# MHD Induced Fast-Ion Redistribution & Loss in AUG

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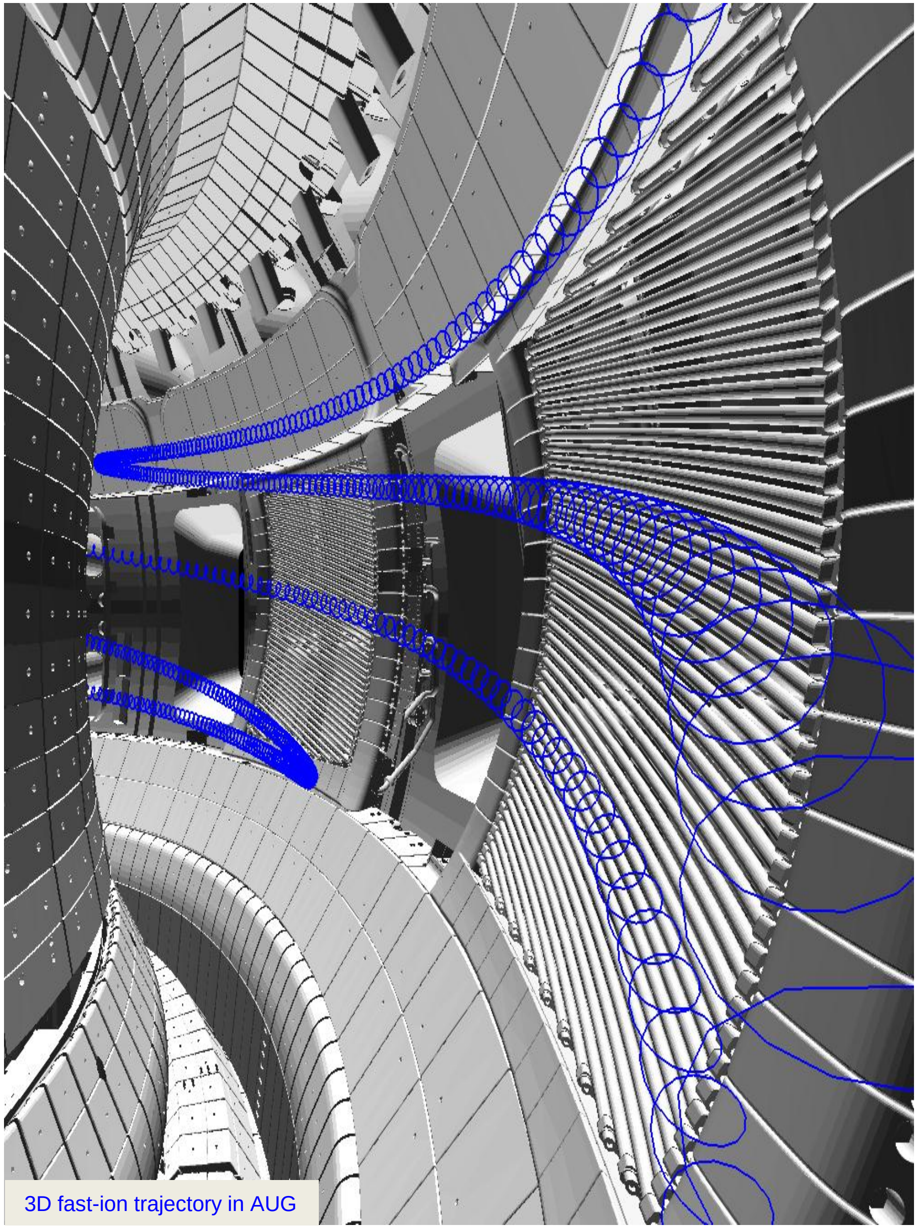
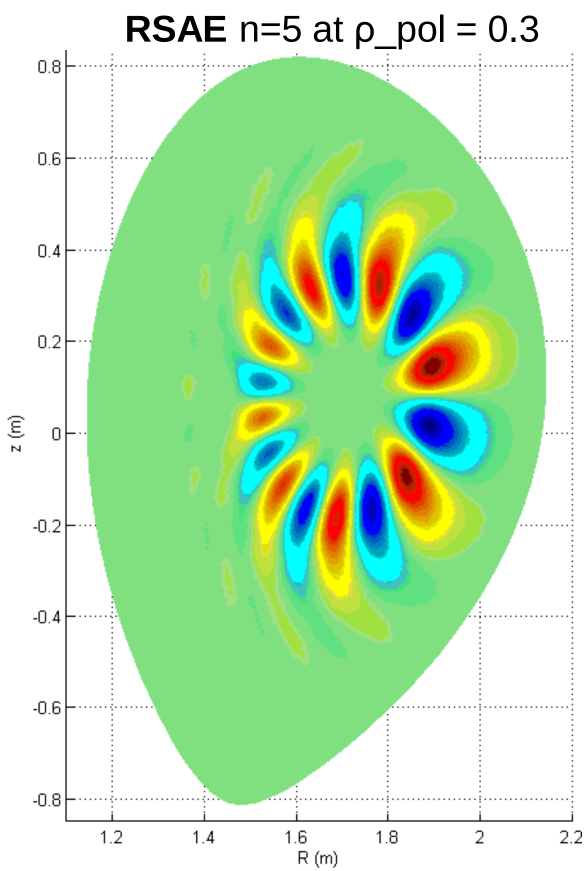


