17th Technical Meeting on Energetic Particles and Theory of Plasma Instabilities in Magnetic Confinement Fusion

EUROfusion

# Mitigation of AE induced ICRF fast-ion losses using deuterium NBI in the ASDEX Upgrade tokamak

J.Galdon-Quiroga, J.Manyer, R.Bilato, M.Weiland, B.Simmendefeldt, V.Bobkov, M.Dreval, M.Garcia-Munoz, J.Hidalgo, A.Karpushov, A.Kappatou, Y.Kazakov, Ph.Lauber, M.Mantsinen, R.Ochoukov, J.Rueda-Rueda, M.Salewski, Ph.Schneider, S.Sharapov and the ASDEX Upgrade and WPTE RT10 Teams

IPP ASDEX Upgrade · Universidad de Sevilla · PSFT Plasma Science and Fusion Technology

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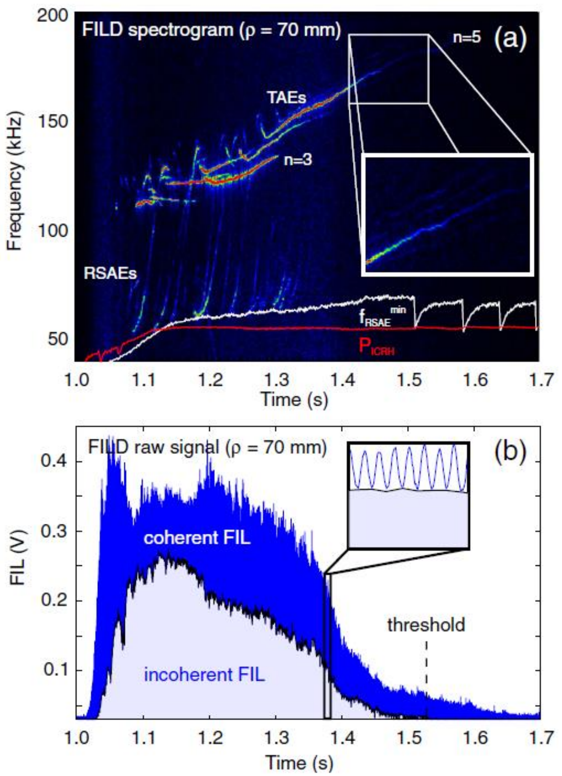
# Control strategies for AEs and associated FI transport are needed

- AEs lead to enhanced fast-ion transport and eventual losses[1]

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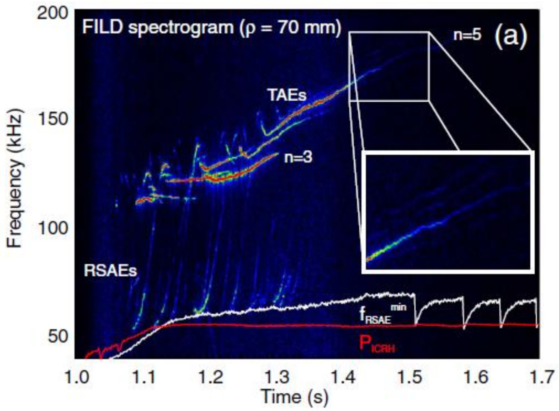


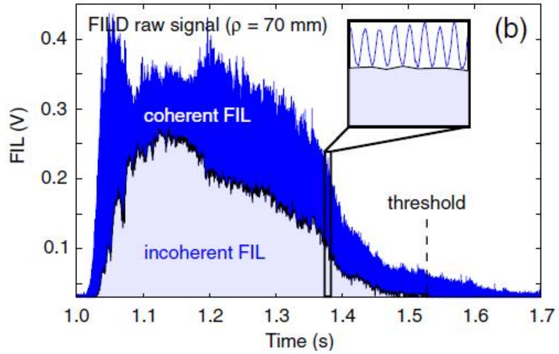


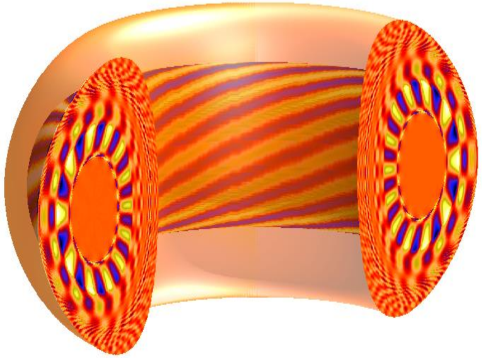

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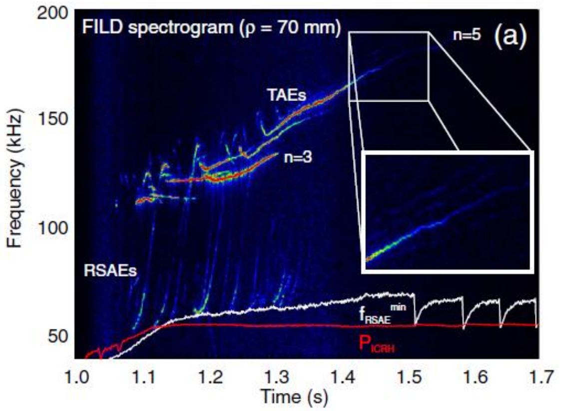
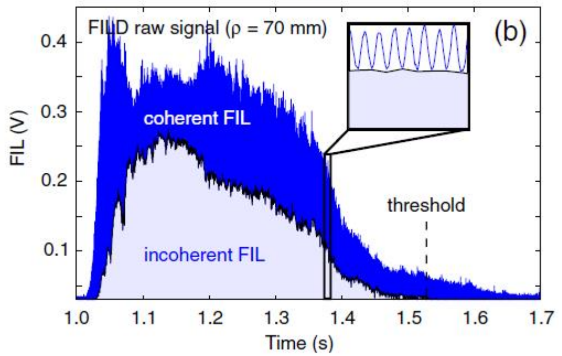
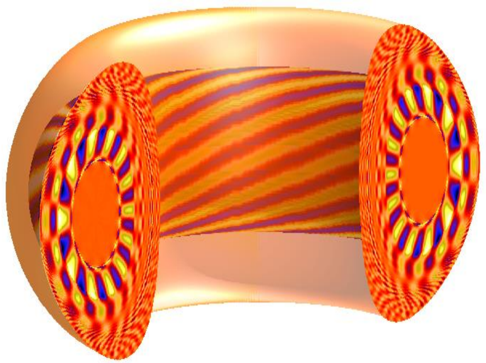
- **If not possible, recipes to minimize fast-ion transport & losses are needed**

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# Outline

- Motivation
- Experimental observations
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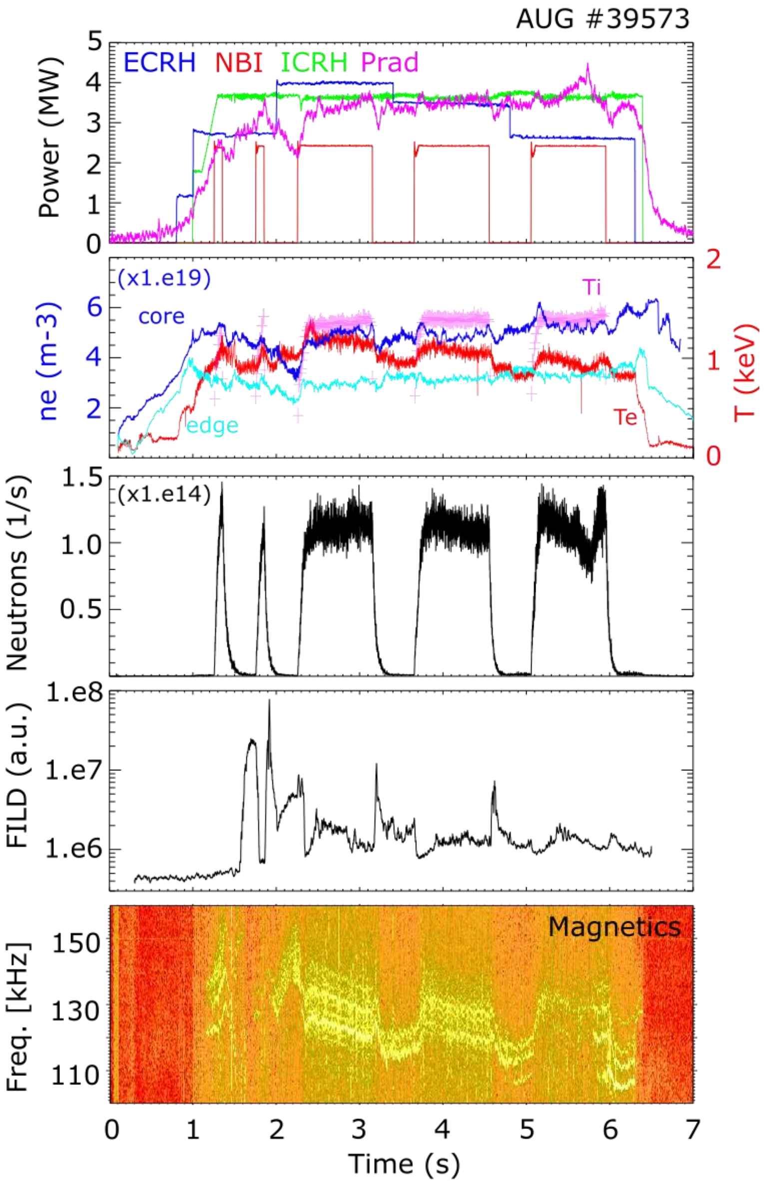
- 4 MW ICRF **central minority H heating** create FI population which drives TAEs unstable



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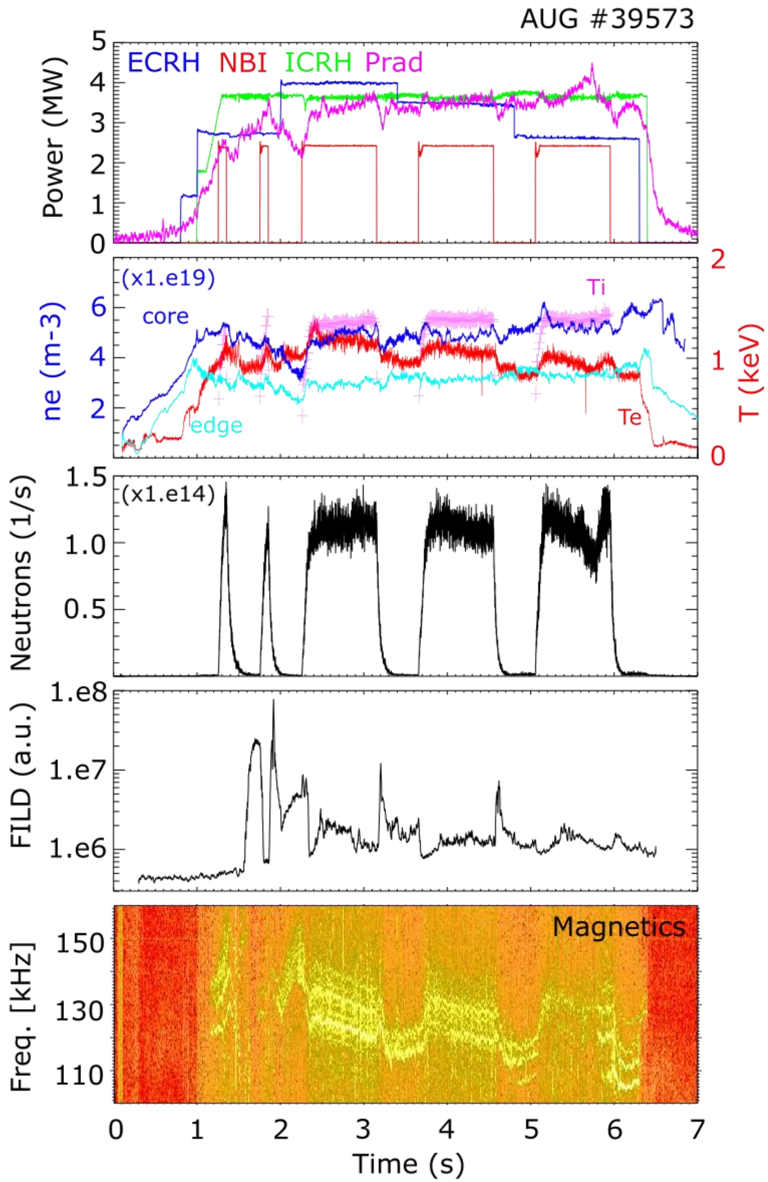

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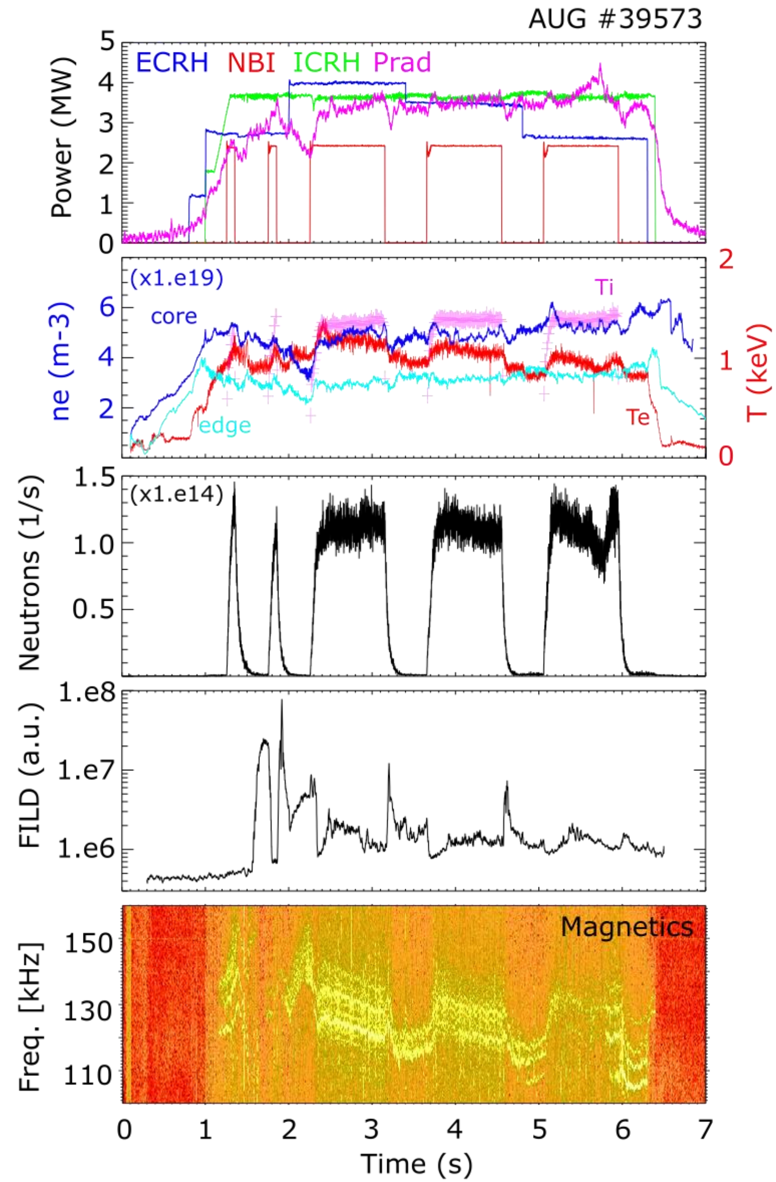

