The role of plasma response on fast ion losses induced by applied 3D fields in the ASDEX Upgrade and DIII-D tokamaks

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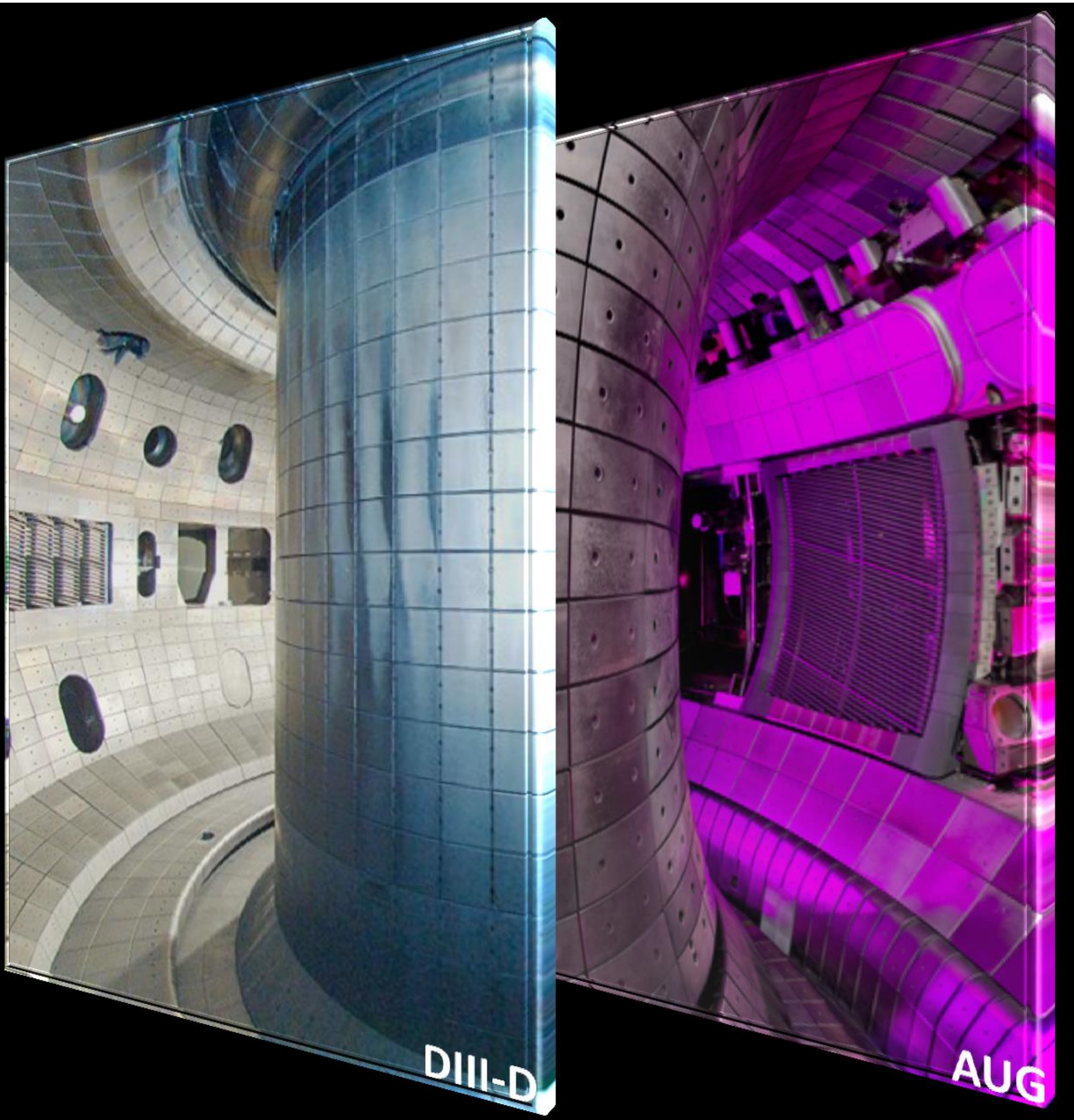
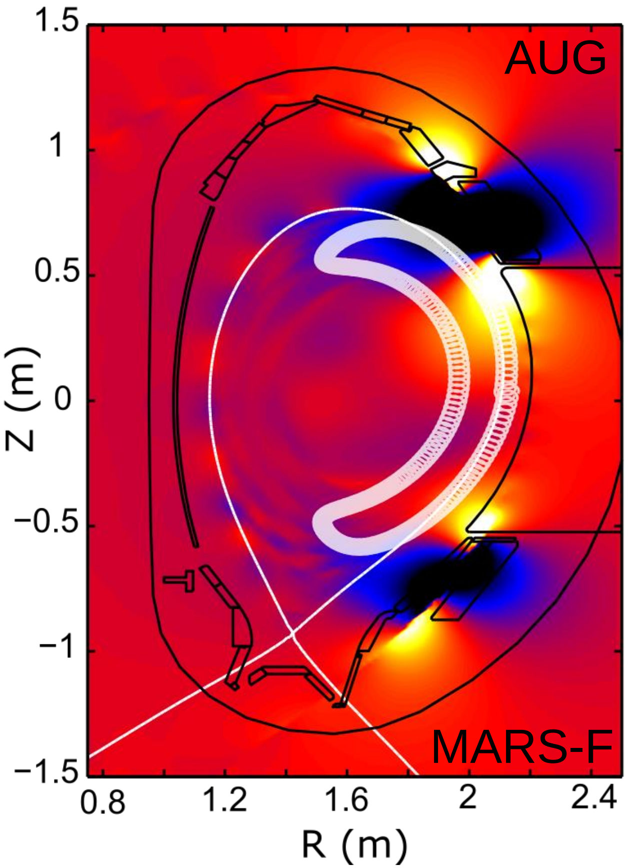


3D Fields Used to Control ELMs Can Cause Intense and Localized Fast-Ion Losses

• Simulations show ELM mitigation coils (using vacuum fields) can cause up to 25% of NBI losses in ITER* reducing

- Heating/current drive efficiency
- Device safety (wall damage)

• Plasma response to applied 3D fields play important role in ELM suppression mechanism**



*K. Shinohara, et.al., NF **51** 063028 (2011)
*T. Koskela et al., PPCF **54** 105008 (2012)
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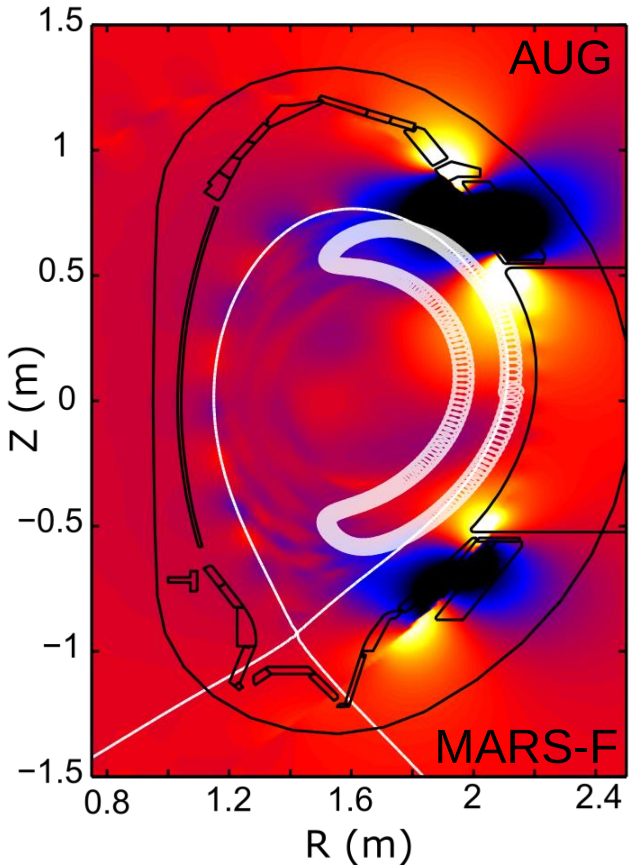
How does the plasma response affect the fast-ion confinement?



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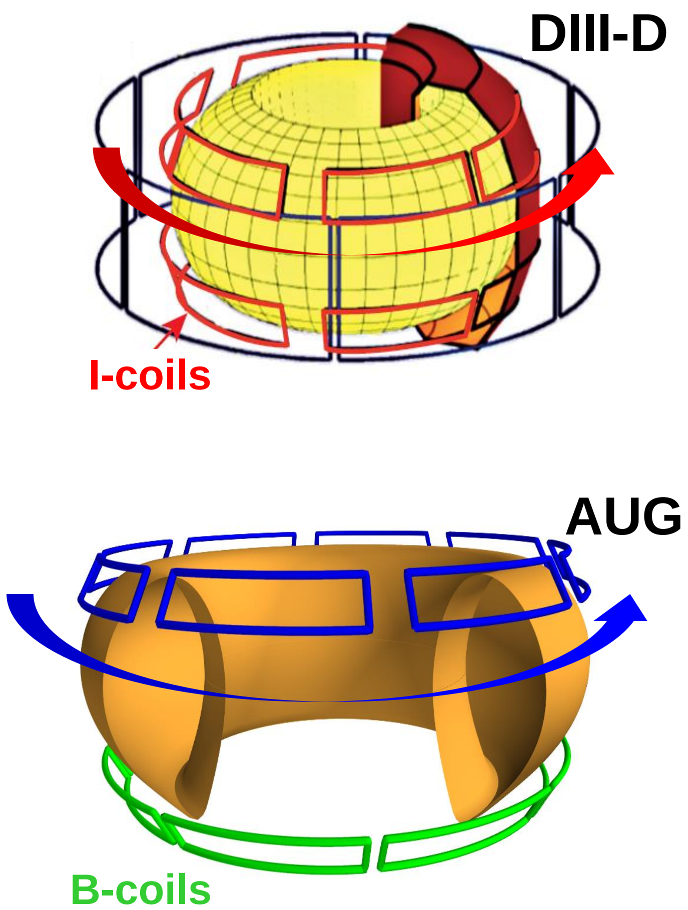
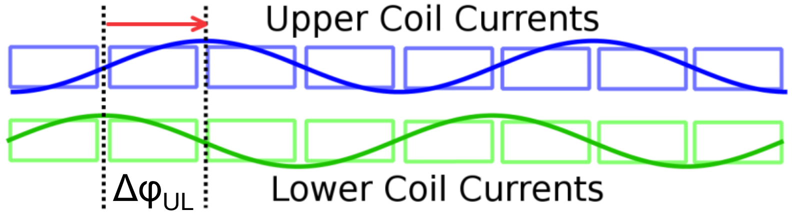
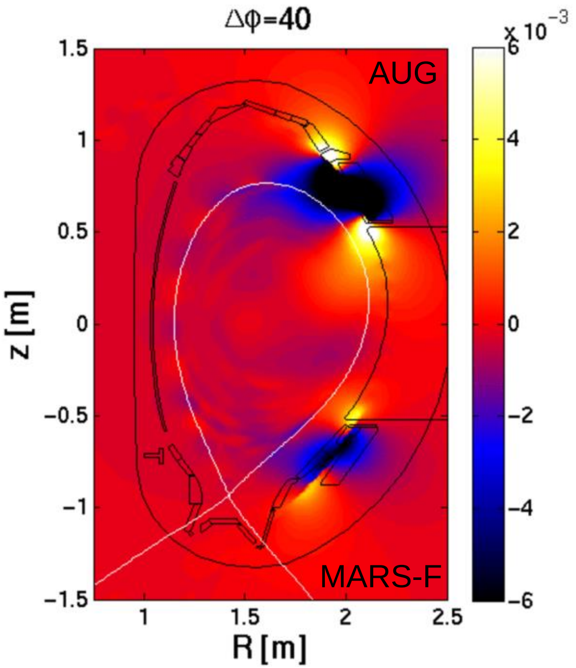
Plasma Response to Applied 3D Fields Studied Varying 3D Field Poloidal Spectrum at Different β_N