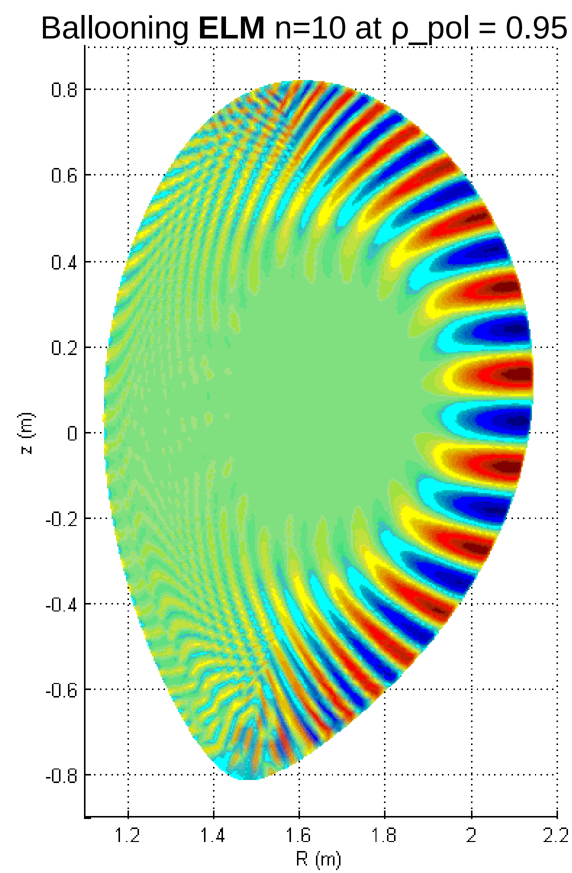
3D fast-ion trajectory in AUG

# Outline






Redistribution / Loss Due To NBI Driven Alfven Eigenmodes

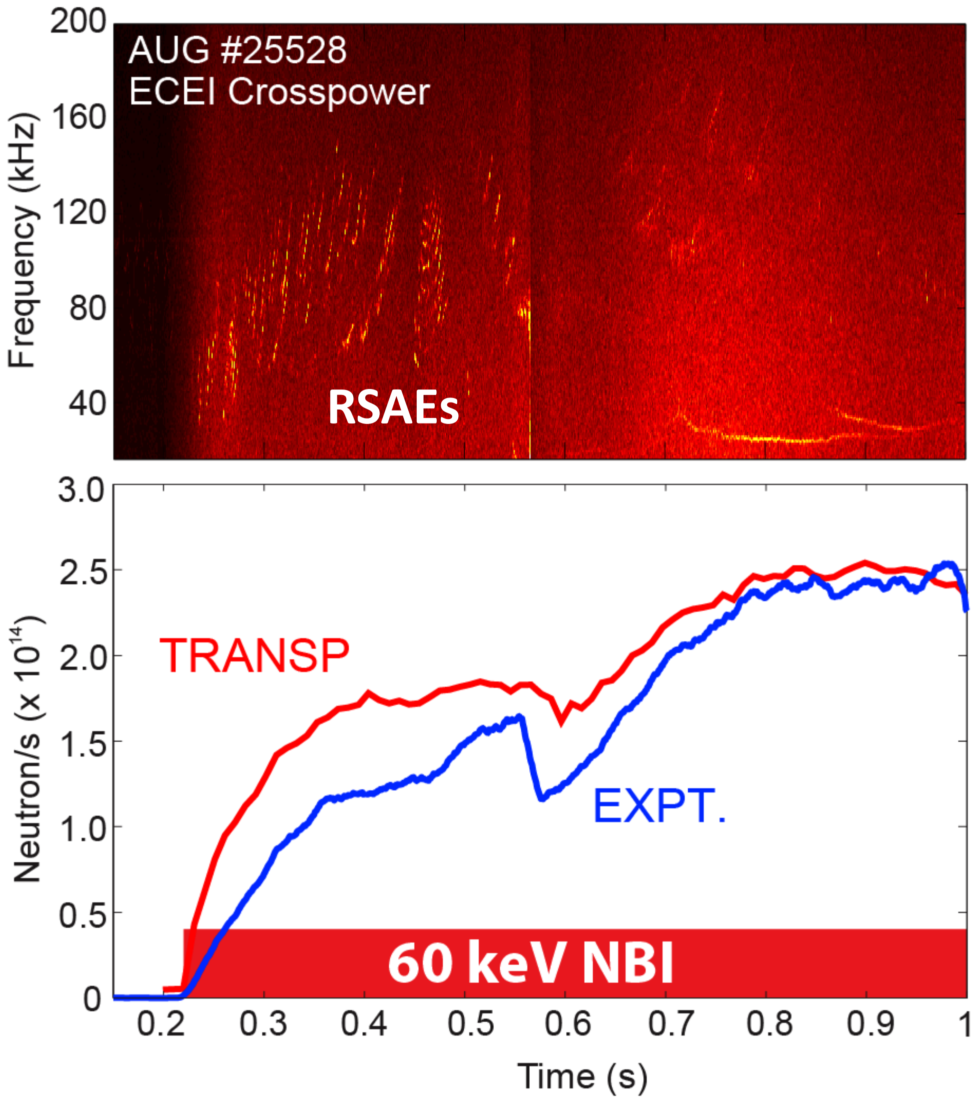



Role of Fast-Ions in ELM Cycle. Especially In The Presence Of Other Core Modes

Cartoon of 2D poloidal structures in AUG

# Alfvén Eigenmodes Obtained With Early 60kV Neutral Beam Injection In AUG

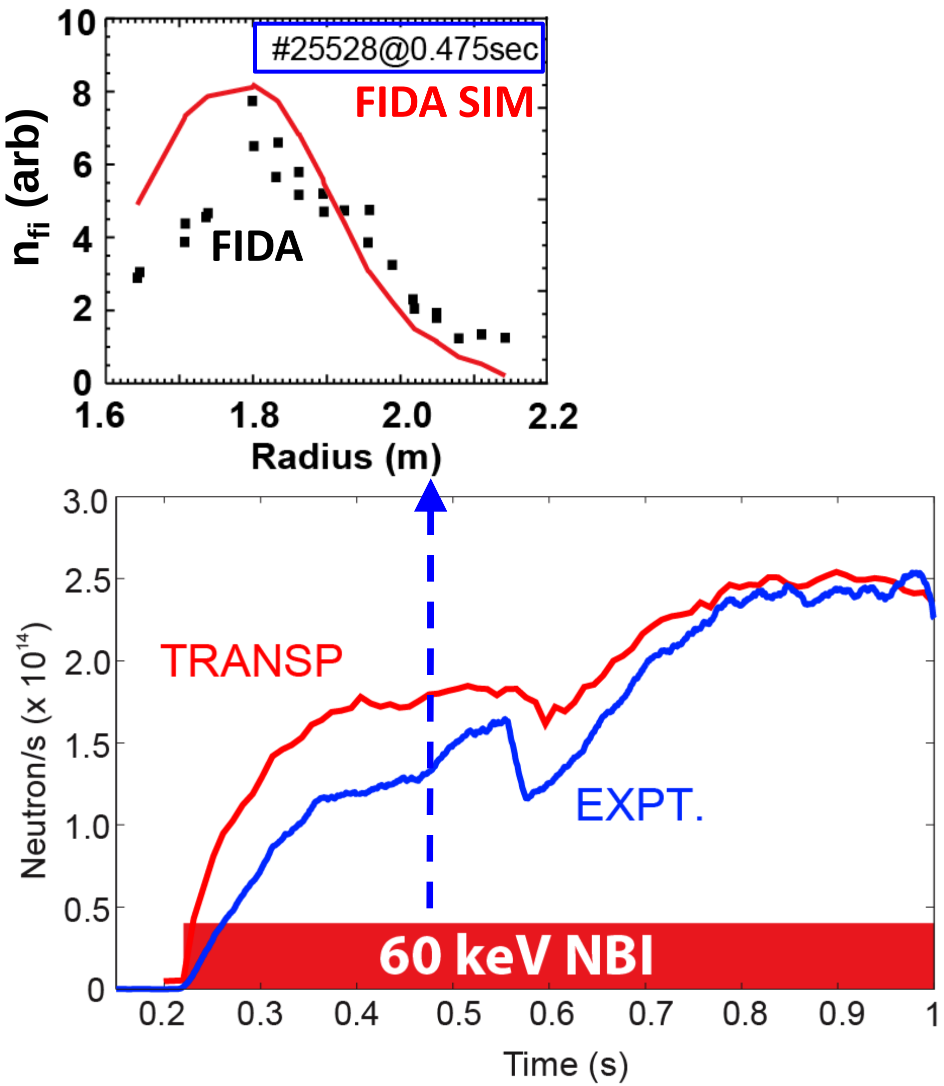





- Early 60 kV neutral beam injection, similar to DIII-D reference case, created spectrum of RSAEs
- Modes are accompanied by large neutron deficit (relative to TRANSP predictions) - indicative of fast ion transport
- As RSAEs disappear, neutron emission returns to classical levels

*M. A. Van Zeeland et al., APS (2011)*
*M. A. Van Zeeland et al., PoP **18** (2011)*