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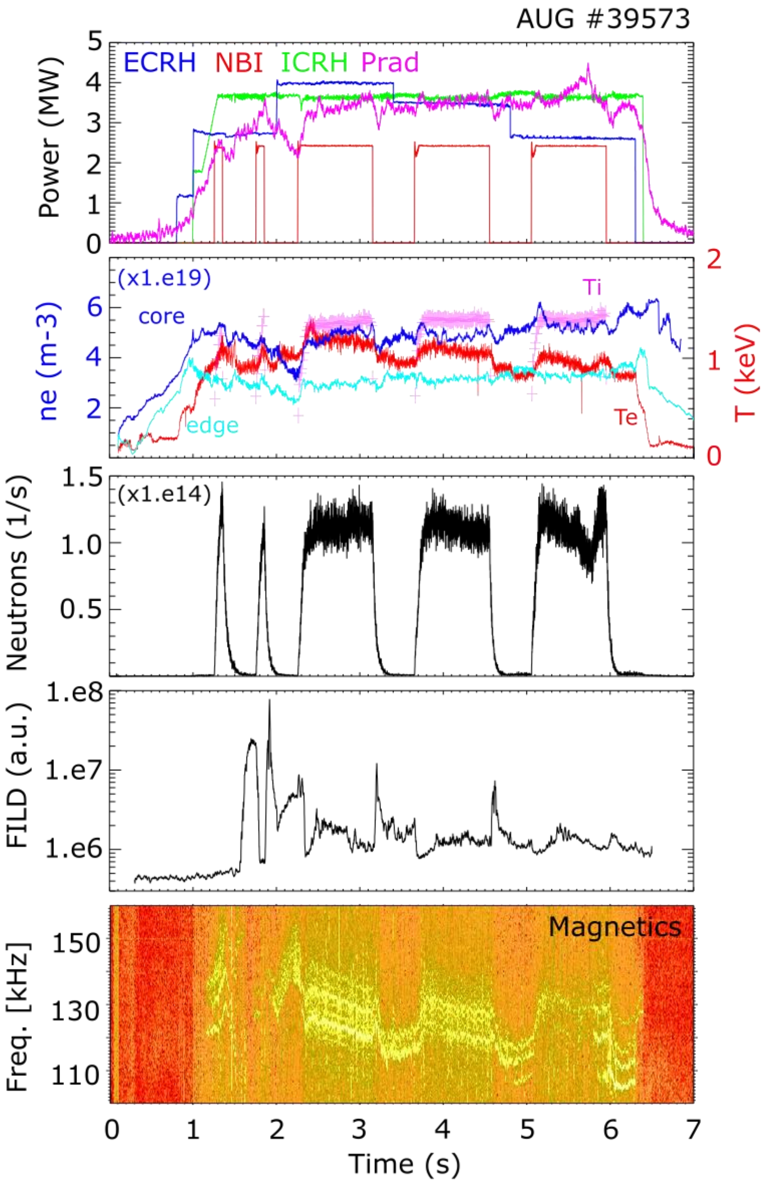
- **Deuterium NBI**, originally for diagnostic purposes



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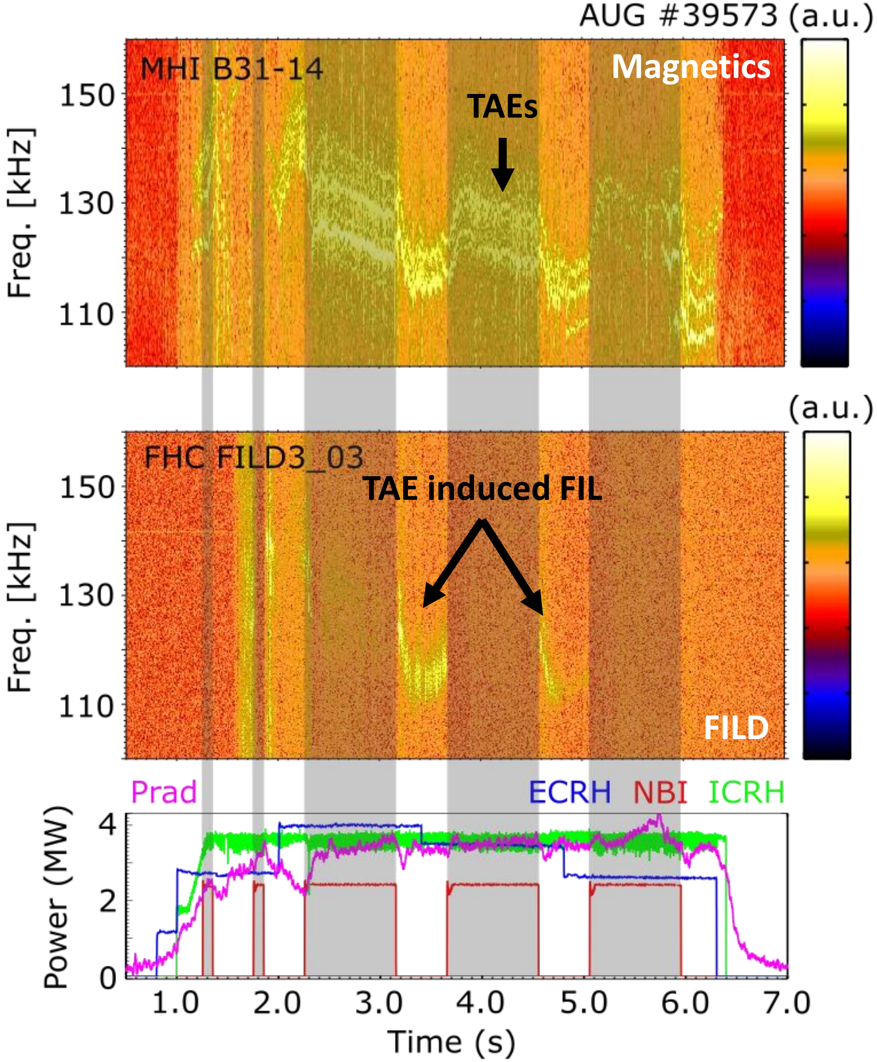

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- Full or partial mitigation when NBI is applied, depending on ECRH power level
  - ➢ **Phase I: high $\tau_{SD}$**
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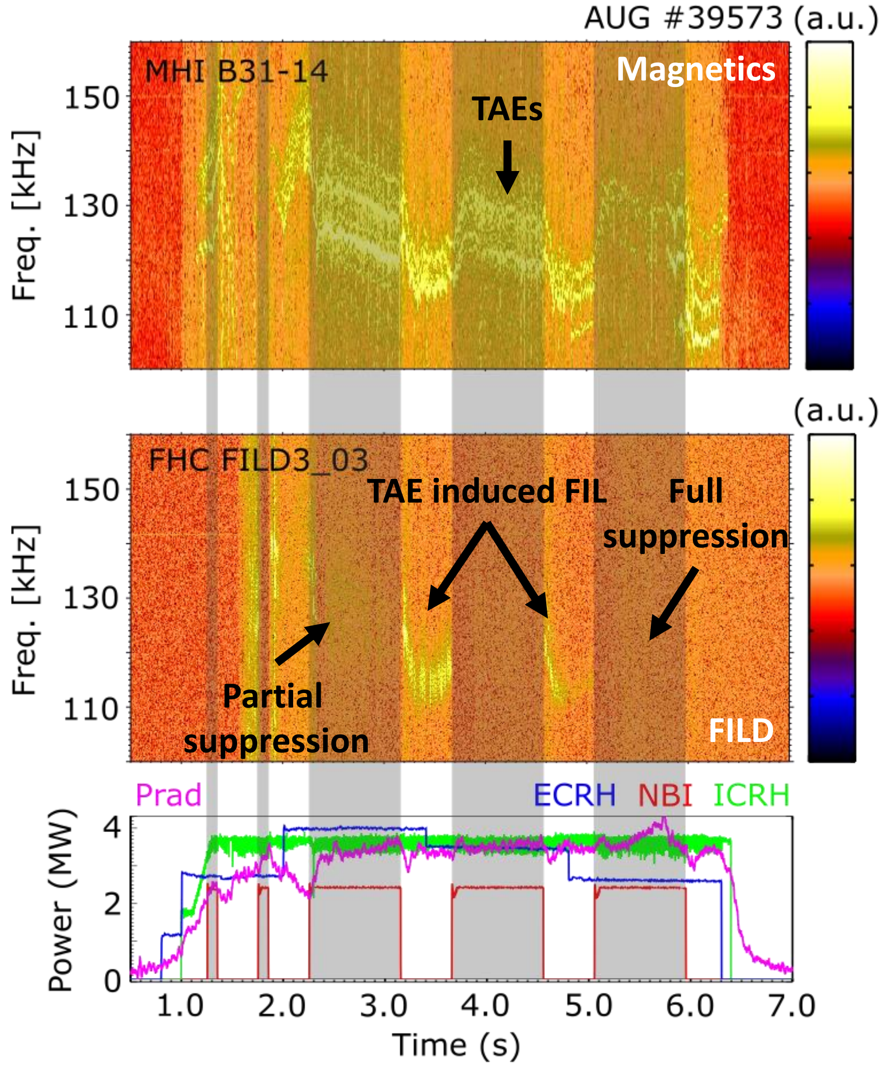

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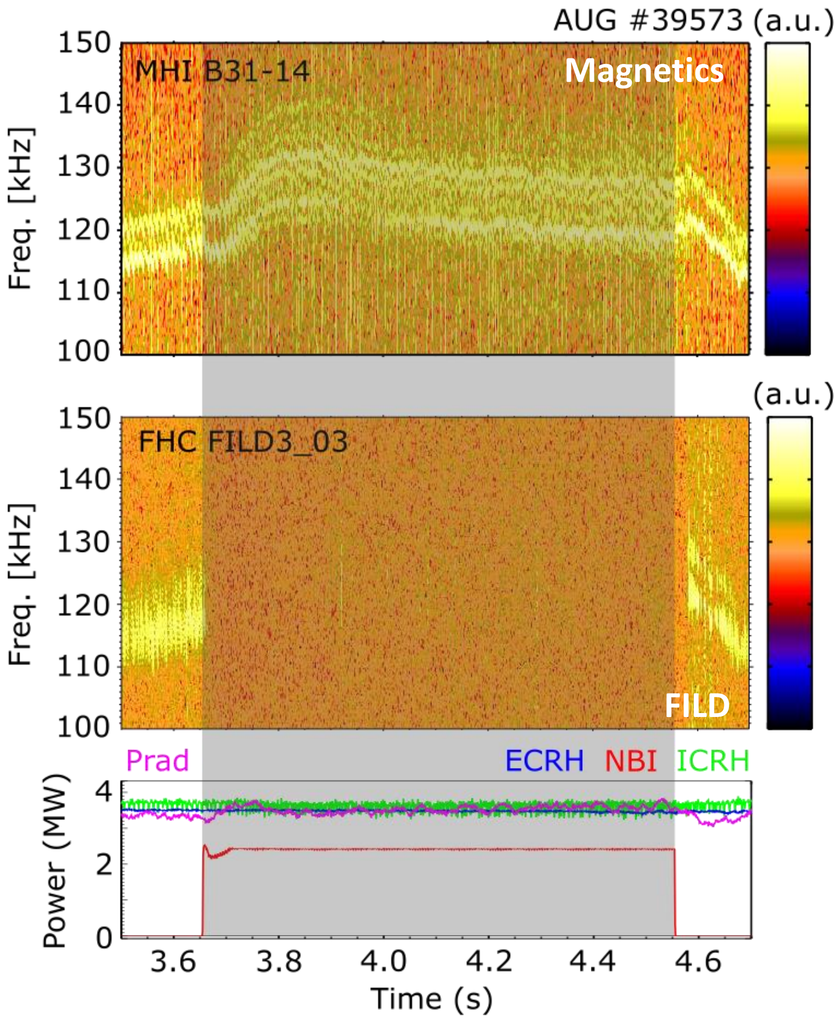

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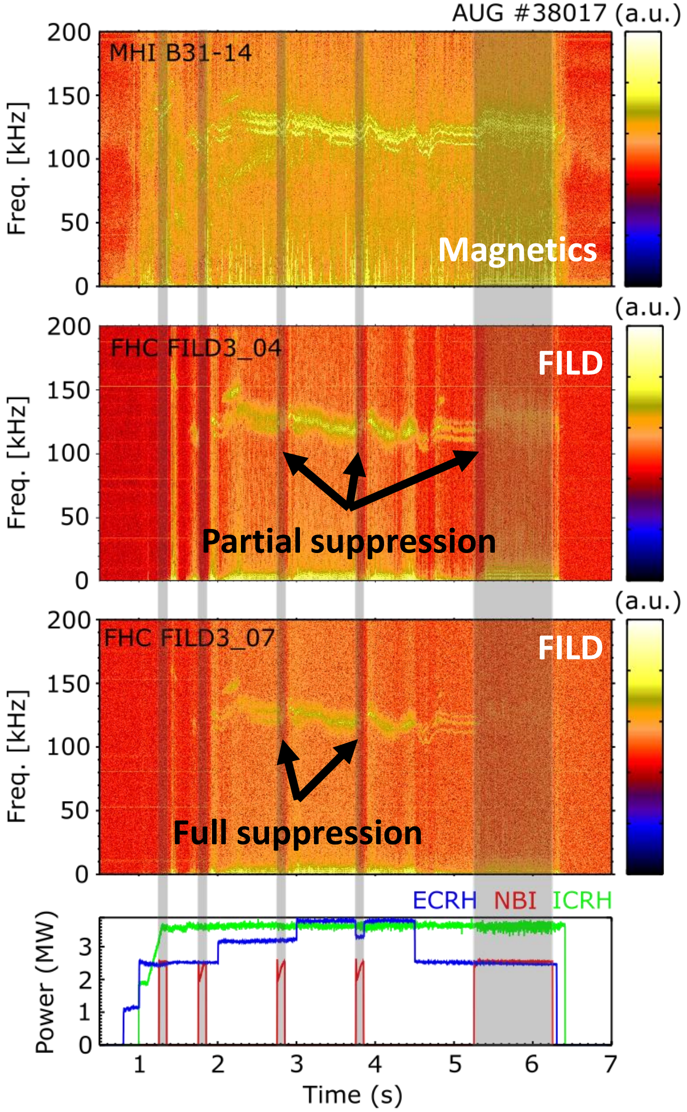
  - #39573: 93 keV (Q8) ~radial
  - #38017: 60 keV (Q3) ~radial

- Differences between channels suggest velocity-space dependency



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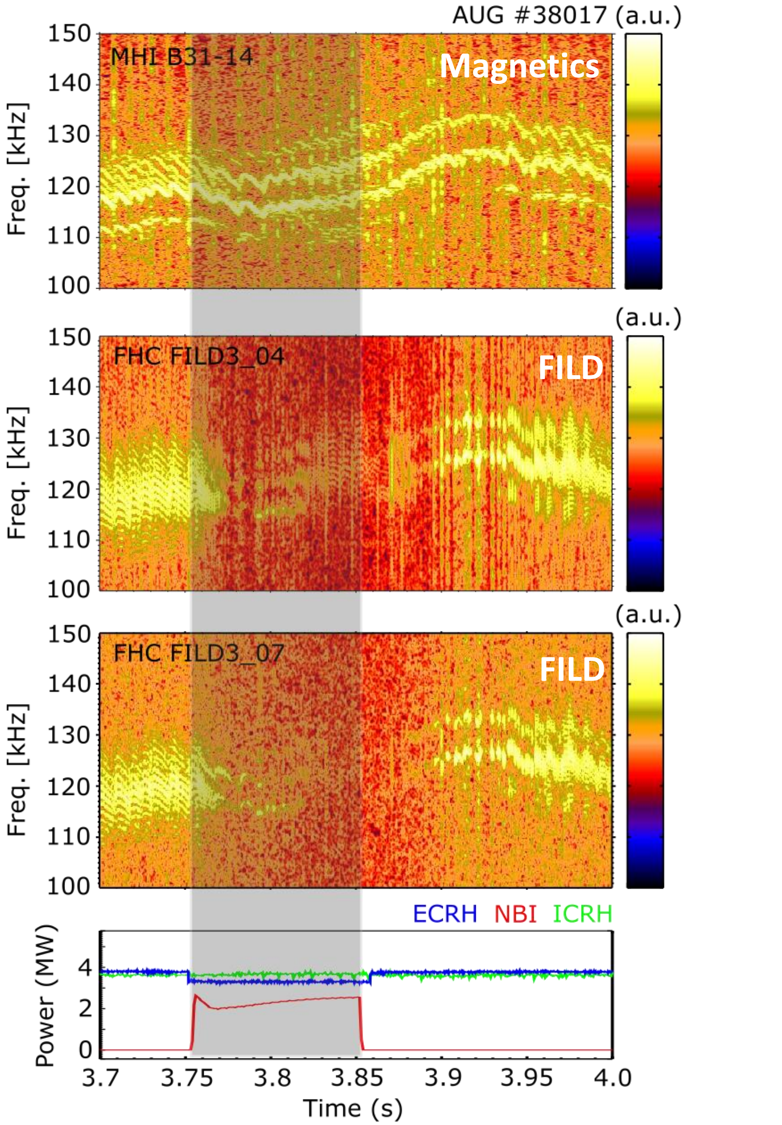
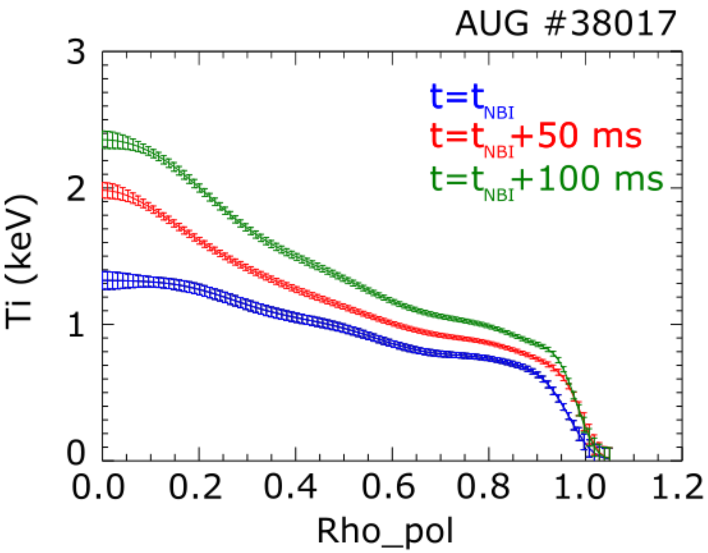
- **FILD signal mitigated/recovered in a timescale of ~50 ms**

