EUROfusion

Experimental assessment of TAE control using externally applied resonant magnetic perturbations in the ASDEX Upgrade tokamak

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Universidad de Sevilla

PSFT Plasma Science and Fusion Technology

IPP

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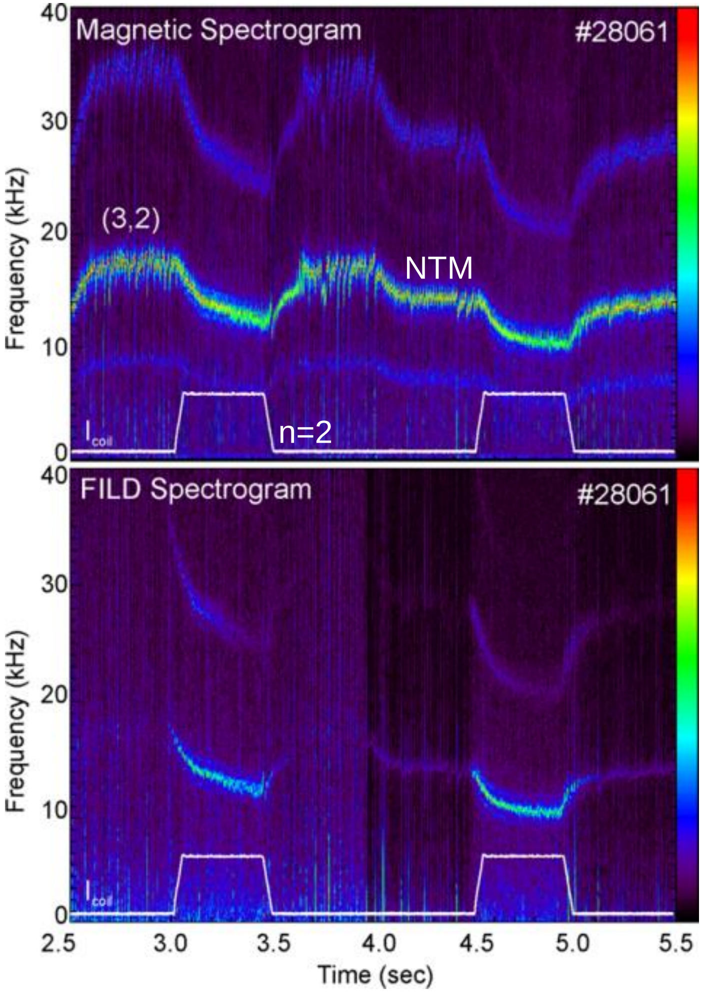
Externally Applied RMPs Have Strong Impact on Fast-Ion Population and MHD Fluctuations

Symmetry breaking 3D fields such as those from ELMs and ELM mitigation coils can cause significant fast-ion losses

- Simulations show ELM mitigation coils can cause significant NBI losses in ITER* reducing NBI heating efficiency and machine safety

- 3D fields can increase losses from core MHD that would otherwise only cause redistribution**



*K. Shinohara, et.al., NF **51** 063028 (2011)
*T. Koskela et al., PPCF **54** 105008 (2012)
M. Garcia-Munoz et al., NF **53 123008 (2013)

Outline

- **Motivation**
- **Experimental Observations**
  - ➢ **TAE Suppression / Excitation with n=2 RMP**
  - ➢ **TAE Mitigation with n=1 RMP – diff phase scan**
  - ➢ **TAE Mitigation with n=4 RMP**
  - ➢ **TAE Mitigation with mix n=2+4 RMP**
- **MEGA Simulations**
  - ➢ **Plasma Response**
  - ➢ **TAE Supression / Excitation with n=2 RMP**
- **Summary and Conclusions**

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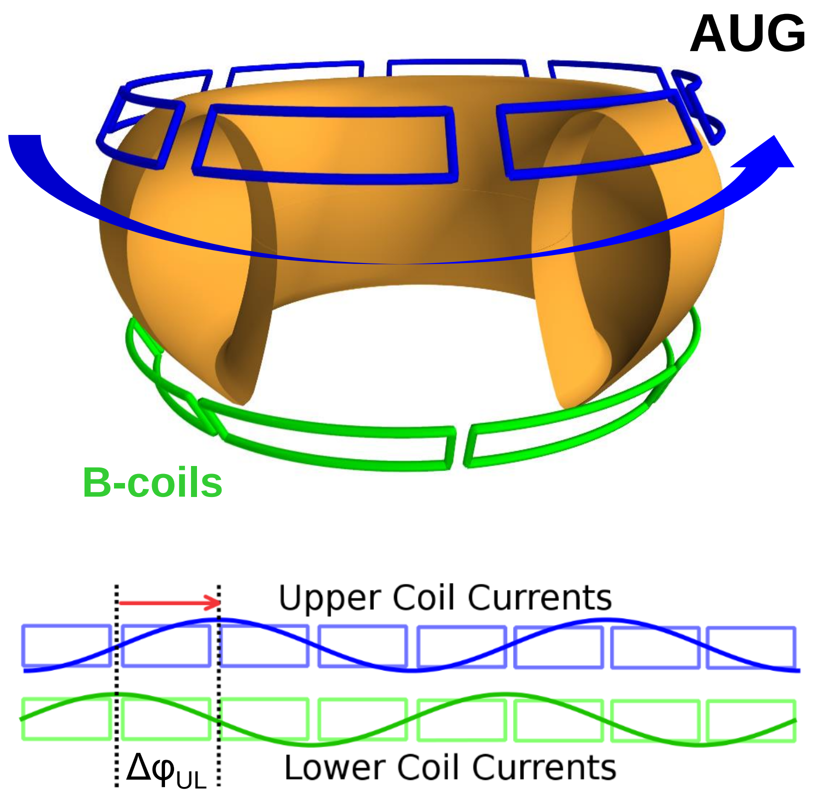
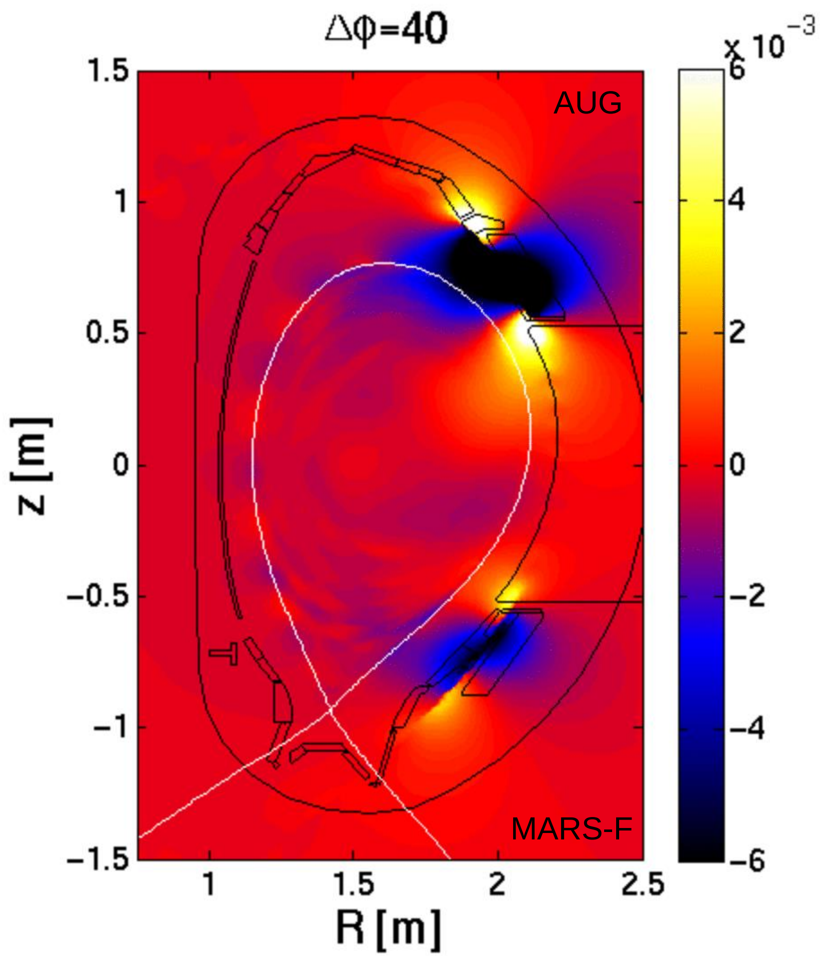
Externally Applied RMP Are Used To Manipulate Fast-Ion Distribution Through Their Toroidal / Poloidal Spectrum

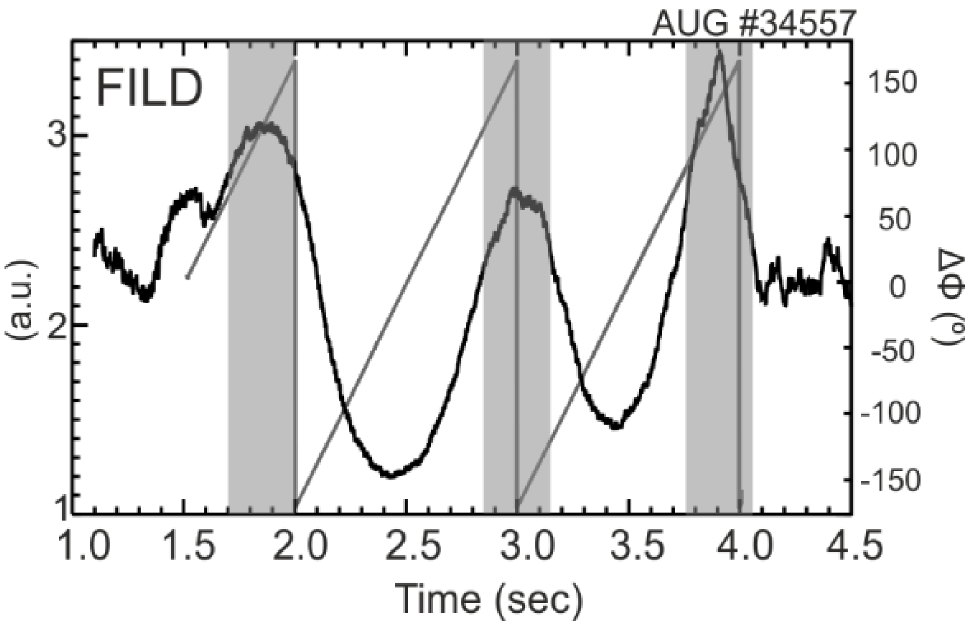
- 3D fields poloidal spectrum is modified by applying a toroidal phase difference between the upper and lower sets of coils, $\Delta\Phi_{UL} = \Phi_{upper} - \Phi_{lower}$





Differential Phase Scan Shows Fast-Ion Losses Depend on n=2 RMP Poloidal Spectrum

- Differential phase scan applied in NBI heated discharges with elevated q-profile
- 5 MW NBI heating with tangential and radial beams to probe different fast-ions phase-space volumes
- 2 MW ECCD to keep high q-profile
- Clear modulation in fast-ion losses observed in FILD measurements with maximal losses for $\Delta\varphi$=100° and minimal for $\Delta\varphi$~-50°