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

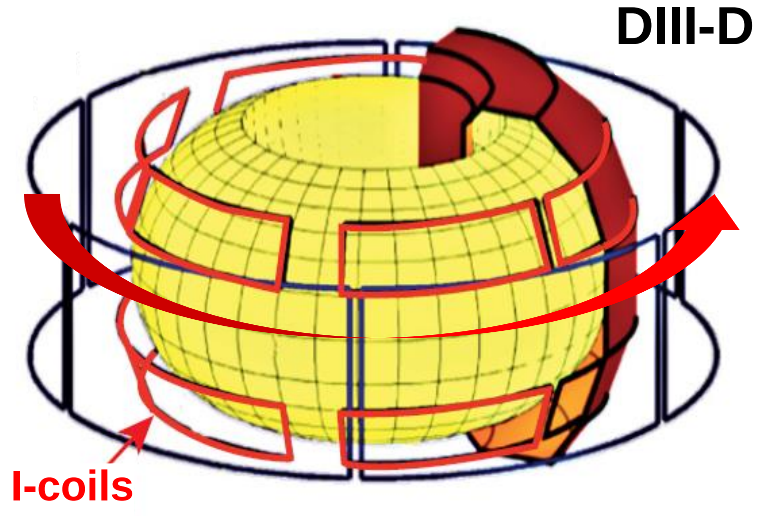


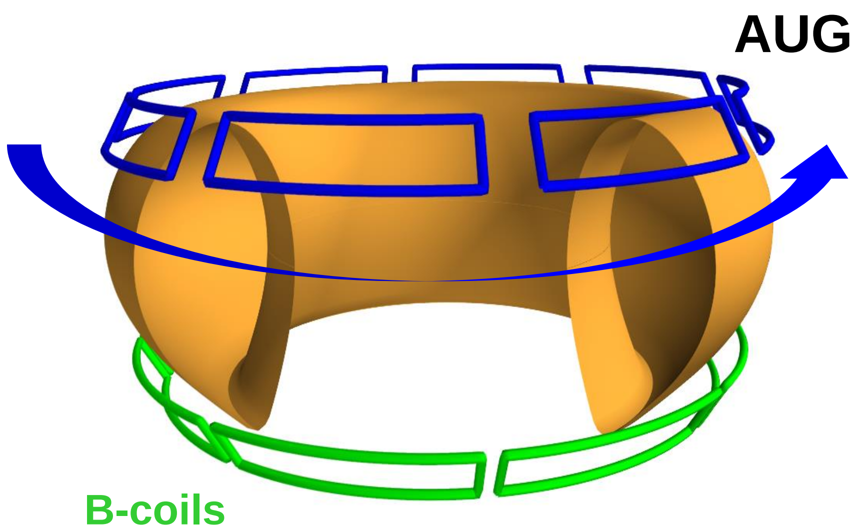




Outline

- **Direct measurement of fast-ion orbit displacement induced by the applied 3D fields in DIII-D**
- **Impact of 3D fields poloidal spectrum on plasma response and fast-ion losses**
  - ➢ **in DIII-D**
  - ➢ **in AUG**
- **Edge Resonant Transport Layer**
- **Conclusions**





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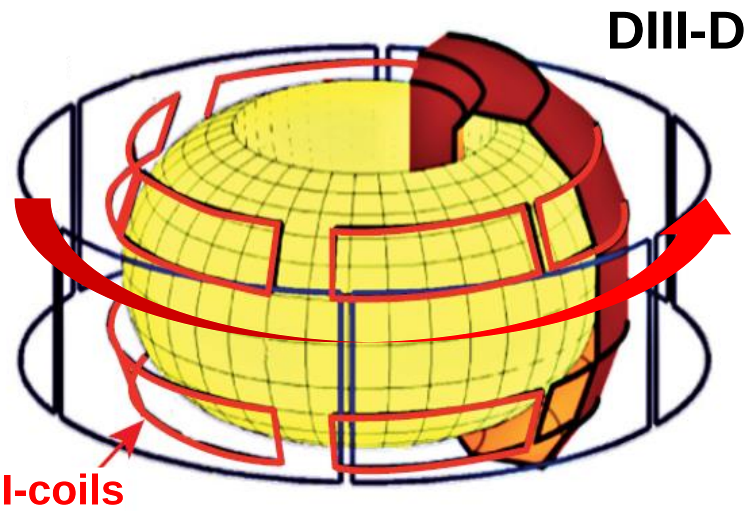
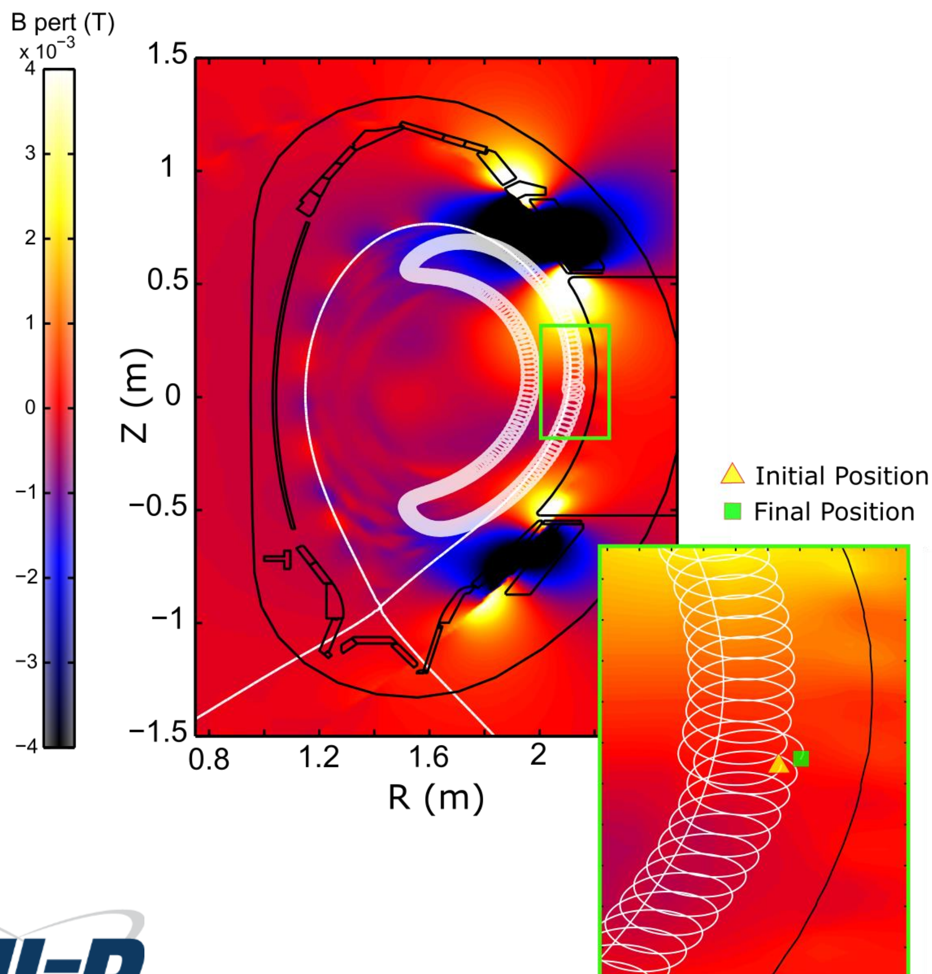


Light Ion Beam Probe (LIBP*) Technique Provides Fast-Ion Kick Given by 3D Fields

- Similarly to Heavy Ion Beam Probe (HIBP) technique LIBP infer local perturbation strength using barely confined NBI ions



$$\xi = \frac{\Delta F}{\bar{F}} \cdot L_i$$

ξ → Radial kick (displacement)

ΔF → Amplitude of fluctuating FILD signal

$\bar{F}$ → Amplitude of the unperturbed losses at FILD

L_i → Ionization scale length at orbit birth position

* *Xi Chen et al., RSI'14*

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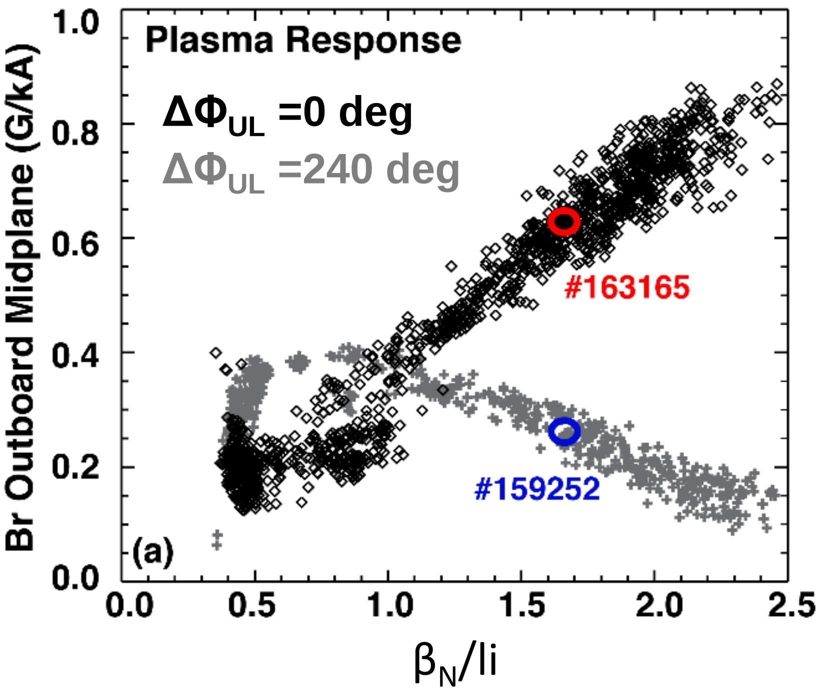
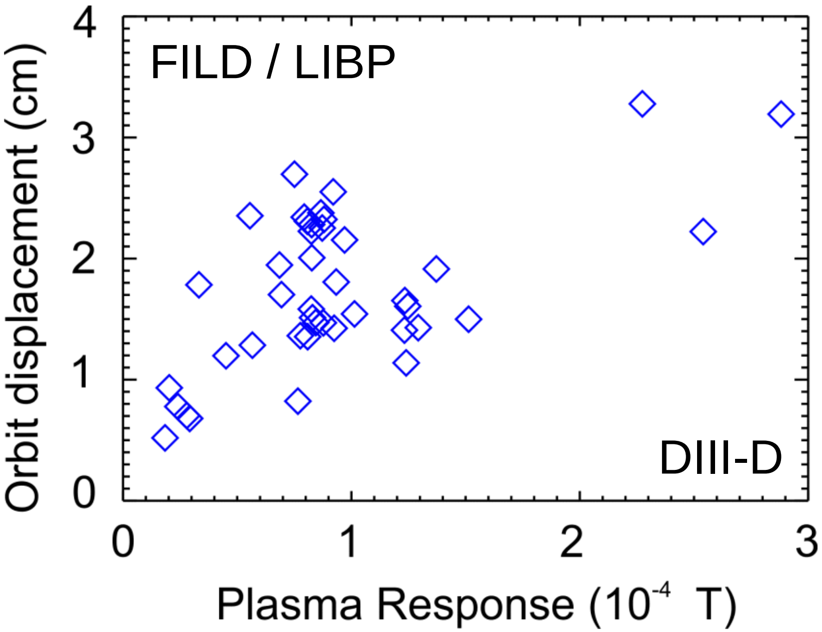
Orbit Displacement Induced by 3D Fields Shows Linear Dependency On Plasma Response to Applied 3D Fields

- Fast-ion kick – loss studied for two different $\Delta\Phi_{UL}$ and wide β_N range
- Fast-ion kicks by 3D fields can be up to 3 cm