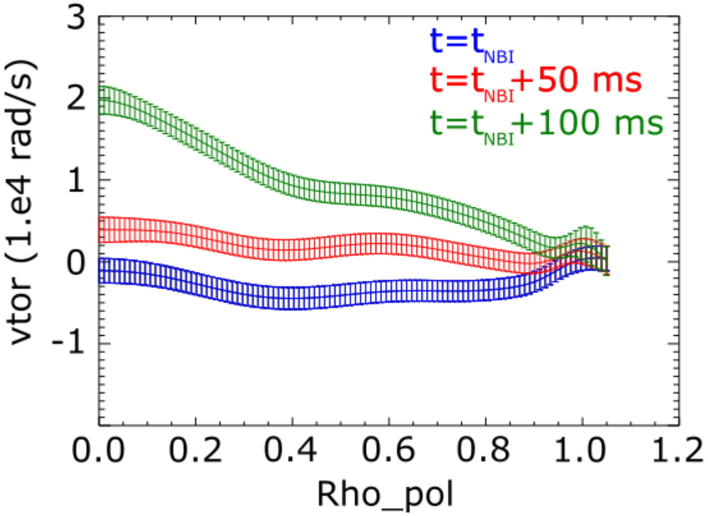


# NBI impacts kinetic profiles and TAEs

- NBI leads to:
  - ➢ Increase in Ti
  - ➢ Increase in toroidal rotation

- Changes in kinetic profiles can impact ICRF tail and TAE structure



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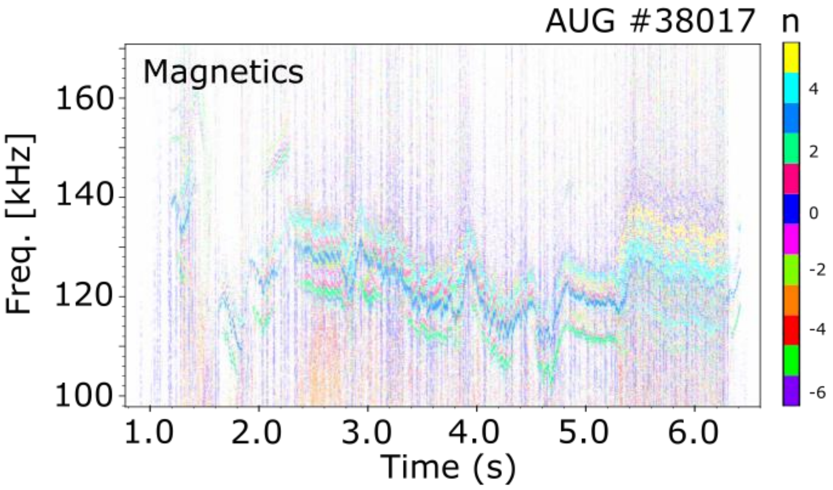


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  - ➢ Toroidal mode numbers are affected (n=2-4 → 3-5)
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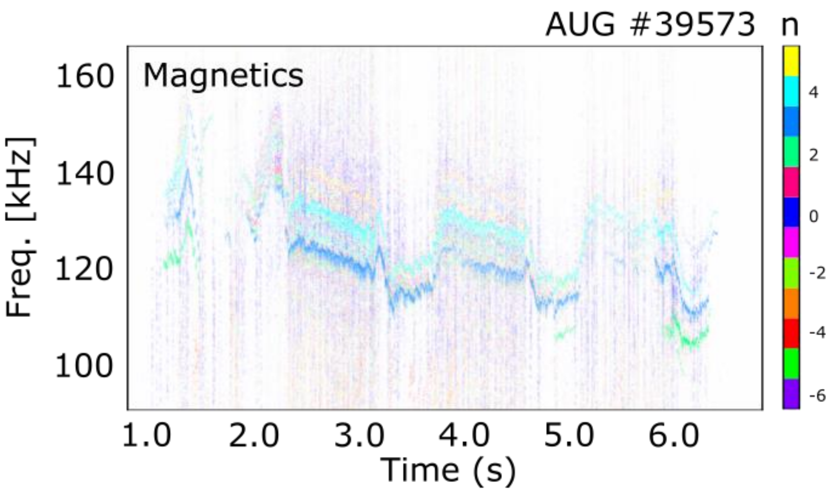

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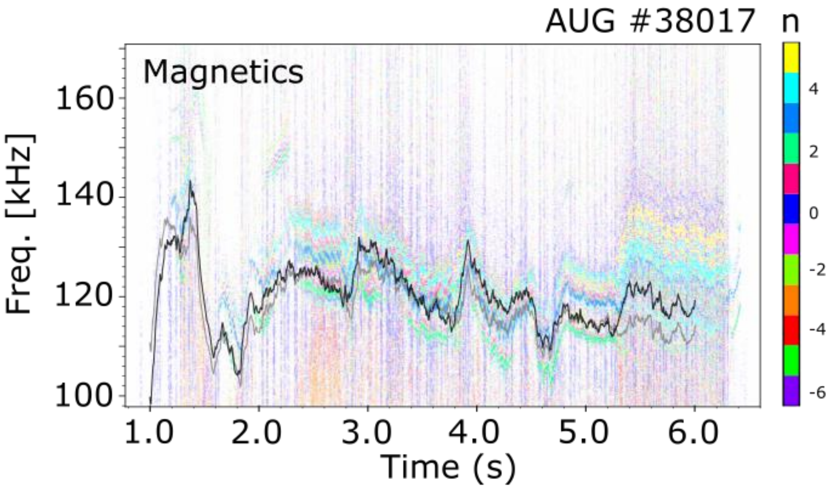


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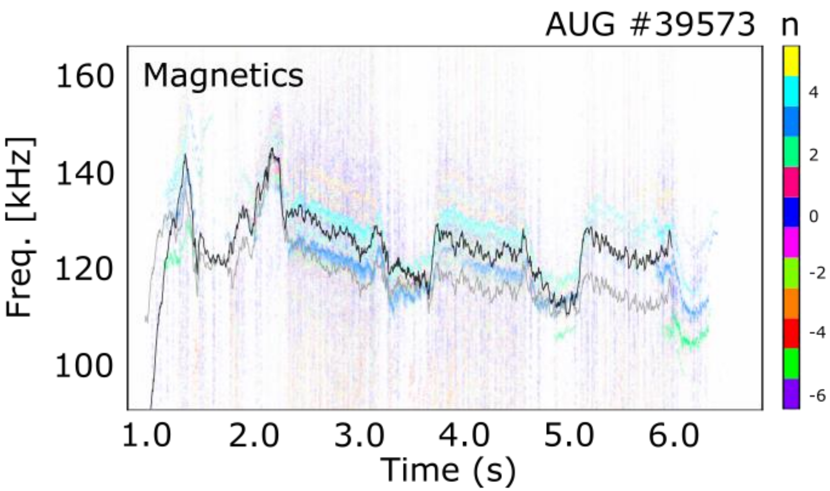


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Wave $\longleftrightarrow$ Particle

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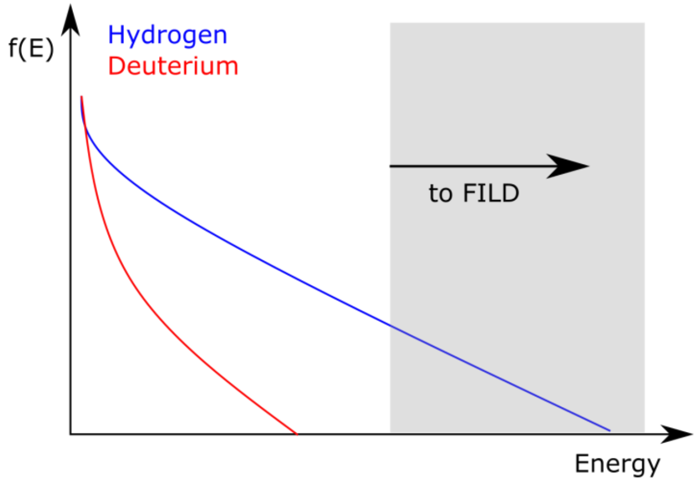
- **Modification of FI distributions via 2nd harmonic D heating**
  - $\omega_{c_H} = 2 \times \omega_{c_D}$
  - D “steals” power from H
  - H-tail clamps at lower energies
  - Consistent with timescale of FILD mitigation



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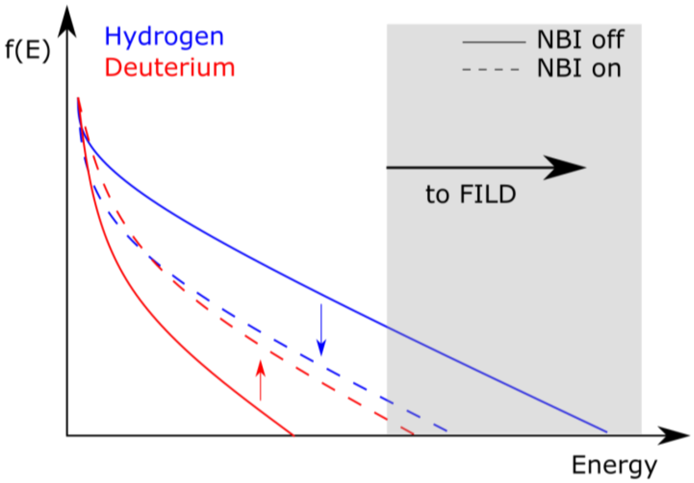

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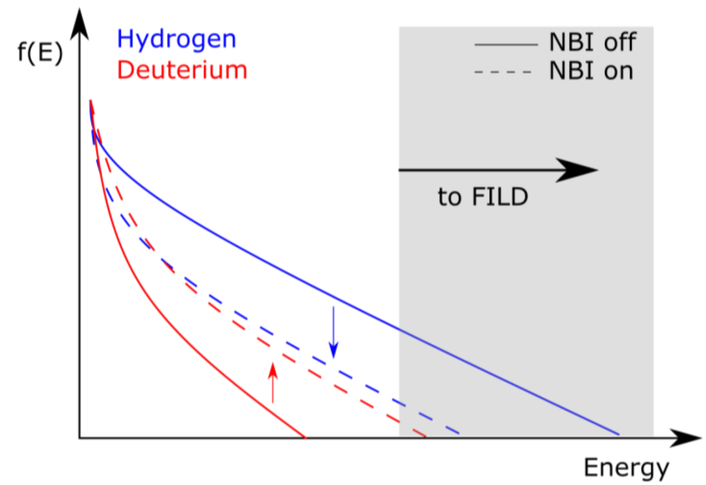


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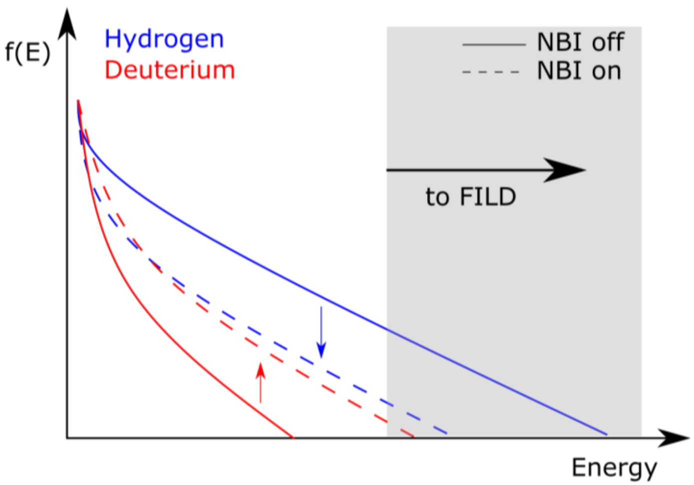


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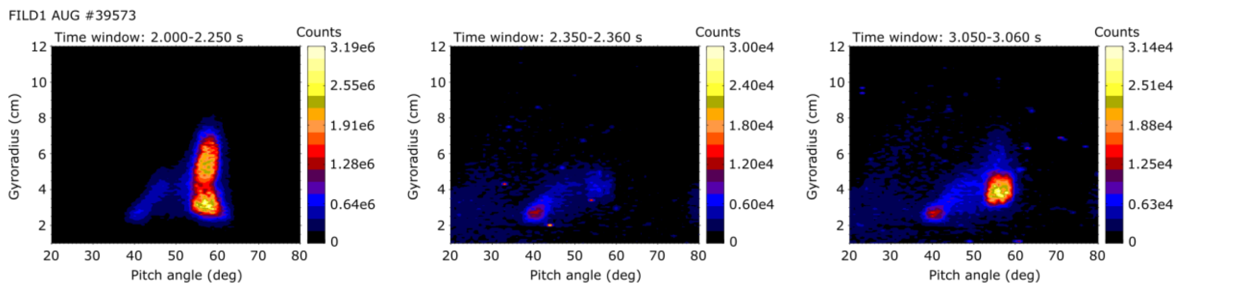
# Fast-ion losses show rich velocity-space dynamics

NBI Q3 (60 keV)

Phase I: high Te
(Partial suppression)

$t_{NBI} - 250\ ms$ | $t_{NBI} + 100\ ms$ | $t_{NBI} + 700\ ms$

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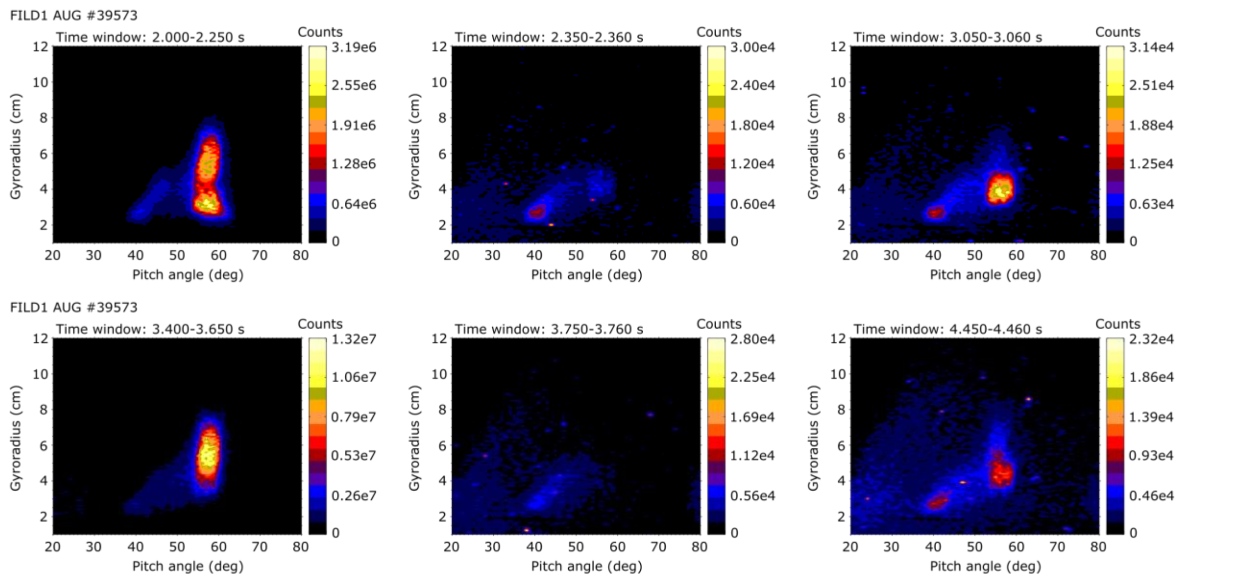