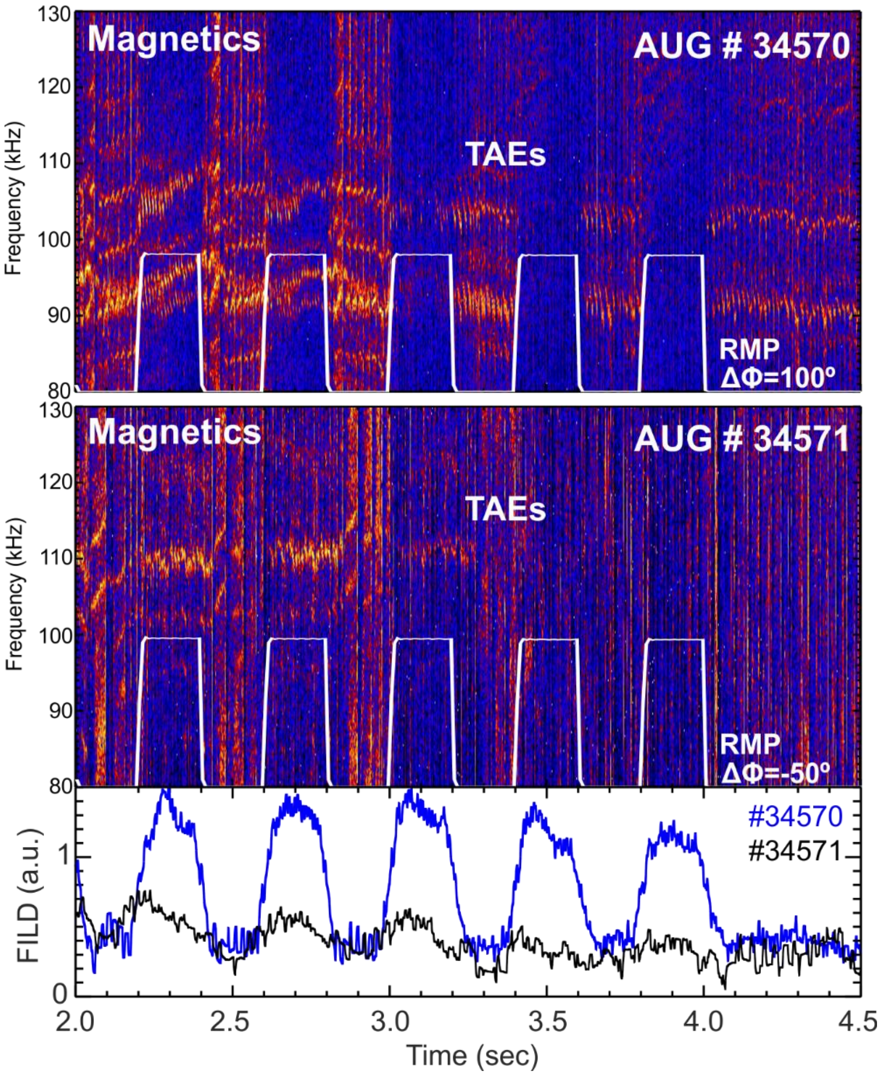


TAEs Suppressed / Excited on Command Varying Poloidal Spectrum of n=2 RMP

- NBI driven TAEs in advanced scenario with elevated q-profile
  - ➢ TAEs become weaker as q-profile relaxes

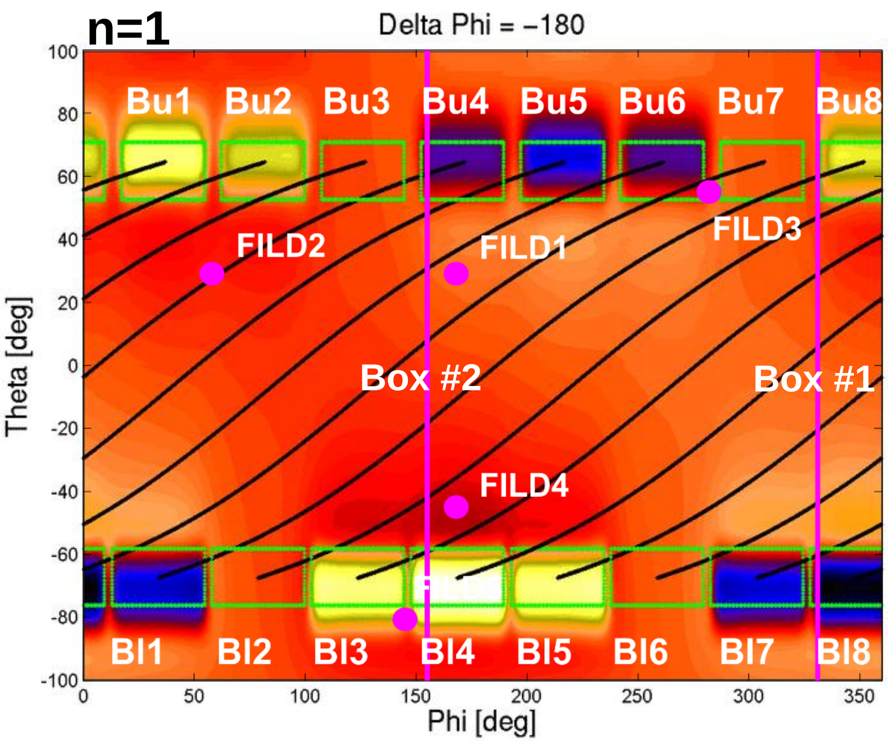
- TAEs are mitigated or even suppressed with Δφ=100° RMPs

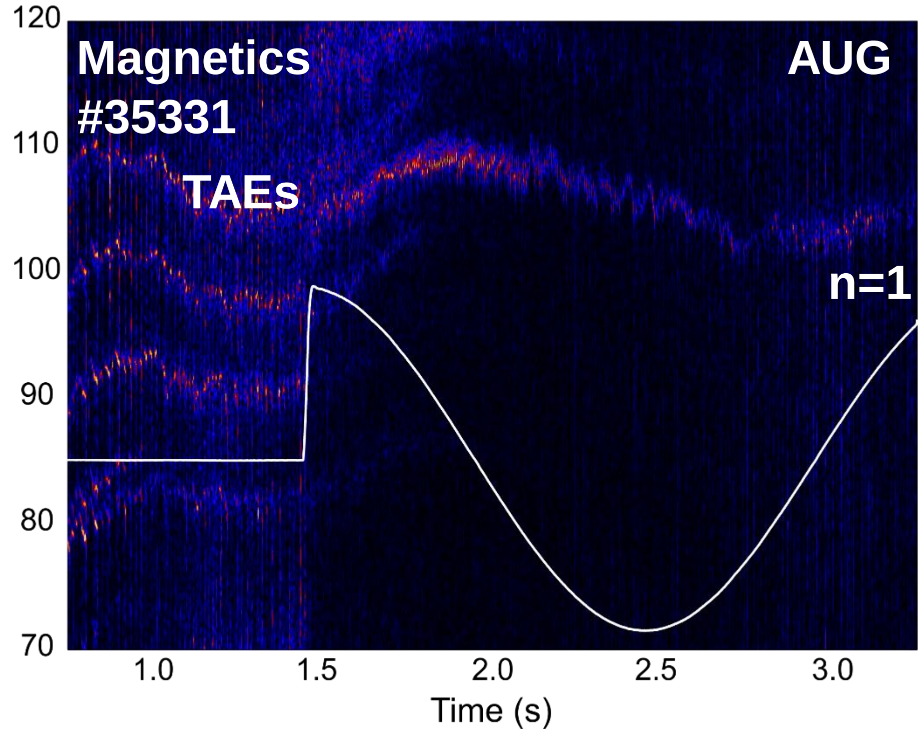
- TAEs are excited with Δφ~-50° RMPs in plasma with slightly higher radiative damping due to higher T_e



n=1 RMP Has **Strong** Impact on Overall Plasma Parameters, Including Fast-Ions and TAEs

- Diff phase scan carried out to identify optimal coils configuration





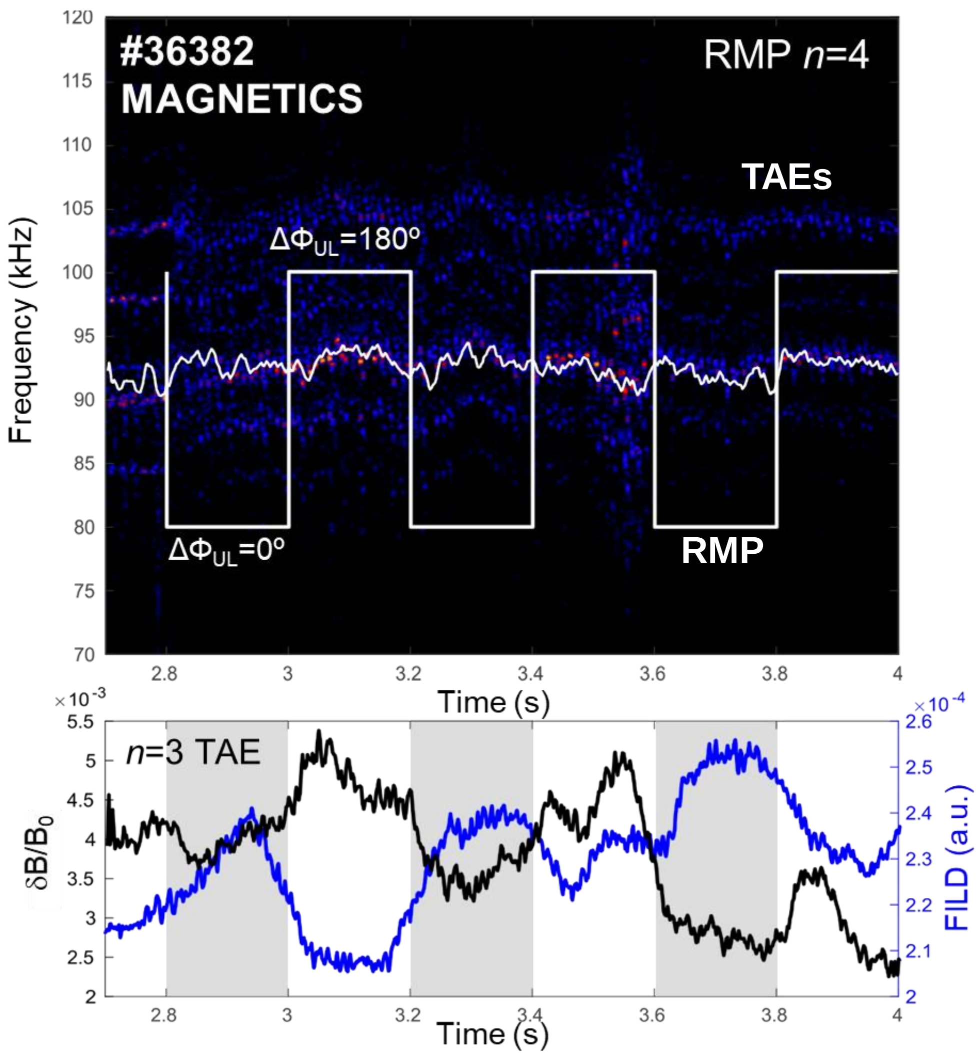
- TAE amplitude clearly modulated with n=1 RMP diff phase scan
- Temporal evolution of TAE frequency reflects density pump-out

n=4 RMP Has Moderate Impact on Fast-Ion Losses and TAE Amplitude

- **In AUG, n=4 RMP creates moderate perturbation in plasma with narrow ERTL**
  - ➢ **Impact on little fast-ion population**

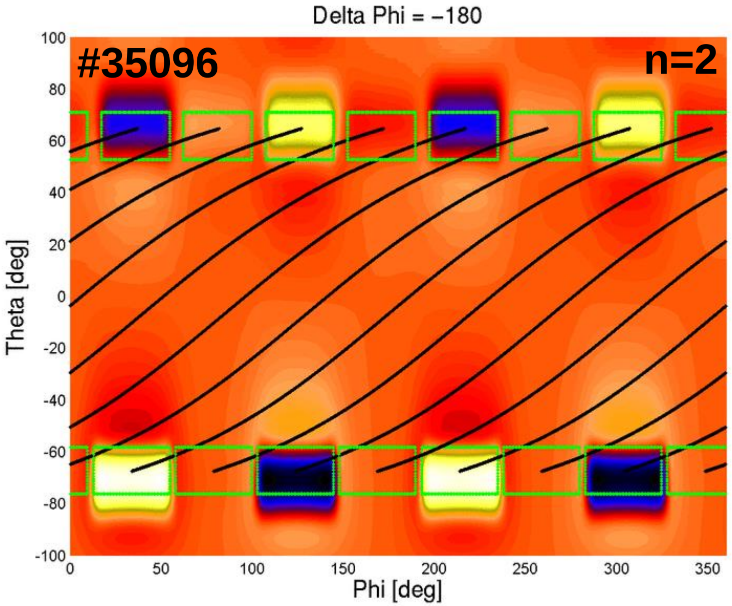
- **n=4 RMP with $\Delta\Phi_{UL}$=0º and $\Delta\Phi_{UL}$=180º slightly mitigate and drive TAE stronger respectively**