*M .Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)*
*M. Garcia-Munoz et al., Nucl Fusion **51** 103013 (2011)*

# FIDA Data Indicate Large Reduction in Core Fast-Ion Density During RSAE Activity




- FIDA SIMulation code predicts FIDA emission assuming classical fast ion profile
- Large deficit in FIDA emission relative to FIDA SIM indicates central depletion of fast ion density

*M .Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)*
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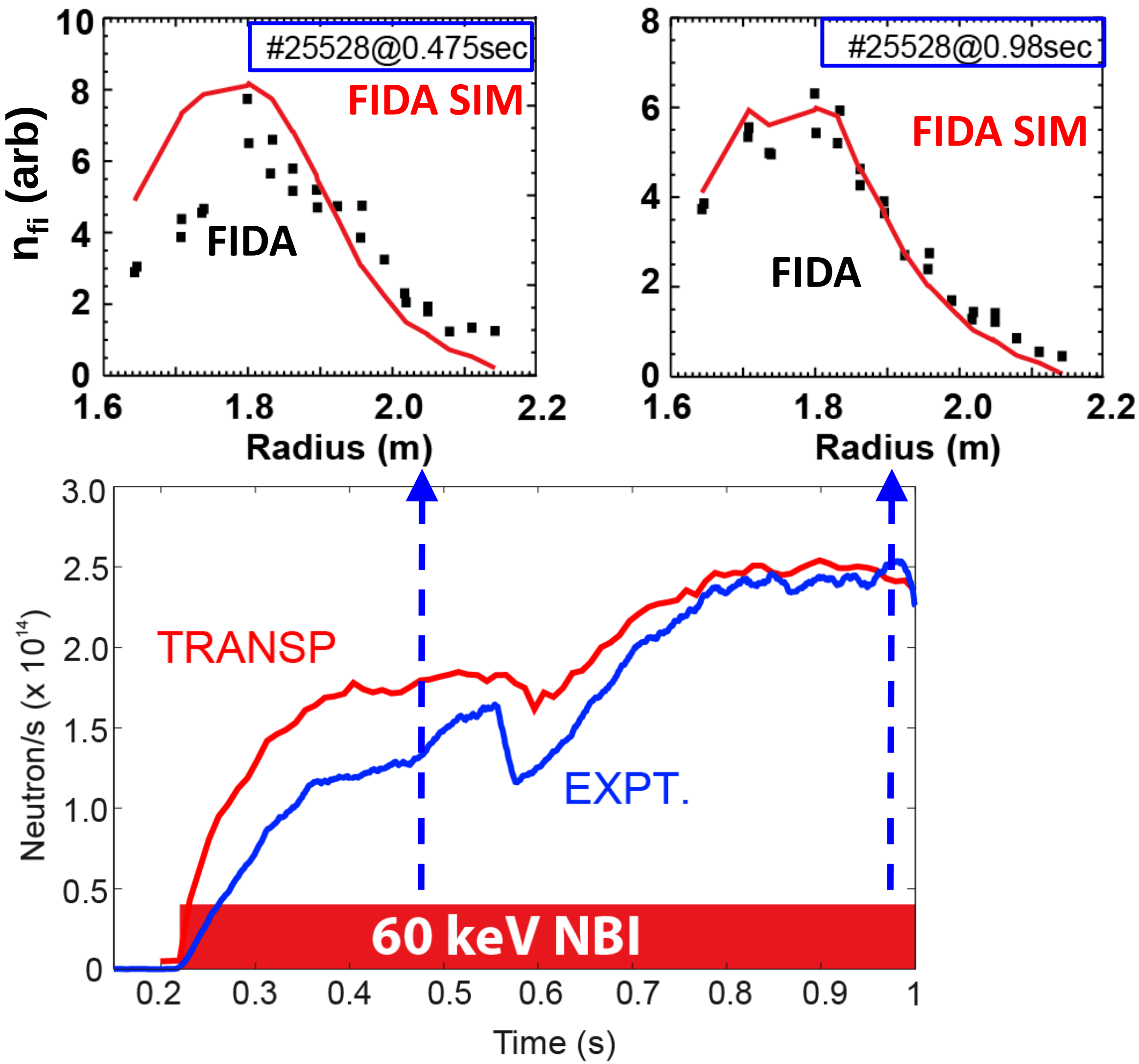


- FIDA SIMulation code predicts FIDA emission assuming classical fast ion profile
- Large deficit in FIDA emission relative to FIDA SIM indicates central depletion of fast ion density
- As with neutron emission, FIDA profile returns to classical levels after modes disappear