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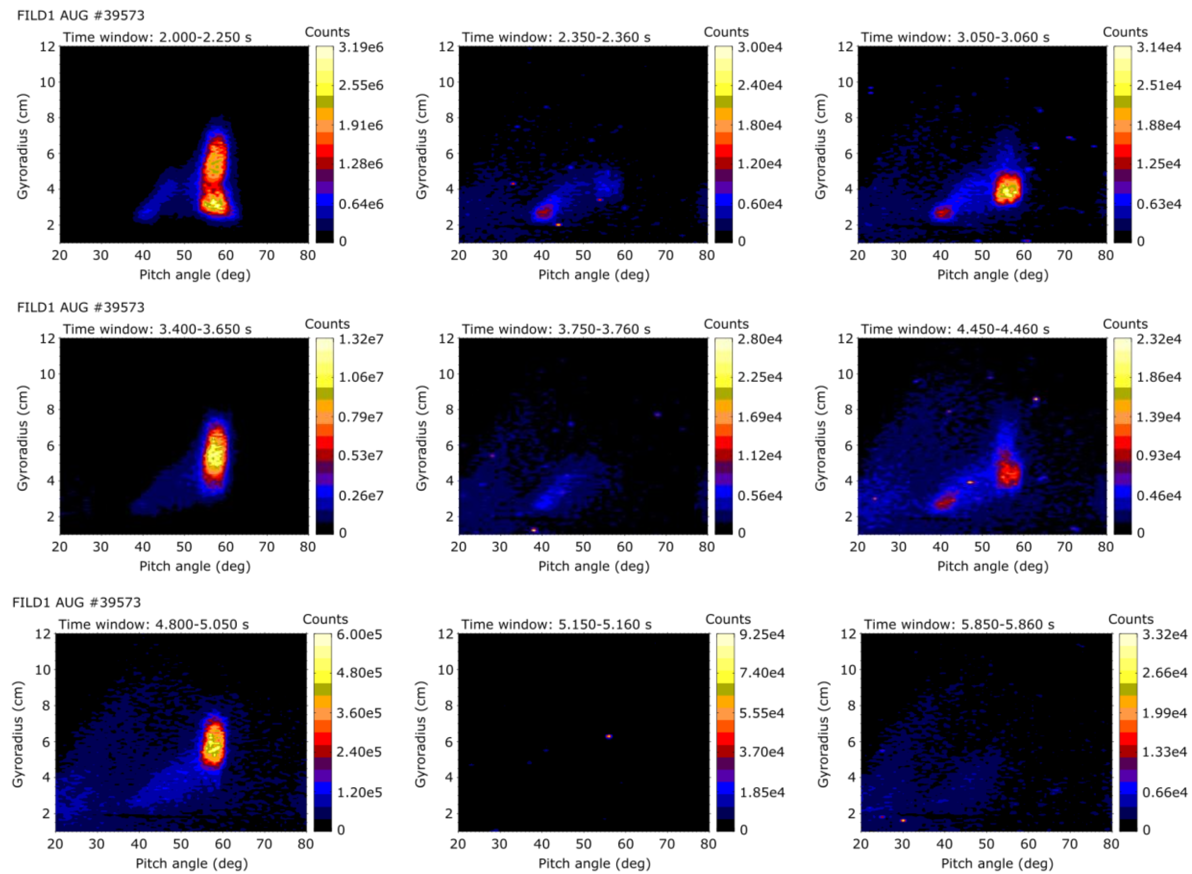


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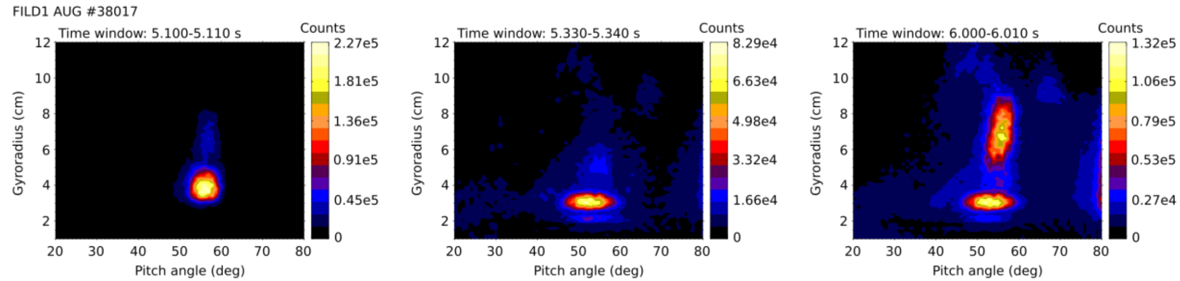


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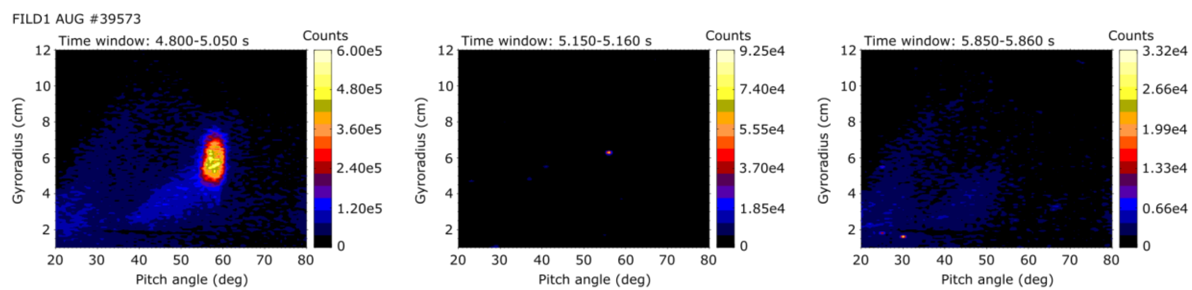


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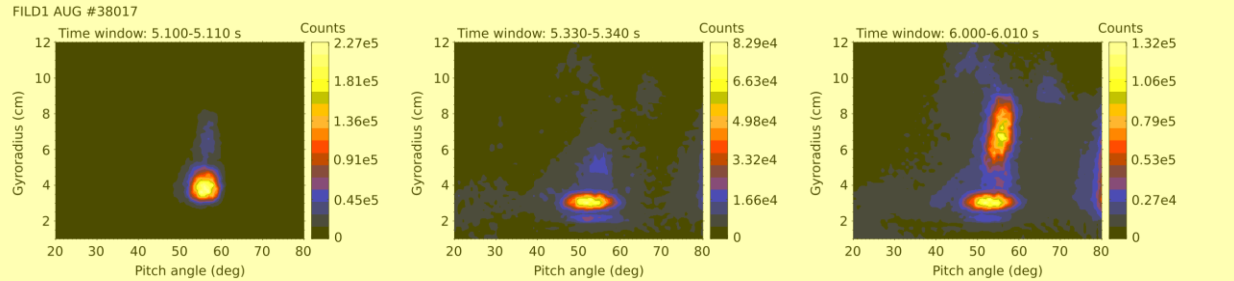


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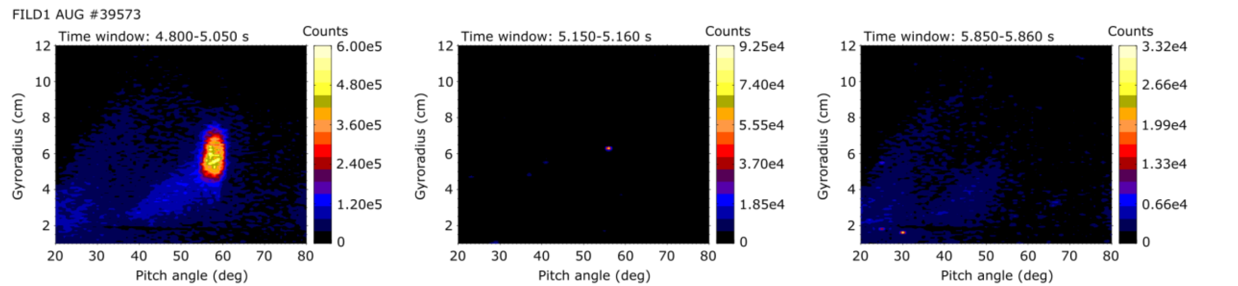


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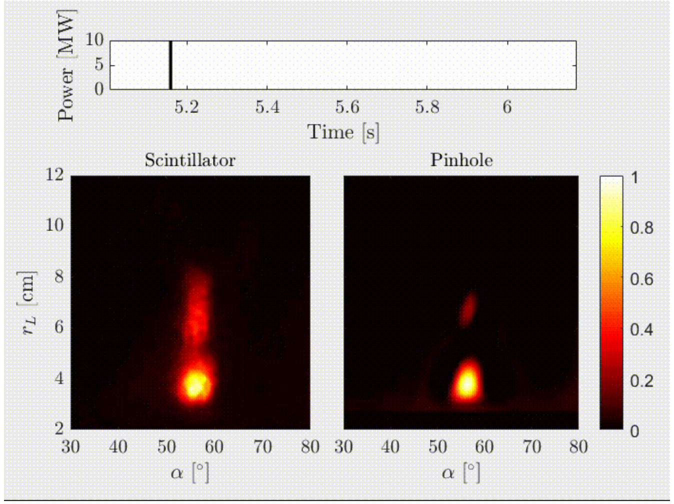



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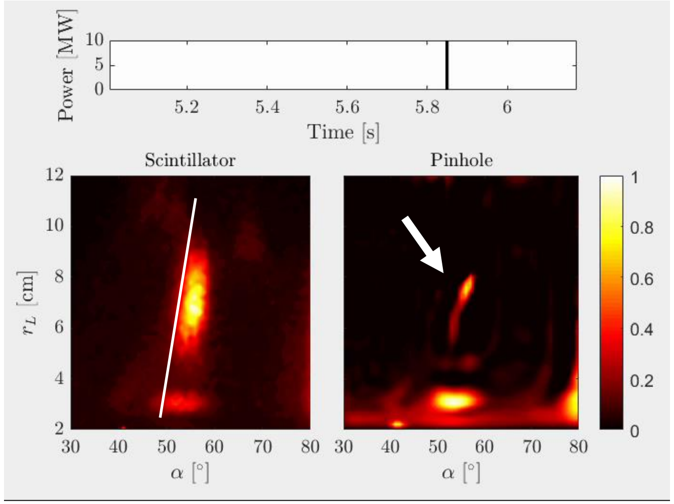


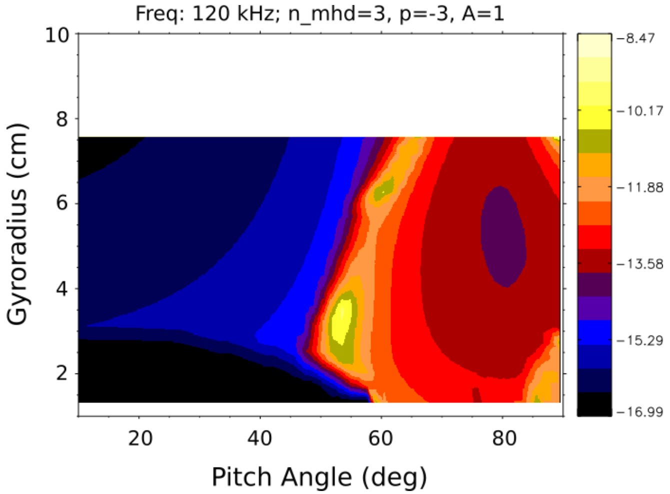



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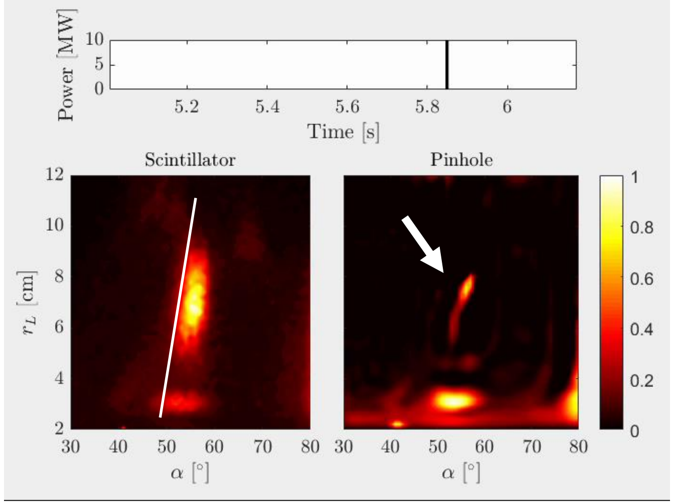
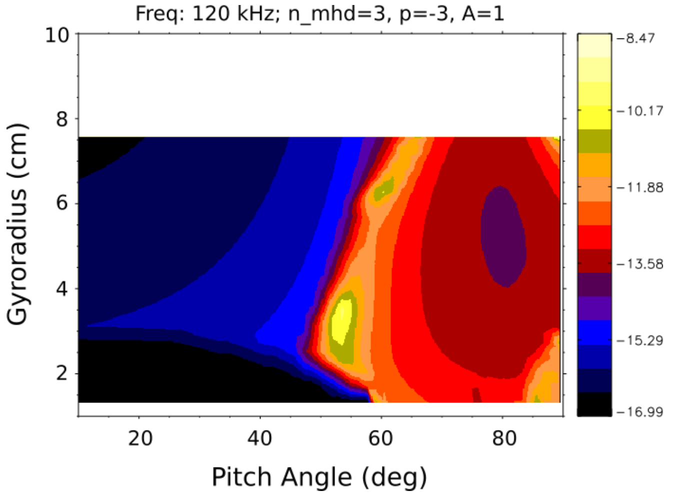
- FILD cannot distinguish between H & D

| E (keV) | NBI off-phase | NBI-on Q3 | NBI-on Q8 |
|---|---|---|---|
| H | 200-1000 | 200-300 | 600-1000 |
| D | - | 100-150 | 300-500 |





