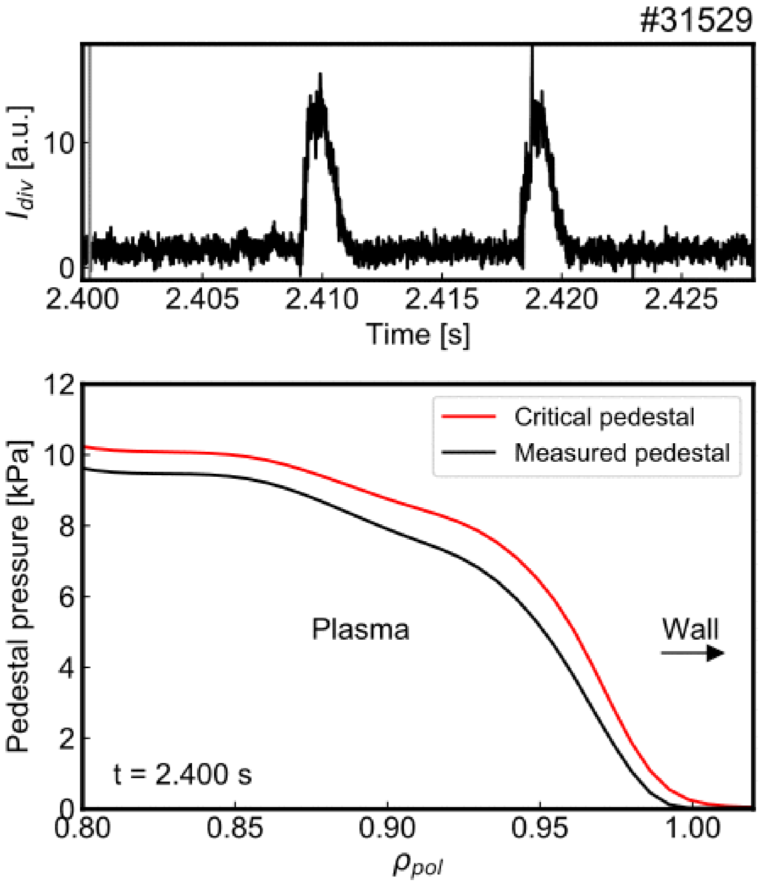
# Motivation

- ELMs appear in H-mode
  → Peeling-ballooning unstable

- ELMs expel particles and energy from plasma
  → Degradation of pedestal
  → Intolerable for future fusion devices

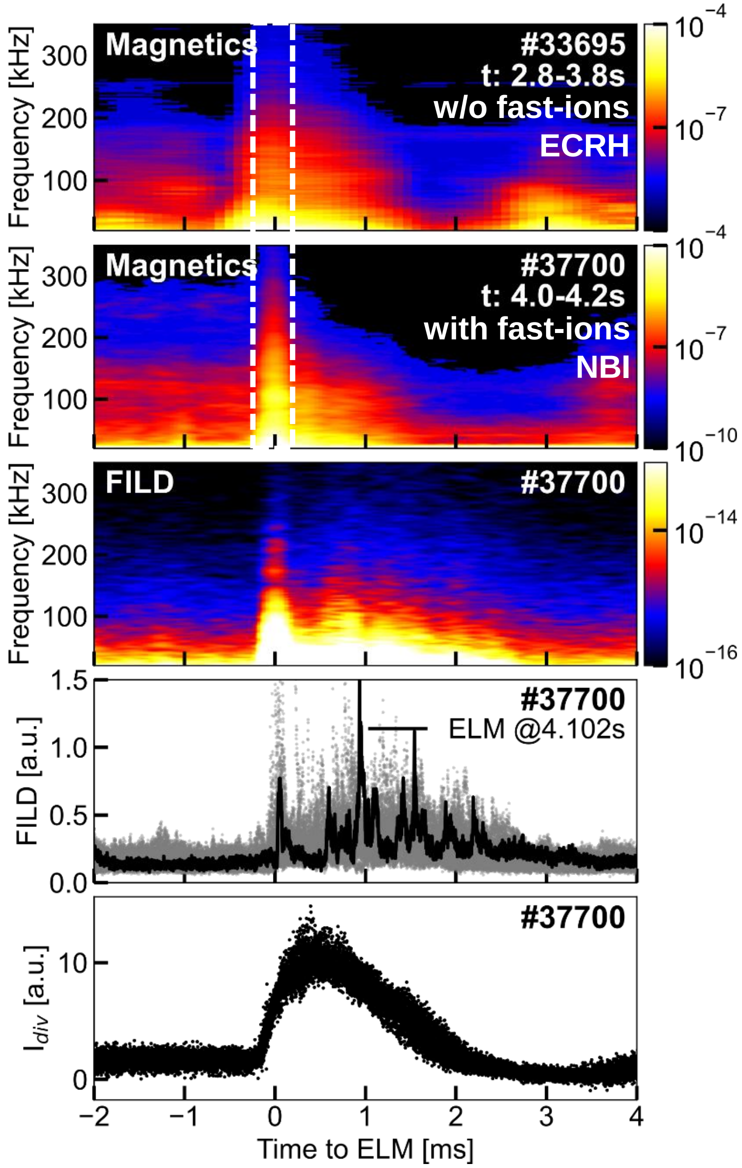
- **What is the role that fast-ions play on ELMs?**




*P. Cano-Megias

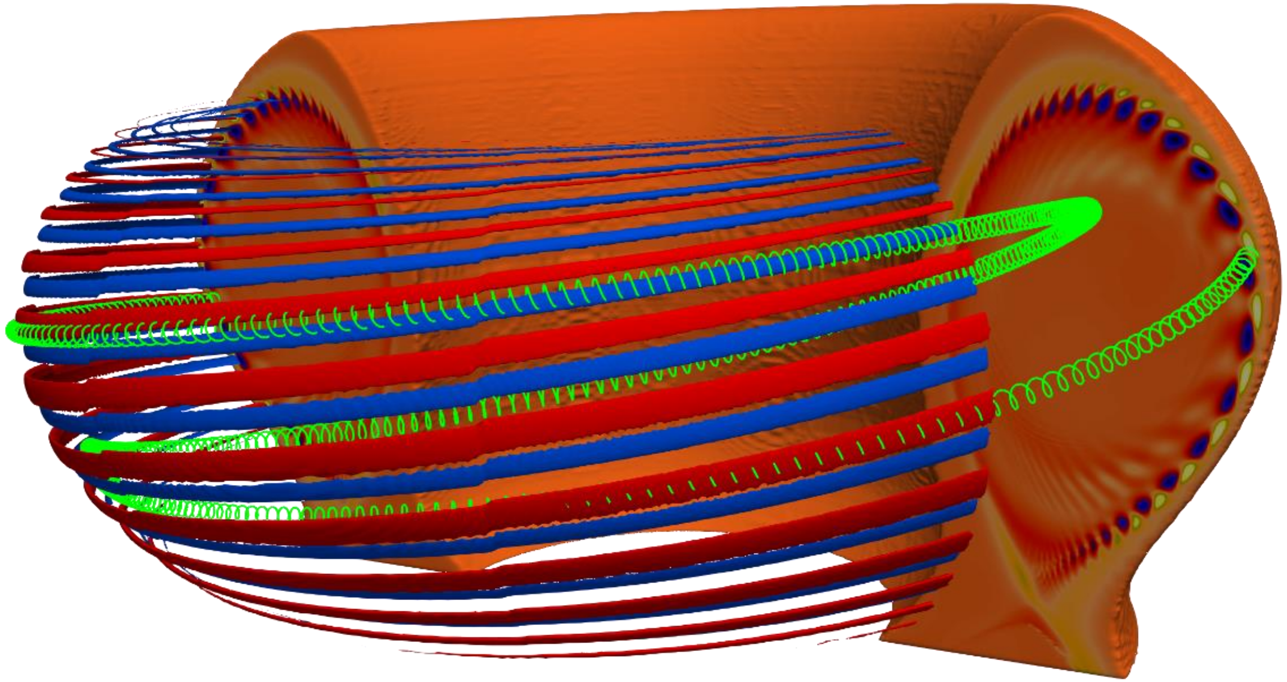
# In experiments, ELM looks remarkably different with and w/o fast-ions

- **ELM synchronised magnetic spectrograms seem to depend strongly on fast-ion population**
  - **Large fast-ion content** in NBI heated discharges with low collisionality lead to abrupt crashes (<**100 μs**) that are extended to high frequencies (~**300 kHz**)
    - Amplitude of low-frequency oscillations (<200 kHz) decay in ~ 2 ms
  - In discharges with **no fast-ion** sources and high collisionality, ELM crashes seem to last longer and have lower amplitudes especially at high frequencies
- **In NBI heated discharges, FILD and magnetic spectrograms show striking similarities**



# Outline

- Simulation tool MEGA
- MHD and hybrid kinetic-MHD ELM simulations
  - ➢ Single-n
  - ➢ Multi-n
- Conclusions