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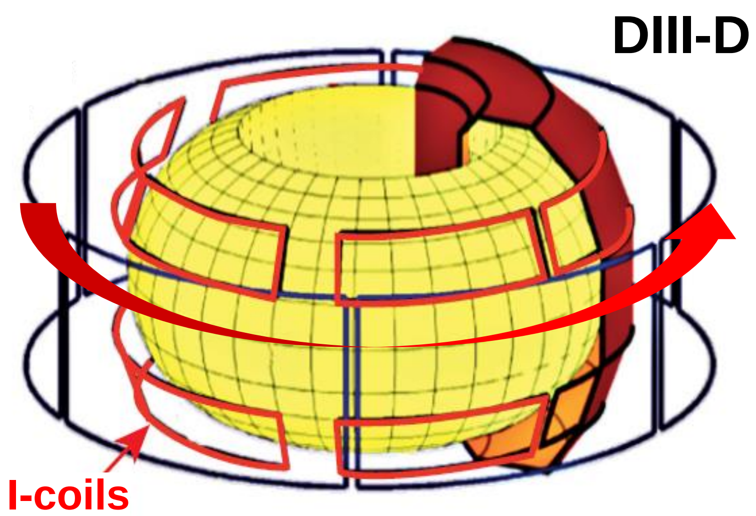
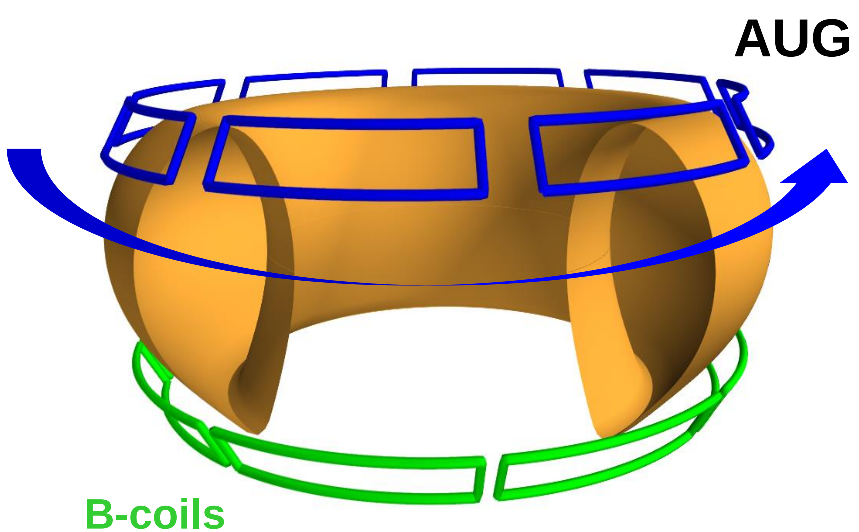
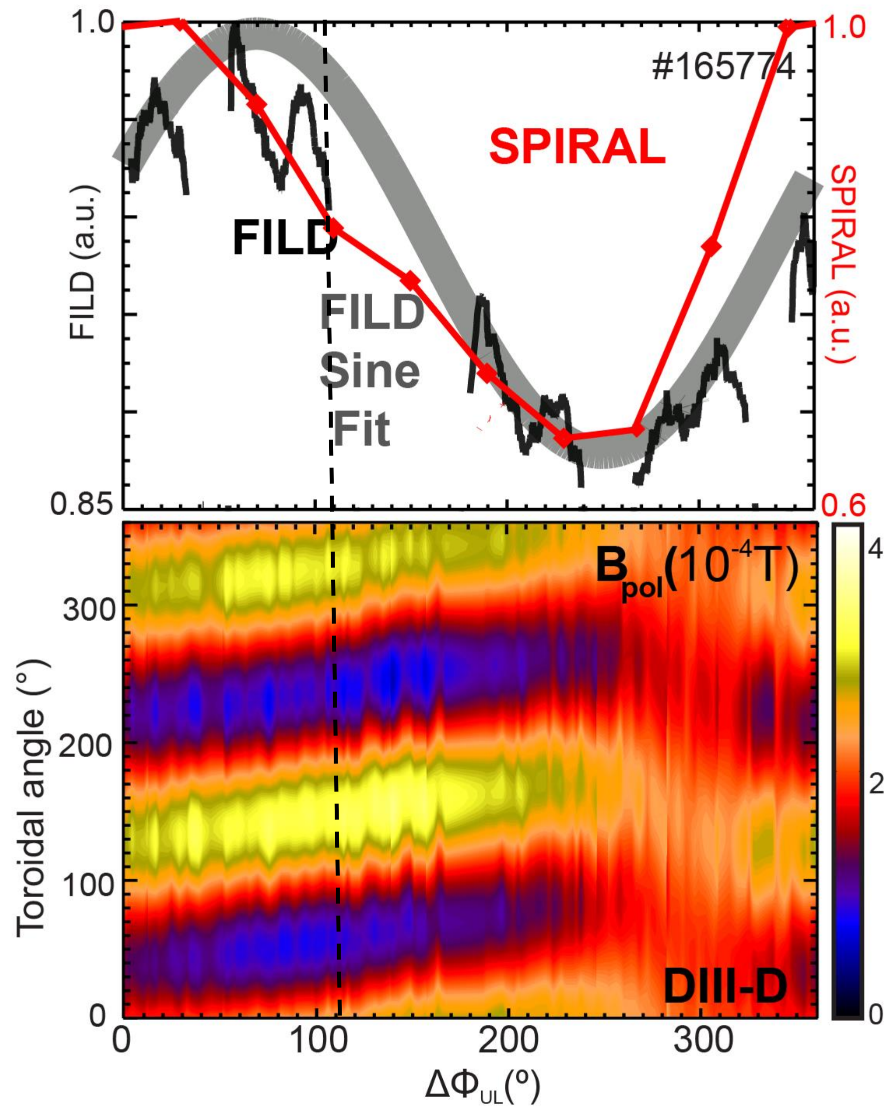


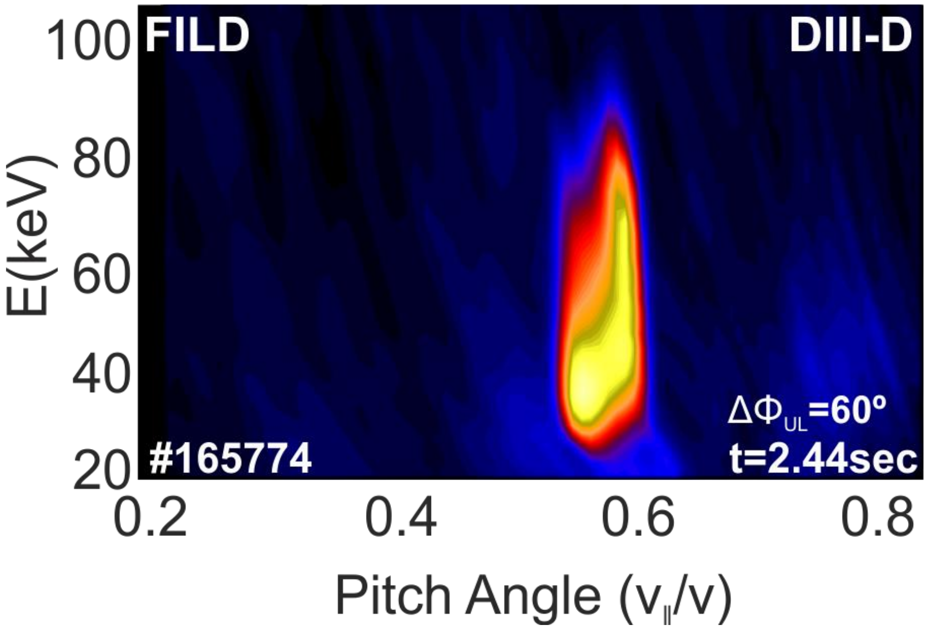


$\Delta\Phi_{UL}$ Continuous Scan Shows 15% Variation in Fast-Ion Losses

- Plasma response and fast-ion losses depend strongly on applied poloidal spectrum
- Slight phase shift, ~40º, between measured losses and magnetic response
  - Resonant spectrum for thermal plasma and fast-ions might not be the same
- SPIRAL simulates fast-ion losses in M3D-C1 fields using realistic NBI distribution



FILD Measurements Help Identifying Orbit Topology of Fast-Ion Losses Induced by 3D Fields



- Maximum losses appear at well defined pitch-angle and broad energy

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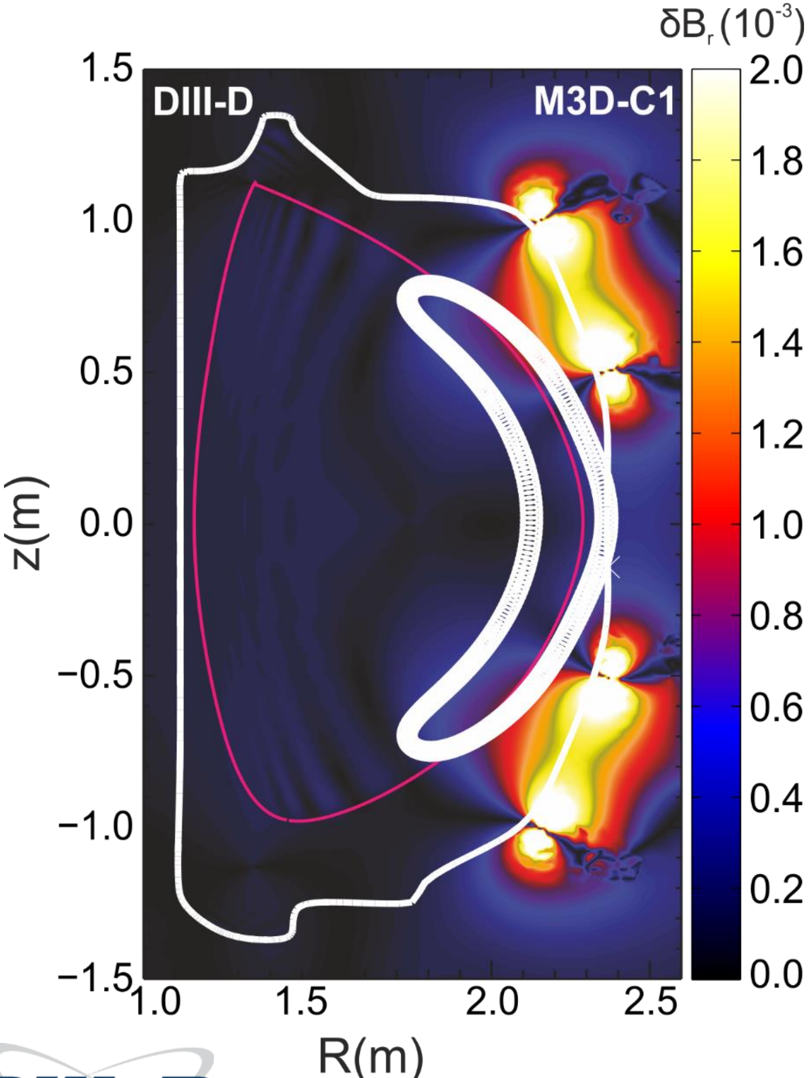

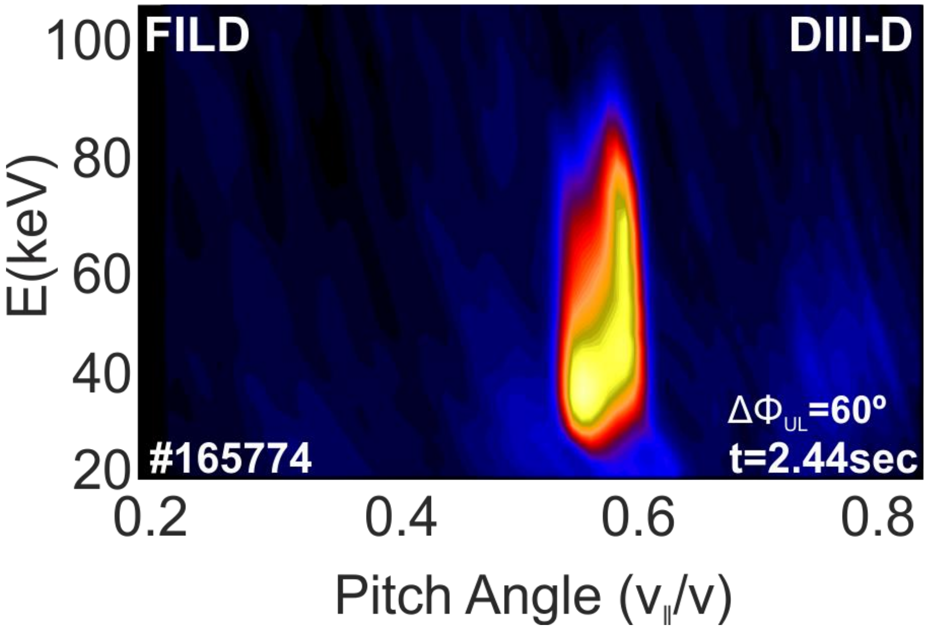

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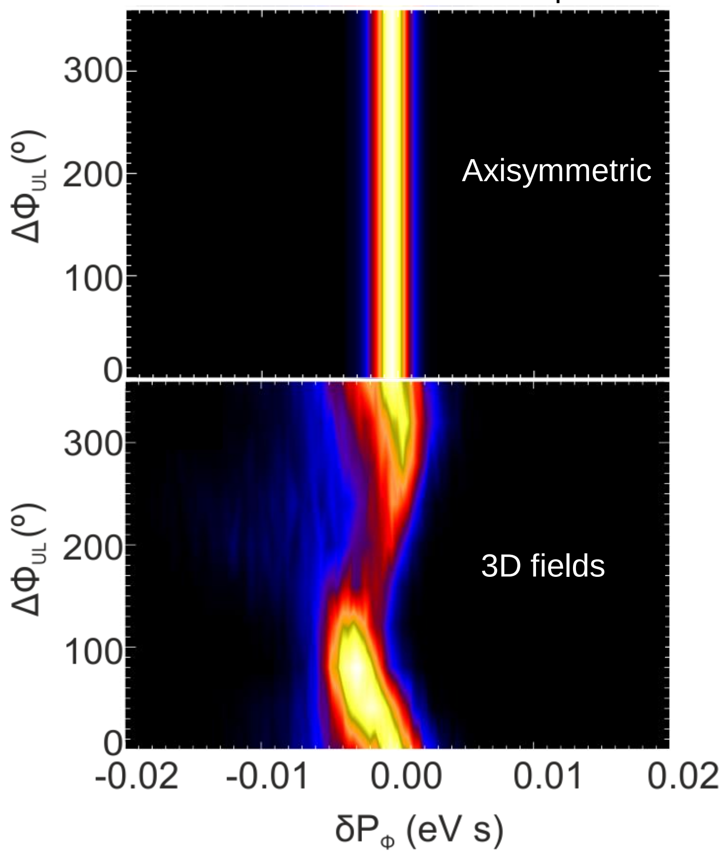
Poloidal Spectrum of 3D Fields Has Strong Impact on Fast-Ion Toroidal Canonical Momentum (P_Φ)