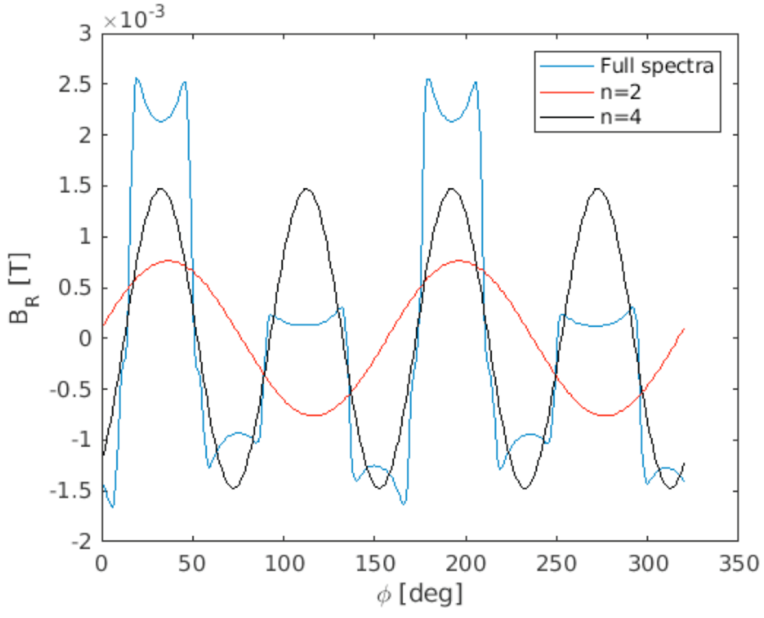
- **Measured fast-ion losses and TAE amplitude are anticorrelated**

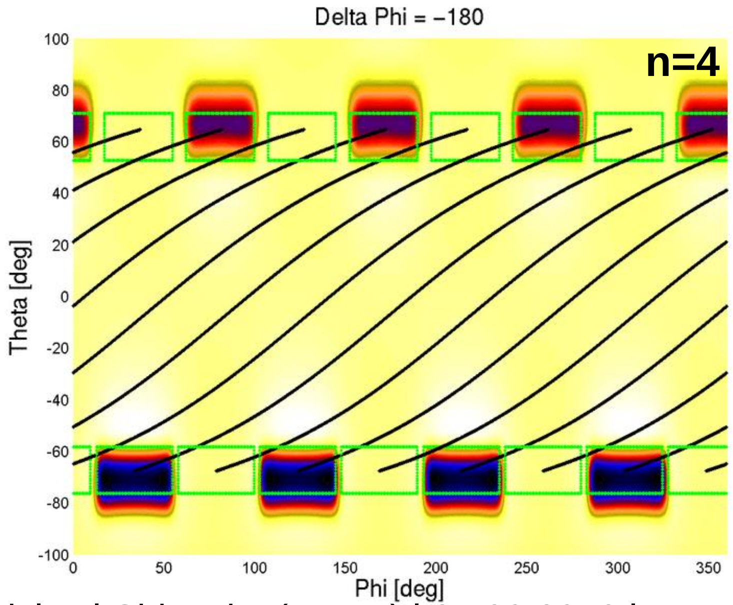


Mix n=2+4 RMP Has Moderate Impact on Fast-Ion Losses and TAE Amplitude

- **In AUG, mix n=2+4 RMP is composed by low amplitude n=2 + somewhat larger amplitude n=4 RMP**
- **Finite RMP coils geometry include higher n-harmonics**







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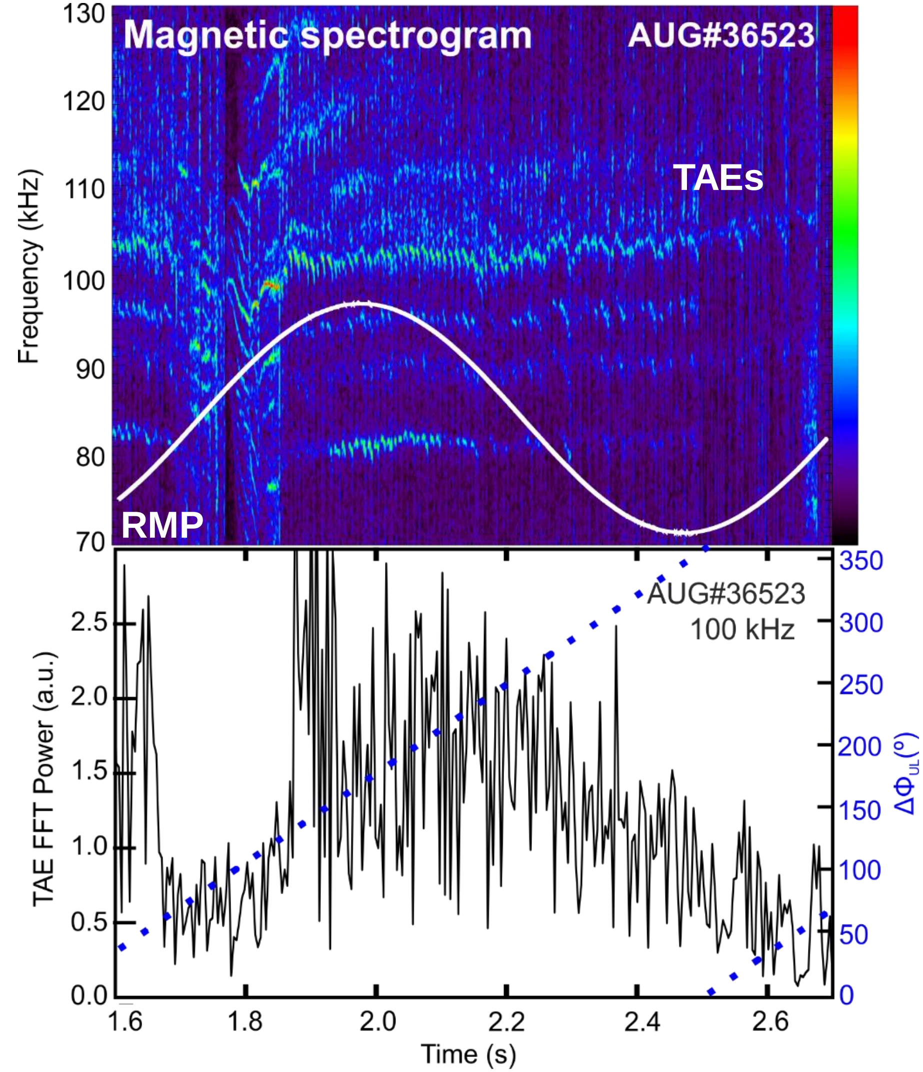
- **In AUG, mix n=2+4 RMP is composed by low amplitude n=2 + somewhat larger amplitude n=4 RMP**
- **Finite RMP coils geometry include higher n-harmonics**
- **Partial mitigation / excitation observed for similar $\Delta\Phi_{UL}$ as for pure n=2 RMP**
  - **n=2 resonances play key role**
  - **n=4 resonances shift $\Delta\Phi_{UL}$**



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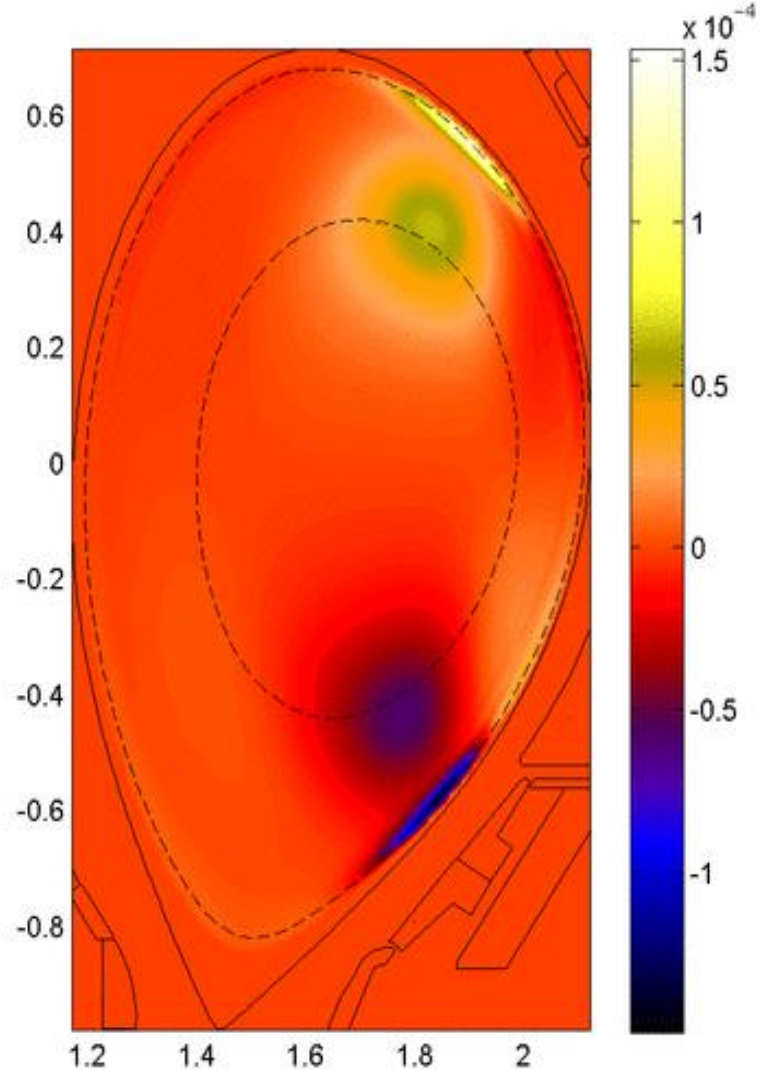
3D Hybrid MHD MEGA* Code Modified to Include RMP Fields

See P1-4 by J. Gonzalez-Martin

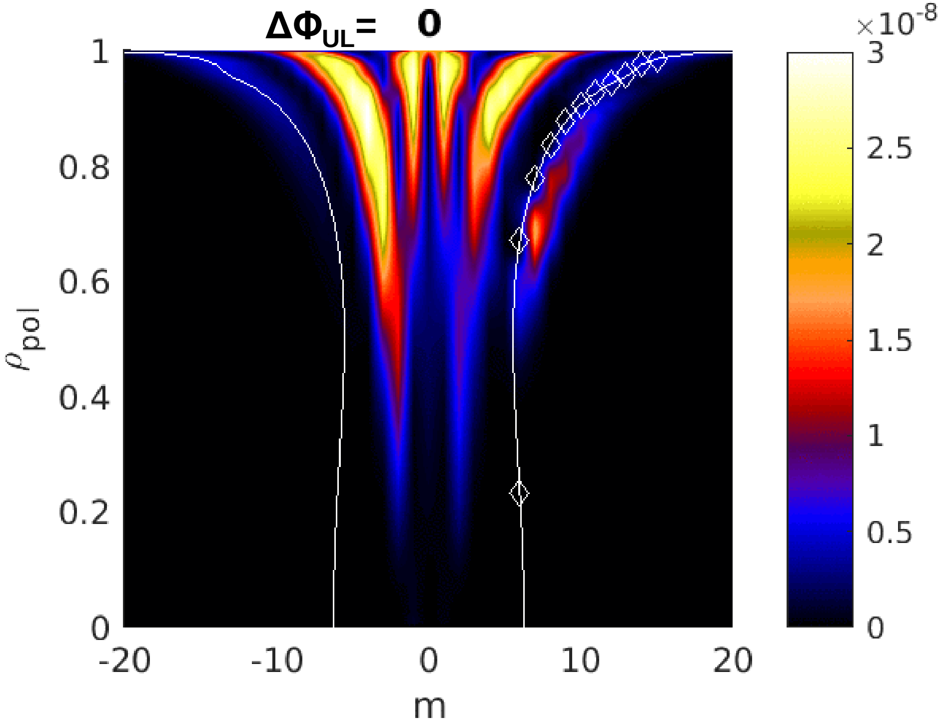
- Kinetic fast-ion contribution include in MHD code through current terms
- 3D fields can be included **before** and **after** MHD force balance
  - **3D magnetic fields are in equilibrium with 2D current density**
    - **Vacuum approach**
  - **Plasma response is calculated by MEGA**