*M .Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)*

*M. Garcia-Munoz et al., Nucl Fusion **51** 103013 (2011)*

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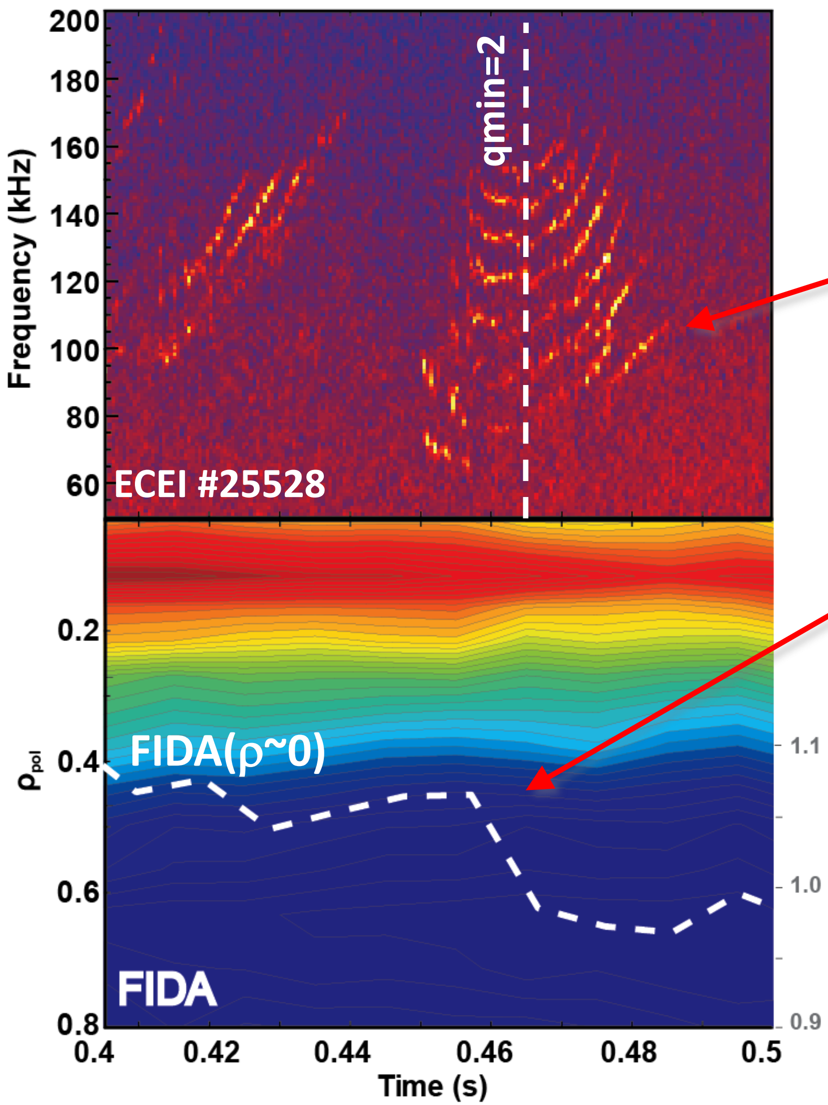
# FIDA System Measures a Drop in Central Fast-Ion Population as $q_{min}$ Passes Through an Integer



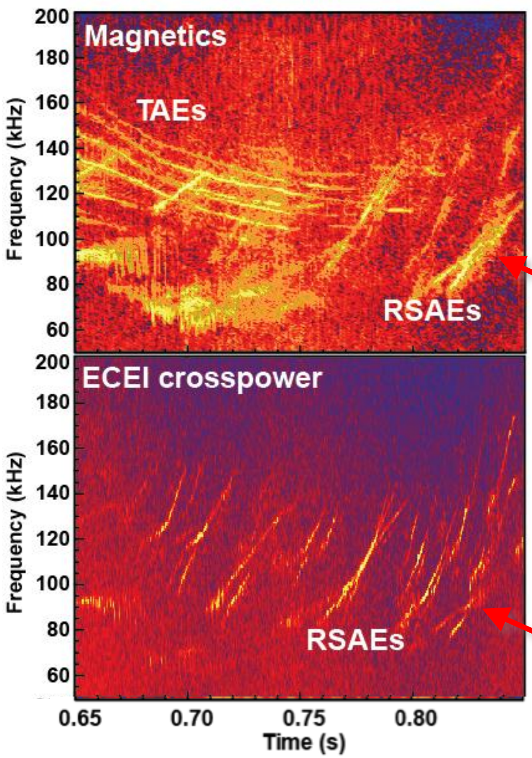

- At qmin=2 crossing, several RSAEs are excited by 60kV beams (Grand Cascade)
- Rapid drop in central fast ion density corresponding to peak in RSAE amplitude
- *No fast ion losses observed during this event*
  - May be geometrical effect. Plasma shape not FILD friendly

*M .Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)*
*M. Garcia-Munoz et al., Nucl Fusion **51** 103013 (2011)*

*B. Geiger at al., PPCF **53** (2011)*

# Higher Energy Beams Observed to Drive Spectrum of TAEs and RSAEs

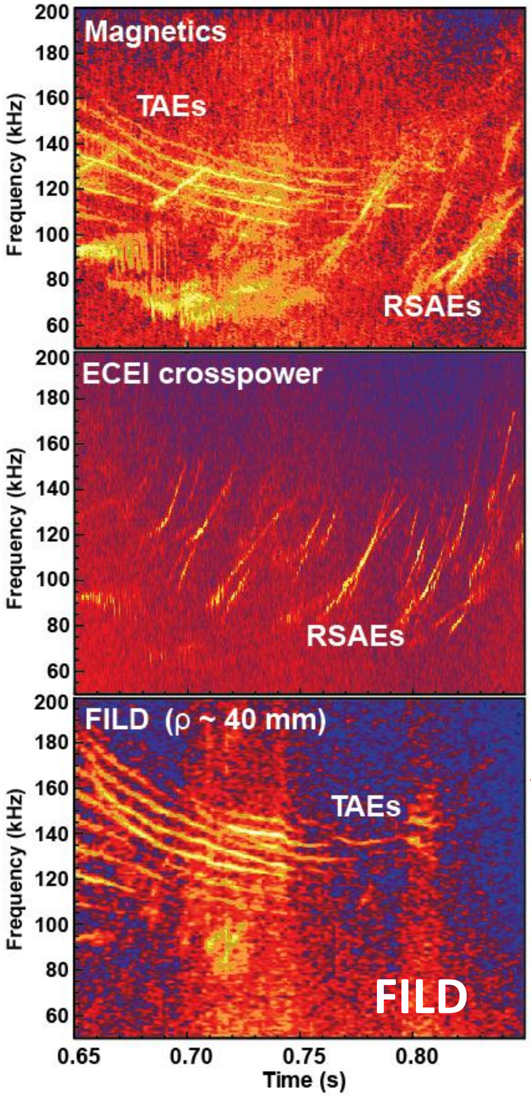





- Repeating discharge with 90 kV beams drove spectrum of RSAEs and TAEs unstable
- Edge magnetics detect combination of RSAEs, TAEs and additional mode
- ECEI at mid-radius detects primarily RSAEs

*M .Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)*
*M. Garcia-Munoz et al., Nucl Fusion* ***51*** *103013 (2011)*