- SPIRAL used to calculate δP_Φ due to applied 3D fields including M3D-C1 plasma response and collisions

- Fast-ion δP_Φ depends strongly on $\Delta\Phi_{UL}$
  - Large δP_Φ for $\Delta\Phi_{UL}$ =90-100º
  - Negligible δP_Φ for $\Delta\Phi_{UL}$ =200º

$$P_\Phi = mRv_\Phi - Ze\Psi_p$$



$\delta P_\Phi < 0 \rightarrow$ outwards transport

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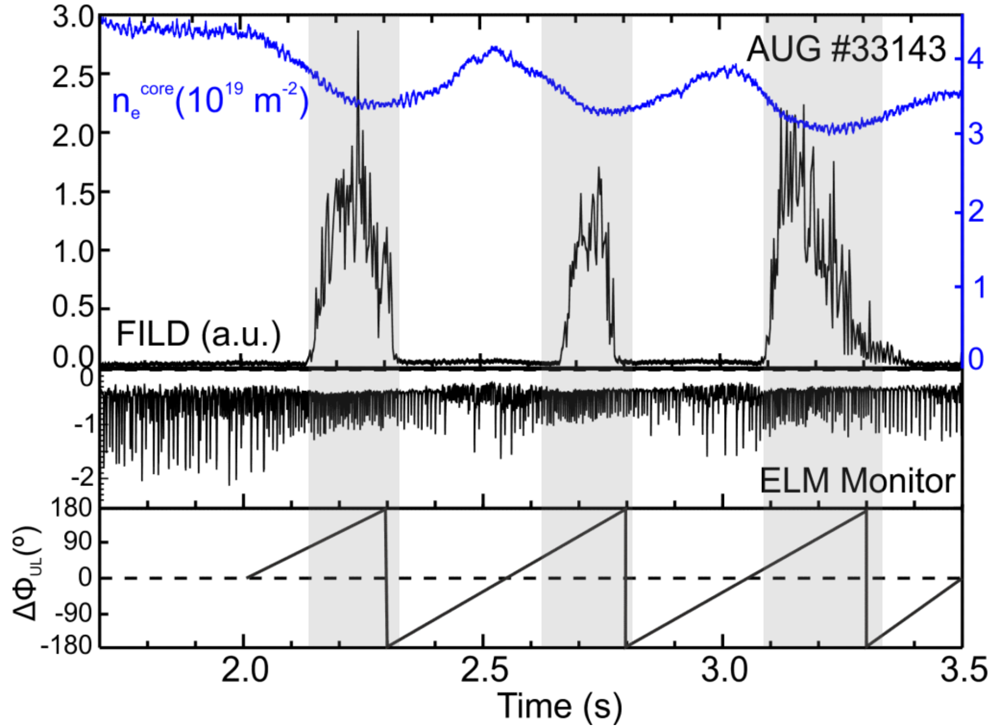
Companion Experiments in AUG Show Fast-Ion Losses Induced by 3D Fields in Narrow Poloidal Spectrum Range

- In ELMy, high β_N, low collisionality and q_{95} H-mode plasma
- Poloidal spectrum of n=2 3D fields is continuously modified by varying $\Delta\Phi_{UL}$
- Density pump-out and partial ELM mitigation observed as soon as coils are ON
- Clear dependency of ELM activity, density pump-out and fast-ion losses on 3D fields poloidal spectrum



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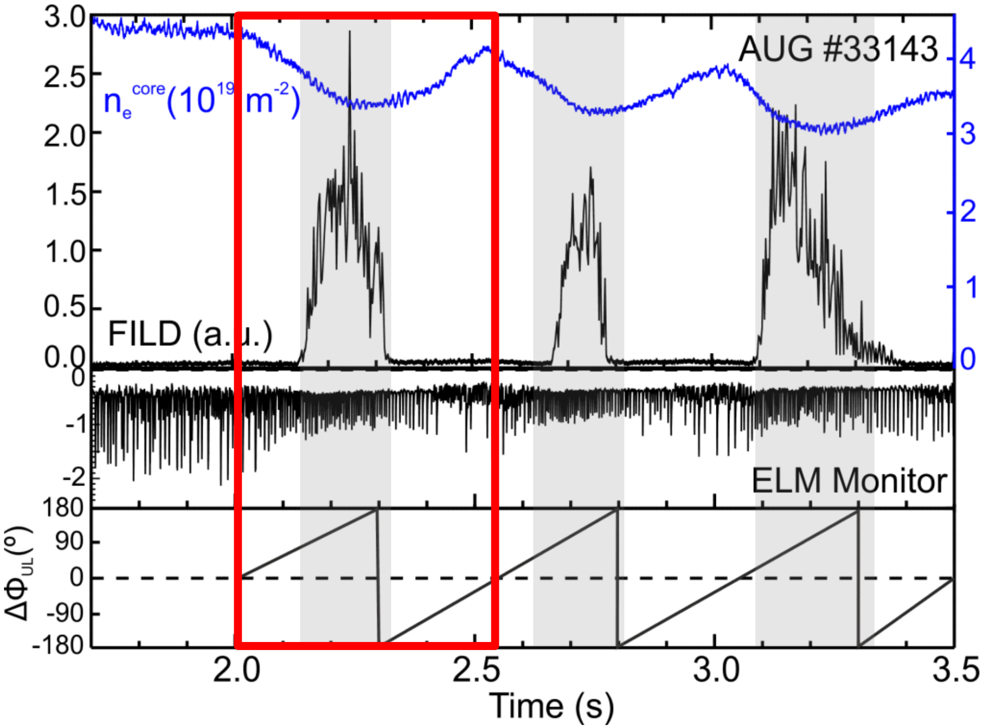
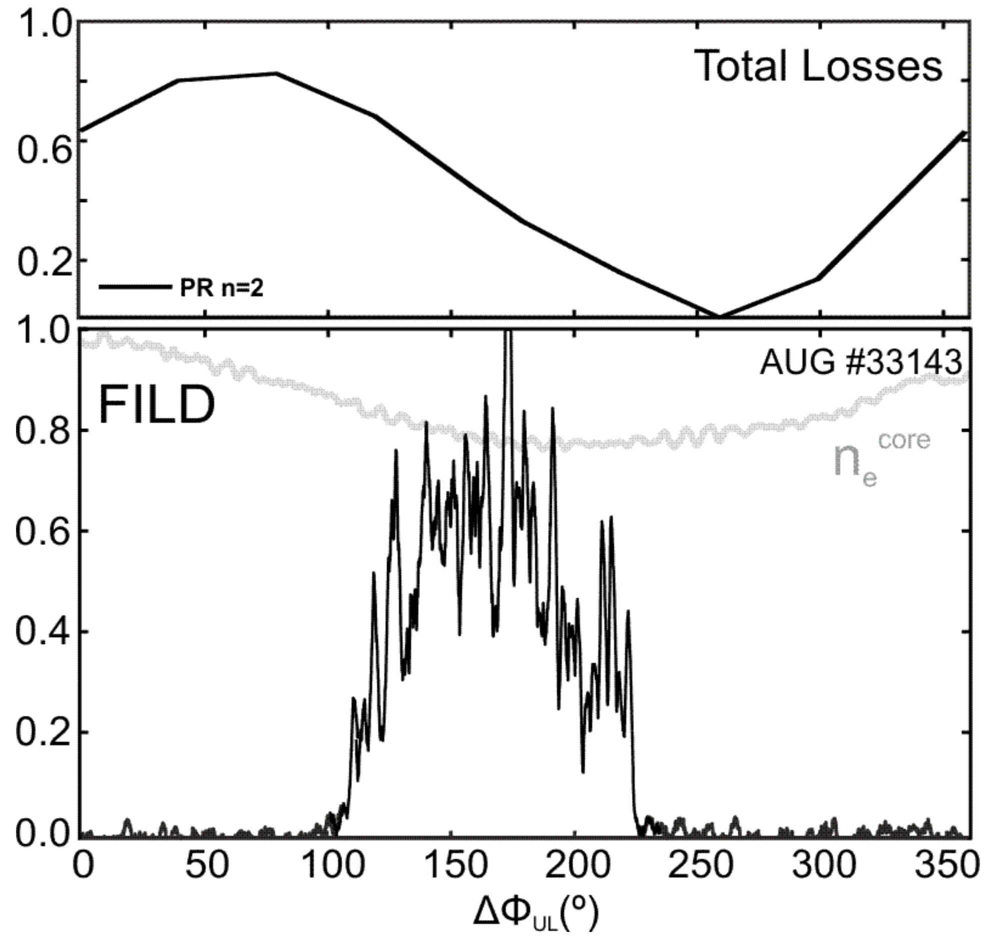


Simulations Predict Strong Dependency of Fast-Ion Losses On 3D Fields Spatial Structure

- Orbit simulations using n=2 MARS-F fields reproduce $\Delta\Phi_{UL}$ (poloidal spectrum) dependency



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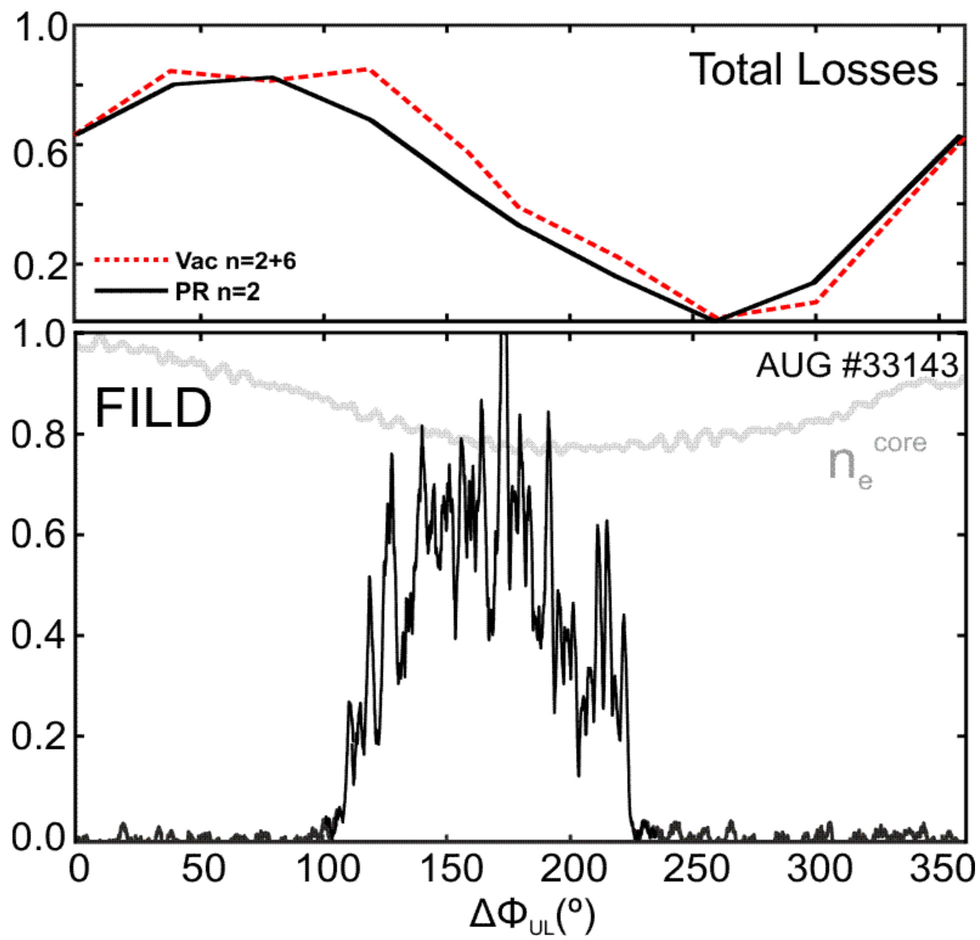