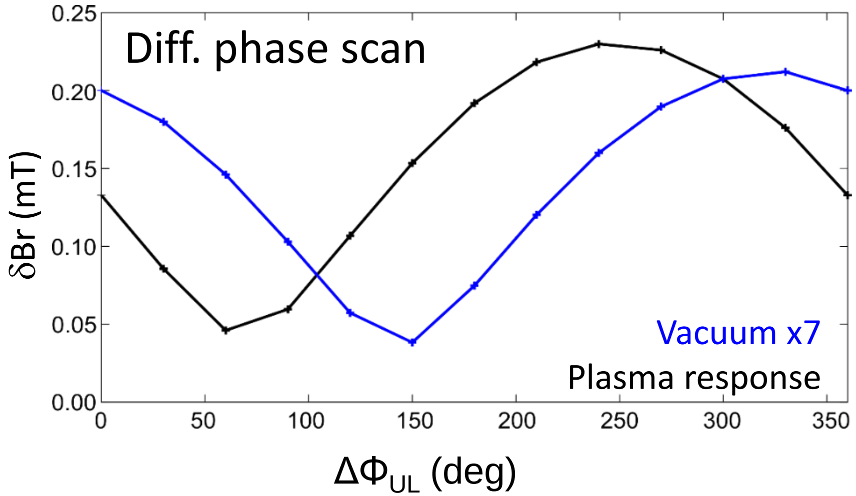


*Y. Todo, Nucl. Fusion **54,** 104012 (2014)

Internal Kink Dominates Plasma Response in MEGA

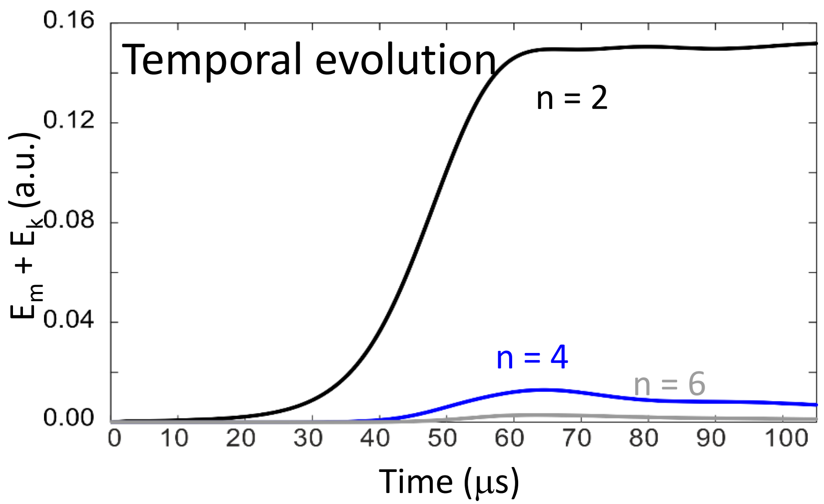
- **Max response shifted about 100º wrt vacuum fields**
- **Perturbation fields up to x7 vacuum**

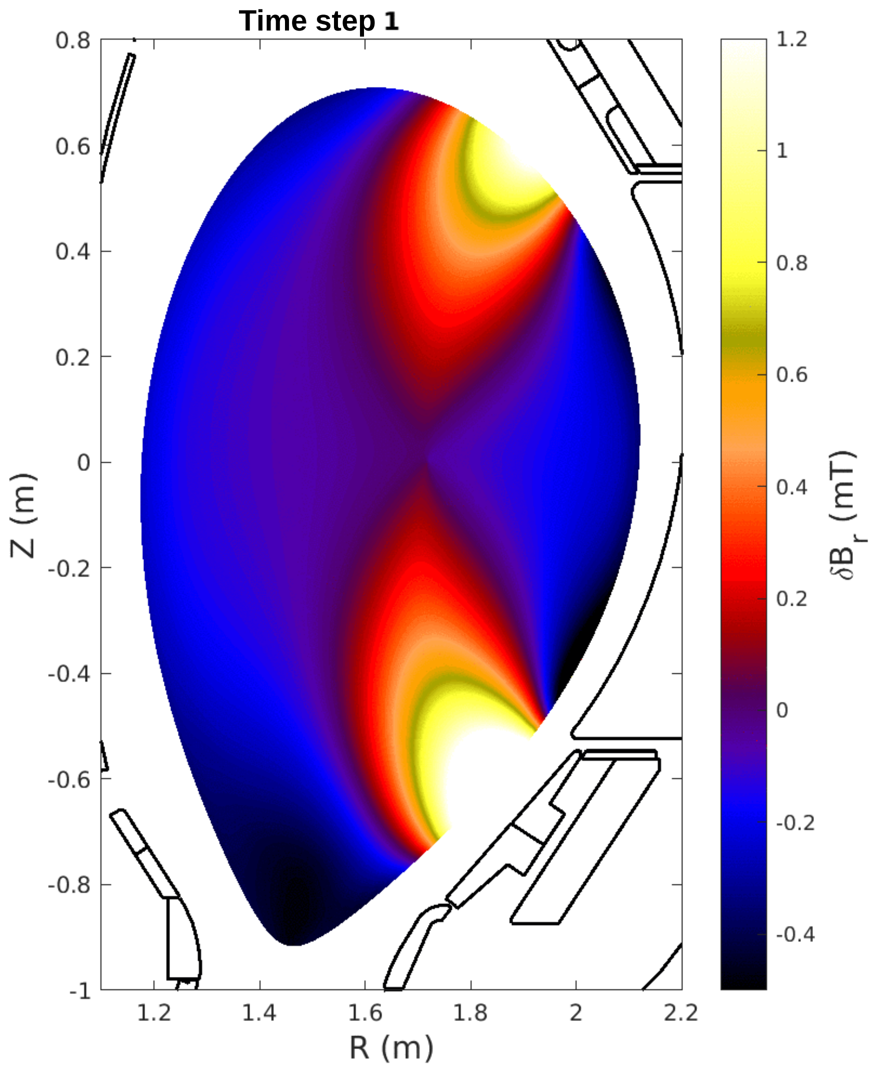




Internal Kink Dominates Plasma Response in MEGA

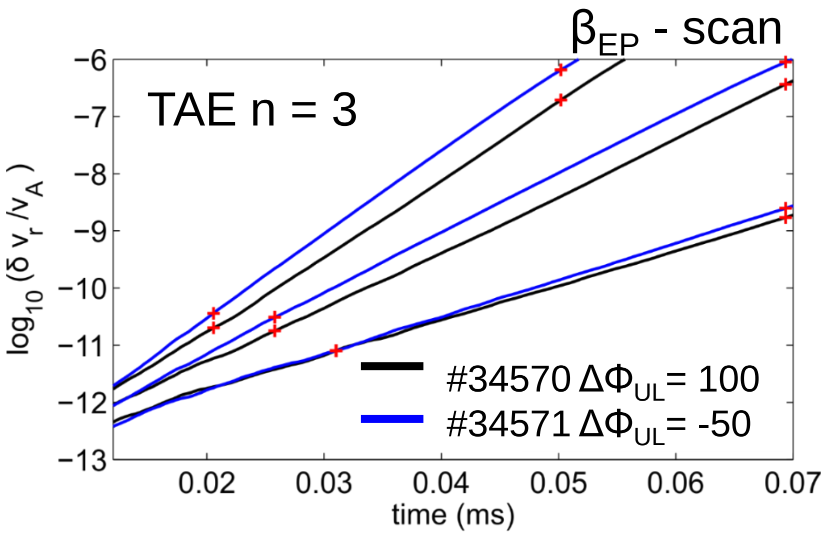
- Max response shifted about 100º wrt vacuum fields
- Perturbation fields up to x7 vacuum
- Plasma develops n=4 and n=6 to low amplitudes
- w/o fast-ions, plasma response saturates within 60 µs





MEGA Simulation Explains RMP Impact on TAE

- **RMP configuration determines TAE growth rate**
- **TAE drive studied in RMP perturbed equilibrium for both coils configurations**
- **Energetic particles injected at t=0sec**



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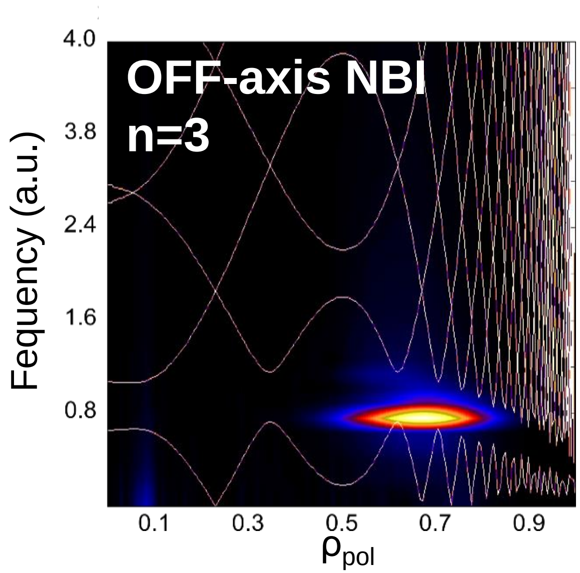
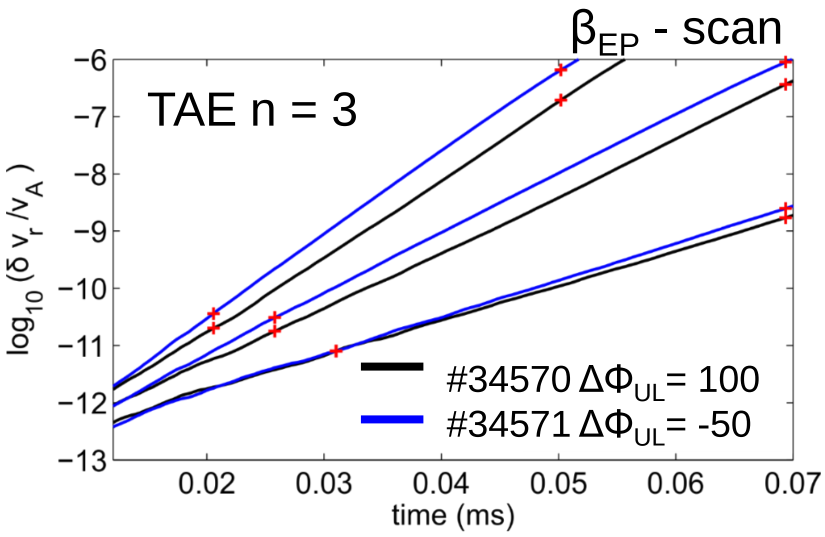
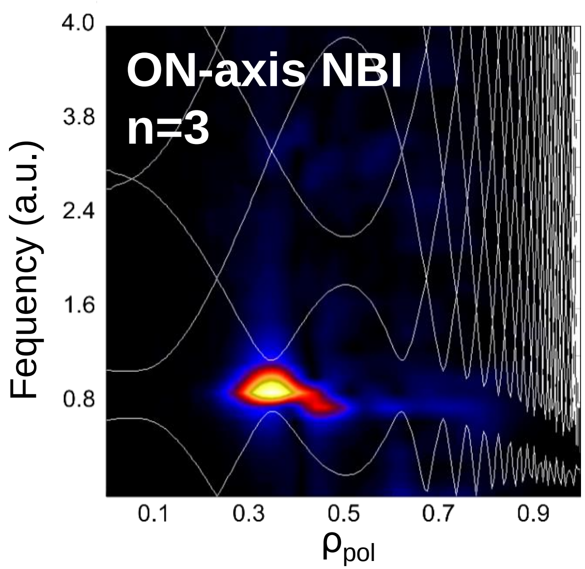




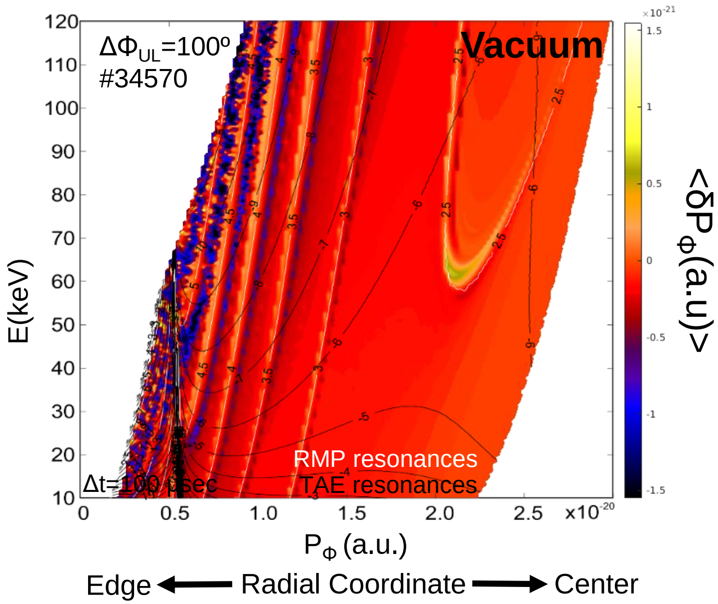


MEGA Reproduces Fast-Ions ERTL

- **Interaction of energetic particles with RMPs and TAEs is studied in phase-space using COM (E, P_Φ, Λ)**
  - ➢ **Scan in E & P_Φ**
  - ➢ **fixed Λ**