# TAEs Observed to Cause Fast Ion Loss




- FILD spectrogram shows clear coherent losses from beam driven TAEs

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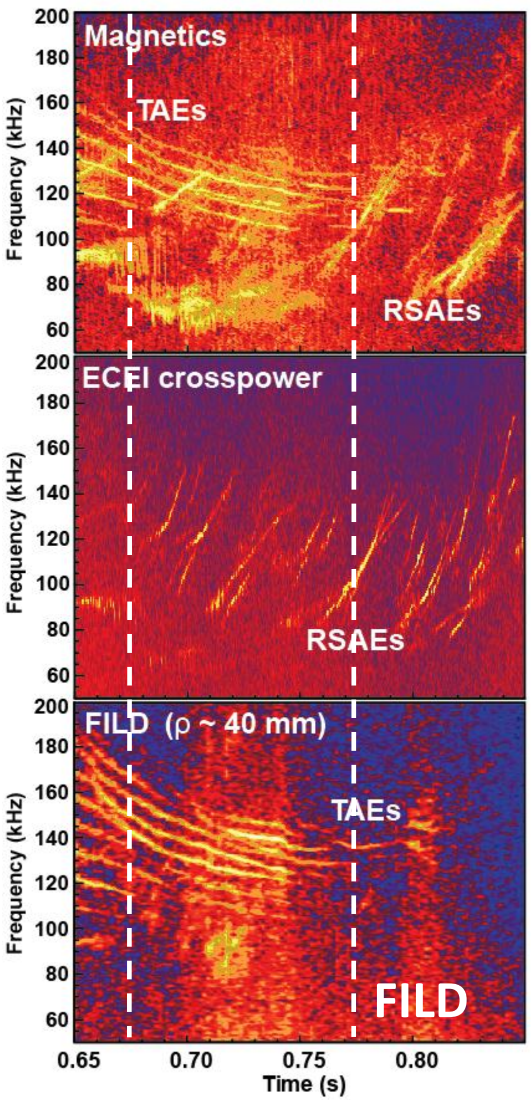
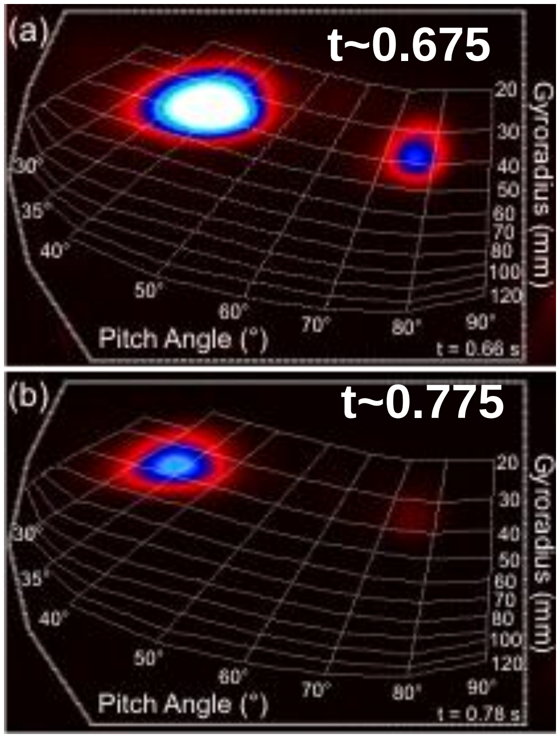