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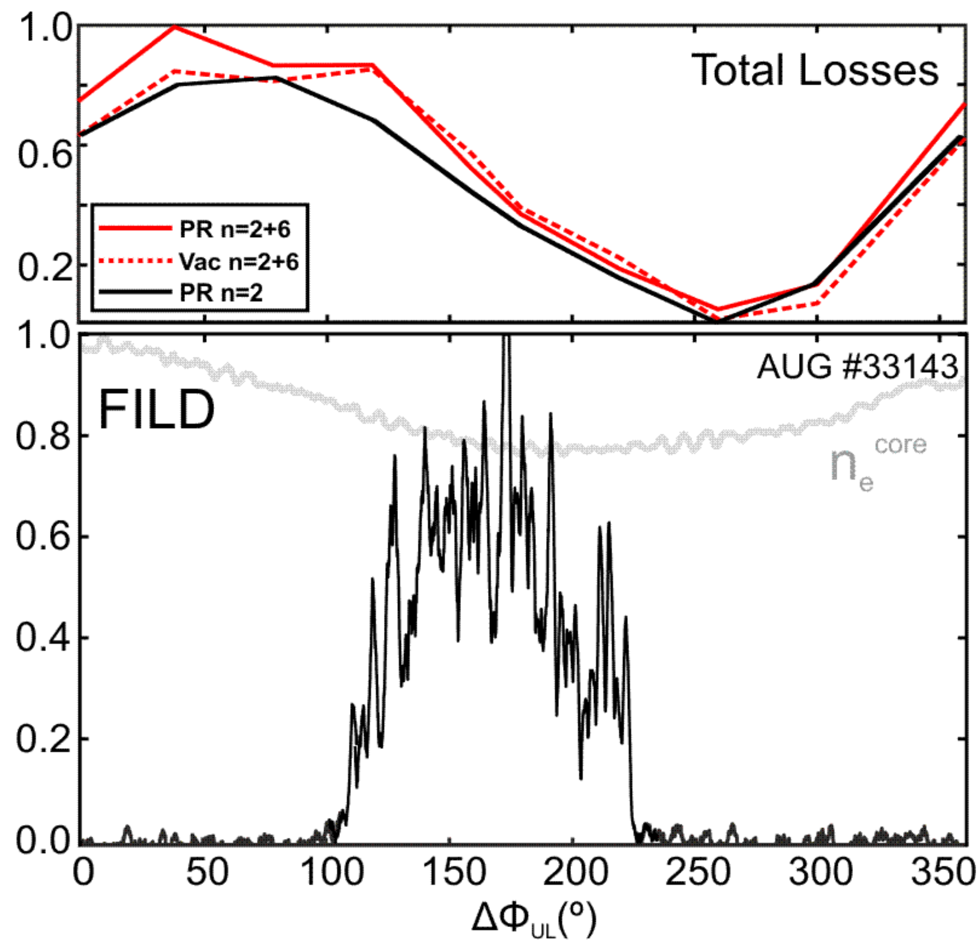

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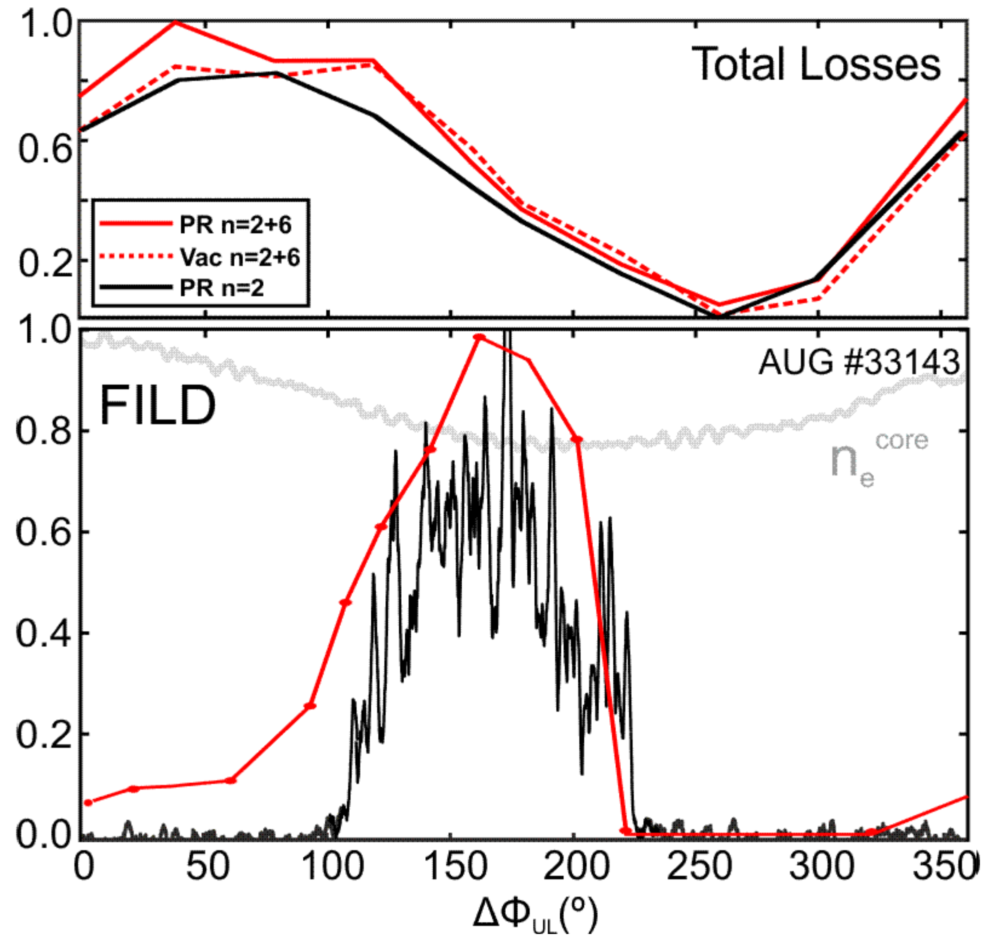

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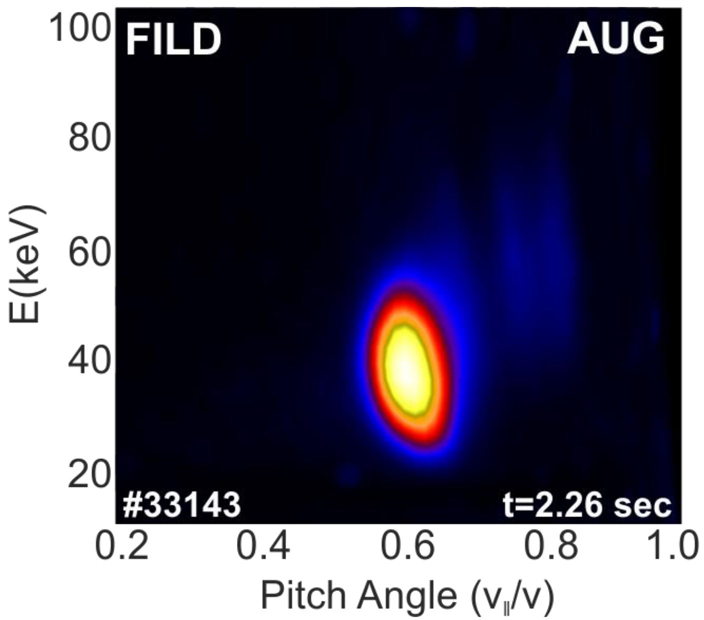

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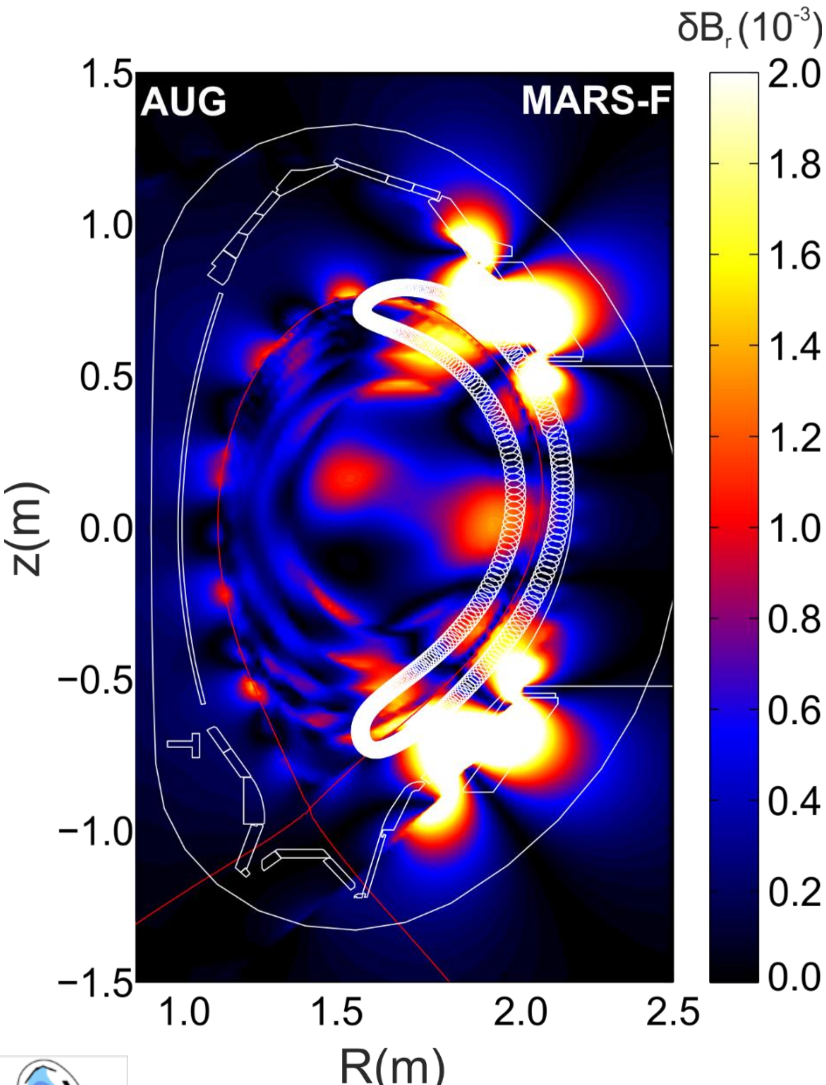