- **Well defined linear resonances emerge with RMP application**
  - ➢ **Excellent overlap with analytical ($\omega_{tor}/\omega_{pol}$=n/p) resonances**

- **δP_Φ figure of merits used to study RMP induced trasnport**



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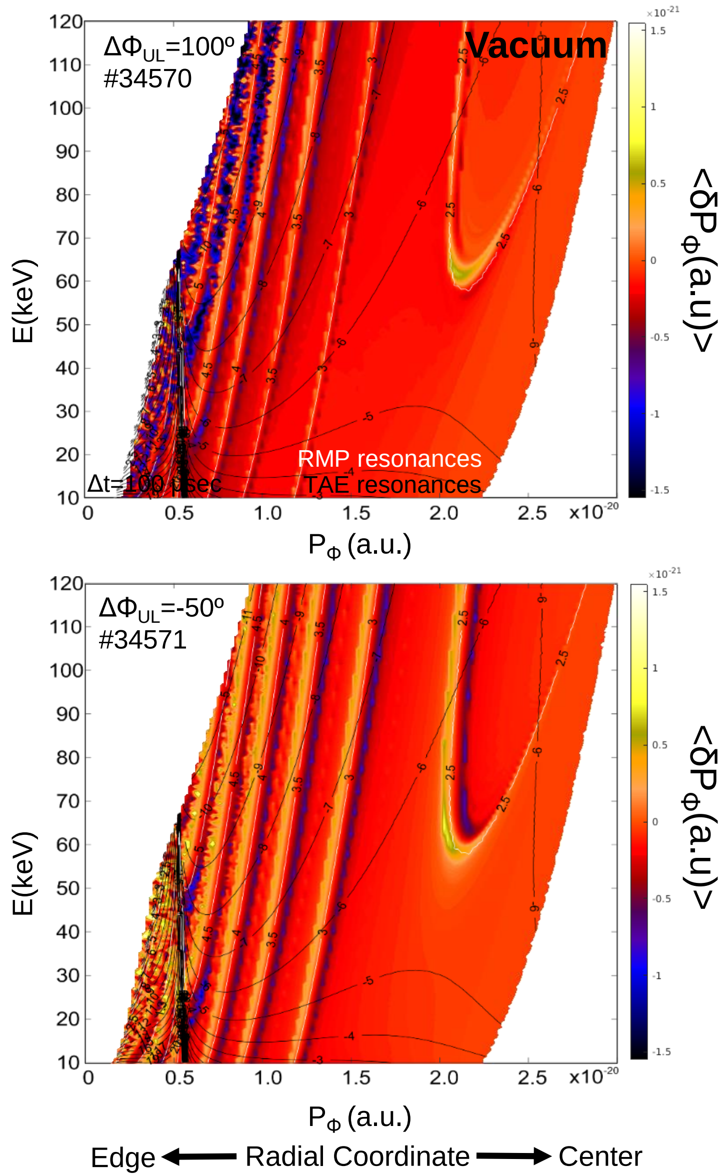
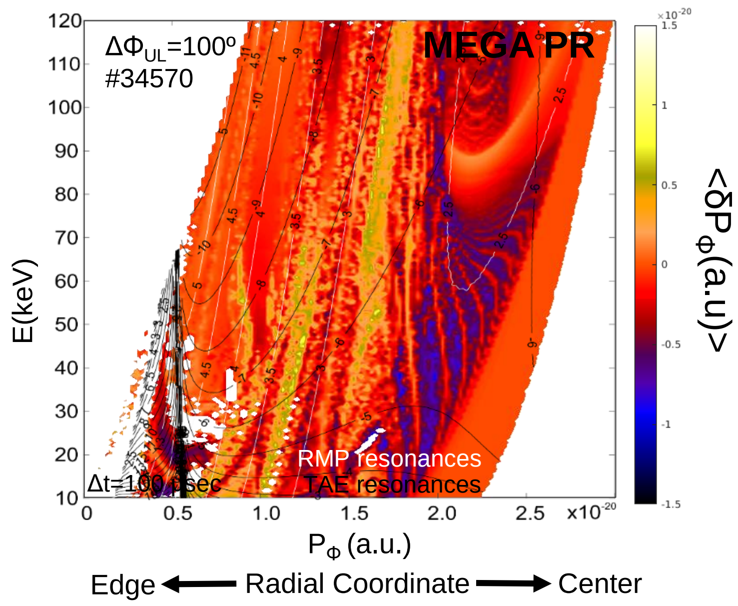


Plasma Response Introduces Additional Fast-Ion Resonances in Entire Plasma

- **Internal kink introduce resonances outside ERTL at TAE location**
- **ERTL resonances are preserved**
- **Internal transport is order of magnitude larger than ERTL**
- **Particle losses increased**
- **Stochastic region emerged**



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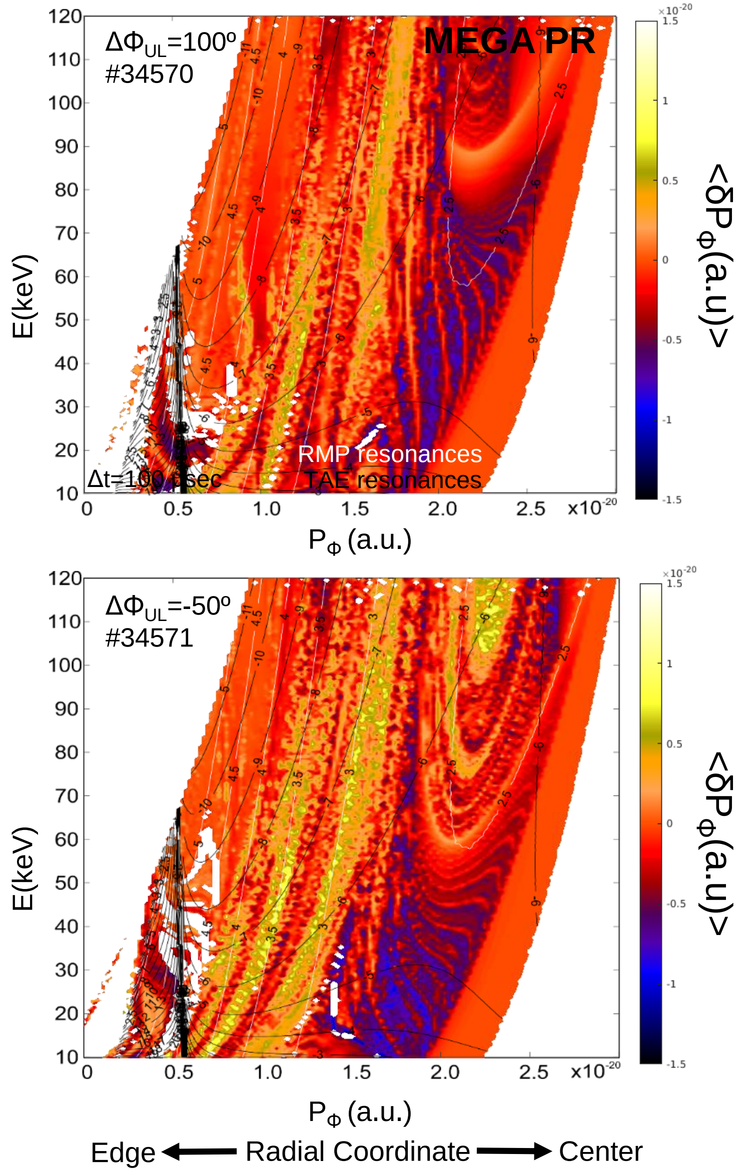
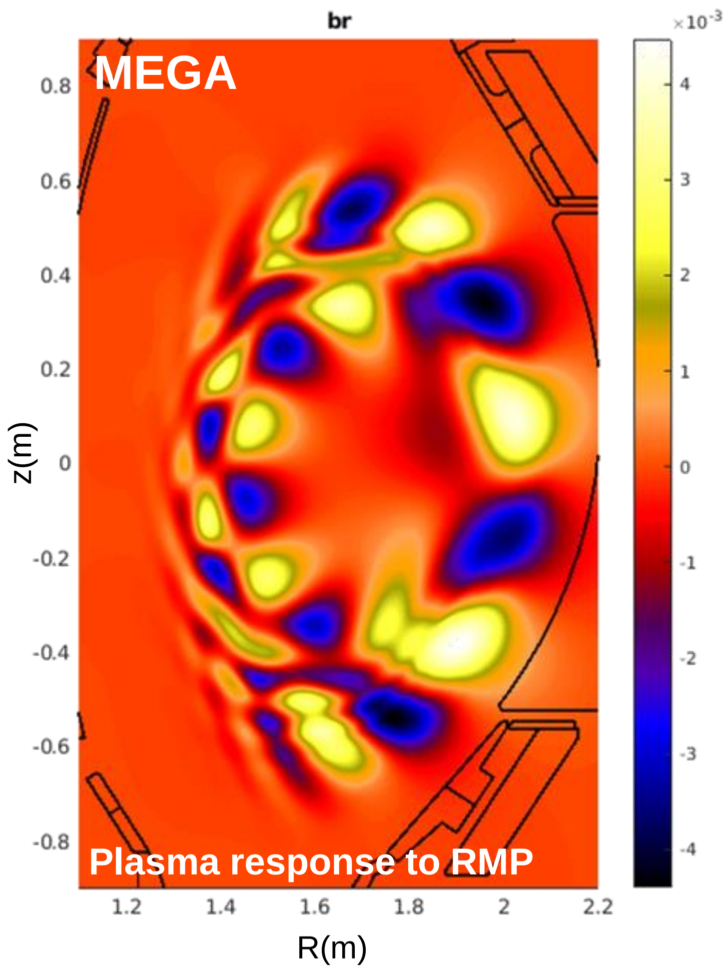
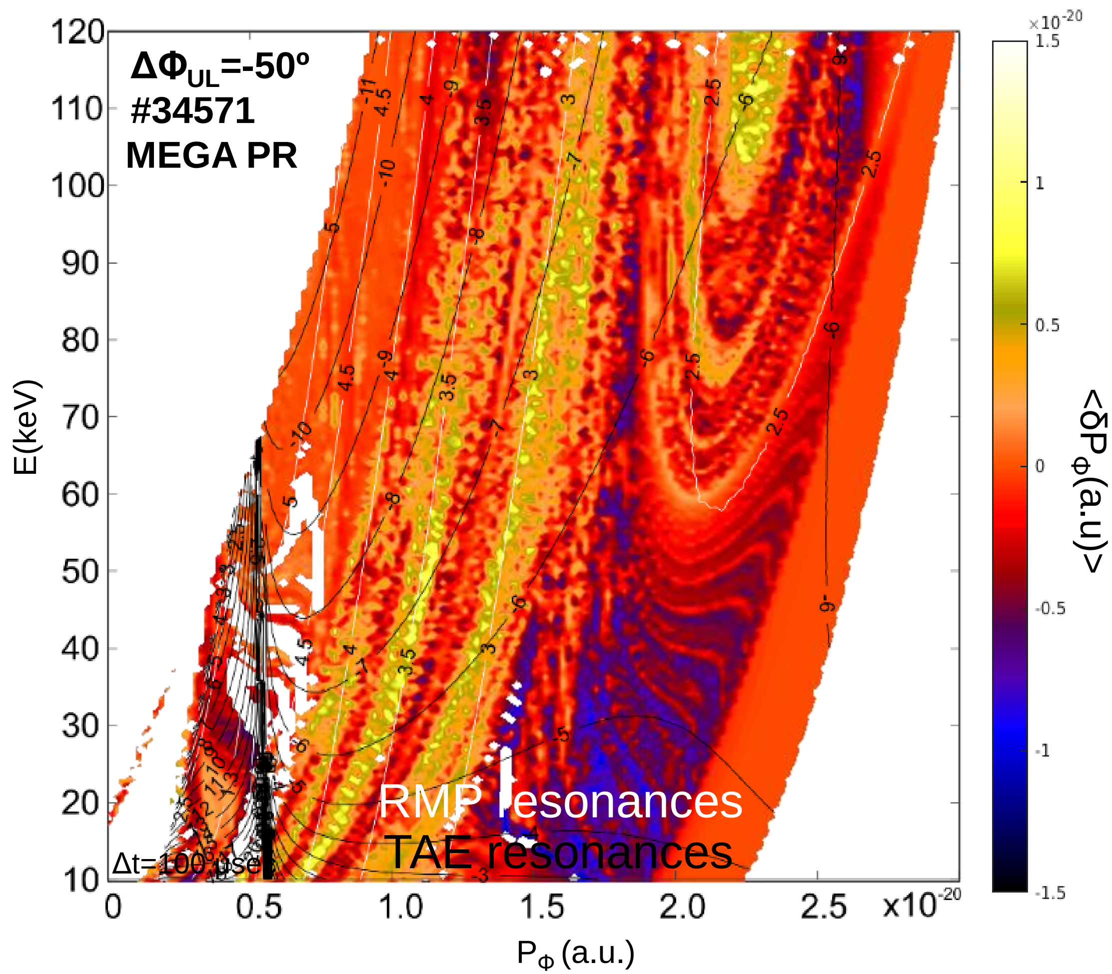