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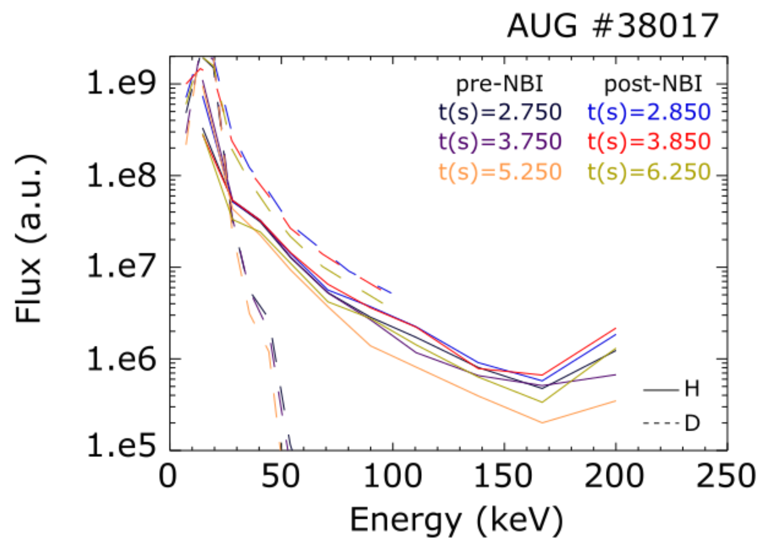
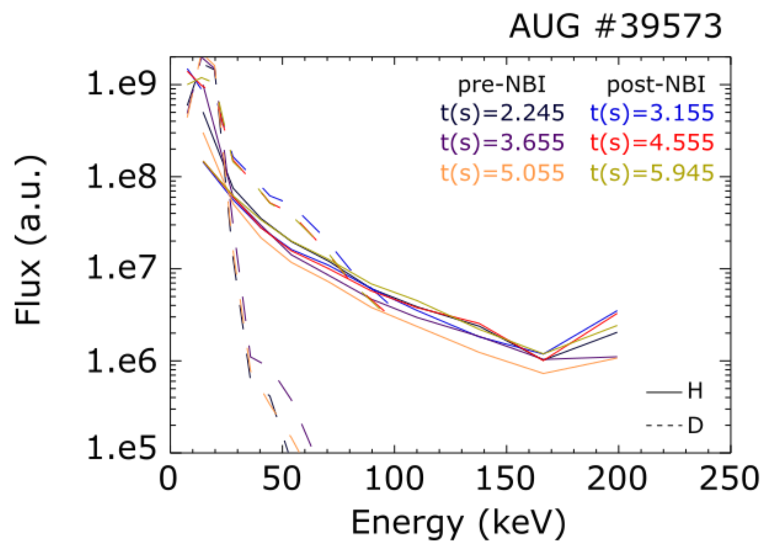
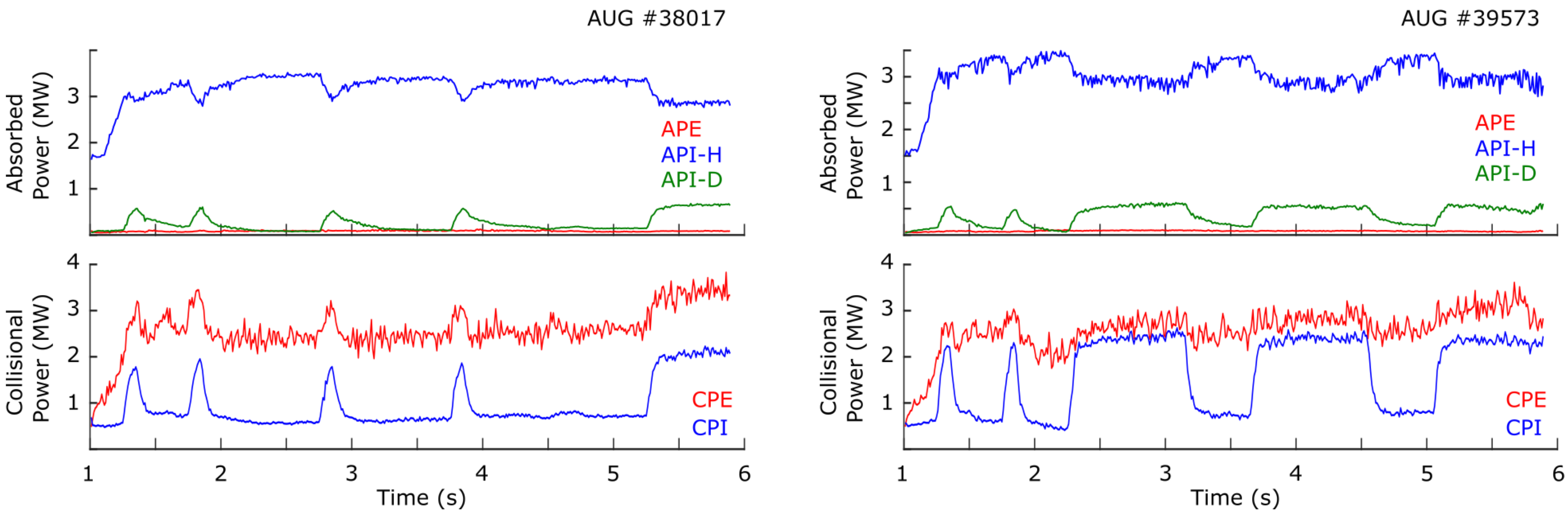
# Passive NPA sees an increase in D-tail during NBI phases




- D- high energy tail increases during NBI phases
- H- high energy tail not much affected, up to 200 keV
- ICRF is effectively accelerating NBI-D ions

# ICRF modelling shows increased fraction of power absorbed by D in NBI phases




- ICRF modelling with PION[1]

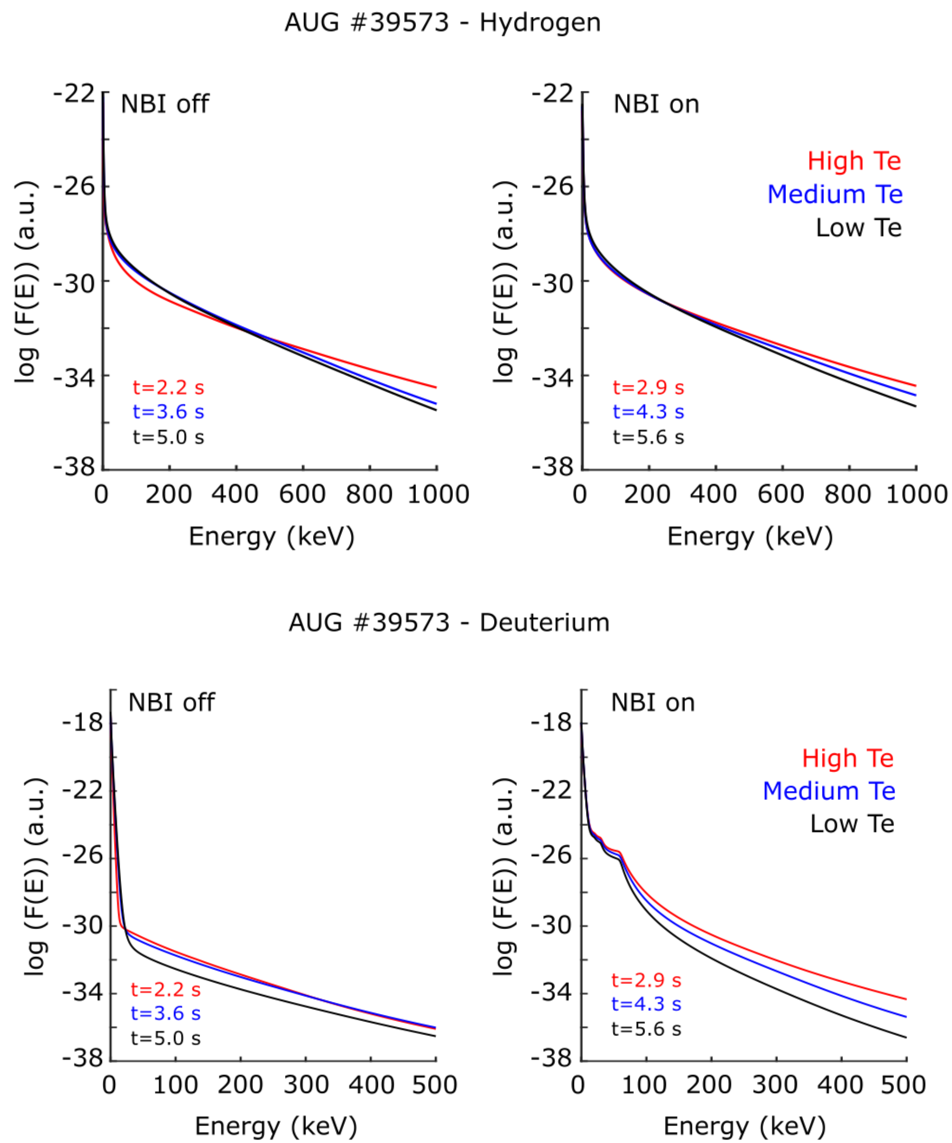
- During NBI phases:
  - ➢ Increased power absorbed by D
  - ➢ Increased collisional power to ions

*[1] L.G.Eriksson et al., Nucl. Fusion 1993*

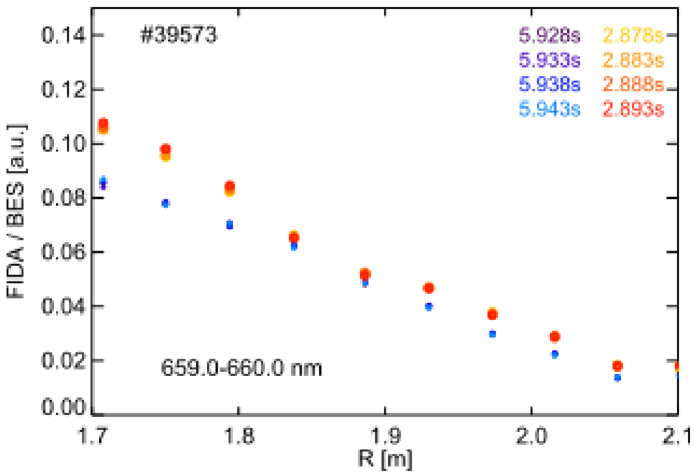
# Modelling of ICRF distribution function is consistent with the experiment

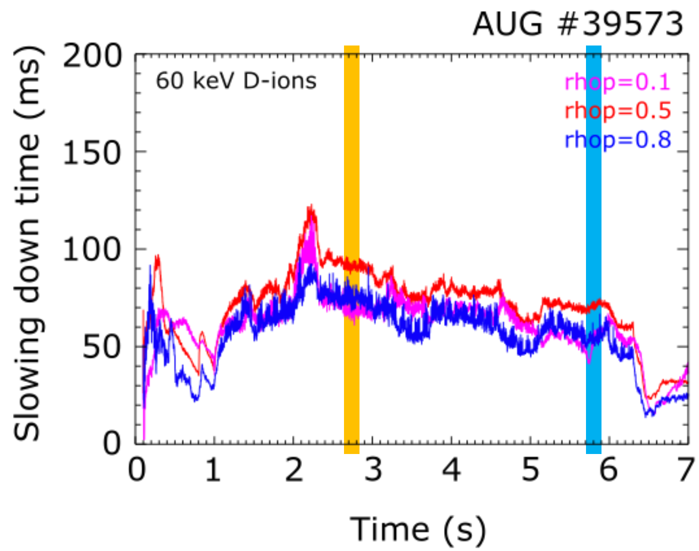
- During NBI phases:
  - ➢ Large increase in D-tail
  - ➢ H tail decreased, but not as clear

- **ICRF tails are decreased for lower Te phases**, when FI loss suppression is facilitated



# FIDA measures larger fast-ion content at higher Te




- FIDA/BES profile indicates larger fast-ion content at higher $\tau_{SD}$

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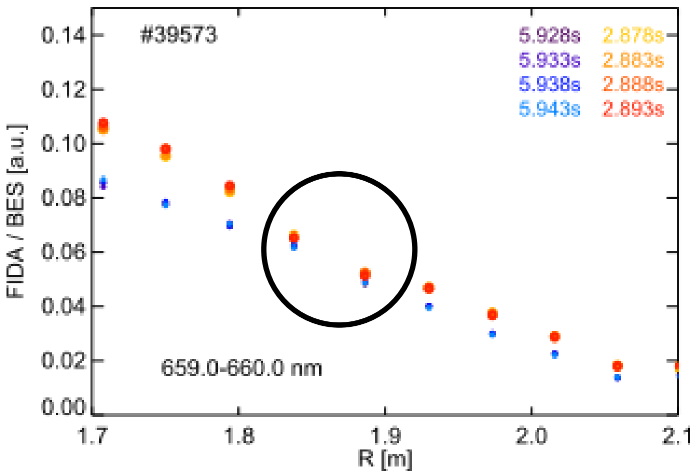
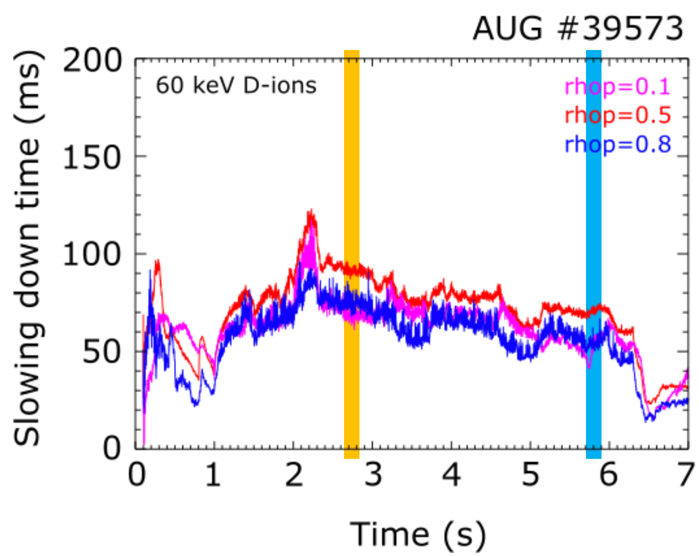
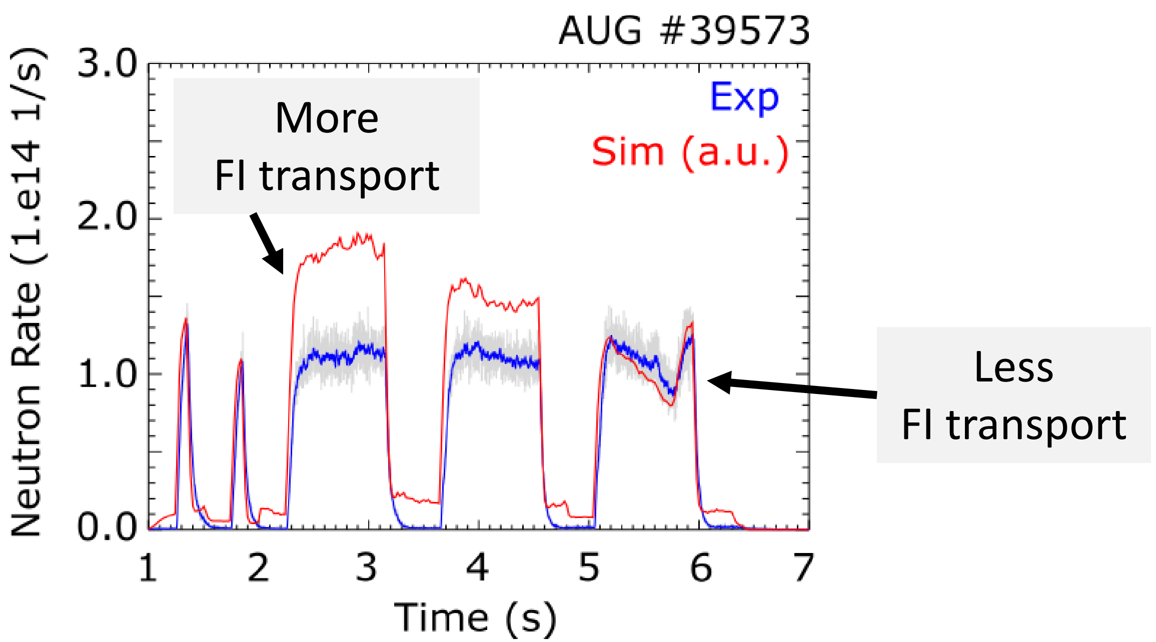



- FIDA/BES profile indicates larger fast-ion content at higher $\tau_{SD}$
- In phase I (high $\tau_{SD}$) the **FIDA/BES profile flattens** at R=1.8-1.9 m, coinciding with TAE location
- This might be indicative of FI transport (need FIDASIM)

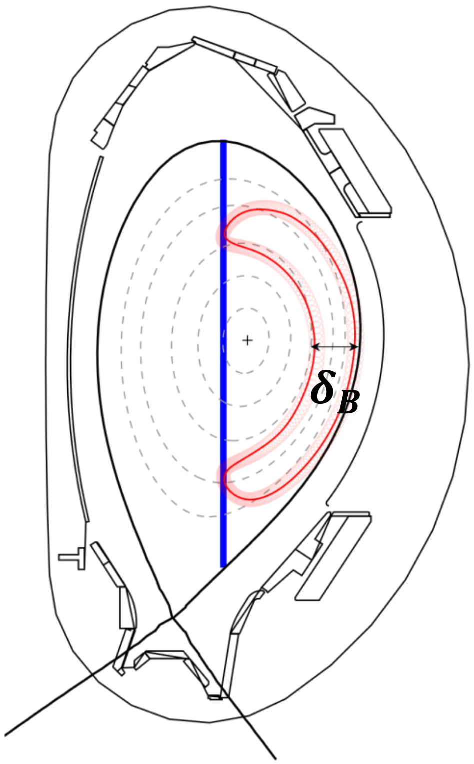
# Neutron rate modelling provides insights on FI transport




- Neutron rate modelling accounts for NBI+ICRF synergy
- Neutron rate ($n_r$) decreases from Phase I to Phase III
- **Relative** decrease in $n_r$ is larger than in experiment
  - ➢ Suggests that anomalous D-FI transport is larger in phase I than in phase III
  - ➢ Consistent with FILD measurements (partial vs full mitigation)

# PION first-orbit loss model qualitatively reproduces FILD trend

- FOL model in PION:
  - Ions are considered lost if orbit width is larger than a threshold
  - Does not account for anomalous FI transport