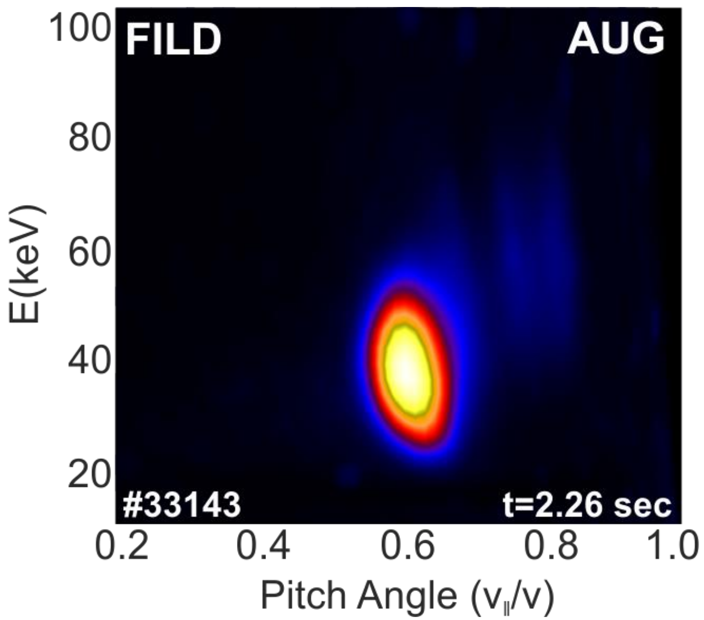

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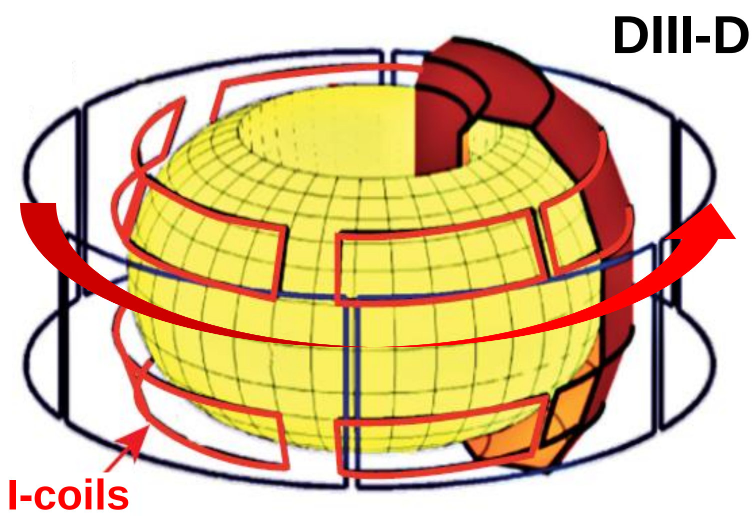
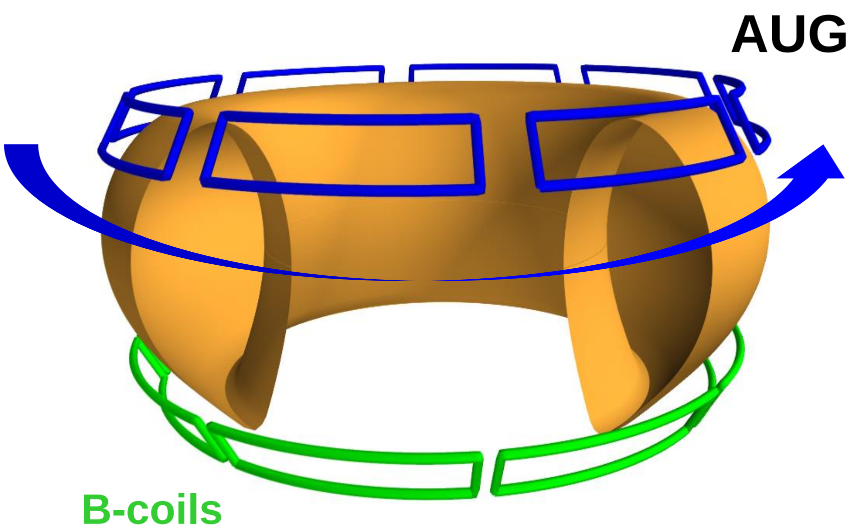
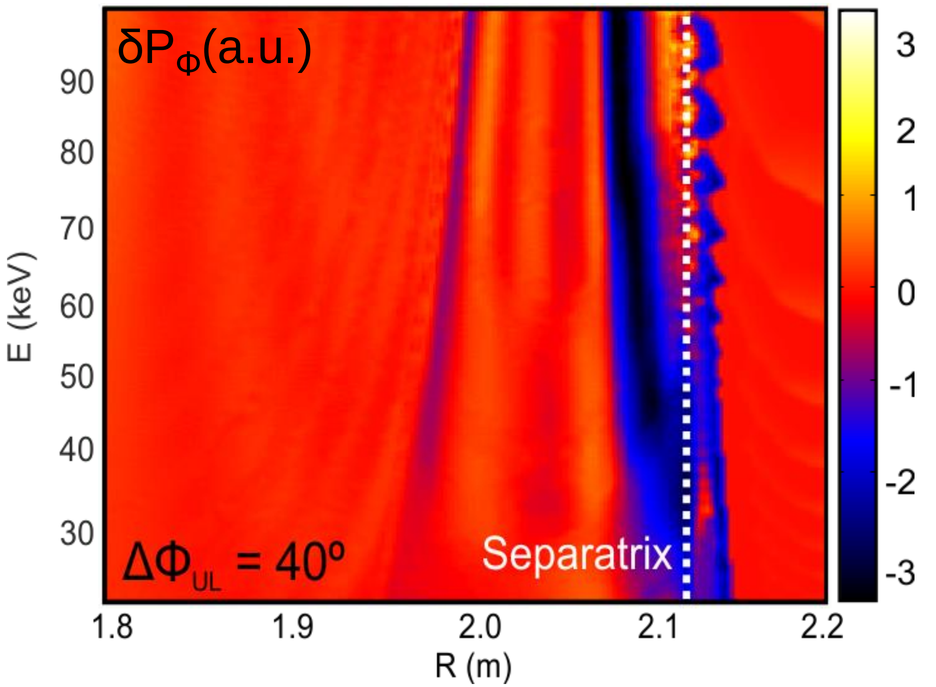




Calculations of Fast-Ion δP_Φ due to 3D Fields Reveal Transport is Resonant and Localized Around Separatrix

- ASCOT is used to calculate fast-ion δP_Φ for all $\Delta\Phi_{UL}$ using realistic NBI distribution
- MARS-F n=2+6 3D fields
- No TF-ripple
- No collisions
- Realistic 3D wall

$$P_\Phi = mRv_\Phi - Ze\Psi_p$$



$\delta P_\Phi < 0$ (blue-black) → outwards transport

$\delta P_\Phi > 0$ (yellow-white) → inwards transport

ASDEX Upgrade

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- Orbital resonances intrinsic to magnetic background

  $\omega_{pol}/\omega_{tor}=n/p$

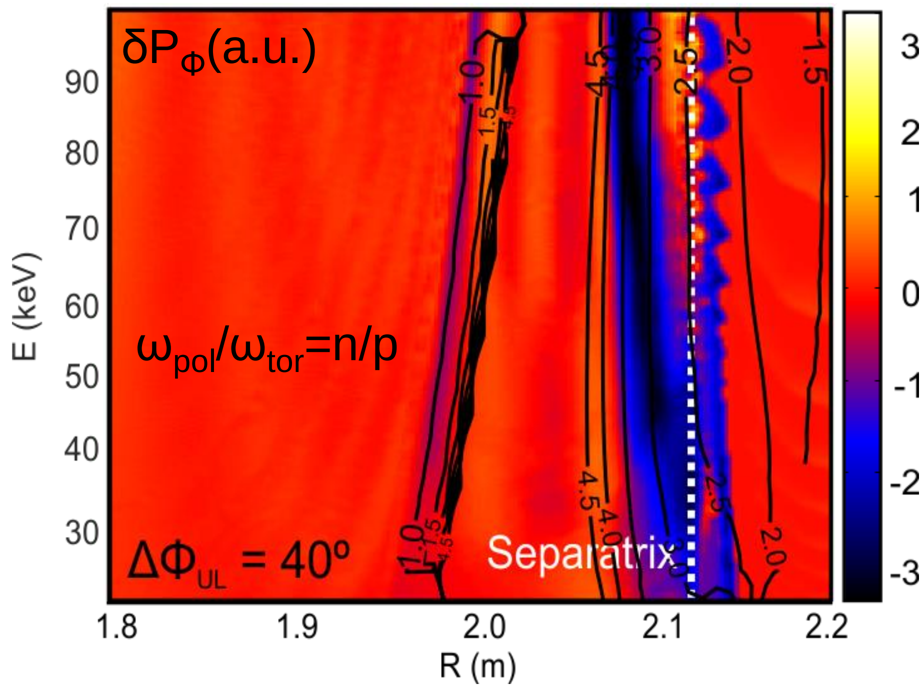
  perfectly match δP_Φ regions

- Maximum transport caused by resonance overlap

- Fractional resonances* seem to play important role

- Poloidal spectrum determines in/outwards transport

$P_\Phi = mRv_\Phi - Ze\Psi_p$



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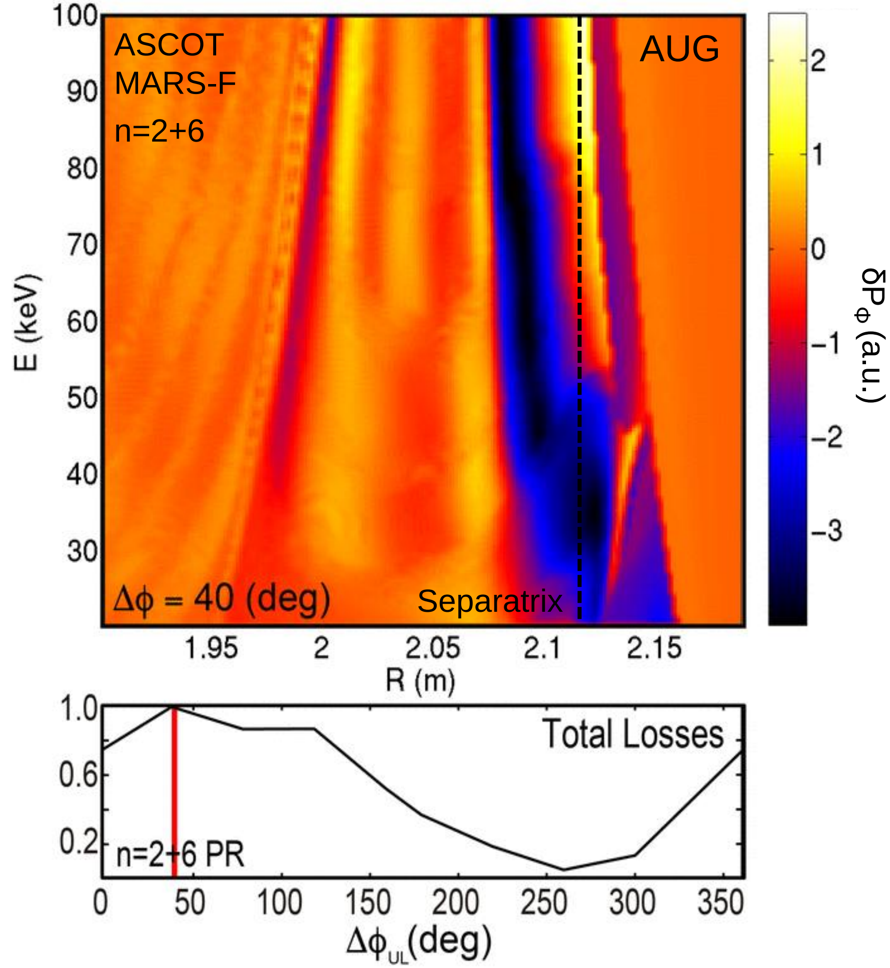