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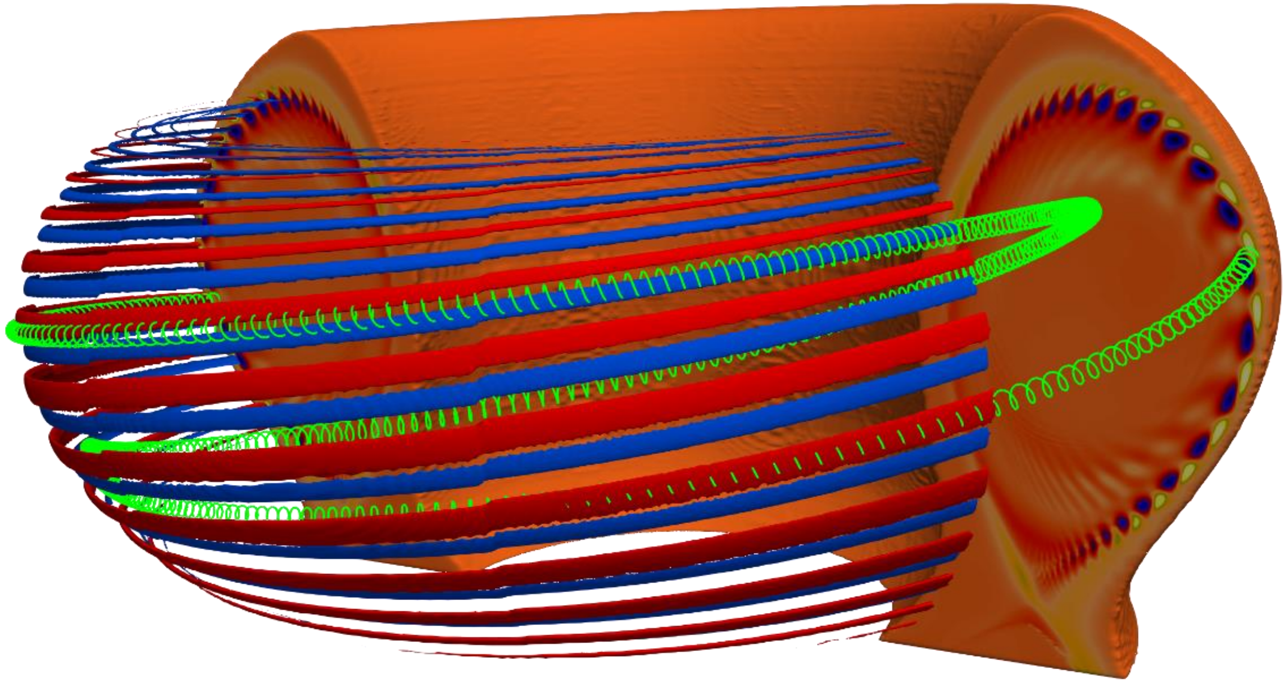


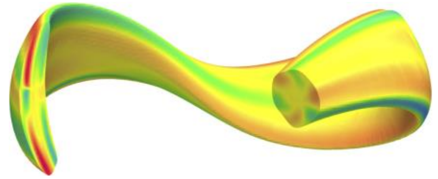
# Nonlinear hybrid kinetic-MHD MEGA

- Non-linear hybrid kinetic-MHD code with current coupling scheme[1] in MHD momentum equation to study toroidal Alfvén mode and dynamics of energetic particles

- Hybrid model extended that includes thermal ion kinetic effects recently developed[2]

- MEGA code is widely used in fusion community

CFQS



H. Wang et al., NF (2022)

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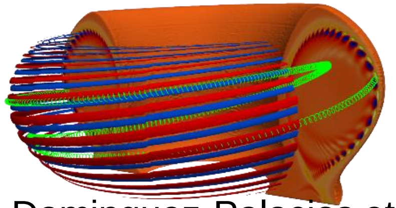
P. Adulsiriswad et al., NF (2020)

AUG



J. Dominguez-Palacios et al., Nat. Phys. (Submitted)

[1] Y. Todo *et al*., Phys. Plasmas **5**, 1321 (1998)
[2] Y. Todo *et al*., Plasma Phys. Control. Fusion **63**, 075018 (2021)

# Numerical methods implemented in MEGA

- Time integration: 4th order explicit Runge-Kutta method

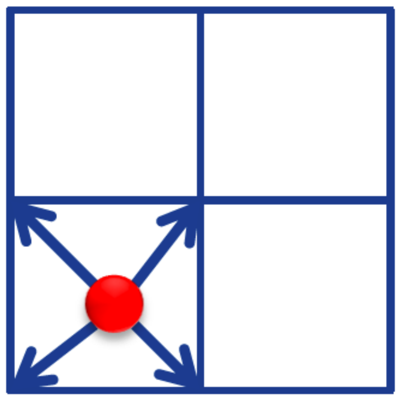
- Fluid fields

  → Spatial derivatives: 4th order finite difference method

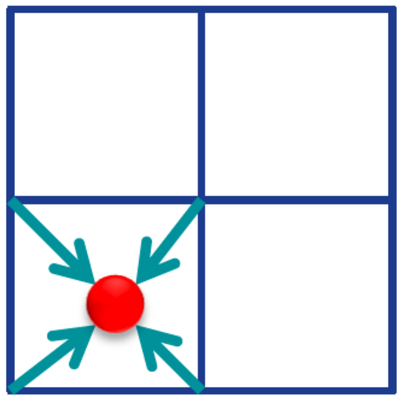
- Particles

  → 1st order particle-in-cell (PIC) with δf or full-f method

  → FLR effects on particle orbits



Information of particle distributions is assigned to grids



Forces on a particle are derived from the fields

# Simulation domain in MEGA

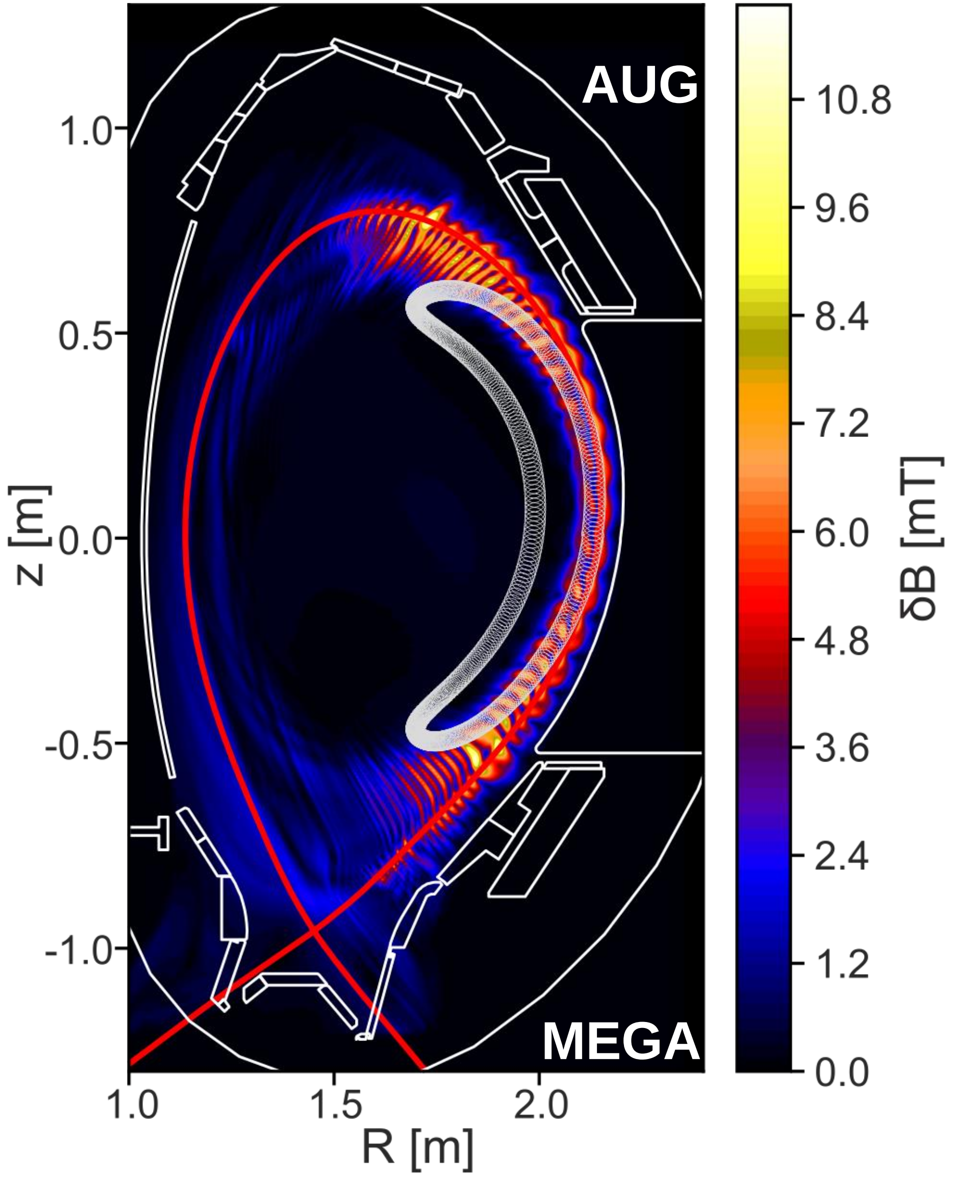
- SOL and Private Flux Region below X-Point included in simulation domain[1, 2]

  → ELM relevant area

  → Important to study the interaction with fast-ions

- Cylindrical coordinates $(R, \varphi, z)$

- Fully 3D rectangular geometry





[1] N. Mizuguchi *et al.*, Phys. Plasmas **7**, 940 (2000)

[2] R. Khan *et al.*, Phys. Plasmas **14**, 062302 (2007)