FILD SCINTILLATOR

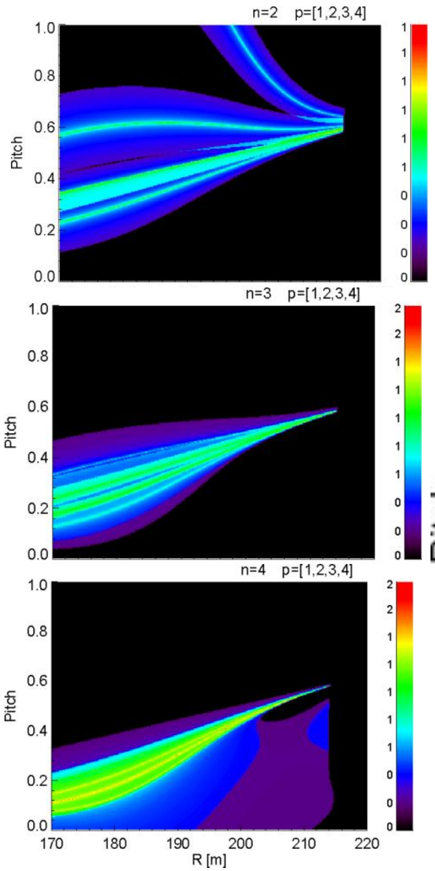


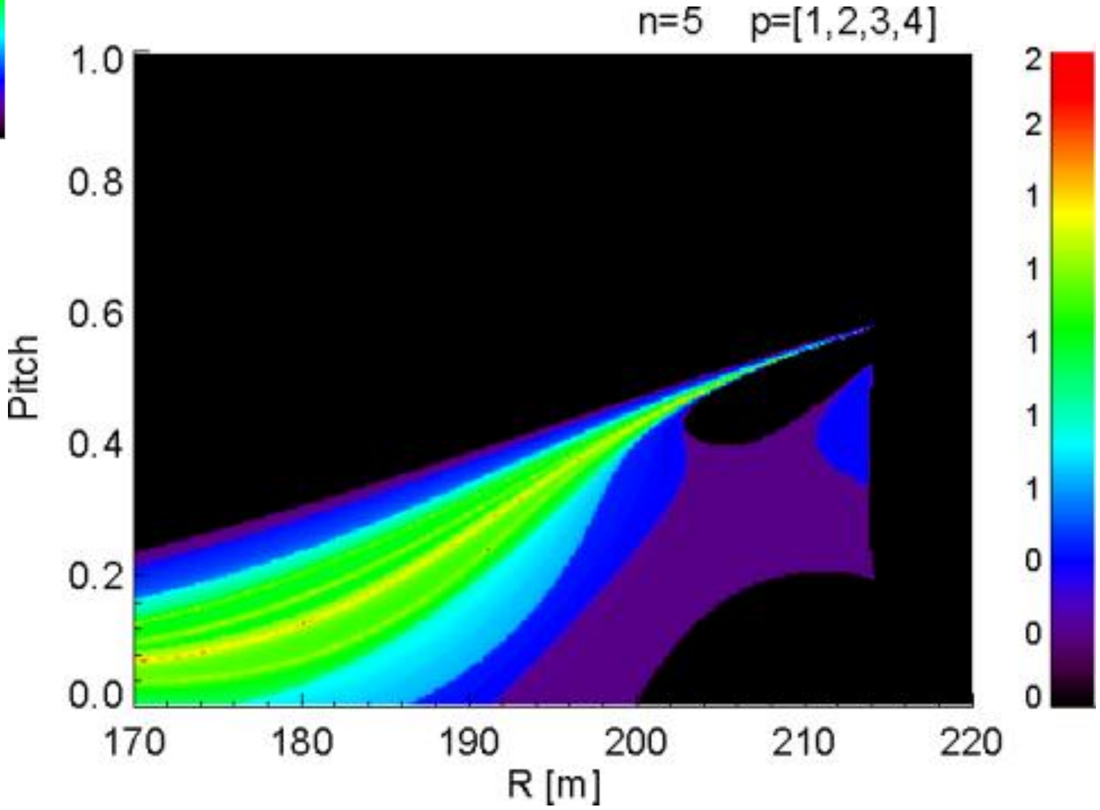

- FILD spectrogram shows clear coherent losses from beam driven TAEs
- FILD Scintillator indicates TAE induced losses appear near gyro-radius corresponding to injection energy

*M .Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)*
*M. Garcia-Munoz et al., Nucl Fusion **51** 103013 (2011)*

## Orbital frequencies calculated at $Z_{FILD}$ & $E_{FILD}$

$$\Omega_{n,p} \sim \omega_{MHD} - n \cdot \omega_{tor} - p \cdot \omega_{pol}$$



# Full Orbit GOURDON Code Used to Identify Orbit Topology of Escaping Ions & Wave-Particle Resonances

## Orbital frequencies calculated at $Z_{FILD}$ & $E_{FILD}$

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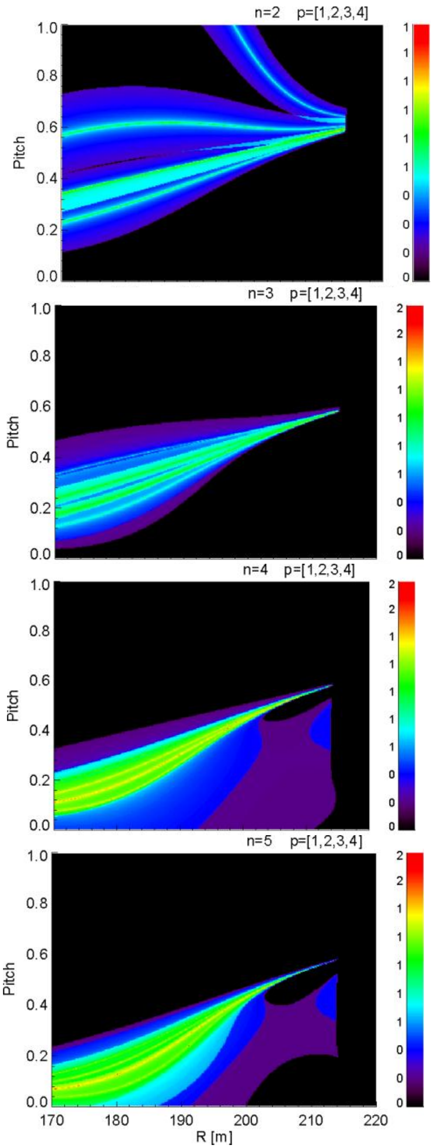
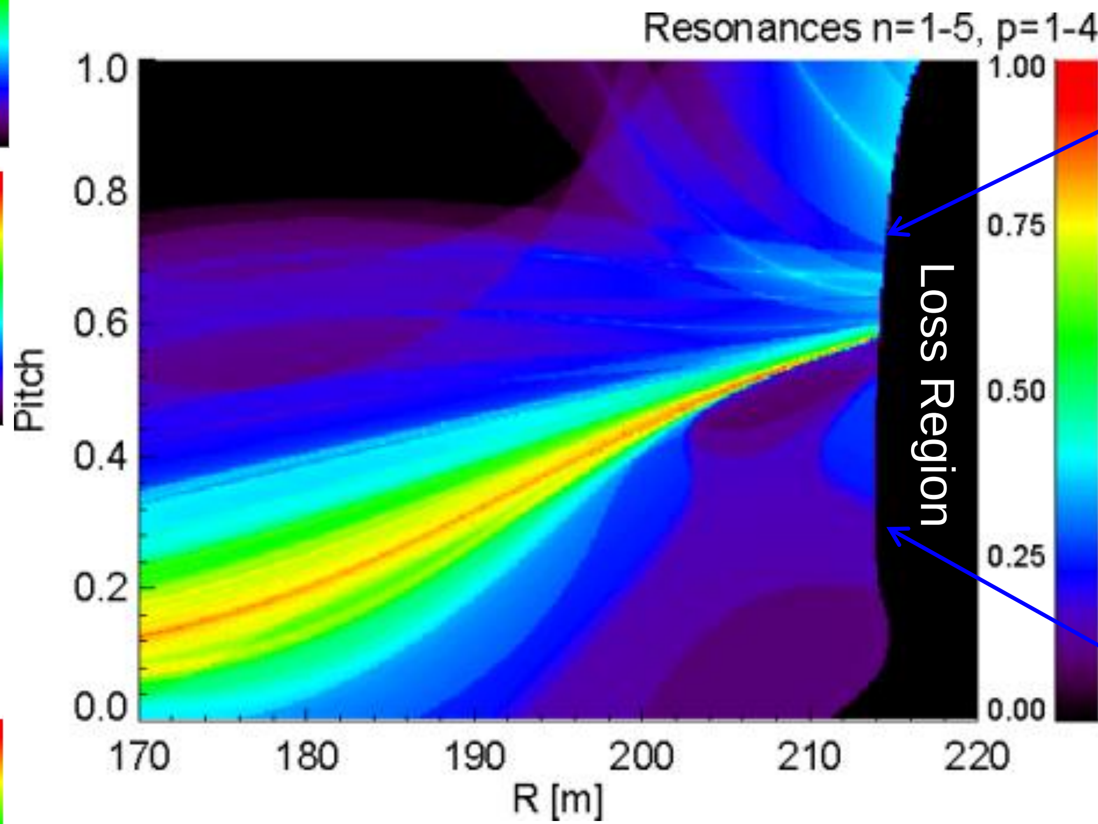
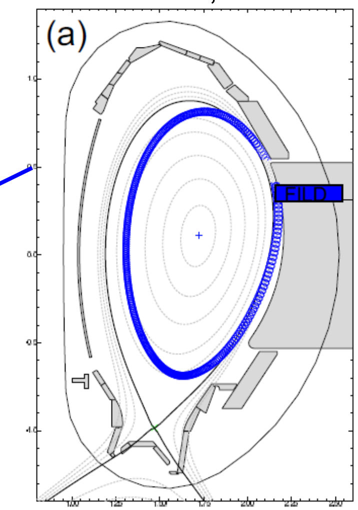
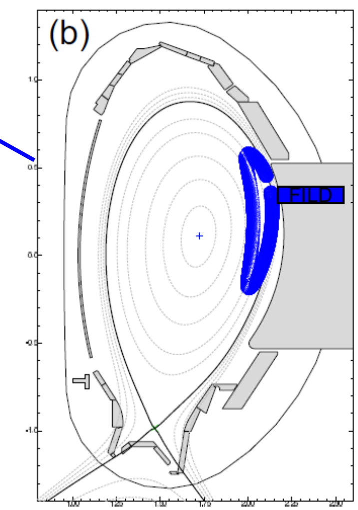