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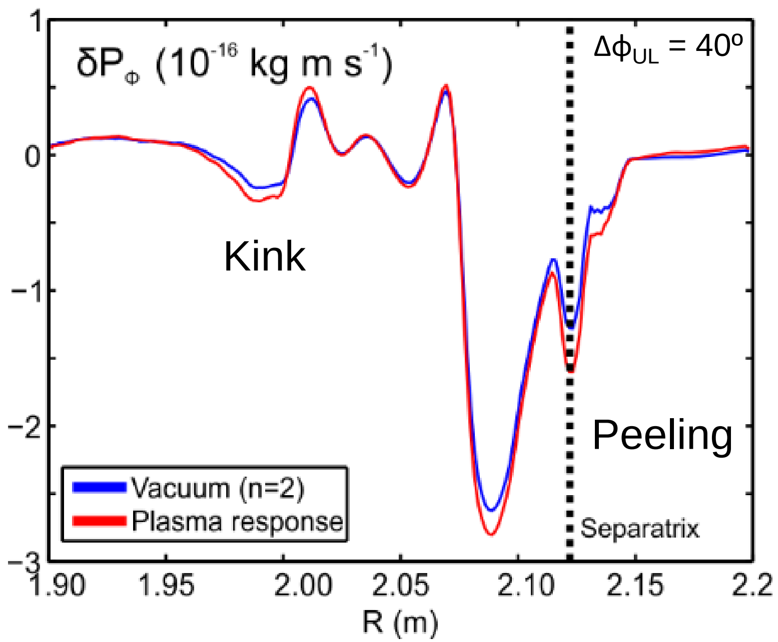
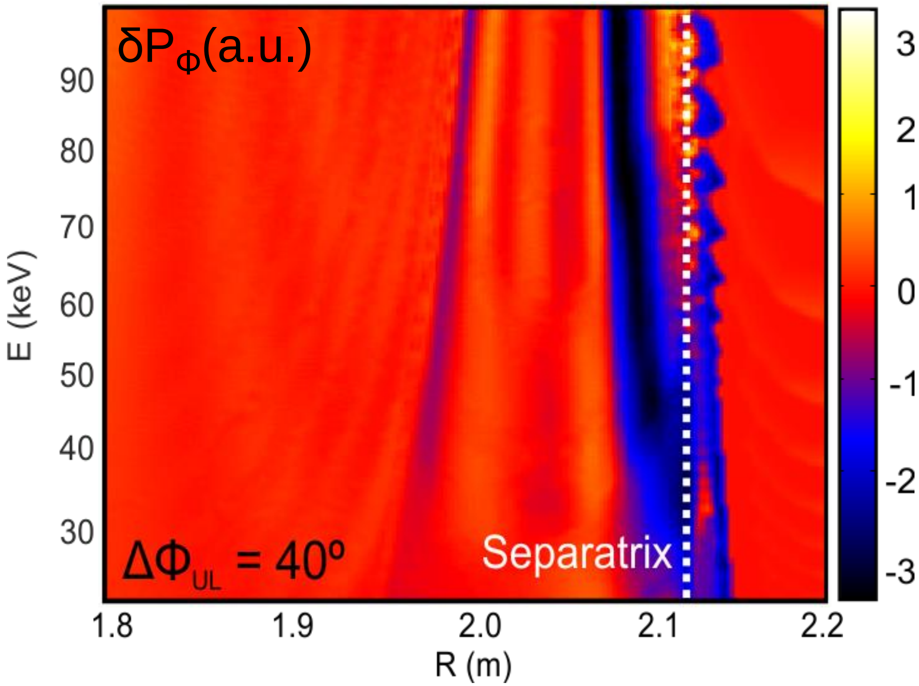
Plasma Response to Applied 3D Fields Modifies Fast-Ion Transport Locally

ASDEX Upgrade

- Edge peeling response has strong impact on fast-ion transport due to Edge Resonant Transport Layer





- Internal kink response causes enhanced local transport due to internal resonance

$\delta P_{\Phi} < 0$ (blue-black) → outwards transport

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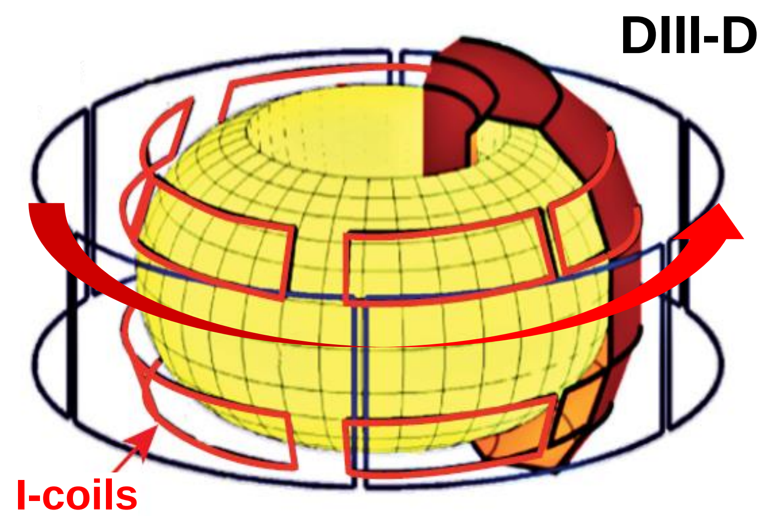
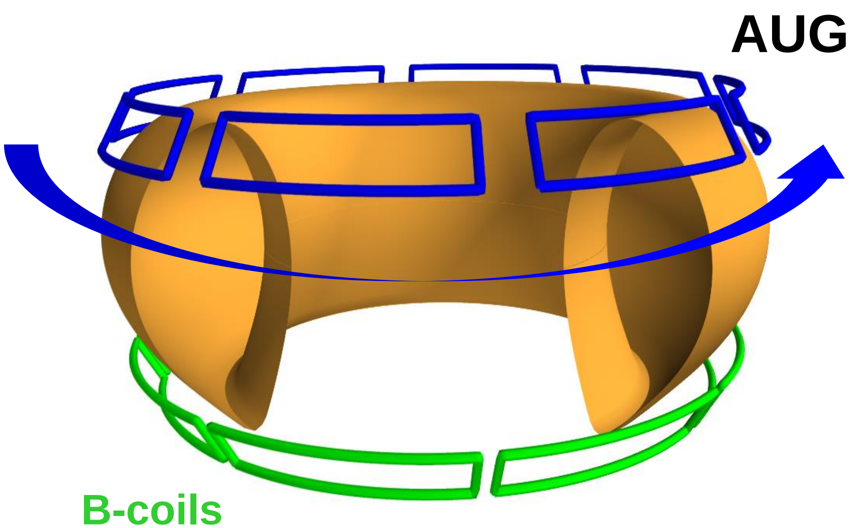
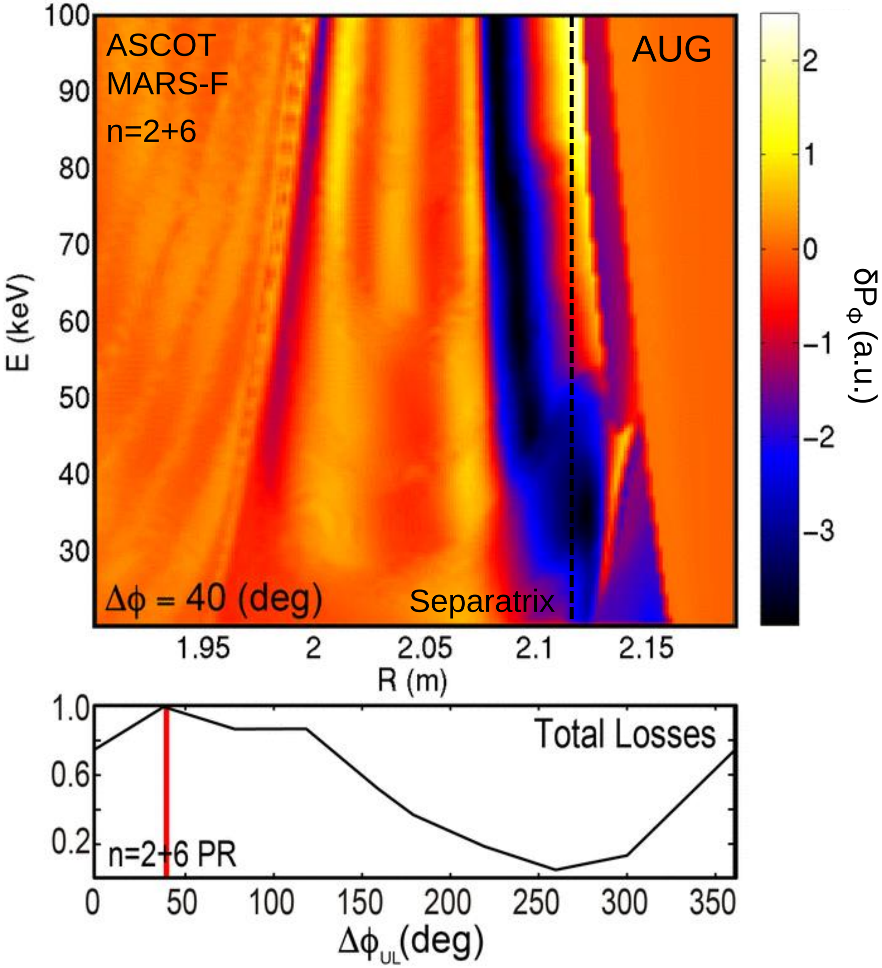




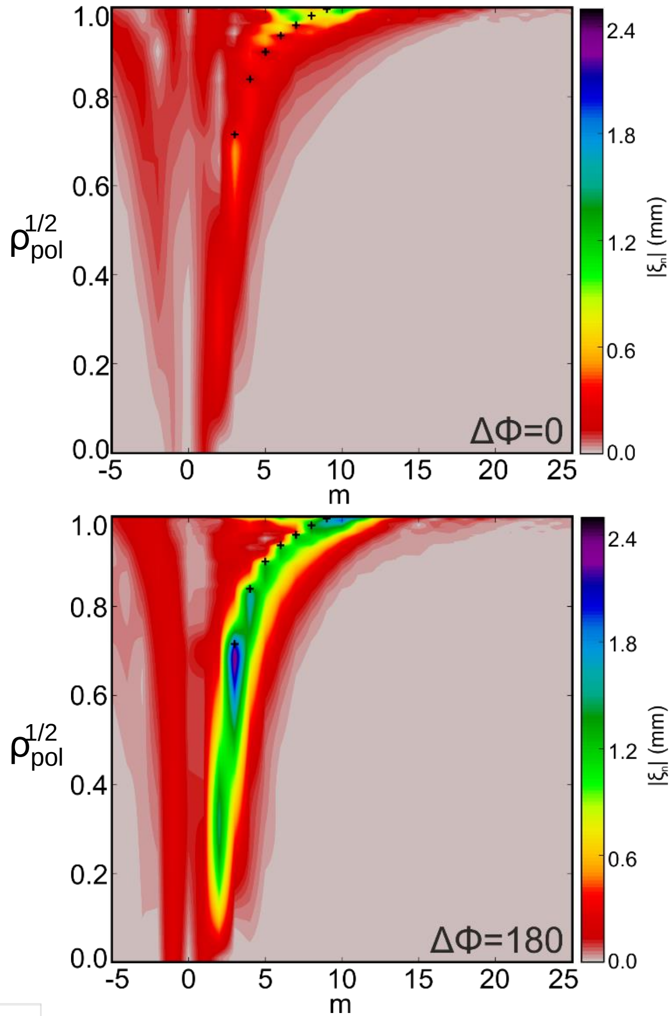
Conclusions

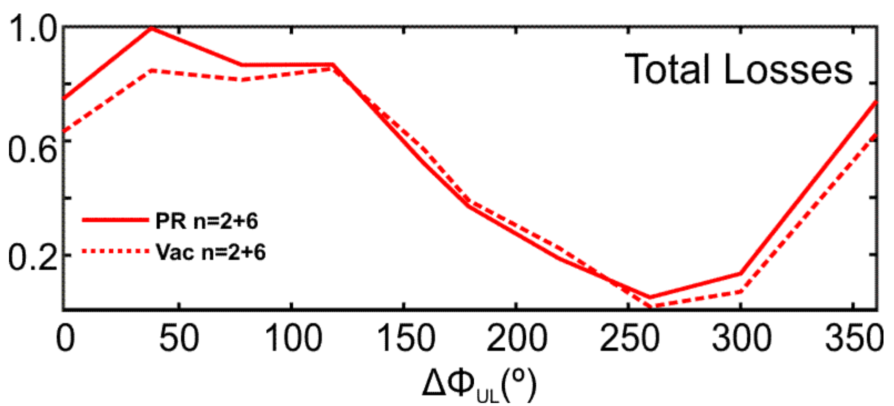
- Joint experiments at AUG and DIII-D show that fast-ions are extremely sensitive to externally applied 3D fields and their:
  - Poloidal spectrum
  - Toroidal spectrum
  - Plasma response
- In AUG, orbital resonances intrinsic to magnetic background are responsible for observed losses
- Fast-ion δP_Φ due to 3D fields reveals existence of Edge Resonant Transport Layer (ERTL)
- ERTL properties may help optimizing 3D fields structure in present and future devices



BackUp

Edge Peeling Amplification Has Stronger Impact on Total Losses Than Internal Kink Amplification