Loss condition: $R + \delta_B > R_{out}$

$$\delta_B = \left(\frac{2\rho_L q_0}{R_0}\right)^{2/3} \cdot R_0$$

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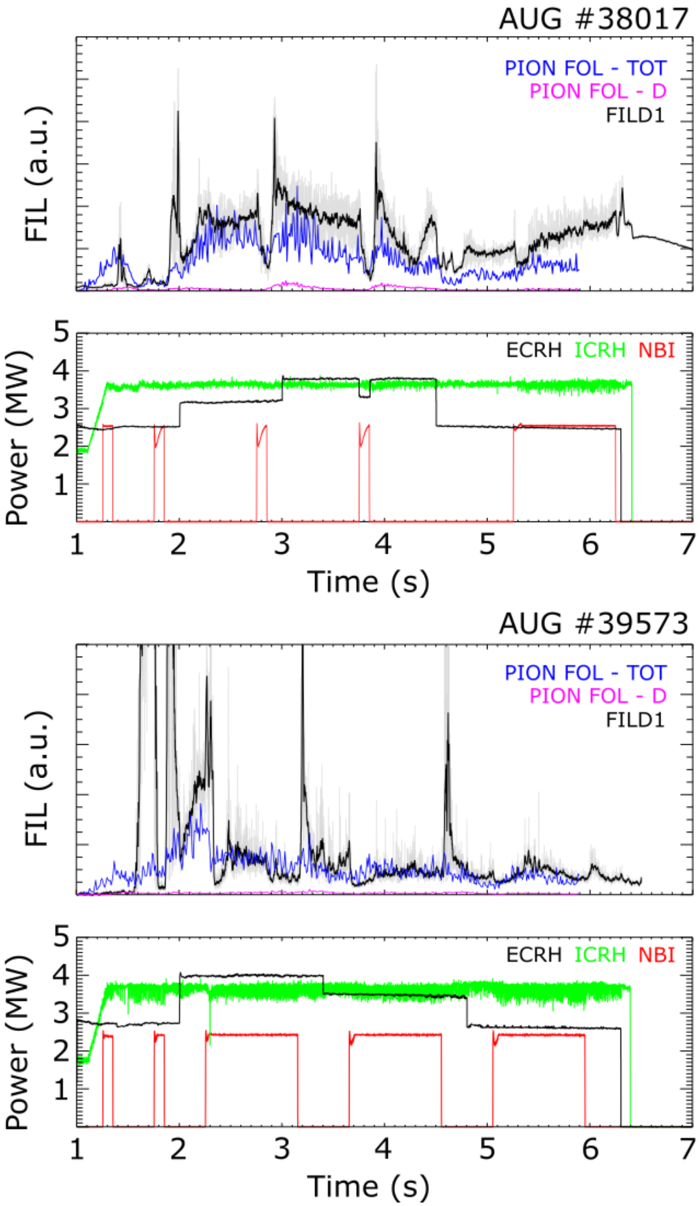

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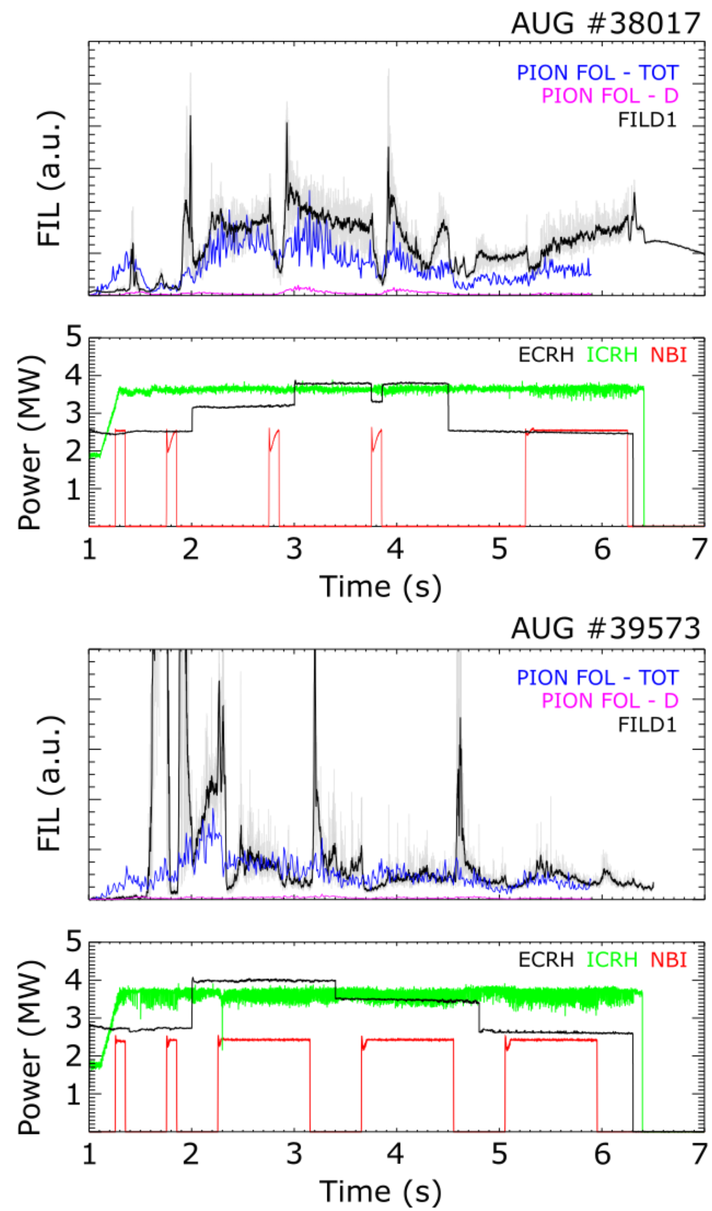

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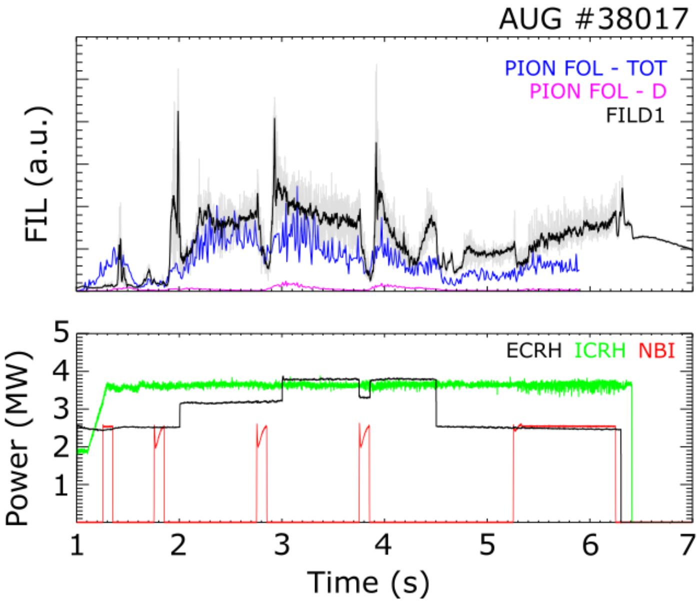
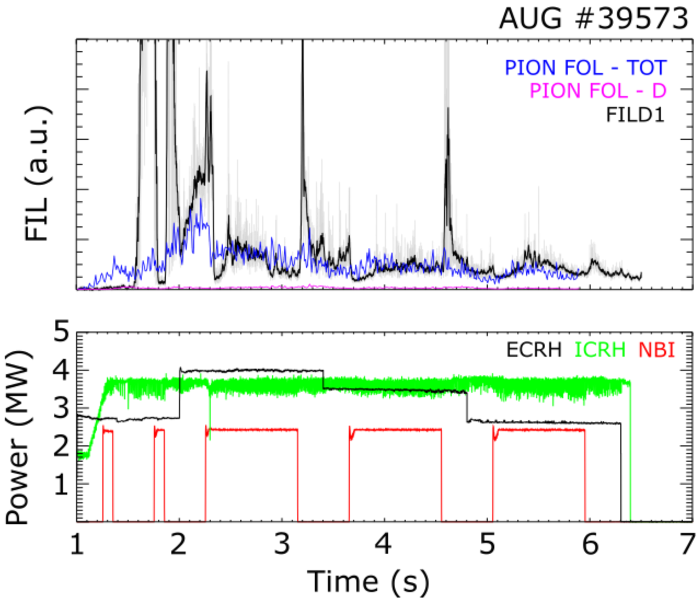
- Time evolution of losses is well captured, **suggesting that ICRF FO losses contribute to FILD signal**
- Relative attenuation during NBI phases is lower than experimental, **suggesting additional contribution from anomalous FI transport due to AEs**



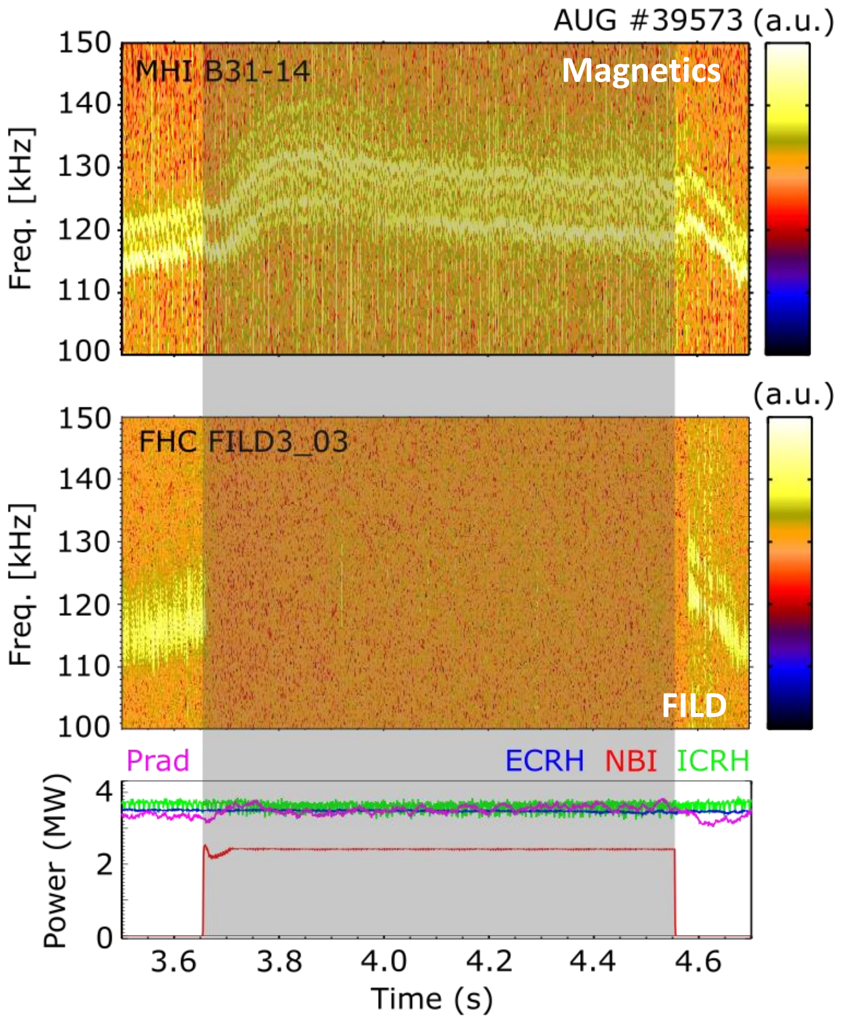



# Outline

- Motivation
- Experimental observations
- Diagnosing the FI distribution
- **Conclusions**

# Conclusions

- **Experiments show coherent AE induced ICRF FI loss mitigation w. NBI**
- **Mechanism not yet fully understood**
  - FI distribution is modified via 2nd harmonic-D heating
  - Low $\tau_{SD}$ facilitates FILD mitigation
  - (H) FOL alone seem not enough to explain FILD signal
  - Neutrons & FIDA suggest transport of fast-D induced by TAEs
- **Modelling of TAEs & their interaction with FI is needed**




Applicability to ITER (?): If we cannot control AEs, an appropriate arrangement of heating sources (ICRF + NBI + ECRH) might help to reduce losses

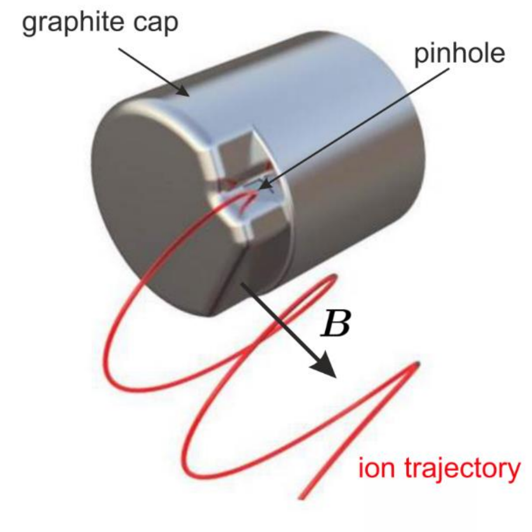
# BACKUP

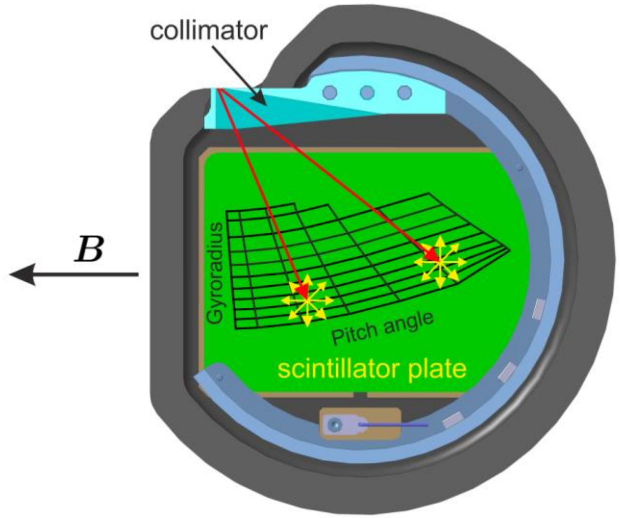
# Fast ion los detector (FILD*) provides full information on velocity-space of escaping ions

- FILD measures the pitch-angle and energy of lost fast ions

- **Large bandwidth** allows measurements at Alfvén Eigenmode frequencies (~100kHz) **– key for identifying coherent losses and impact of individual modes**

- Local velocity-space measurements like these help to isolate fundamental mechanisms



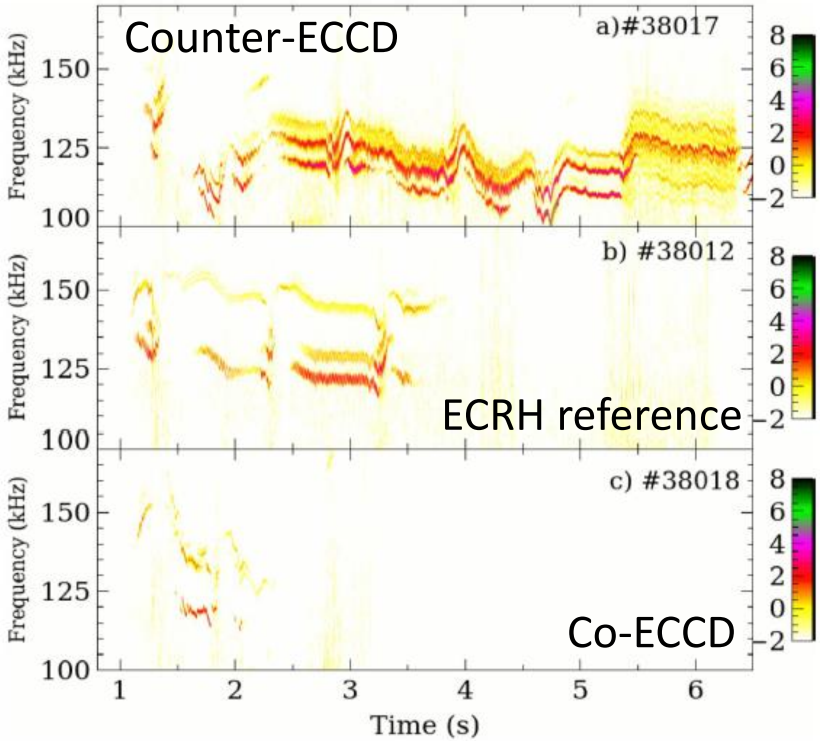

*S. J. Zweben et al., NF (1988)
**M. Garcia-Munoz et al., RSI (2009)