# Realistic initial conditions for bulk plasma and energetic particles

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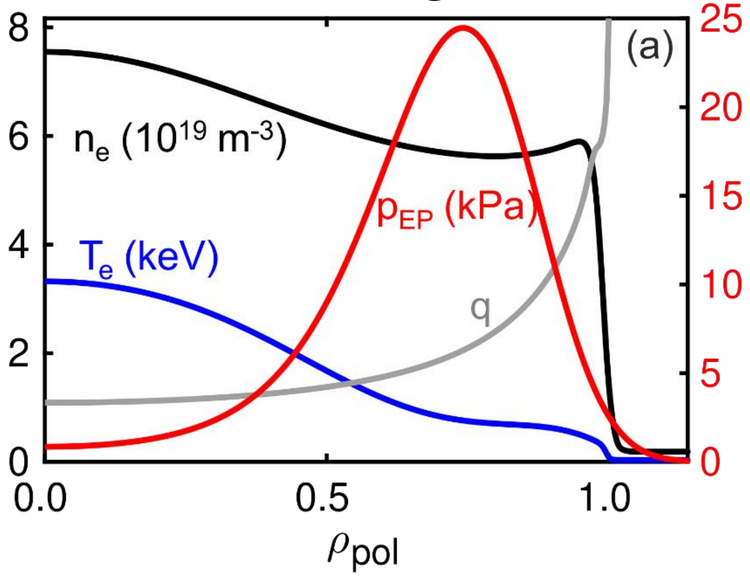
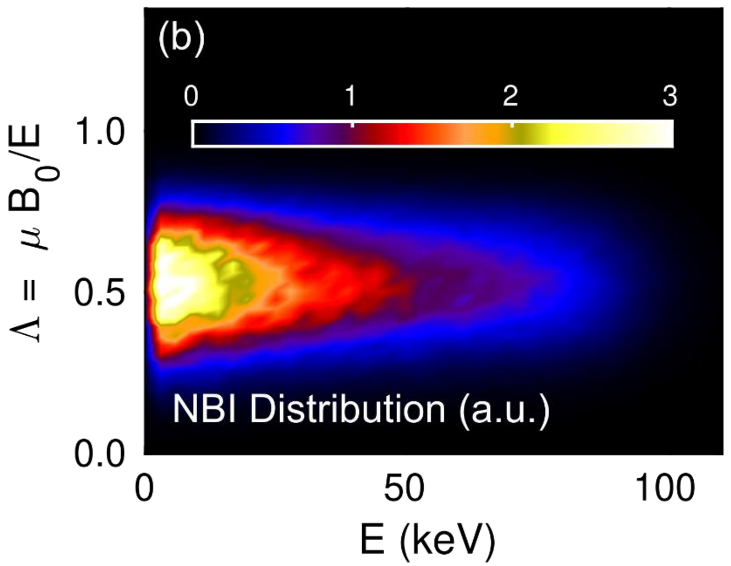



- Thermal plasma: measured kinetic profiles used as initial conditions[1] and standard MHD model[2]

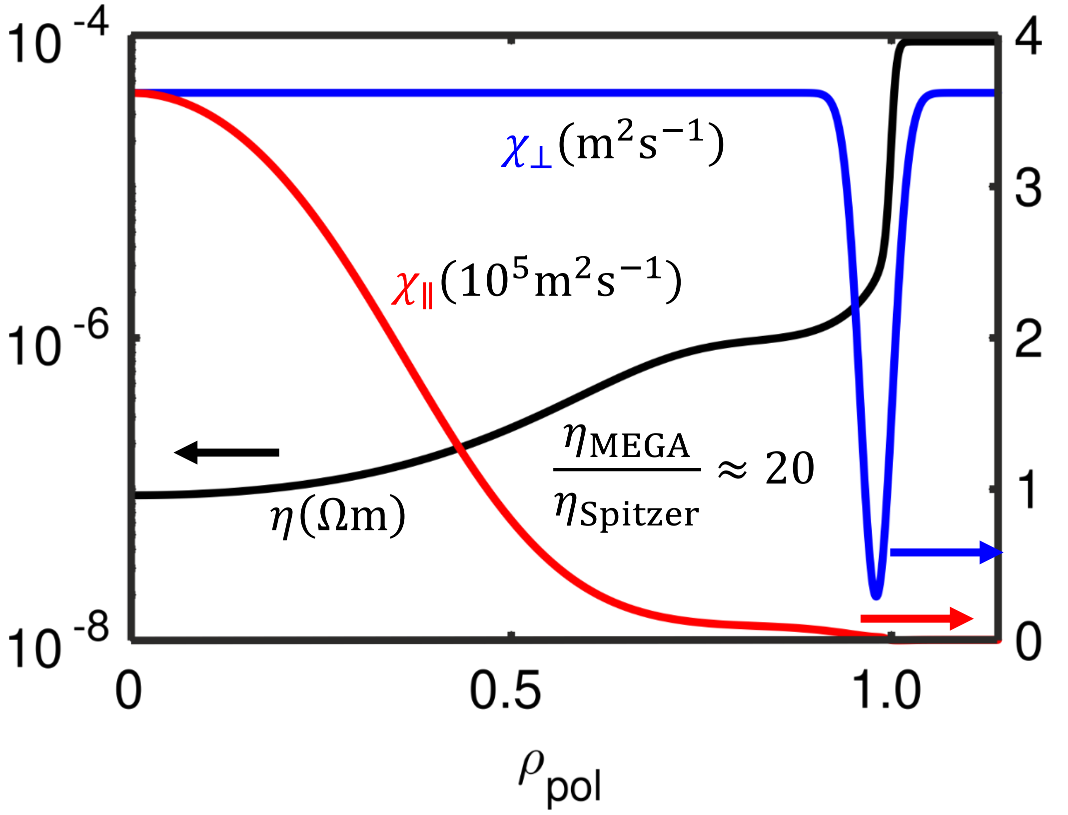
- Fast-ions: off-axis slowing down NBI distribution


[1] A.F. Mink *et al*., Nucl. Fusion **58**, 026011 (2018)

[2] Y. Todo *et al*., Phys. Plasmas **24**, 081203 (2017)

# Transport coefficients in the simulations

- Temperature-dependent viscosity and resistivity follow **Spitzer's law**
- Ad-hoc profiles for perpendicular thermal diffusivity and particle diffusivity are used to mimic **ETB**[1]
- Parallel thermal diffusivity follows **Braginskii's law**




[1] E. Viezzer *et al.*, Nucl. Fusion **58**, 026031 (2018)

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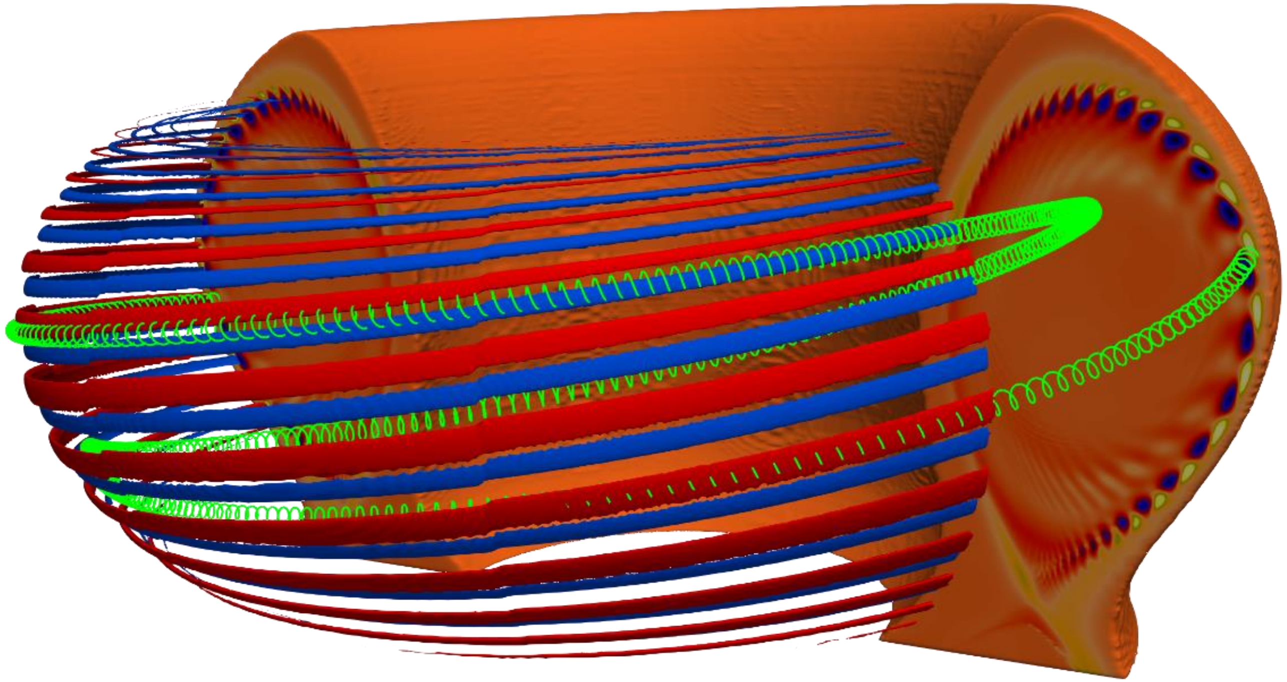