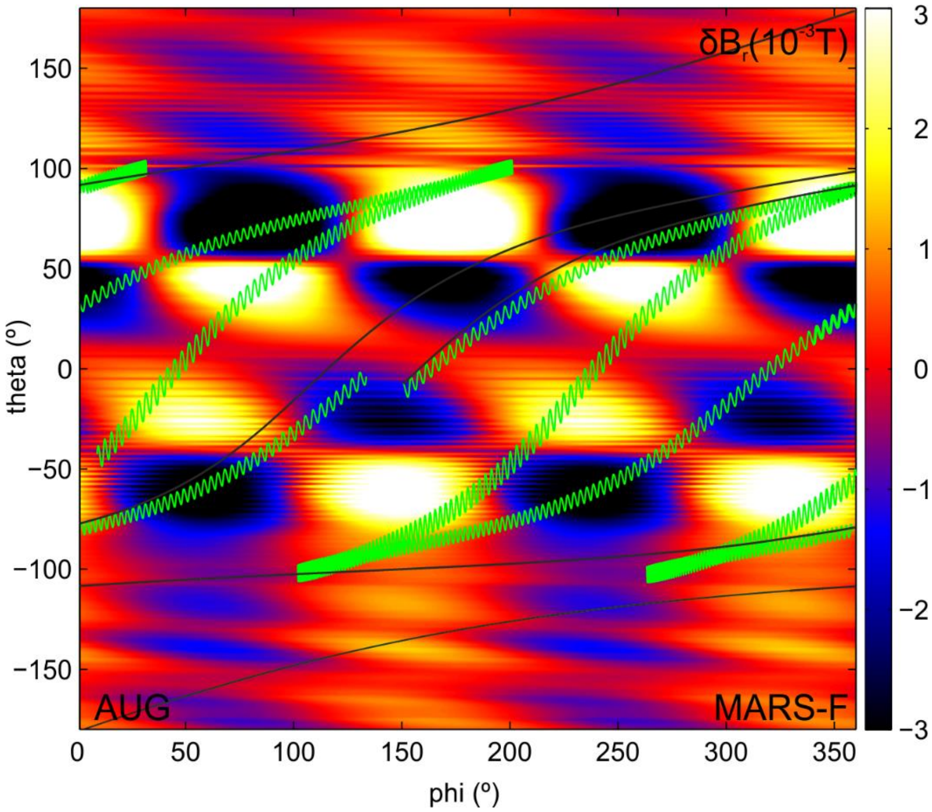


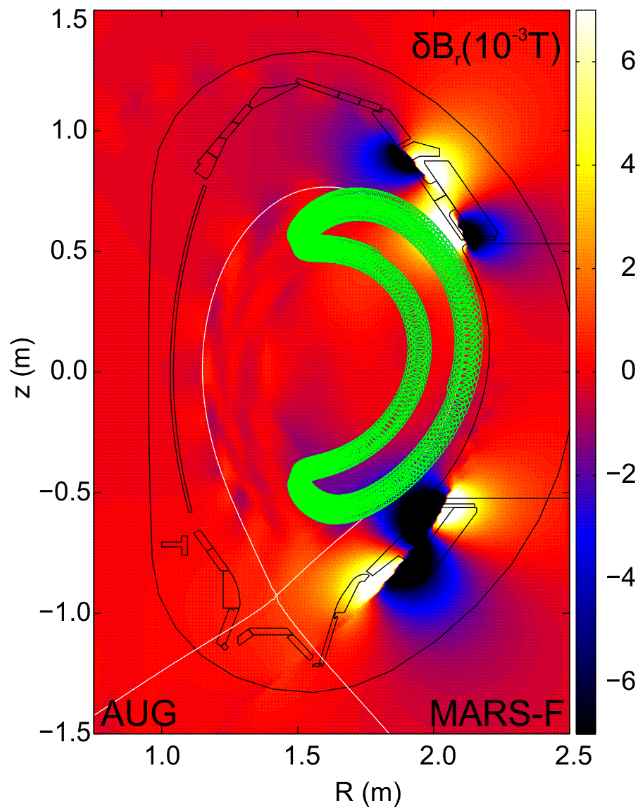


- Strong peeling response at $\Delta\Phi_{UL}$=0º leads to slight amplification of total losses
- Internal kink amplification at $\Delta\Phi_{UL}$=180º does not modify significantly total losses

ASDEX Upgrade

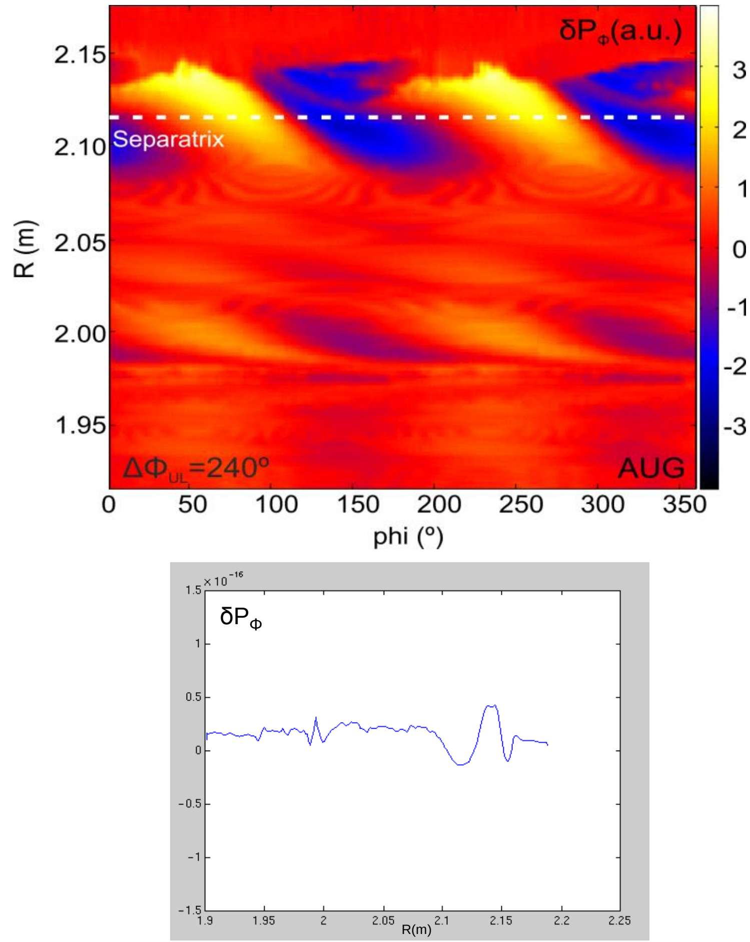
Resonant Ion with 3D Fields

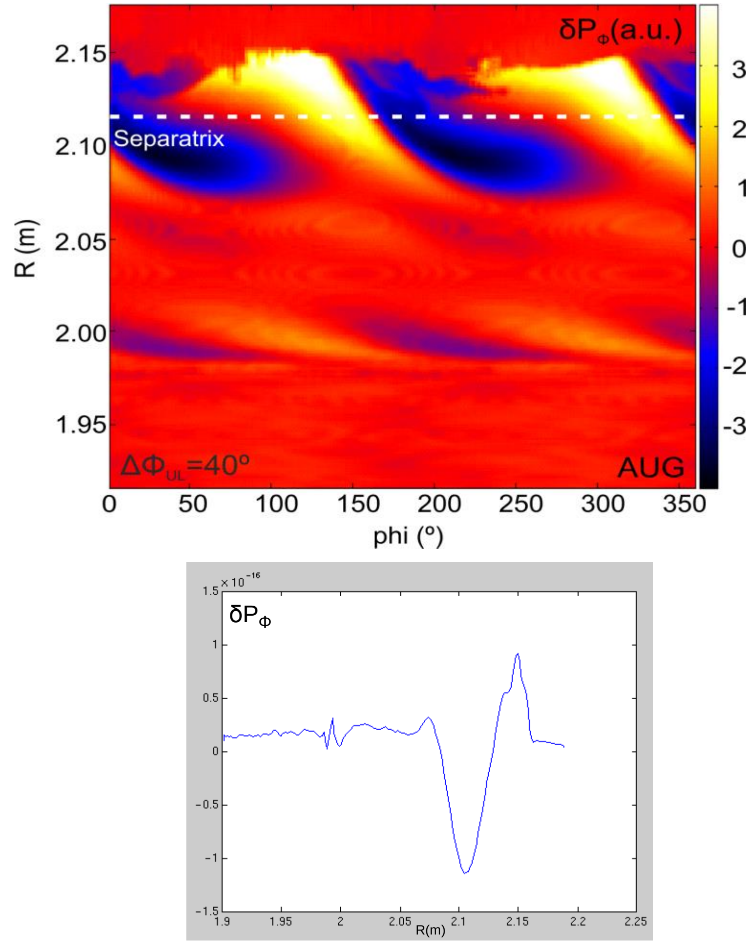




Toroidal Symmetry Does Not Balance Radial Transport in ERTL

ERTL radial profile prevents toroidal symmetry to balance radial transport

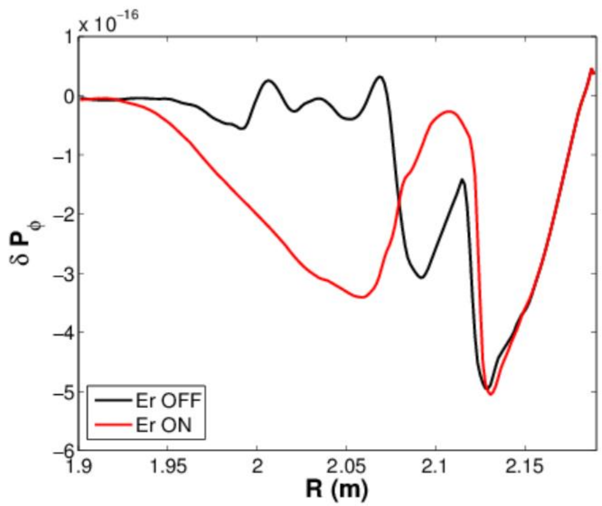


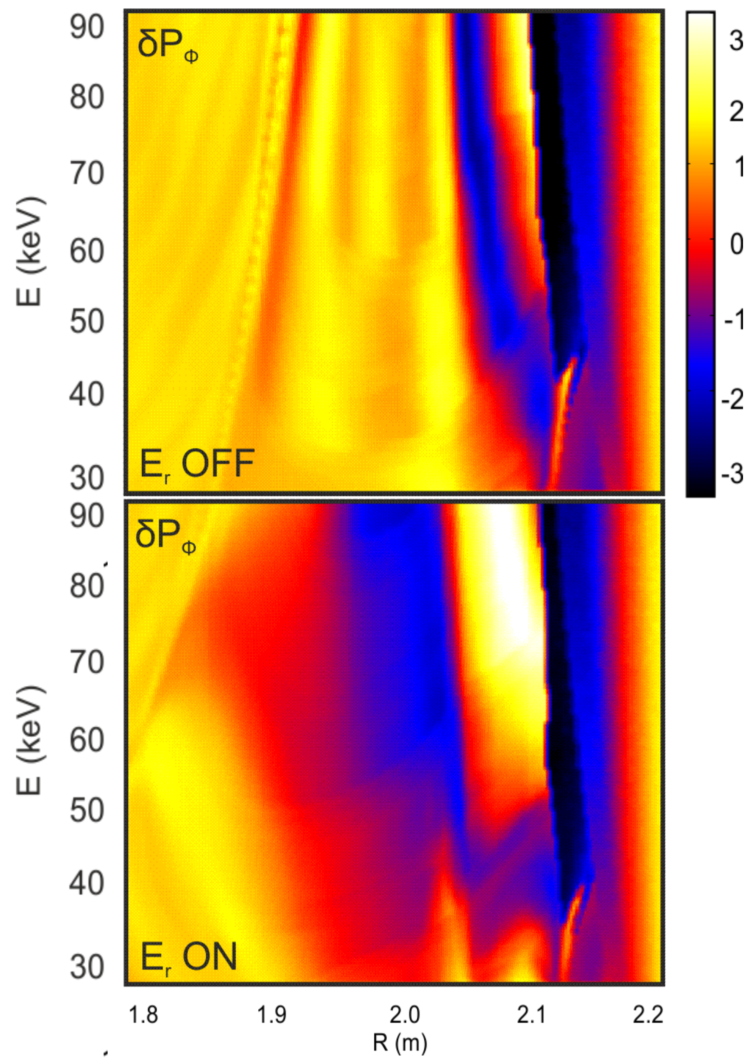


E_r Makes ERTL Wider

- Er reduces losses in ~10% by widening ERTL
- E_r evaluated using radial force balance, assuming neoclassical poloidal rotation

$$E_r = \frac{1}{n_\alpha e}\frac{\partial p_\alpha}{\partial r} - v_\Theta B_\varphi + v_\varphi B_\Theta$$





Resonances Over a Broad Range of Pitch Angles