E = 93 keV, Λ ~ 40º



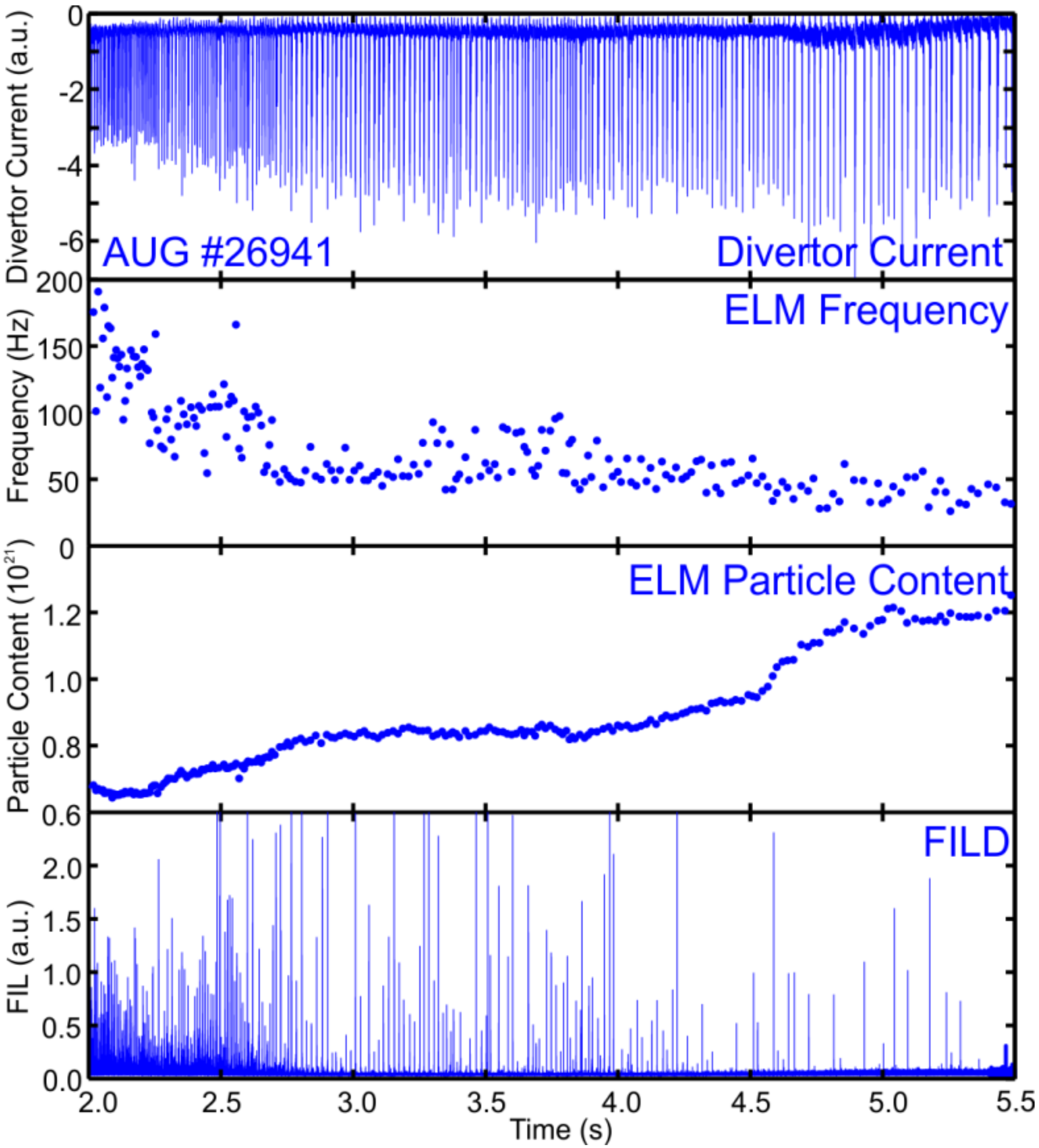

E = 93 keV, Λ ~ 75º




Wave-Particle Resonances are in Phase-Space Region Corresponding to Passing-Ions

⇒ Larger Fast-Ion Losses

# Fast-Ion Role in ELM Cycle



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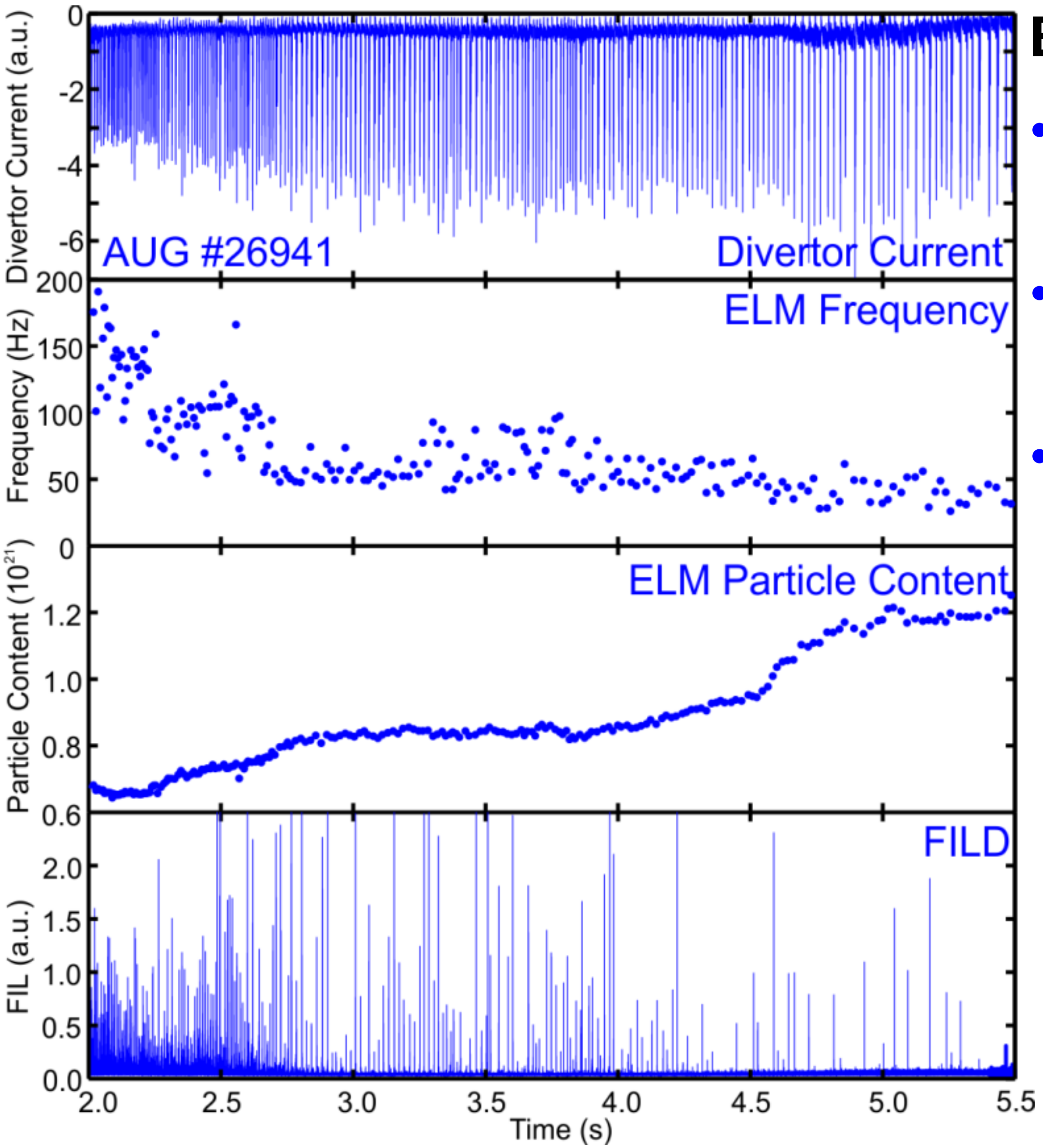