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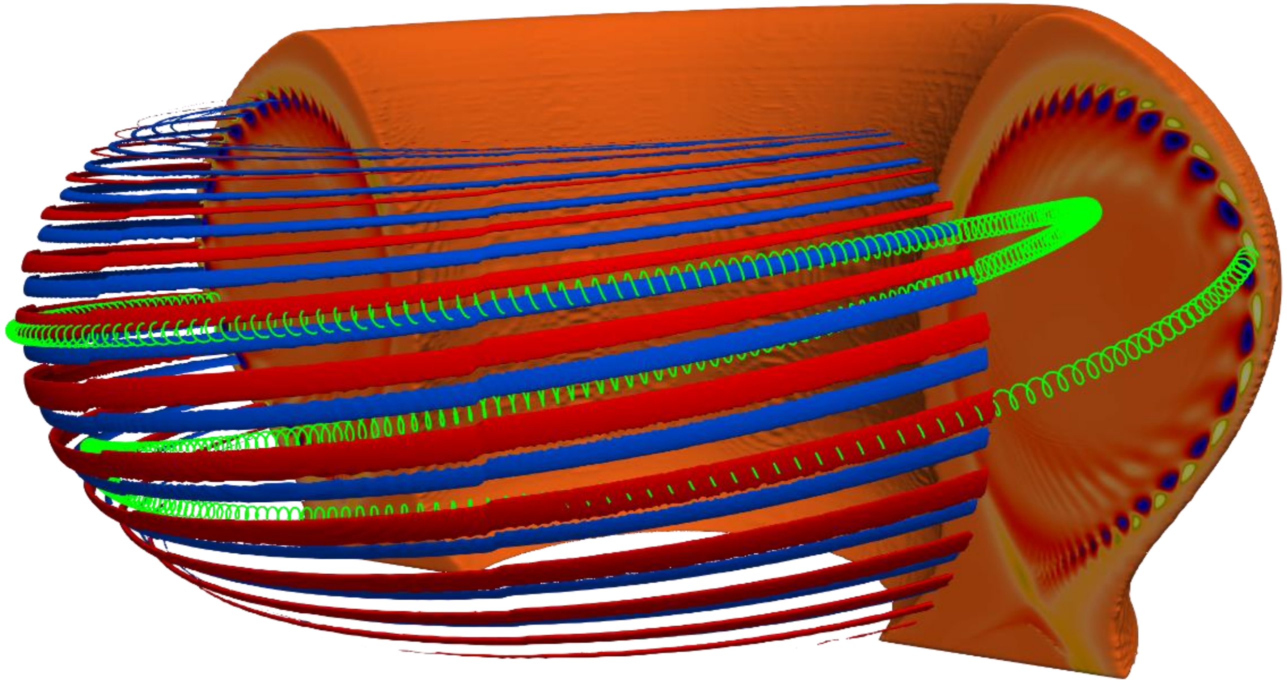
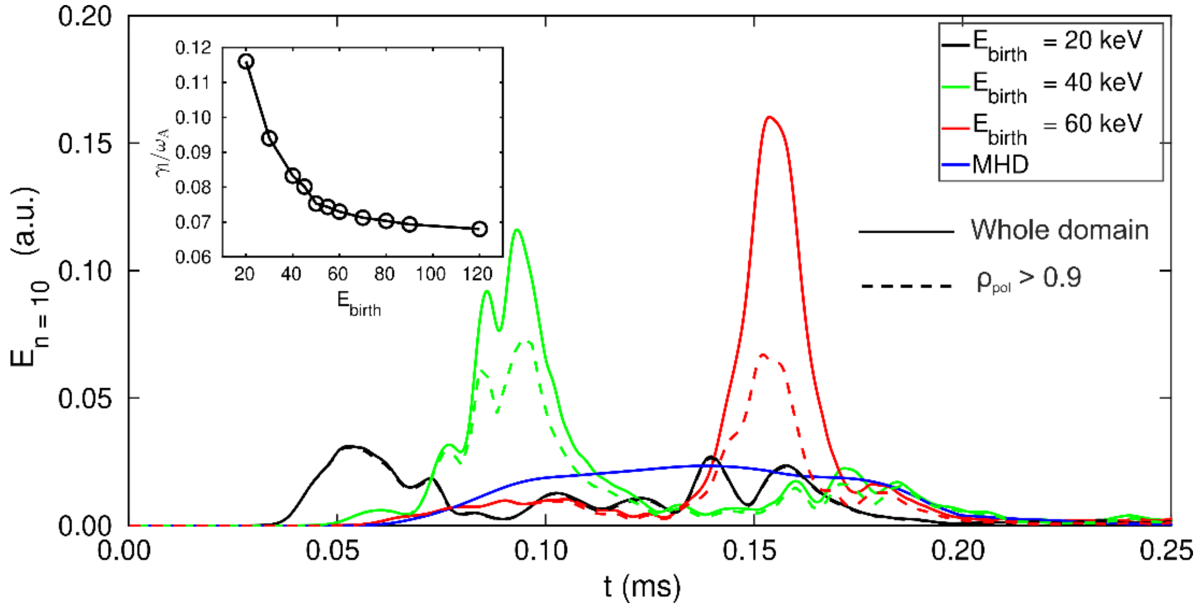


# Fast-ion kinetic effects modify linear growth rate, mode energy and ELM width

- Linear growth rate decreases with $E_{birth}$
- Hybrid simulations with low $E_{birth}$ are closer to pure MHD
- Hybrid simulations qualitatively reproduce abrupt crash and pure MHD mild crash
- ELM radial width is affected by fast-ion kinetic effects

**Single-n**

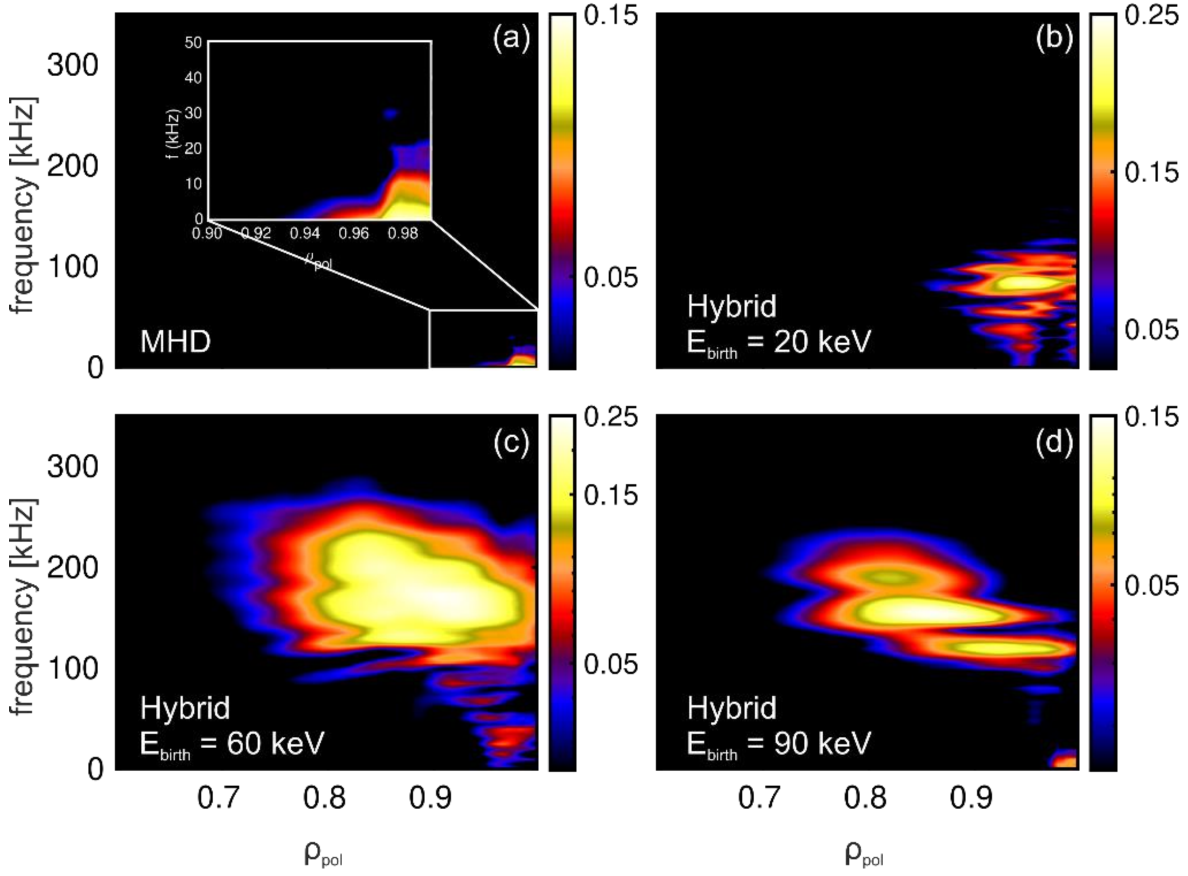


# Fast-ion kinetic effects cause dramatic changes in ELM crash frequency pattern

- In pure MHD simulation, $f < 20$ kHz
- In hybrid simulations, ELM crash frequency pattern depends on fast-ion energy with dominant $f > 100$ kHz