NBI Distribution May Be Effectively Controlled Over a Large Plasma Volume

- **Resonant particles are trapped between δB_{max} and δB_{min} until they leave the plasma or are scattered out of resonance (loss of phase)**





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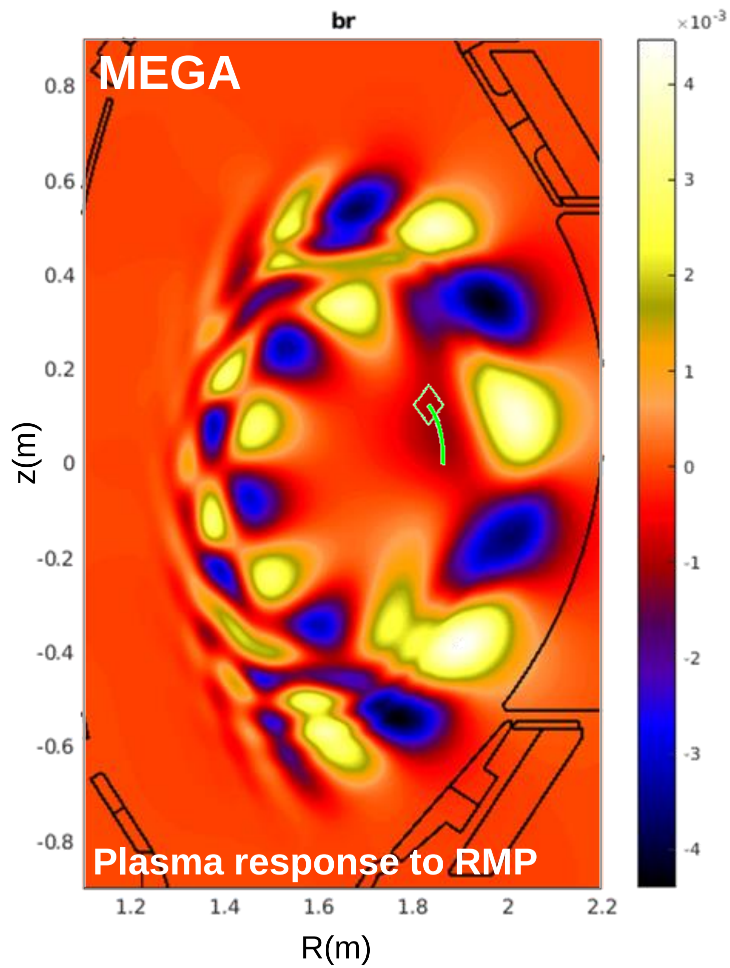

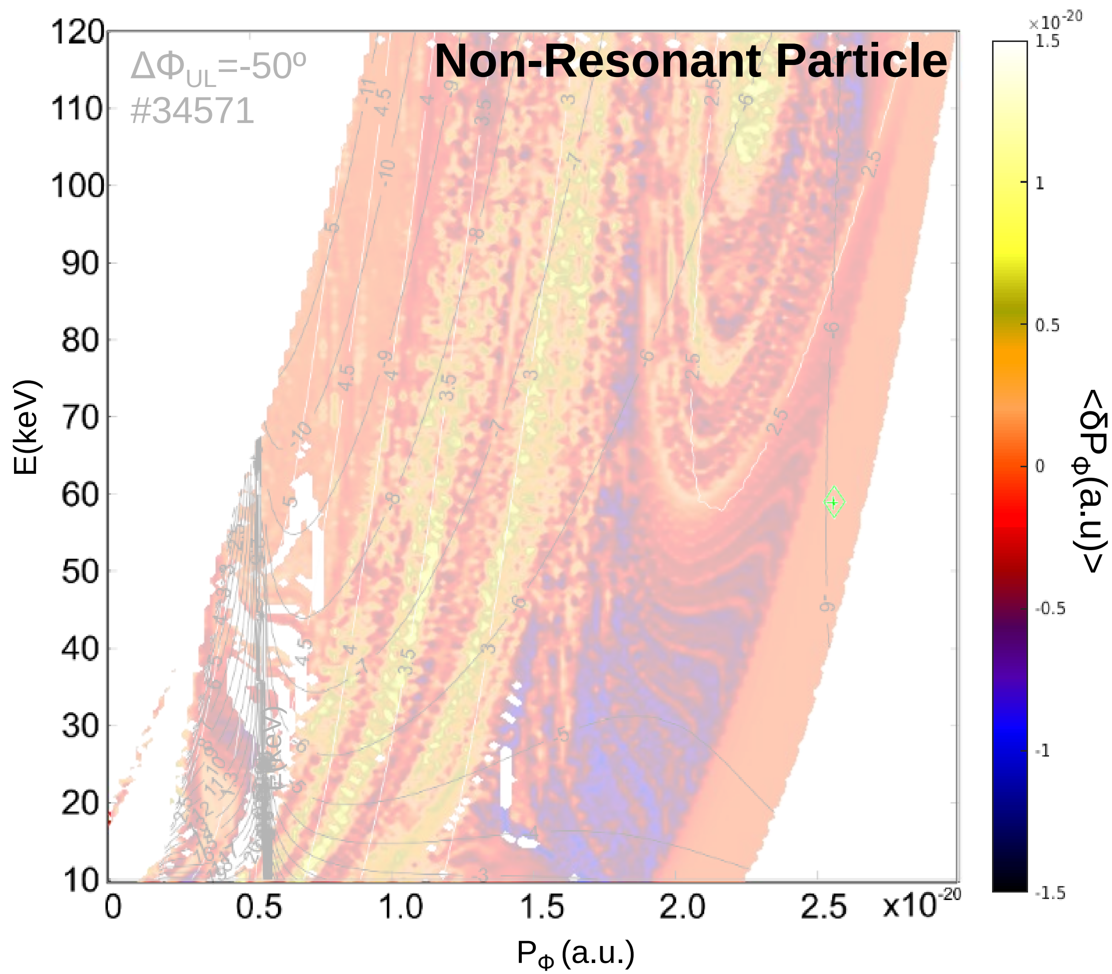

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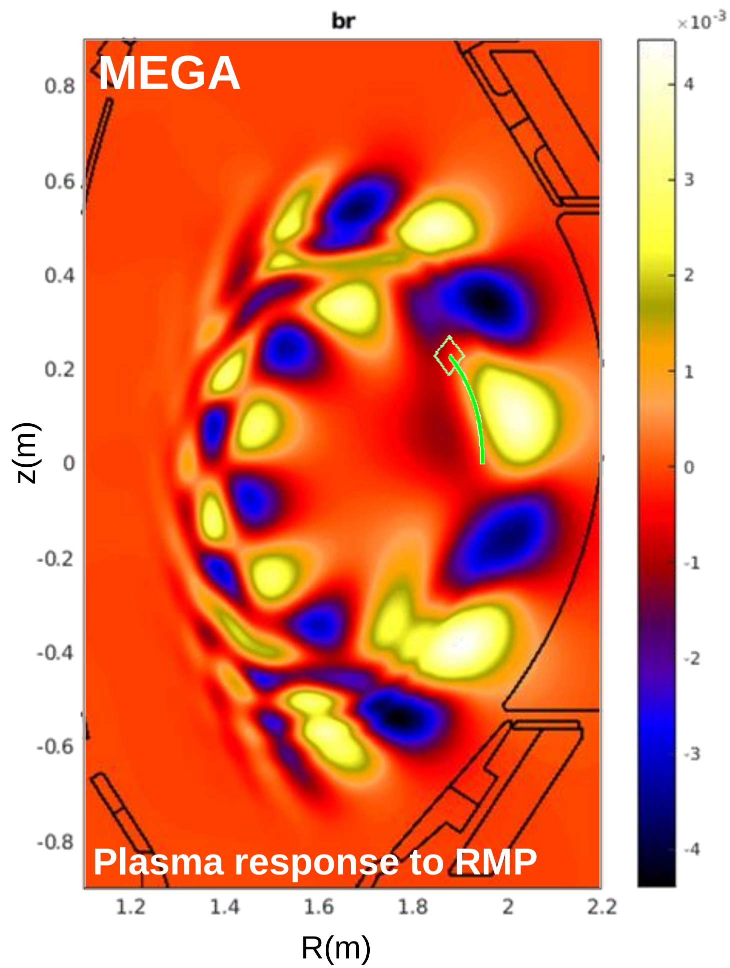