# AE control via ECCD: affecting AE existence condition

- MST1 AUG 2020 Topic 13 experiment: Control of ICRH driven AEs using ECCD/ECRH

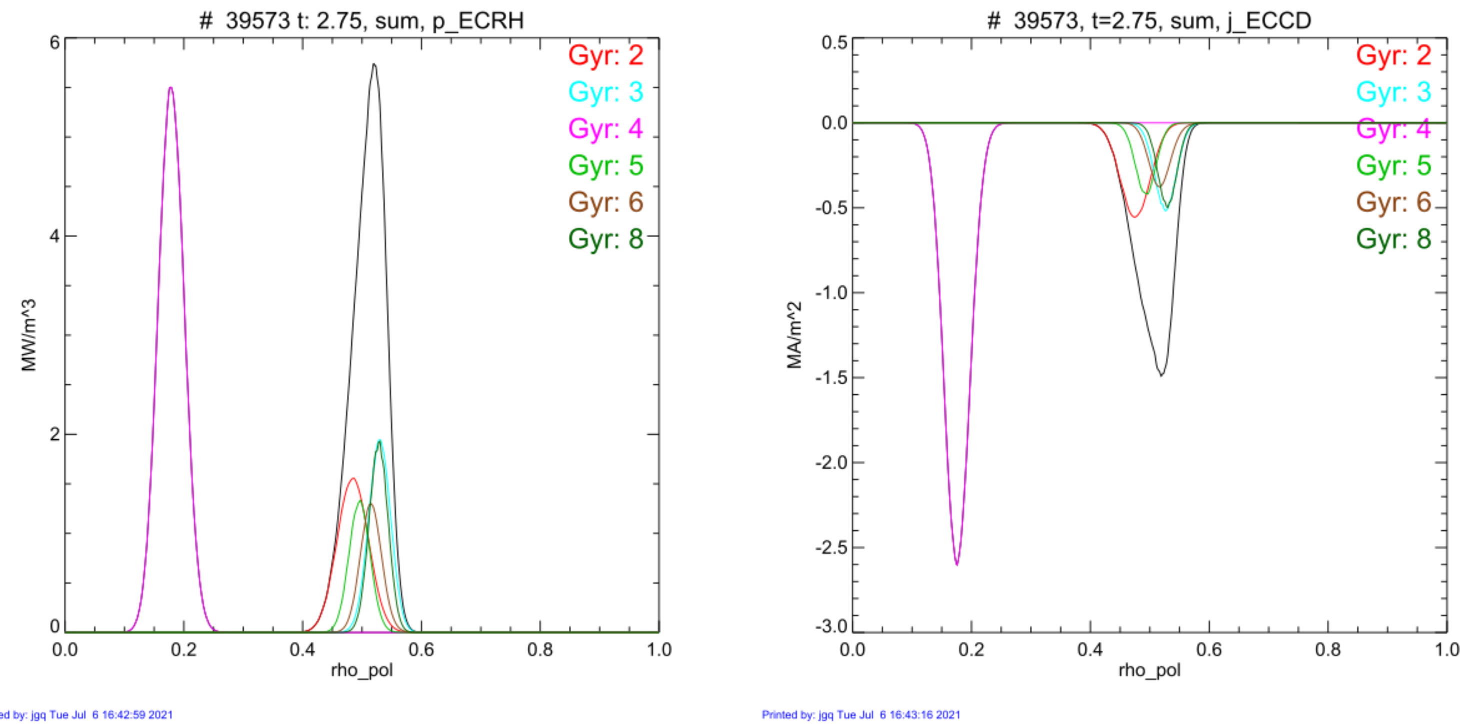
- **Reference scenario is AUG #38017**
  - Ip/Bt=0.7 MA / 2.5 T
  - Counter-ECCD @ rhopol = 0.5 ; 6 gyrotrons (all in)
  - ICRH: < 4 MW H minority on axis (f= 36.5 MHz)
  - NBI source #8 (2.5 MW)
    - 100 ms blips only for profiles (CX & IMSE)
    - 1s steady phase towards the end

*S.Sharapov et al., MST1 TFM 05.10.2020*



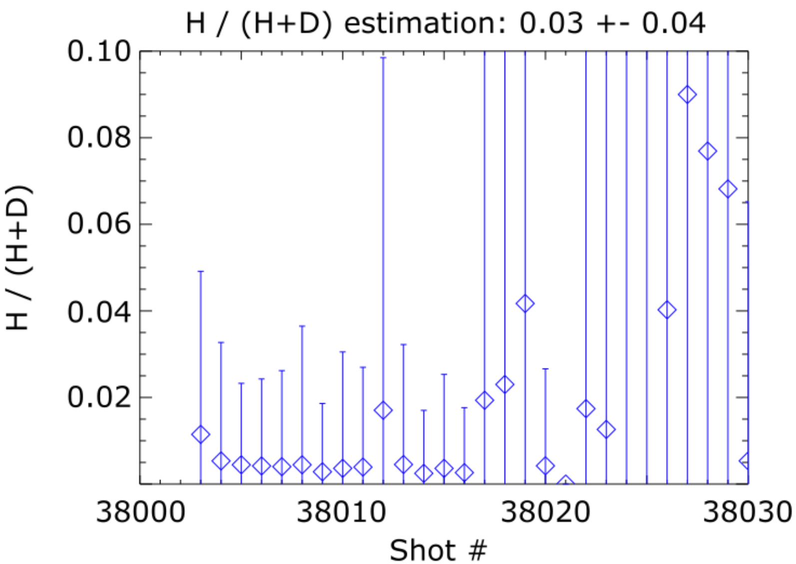

$$\alpha \equiv -R_0 q^2 \frac{d\beta}{dr} > \alpha_{crit} = \left(\varepsilon + 2\Delta'\right) + S^2$$

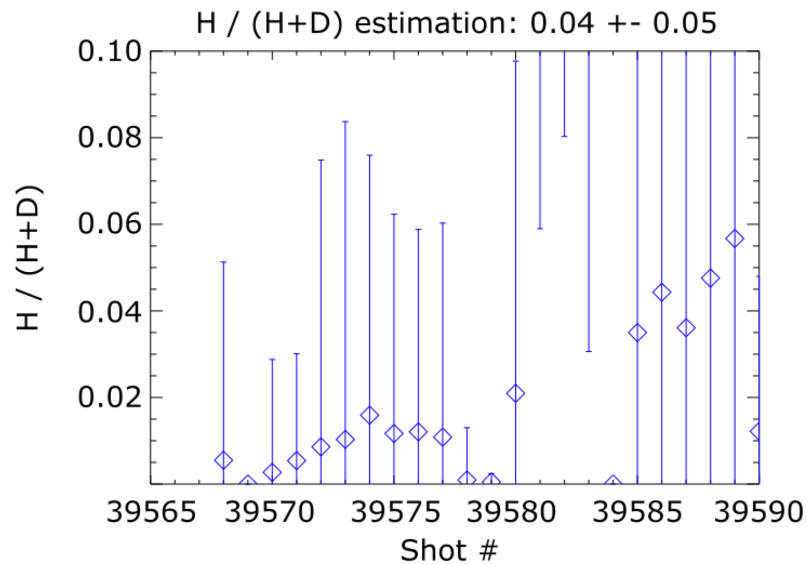
# ECRH/ECCD deposition from TORBEAM simulations




- Counter-ECCD configuration to drive AEs unstable in longer phase
- Gyrotron 6 instead of gyrotron 7 from reference → successful
- Gyrotron 4 in “best-guess” configuration from reference → successful

# Large uncertainty in H/(H+D) concentration

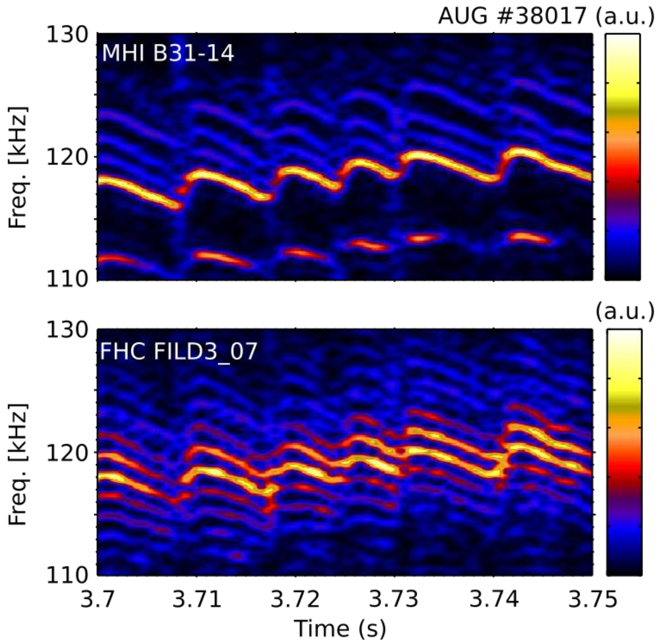


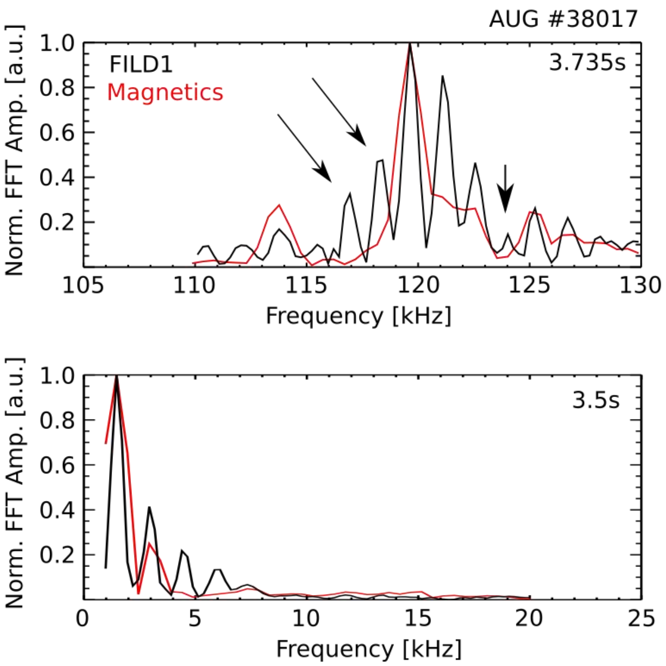




- H/(H+D) concentration ~ 4+-4 %

- Large uncertainty impacts modelling of ICRF power absorption and associated FI tails

# FIL frequency beat between AEs – Low freq. MHD

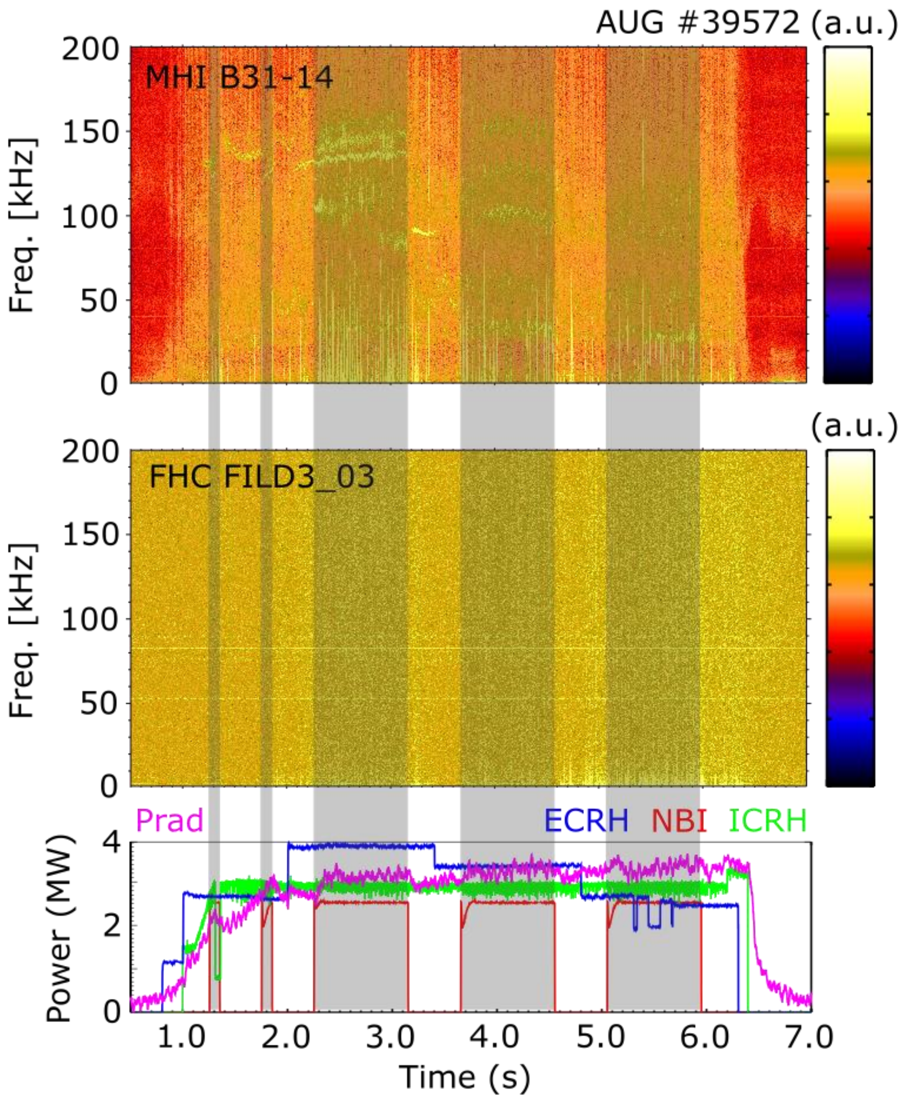



- FILD sees additional peaks at: $f = f_{TAE} \pm f_{MHD} \cdot l$
- Phenomenon already seen in AUG #33147: in this case looks more complicated because a larger number of AE branches is measured

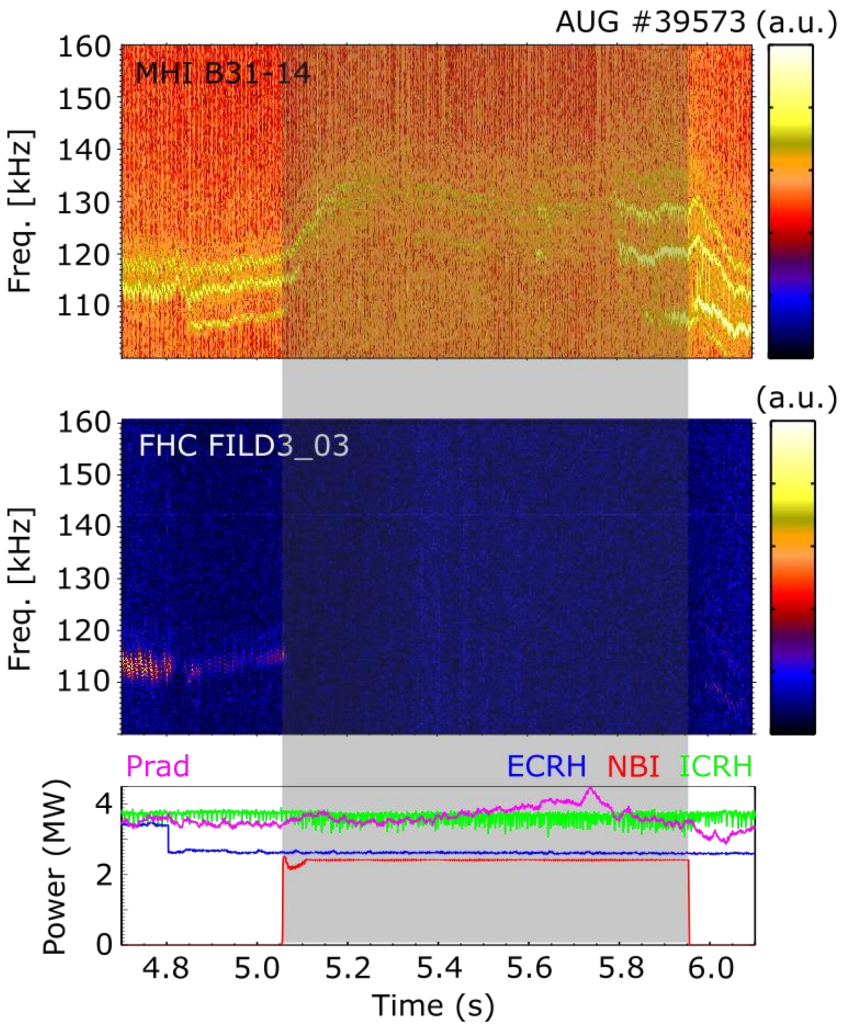
# 3MW ICRF alone not enough to destabilize AEs