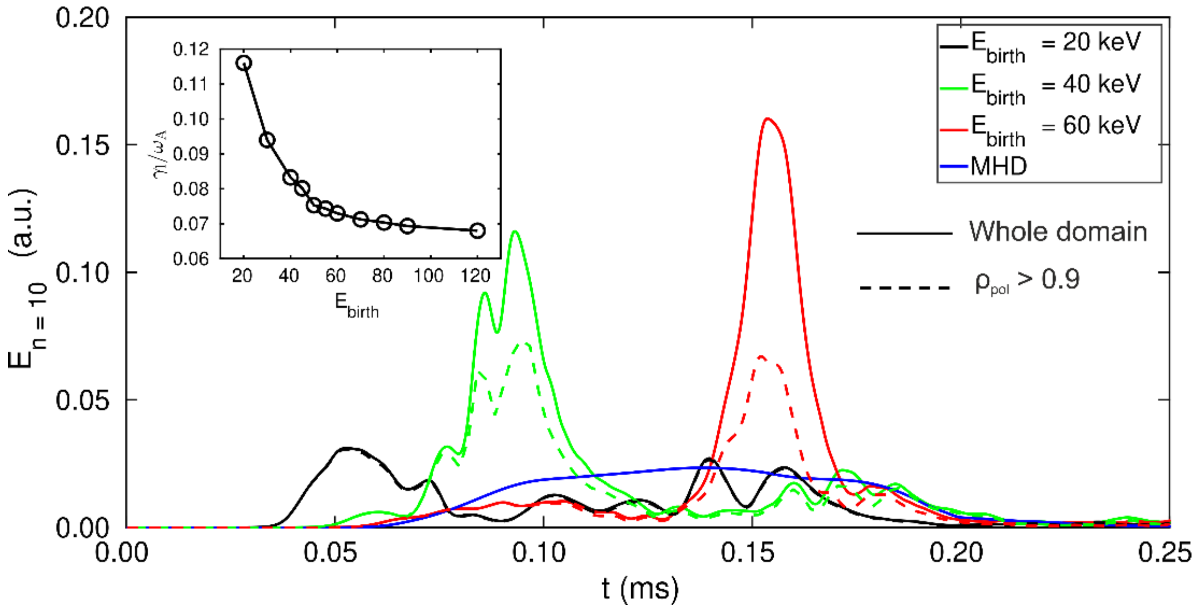
**Single-n**

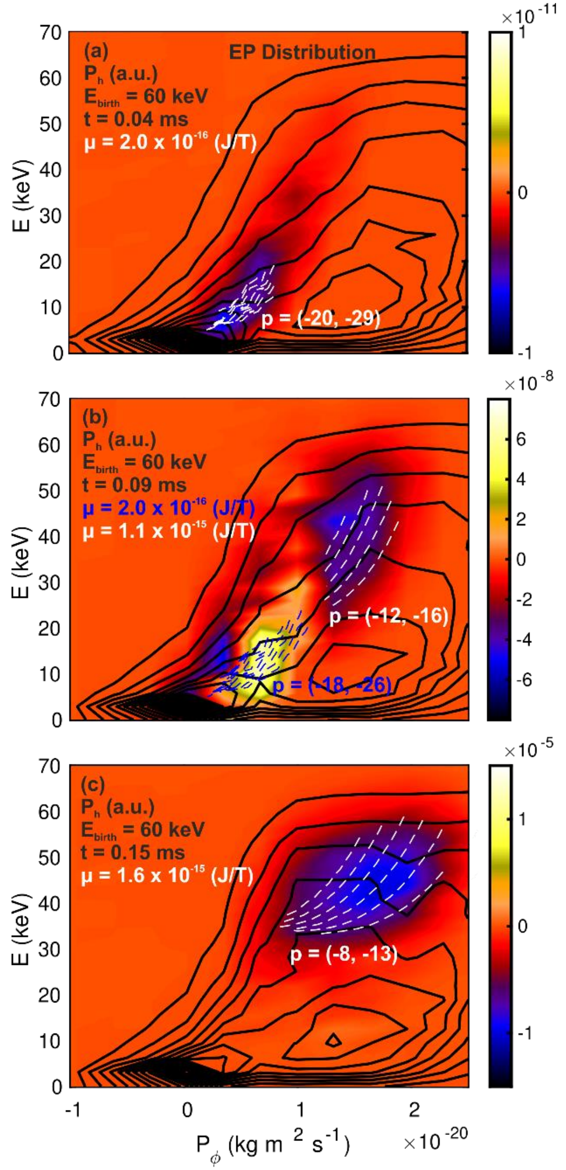
Spectrograms of radial velocity [a.u.]



# Interaction between ELMs and fast-ions is resonant

**Single-n**




- Resonant interaction leads to significant energy exchange
- Power transfer structures are aligned with the resonance condition[1]

$$\omega_n - n\omega_\varphi - p\omega_\theta \approx 0$$

[1] W.W. Heidbrink *et al*., Phys. Plasmas **27**, 030901 (2020)

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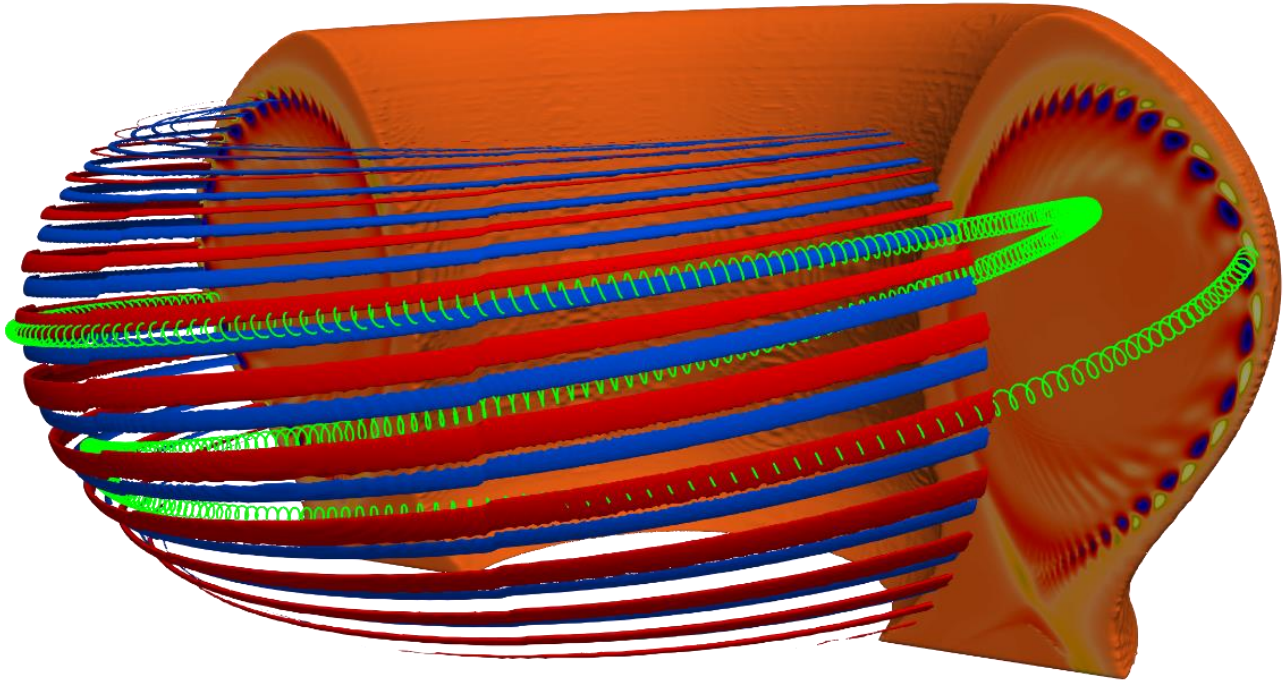
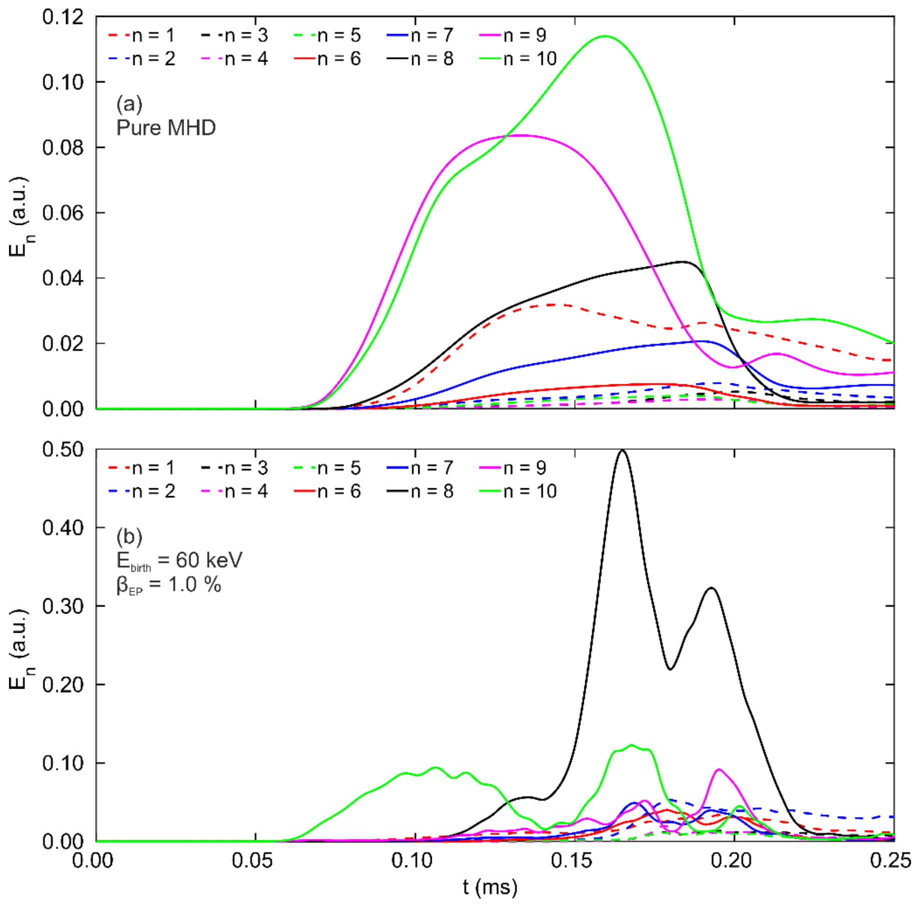
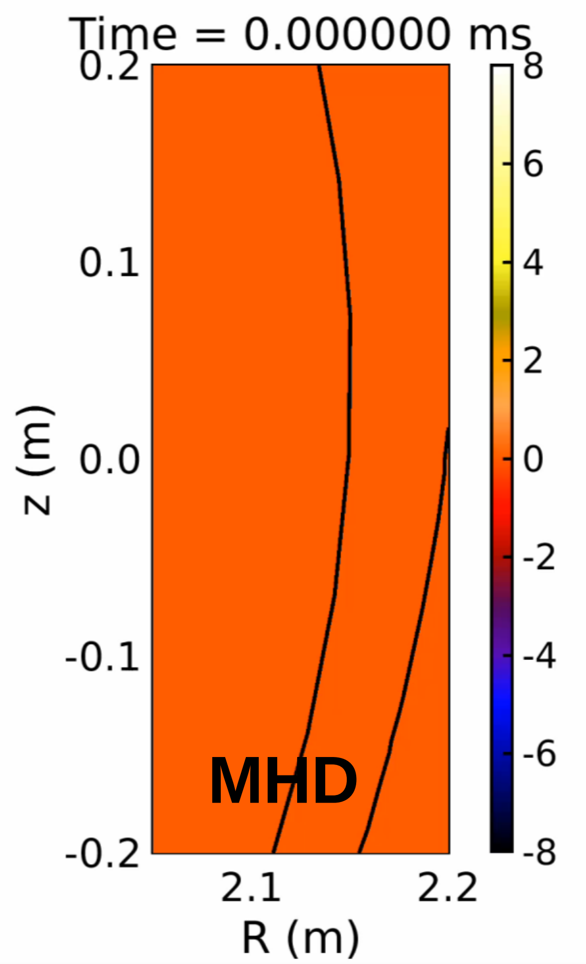