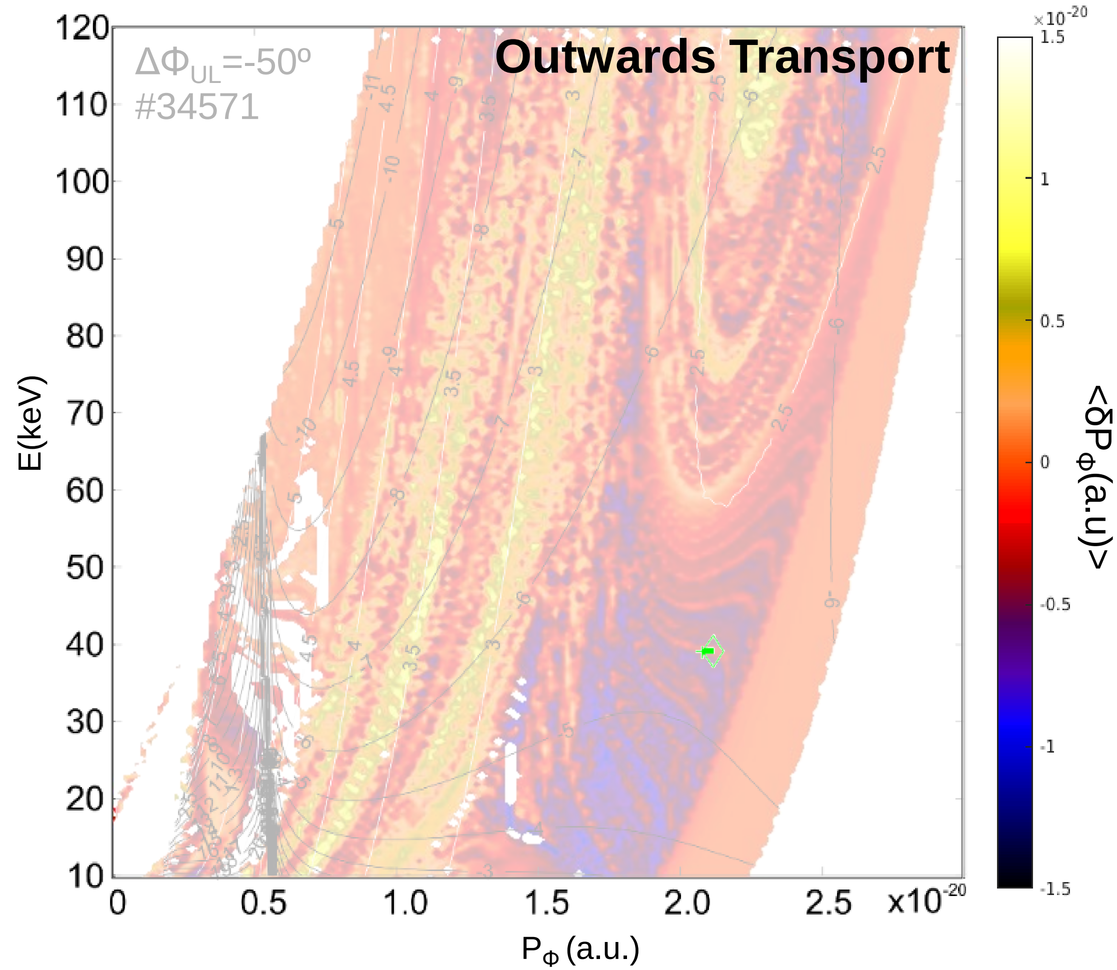

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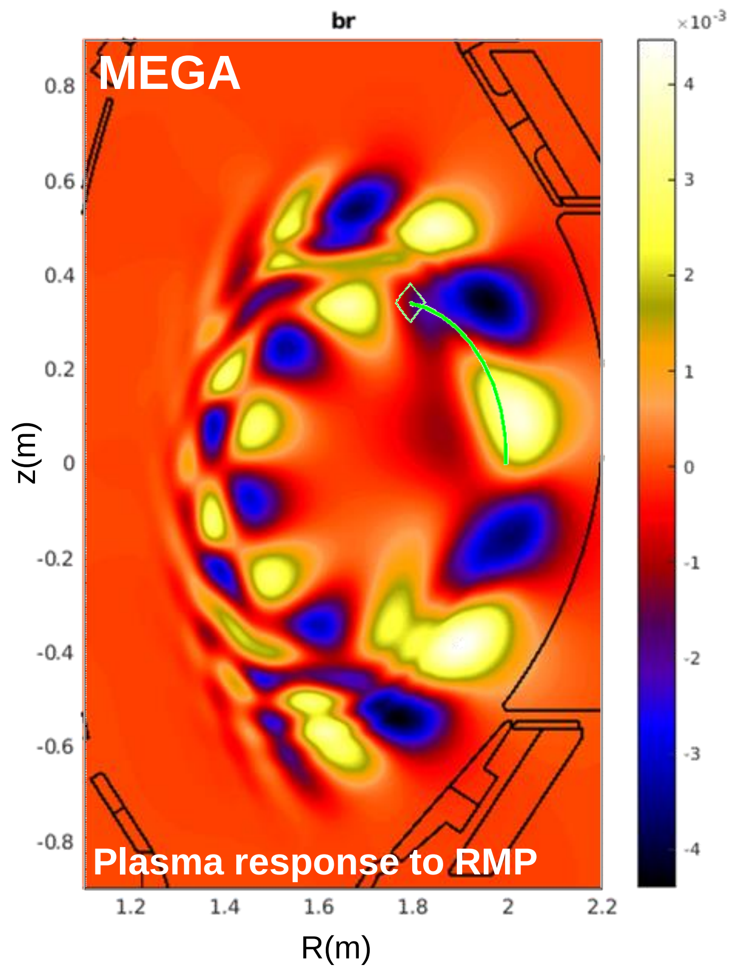

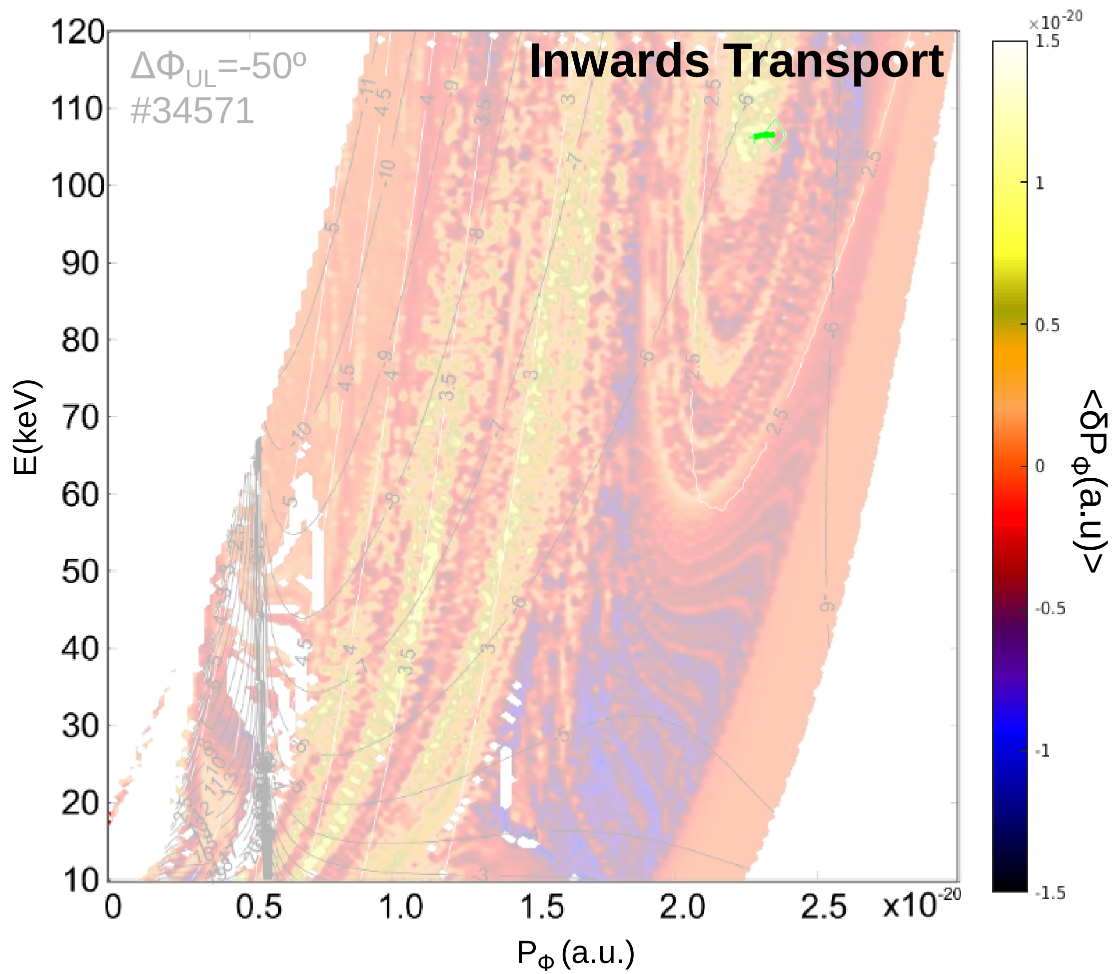

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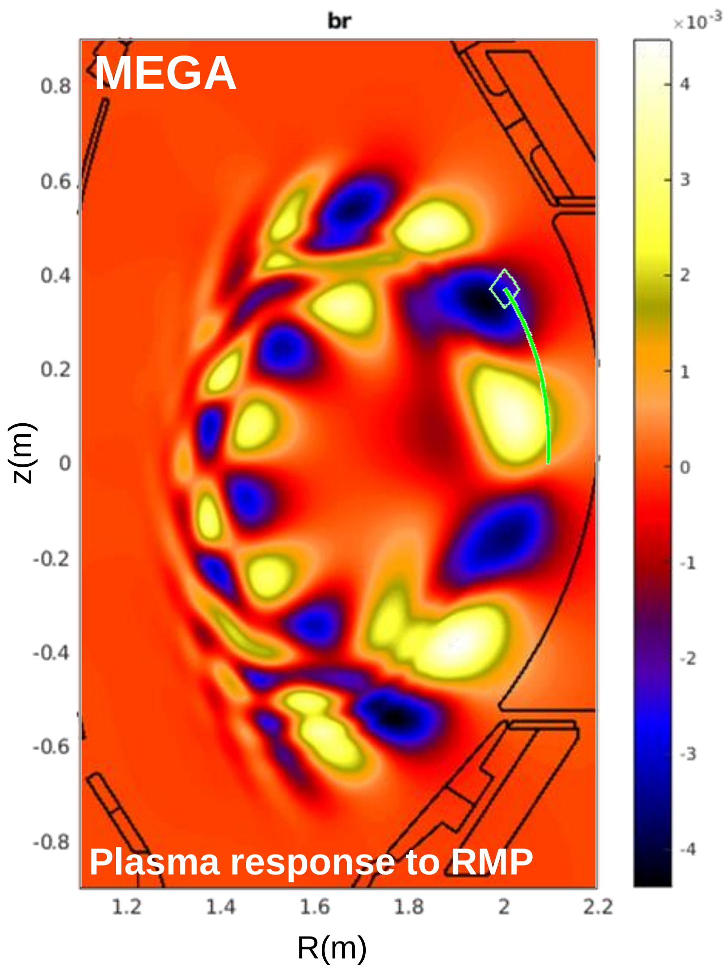
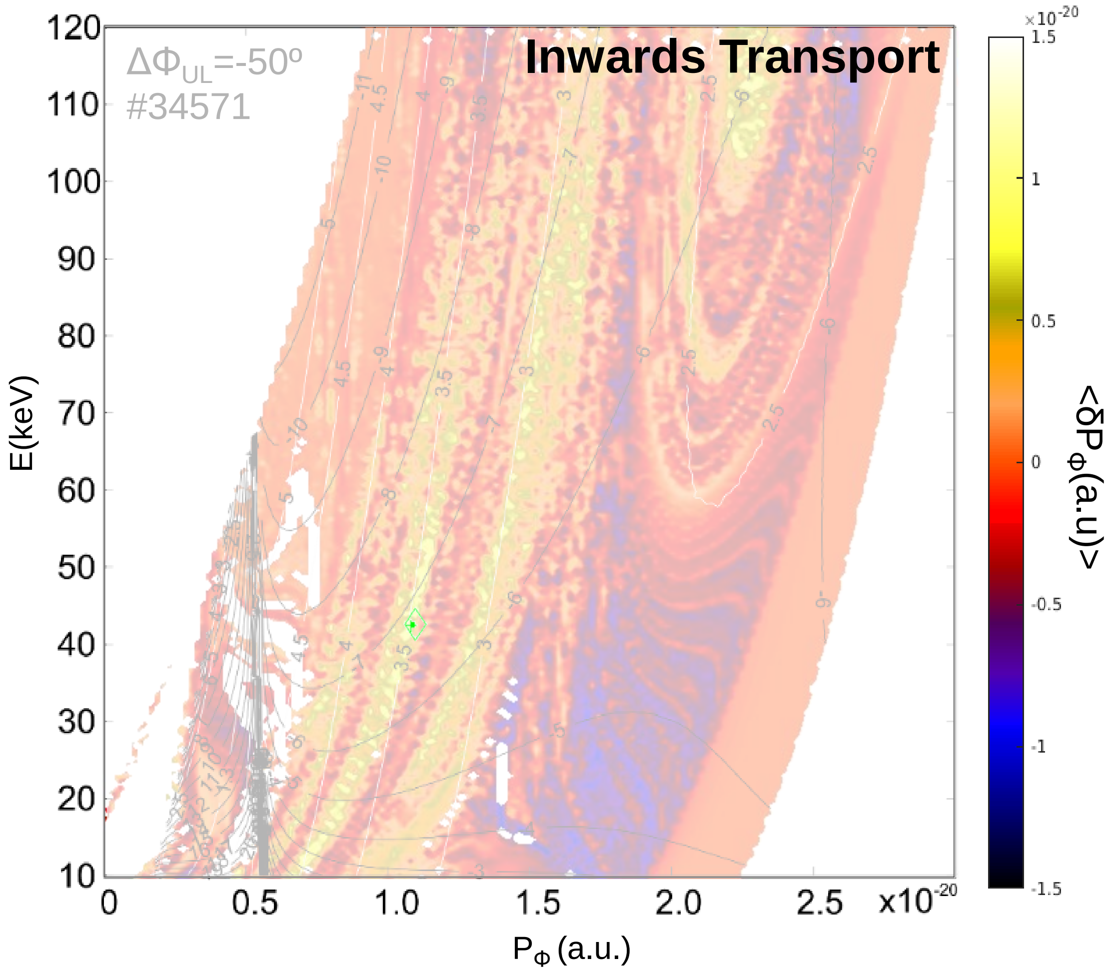
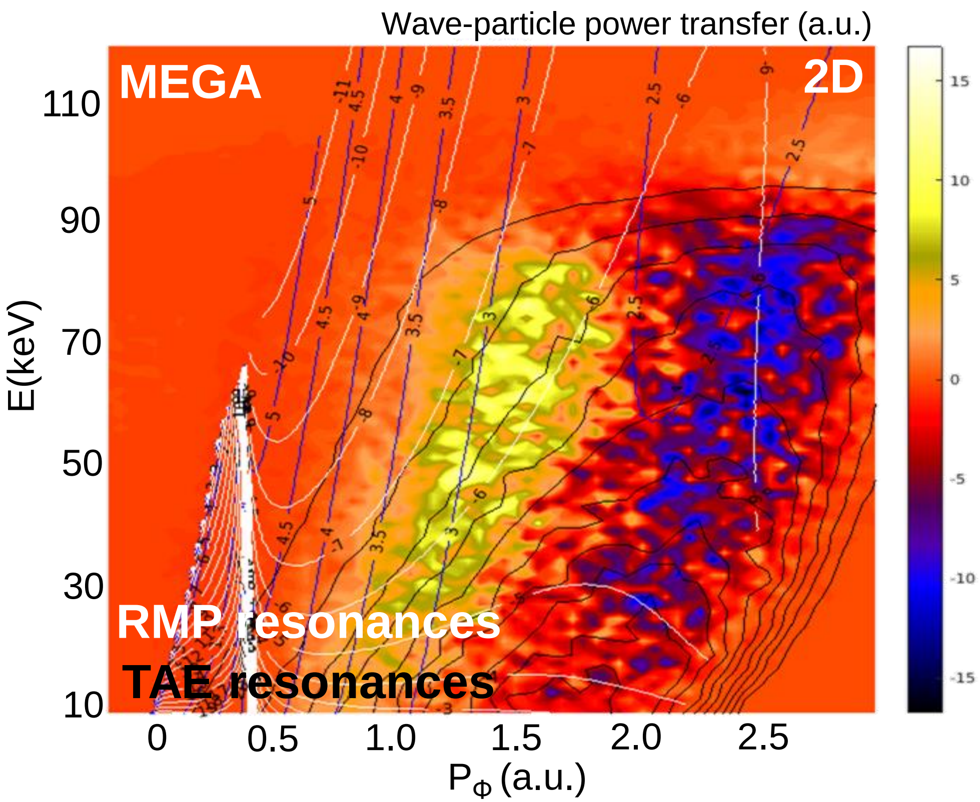
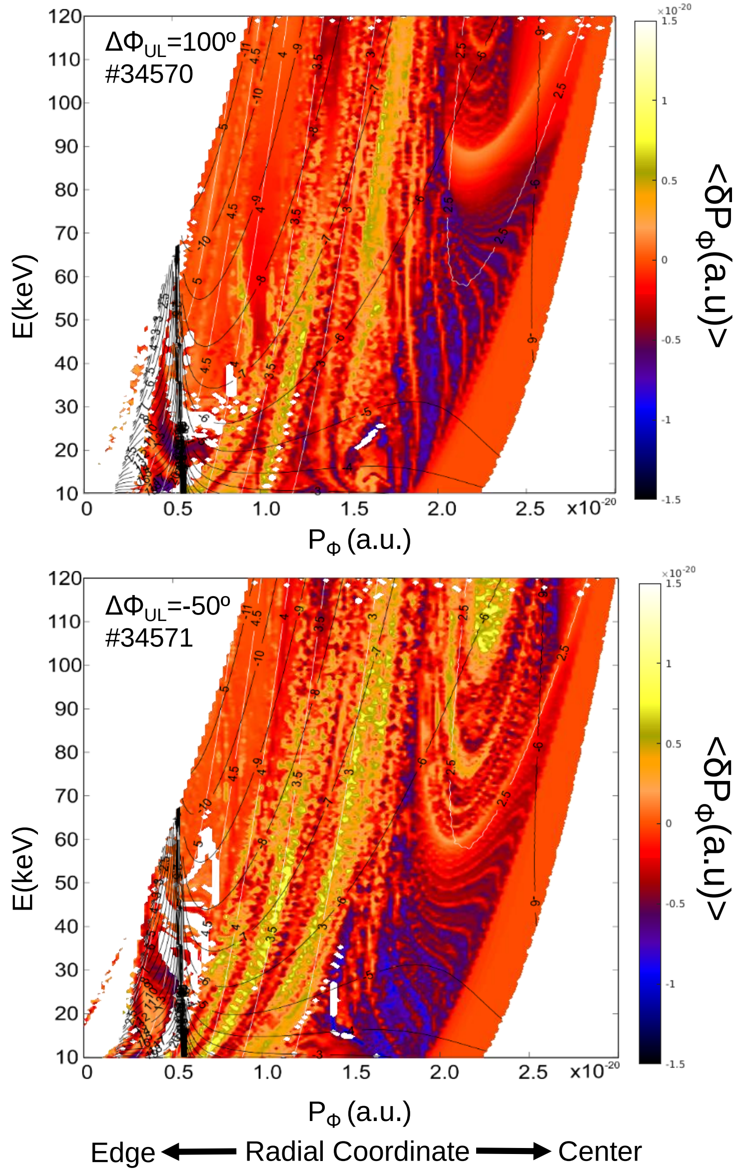