- **With 3 MW ICRF power, AEs are only destabilized in NBI Q8 phases**
- **MHD zoo changes with ECRH power level**
  - ➢ 4 MW: TAEs similar to reference
  - ➢ 3.5 MW: modes between 90-150 kHz but different wrt reference
  - ➢ 2.5 MW: less activity
- **NO AE induced FILD signal**
  - ➢ Not even in 4 MW ECRH pase → full AE induced FIL suppression? → need to compare H & D dist. functions with those in #38017



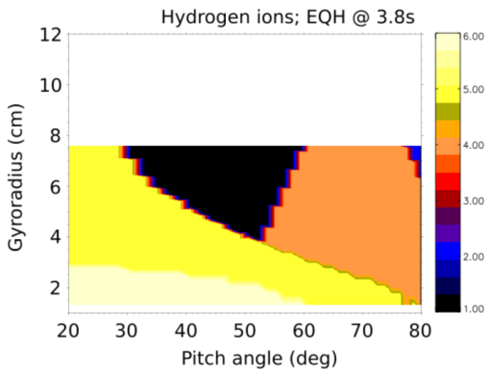
# Low ECRH is not enough to suppress losses: NBI is needed

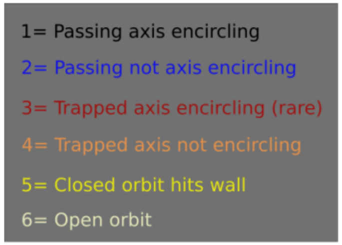
- Long $\tau_{SD}$ leads to decreased FI tails
- AE drive can be affected [Sharapov et al., PPCF 2018]
- In this case: step down in ECRH not enough to suppress losses
  - ➢ NBI is needed

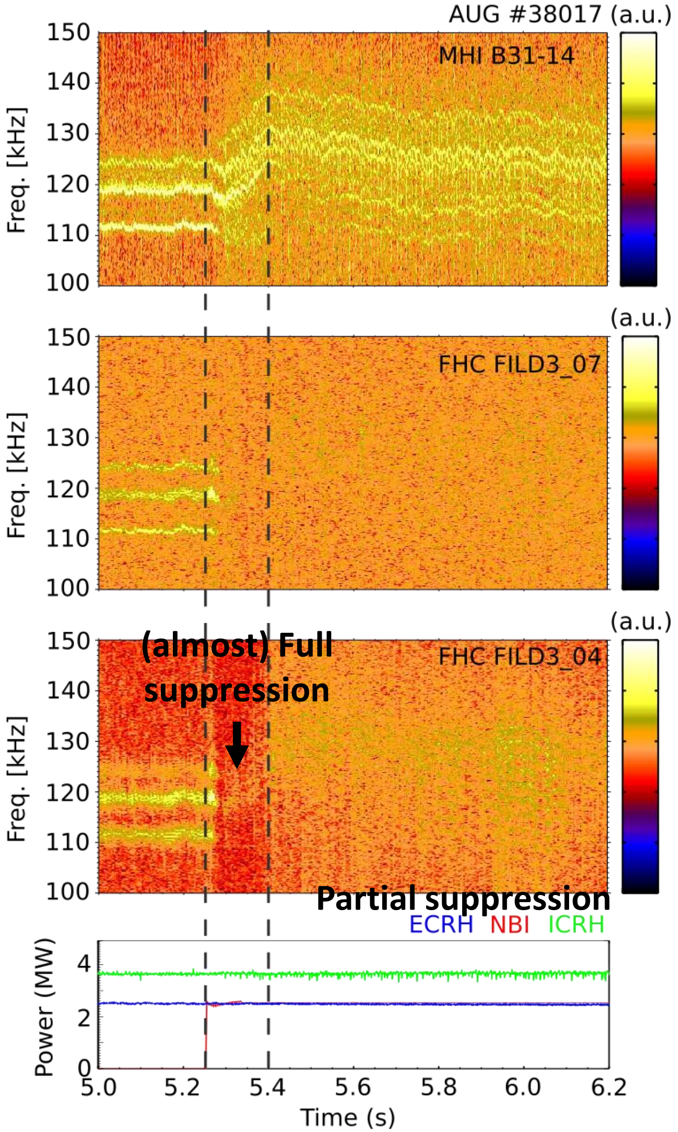


# Partial suppression Q8 low Te phase

- Beam source Q8 @ low ECRH level
- Almost full suppression of AE coherent losses at NBI onset
- Losses recover after 200 ms

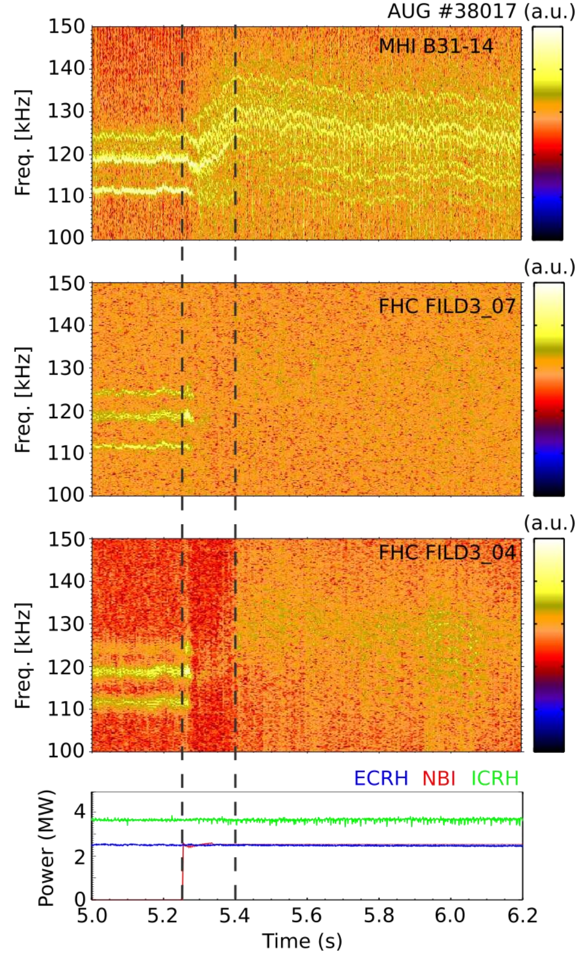


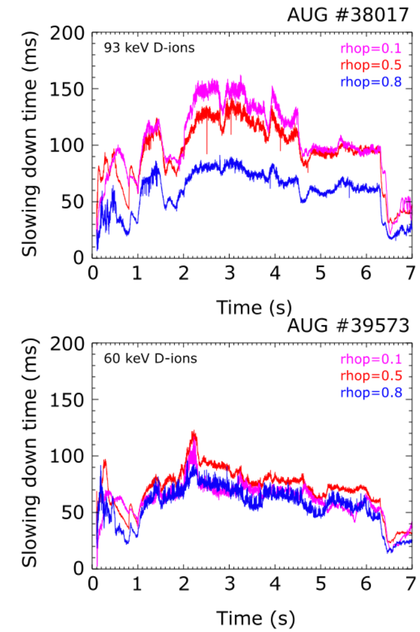



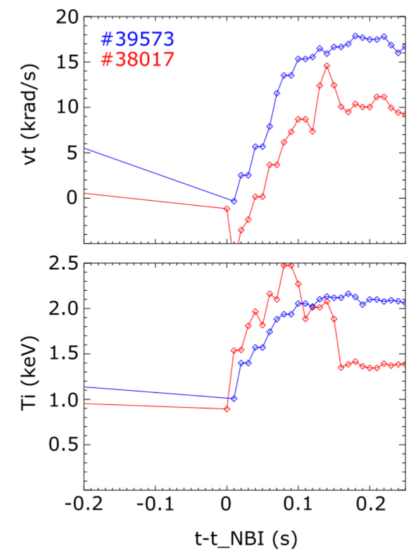



# Timescales

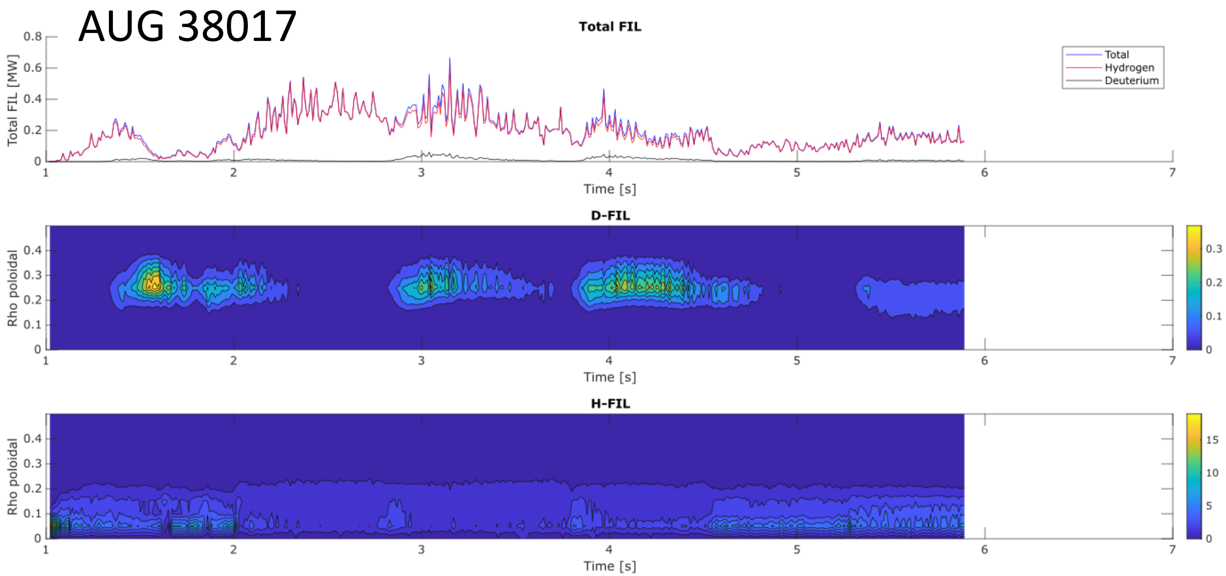
- FILD mitigation after NBI onset
  - ➢ Q3: 10 ms (80 ms in Ph I)
  - ➢ Q8: 20-40 ms
- FILD recovery of losses after NBI offset
  - ➢ Q3: 30-40 ms
  - ➢ Q8: 30-40 ms
- NBI slowing down times
  - ➢ Q3: 50-100 ms
  - ➢ Q8: 70-150 ms
- Neutron decay time:
  - ➢ Q3: 30-35 ms
  - ➢ Q8: 30-45 ms
- Profile evolution time
  - ➢ Q3: ~ 100 ms
  - ➢ Q8: ~ 100 ms

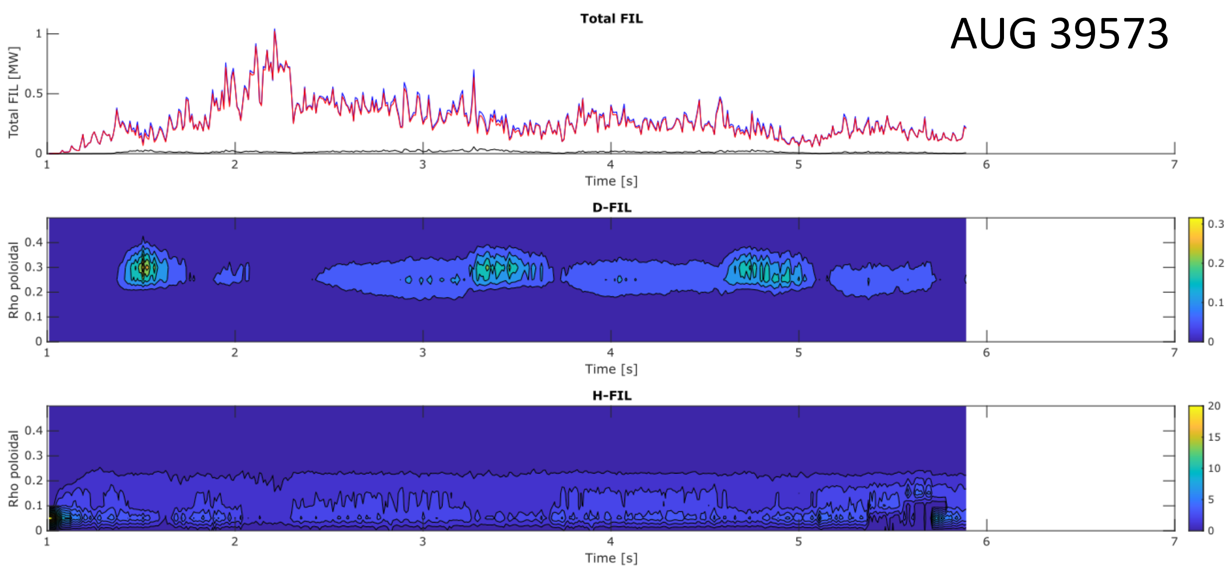


# PION estimation of origin of FIL: from $\rho_{pol}$~0.3, i.e. ICRF resonant layer

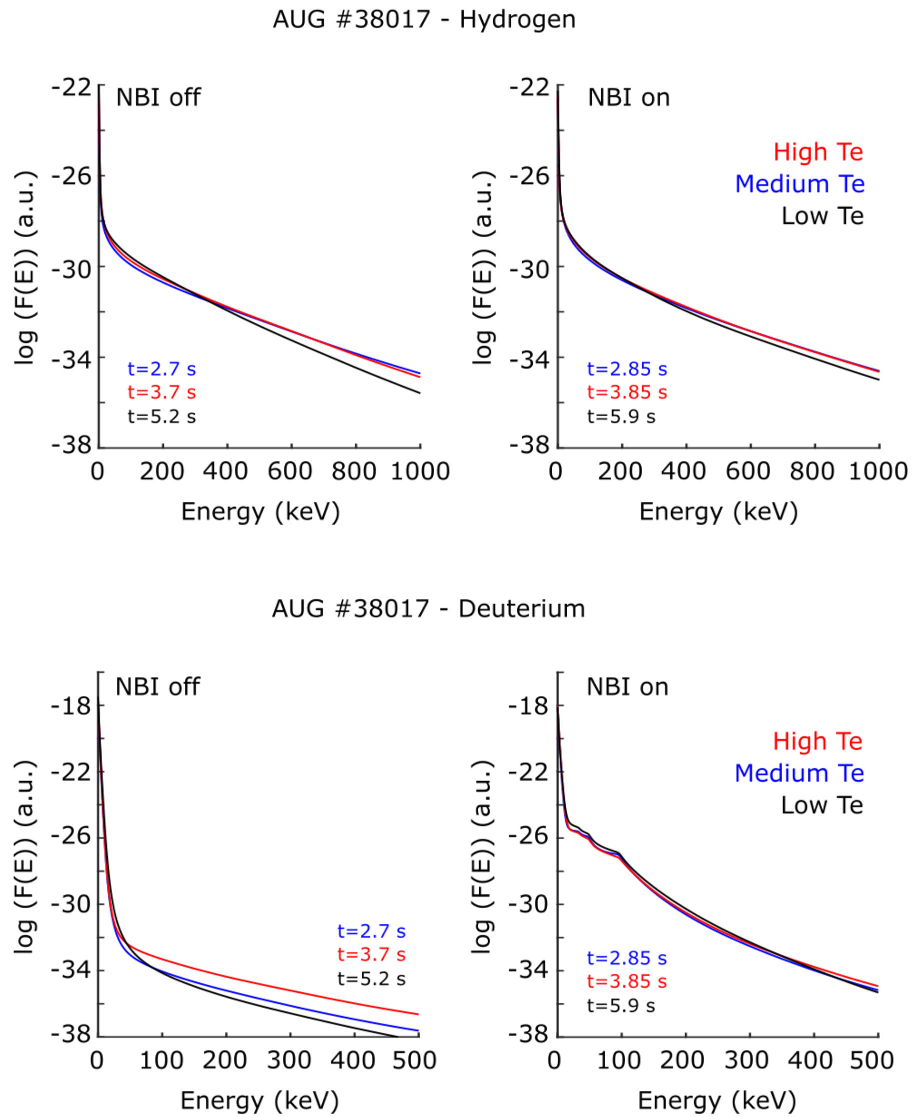


# Modelling of ICRF distribution function is consistent with the experiment

- During NBI phases:
  - ➢ Large increase in D-tail
  - ➢ H tail decreased, but not as clear

- **ICRF tails are decreased for lower Te phases**, when FI loss suppression is facilitated



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