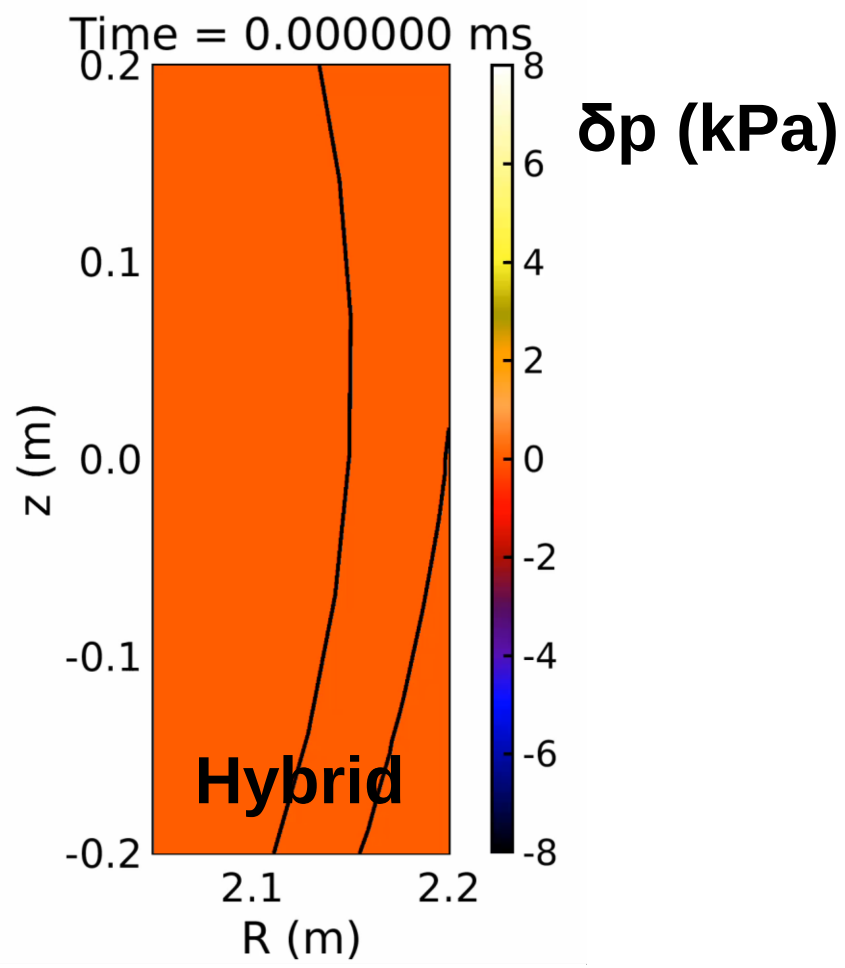
# Fast-ions strongly affect modes energy evolution in multi-n simulations

- Fast-ions modify the most dominant mode
  - ➢ n = 8 most unstable with EP kinetic effects
- What other properties of the mode are modified? What about the interaction between fast-ions and each mode?