Kink Induced Transport Determines TAE Drive

- **Internal fast-ion transport caused by core kink response to RMP overlaps with phase-space region with maximum wave-particle energy exchange**





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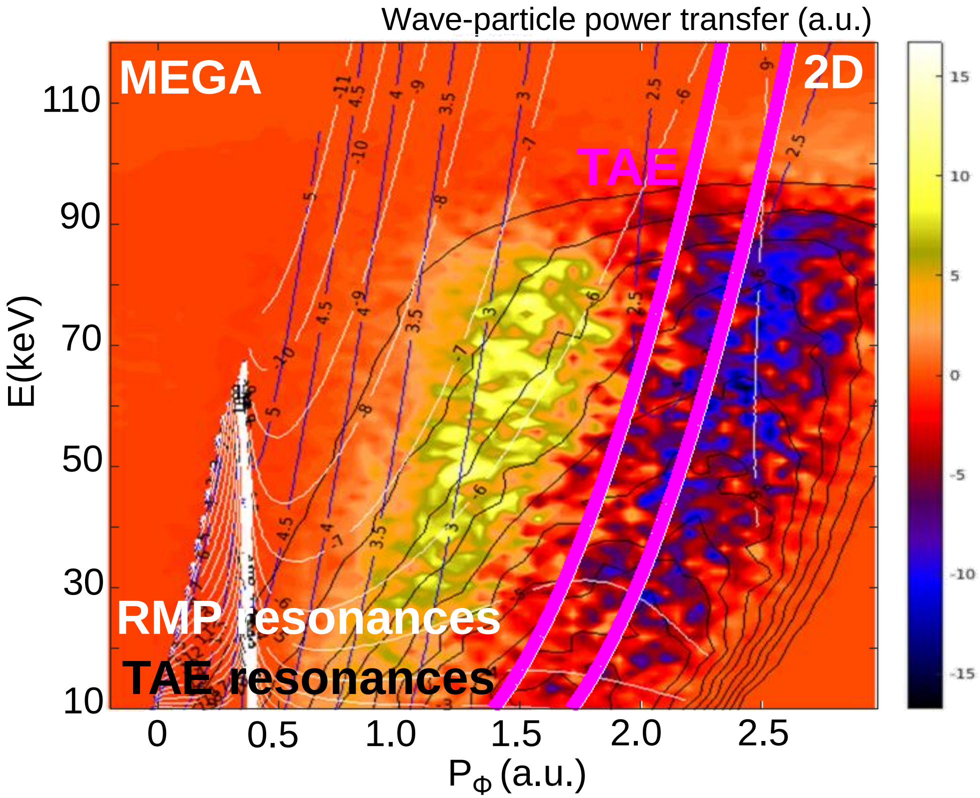

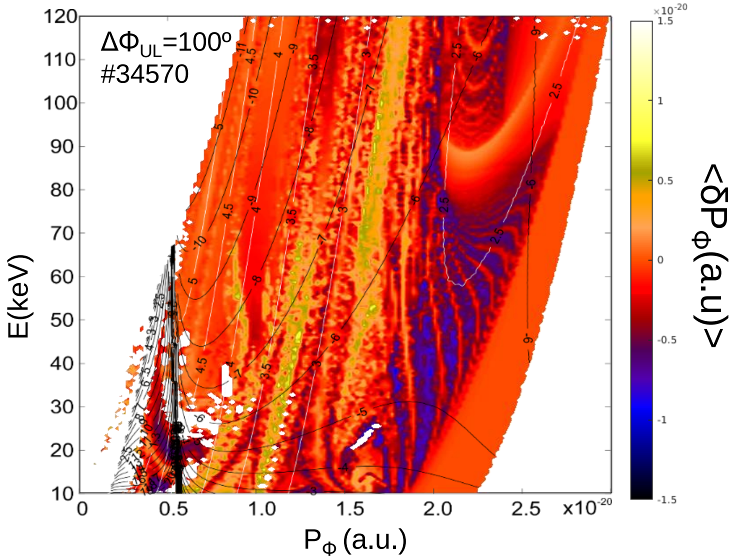

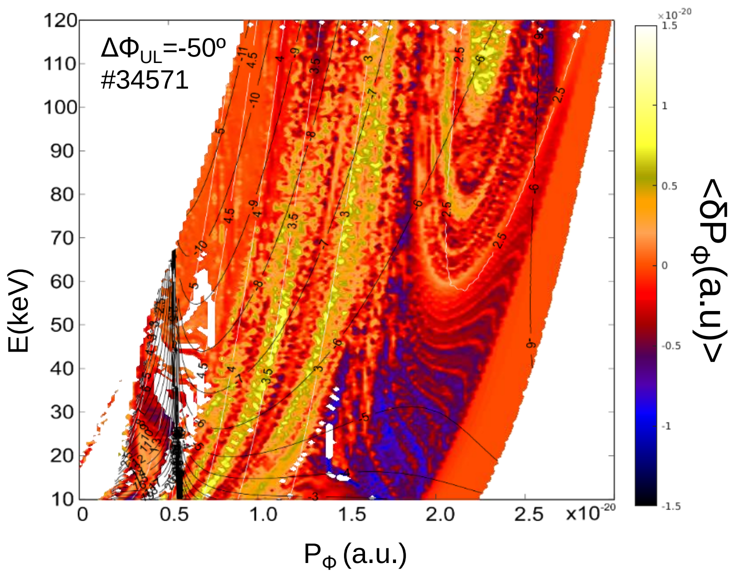

Edge ⟵ Radial Coordinate ⟶ Center

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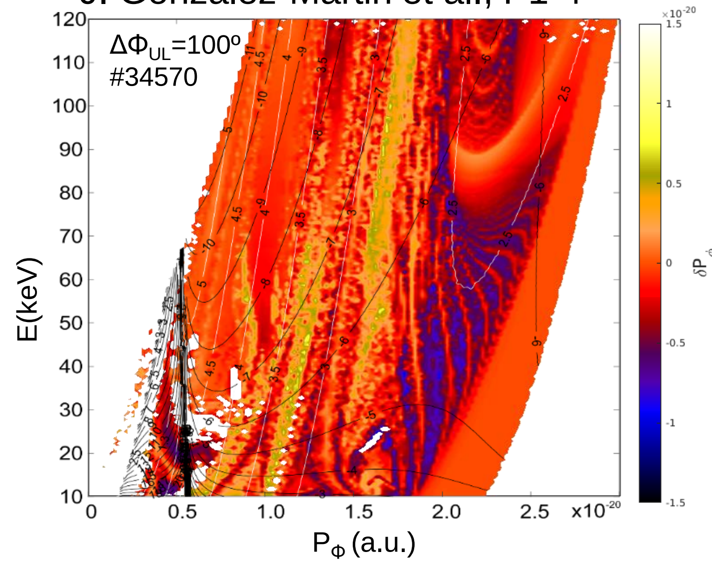
Summary and Conclusions

- NBI driven **TAE activity** can be **controlled** by means of externally applied RMPs with broad n-spectrum
  - ➢ **n=2 RMP** has strongest impact with full suppression / excitation
- **Plasma response** has been successfully modelled using **MEGA**
- **Internal kink** response might be key to manipulate fast-ion distribution and associated TAEs
- Plasma response to RMP may expand our capabilities to **control fast-ion distributions** over large plasma radius in present and future devices

J. Gonzalez-Martin et al., P1-4



Wave-particle power transfer (a.u.)