# Energetic-ions significantly modify perturbation structure

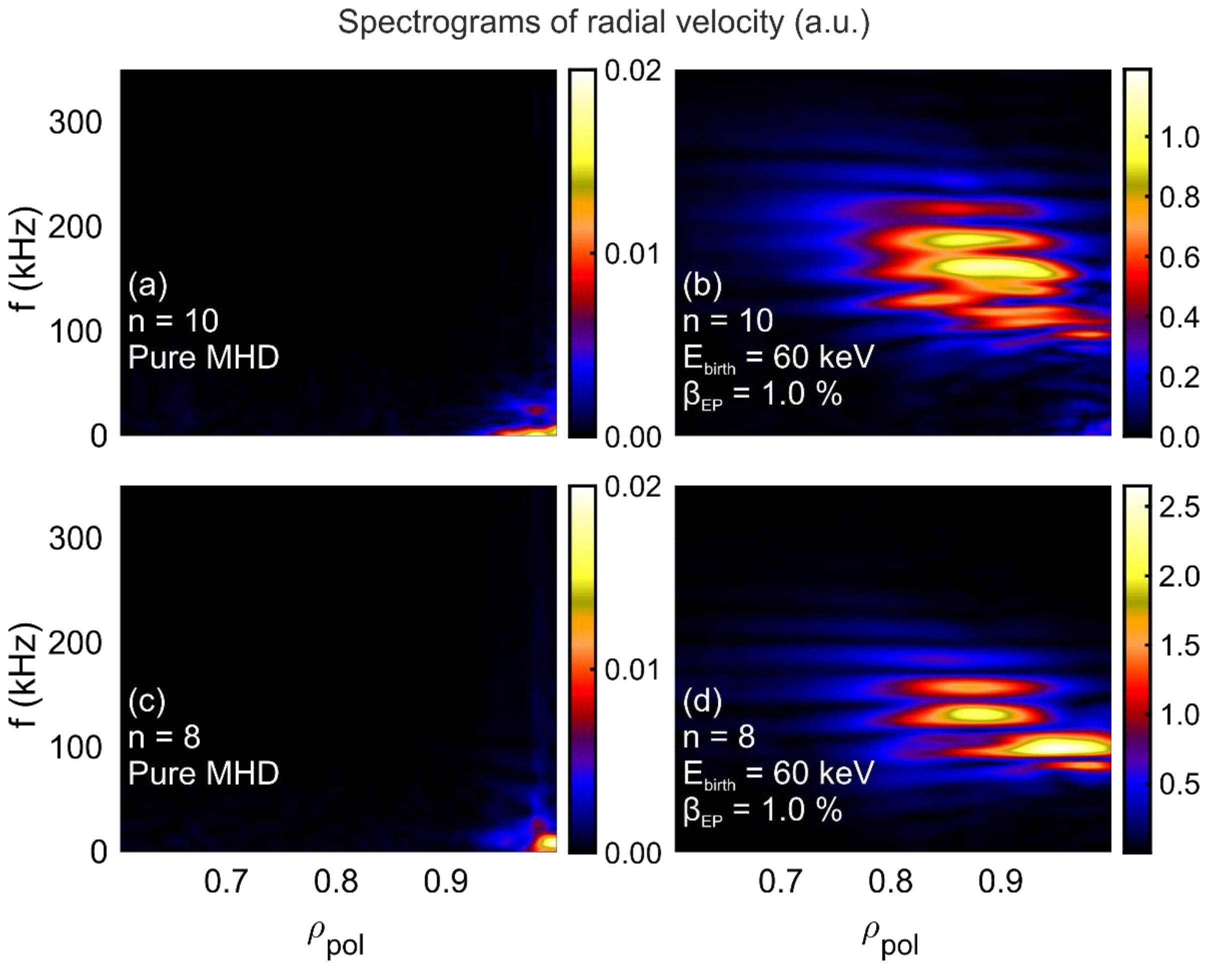


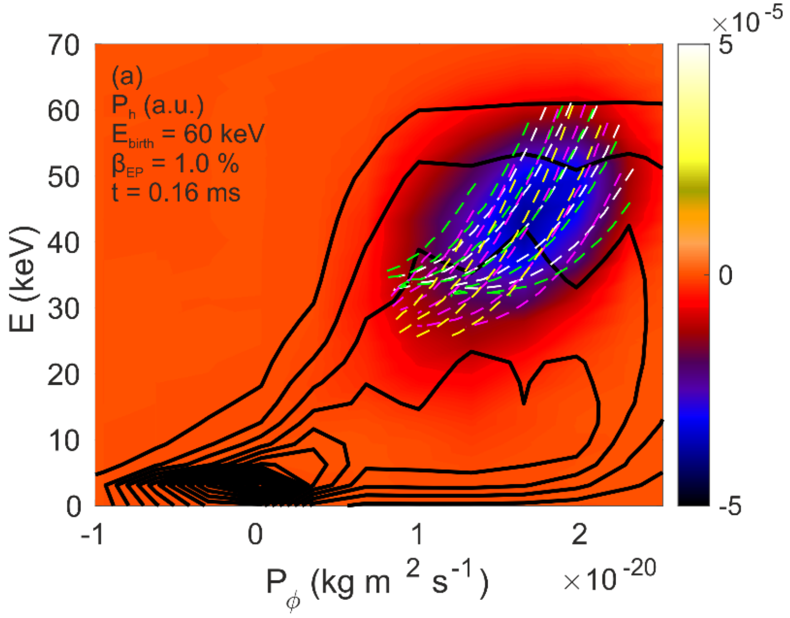

- The interaction with fast-ions clearly modify the plasma flow pattern and, consequently, the shear of the structure

# Fast-ions cause dramatic changes in frequency pattern of high-n modes

- In pure MHD simulations, f ~20 kHz
- In hybrid multi-n simulations, f ~ 200 - 250 kHz (n = 8 - 10)
- High-n modes also become radially broad in the presence of fast-ions
- Frequency increases with mode number



# Resonant power transfer between high-n modes and fast-ions




- Left: power transfer when n = 8 mode energy is maximum

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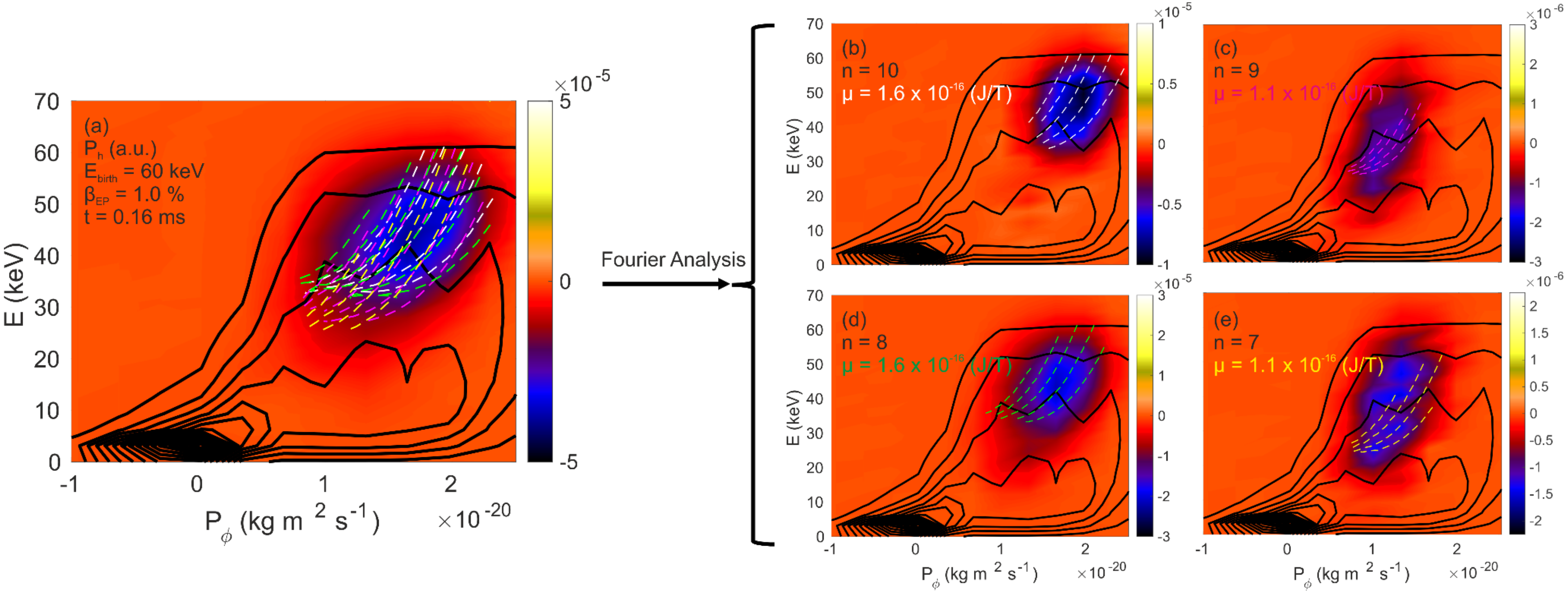
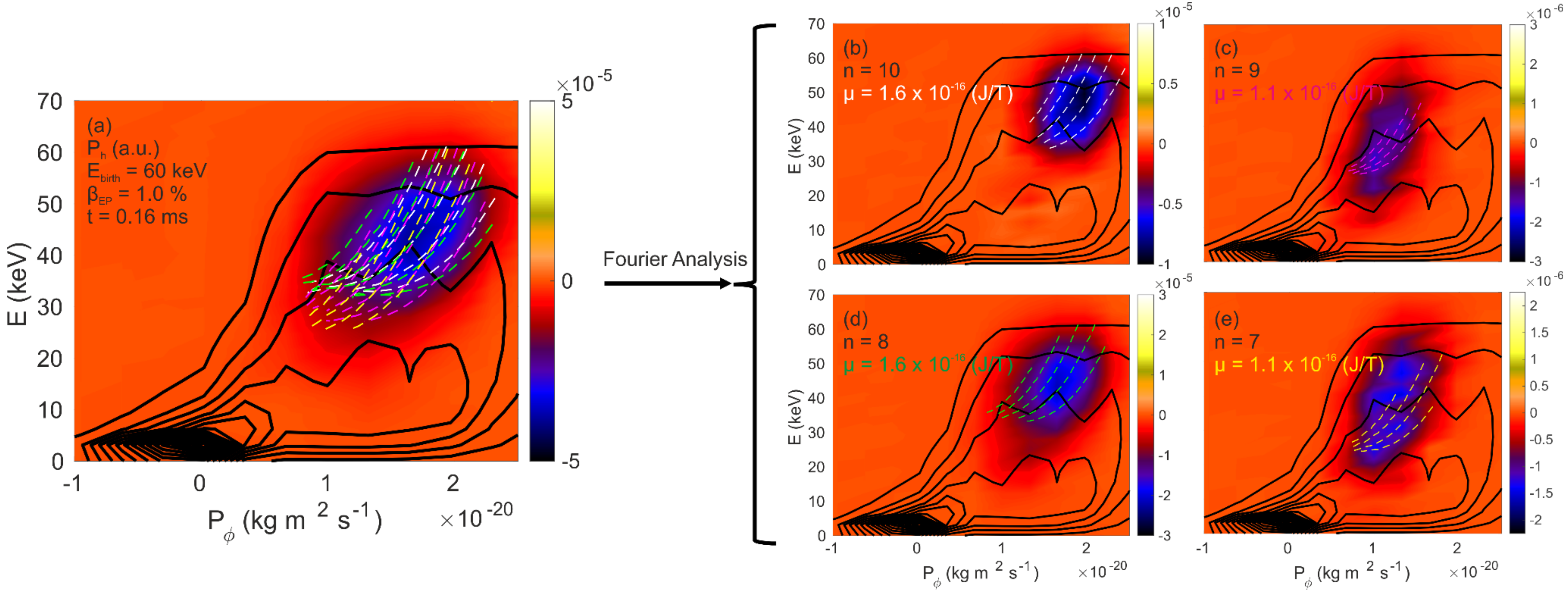



- Left: power transfer when n = 8 mode energy is maximum
- Right: power transfer with n= 7, 8, 9, 10 by separate

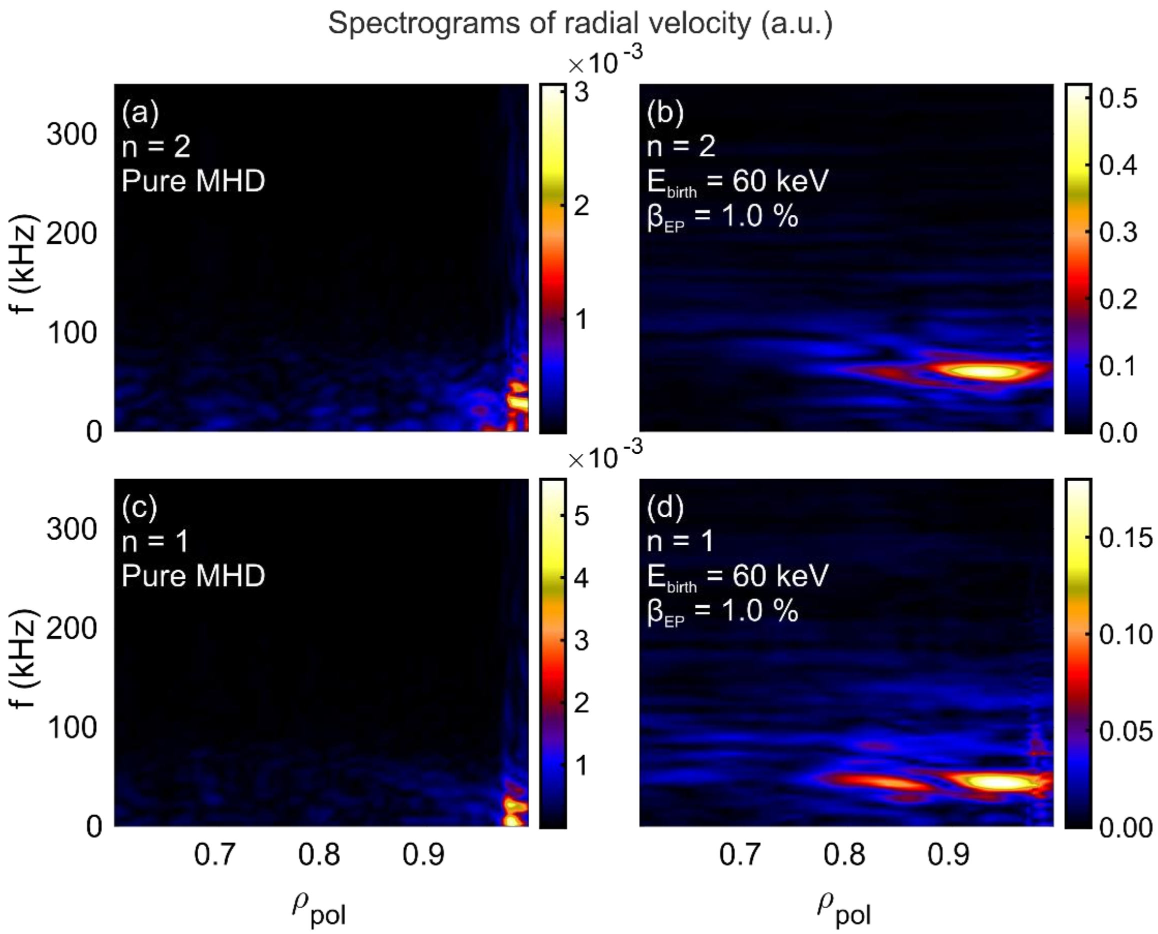
# Resonant power transfer between high-n modes and fast-ions




- Left: power transfer when n = 8 mode energy is maximum
- Right: power transfer with n= 7, 8, 9, 10 by separate
- Phase-space structures aligned with resonant condition[1] $\omega_n - n\omega_\varphi - p\omega_\theta \approx 0$ → resonance overlap between different n!

[1] W.W. Heidbrink *et al.*, Phys. Plasmas **27**, 030901 (2020)

# Spatial-frequency pattern of low-n modes in the presence of fast-ions



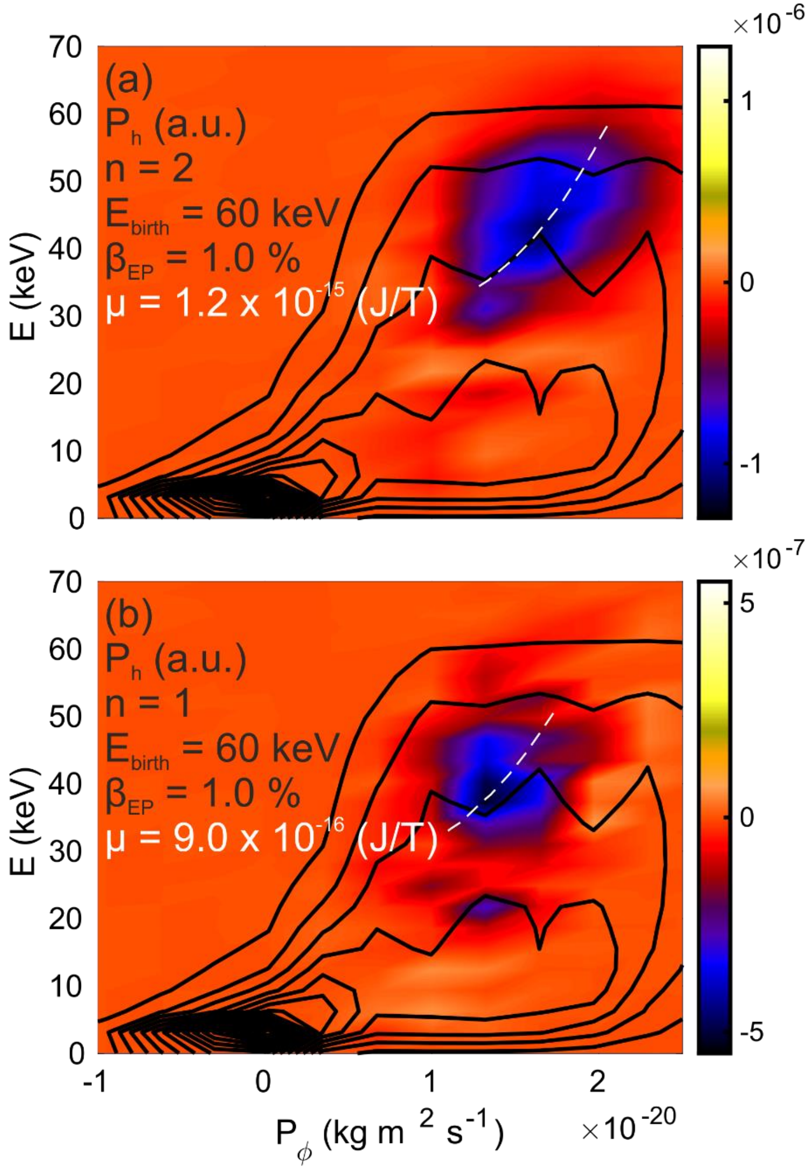

- Low-n mode radial width is affected by fast-ion kinetic effects

# Resonant power transfer between low-n modes and fast-ions

- Phase-space structures aligned with resonant condition[1]

$$\omega_n - n\omega_\varphi - p\omega_\theta \approx 0$$

- Resonant energy between low-n modes and fast-ions leads to significant power transfer with such modes




[1] W.W. Heidbrink *et al.*, Phys. Plasmas **27**, 030901 (2020)

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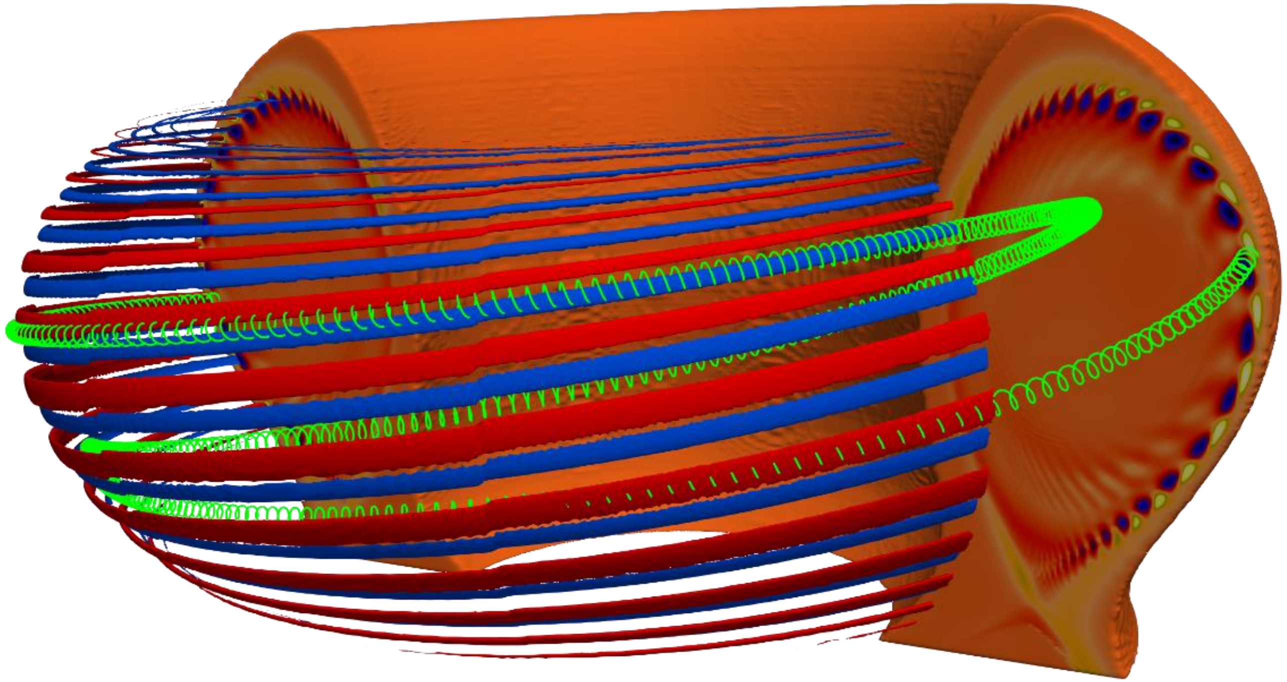

# Conclusions

- Fast-ion kinetic effects makes n = 8 mode more unstable → strong energy exchange with n = 8
- In presence of more modes, spatial-frequency pattern of high-n modes show f ~ 200-250 kHz. Frequency is higher when mode number is higher
- Fast-ions interchange energy with all modes. Resonance overlap between different n modes in phase-space is observed → feature of multi-n