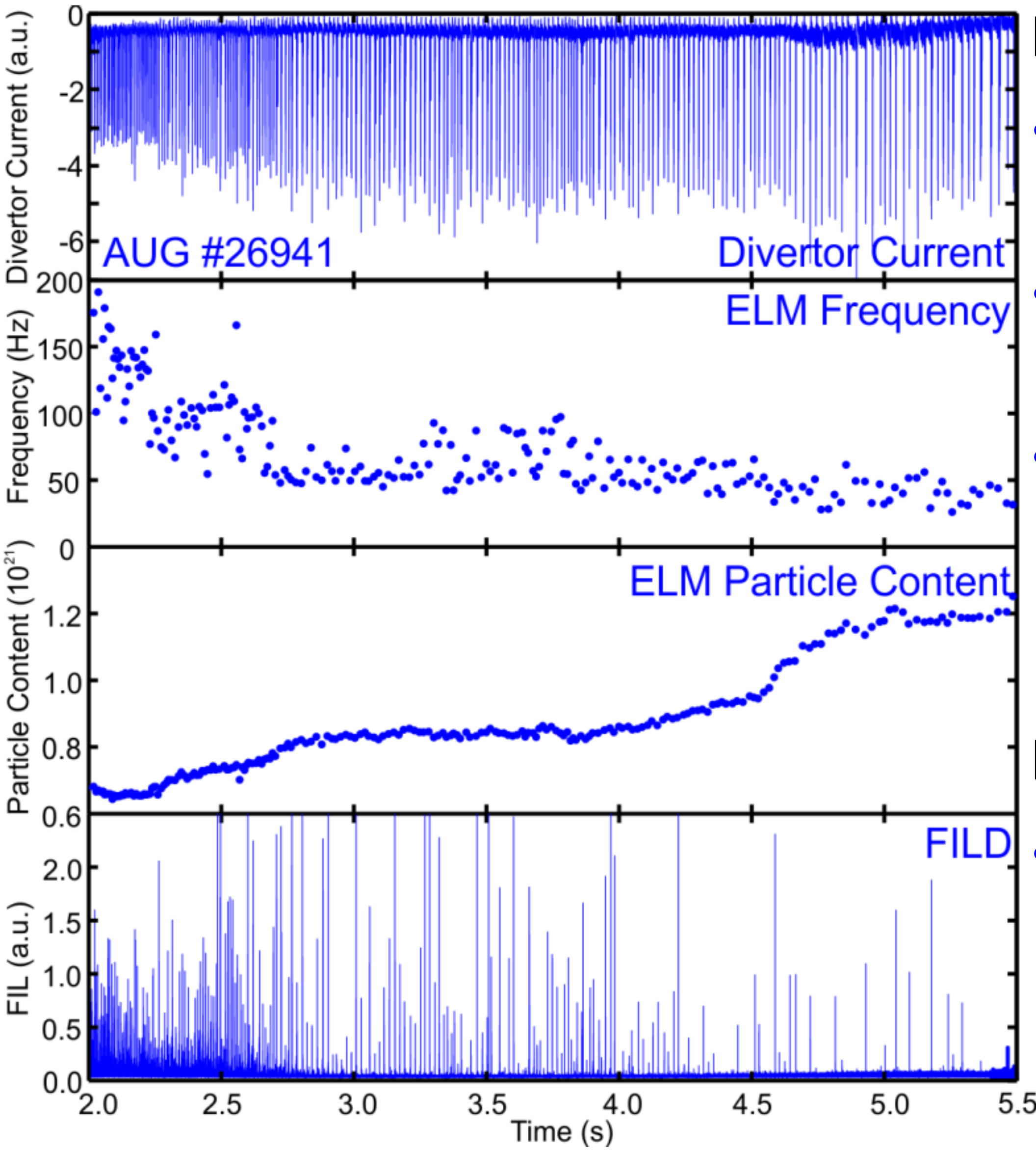



## ELM Induced Fast-Ion Losses

- **Important for machine safety in burning plasmas?**
- **Pedestal Transport mechanisms?**
- **Escaping fast-ions carry extra information on ELM cycle**

# Fast-Ion Role in ELM Cycle



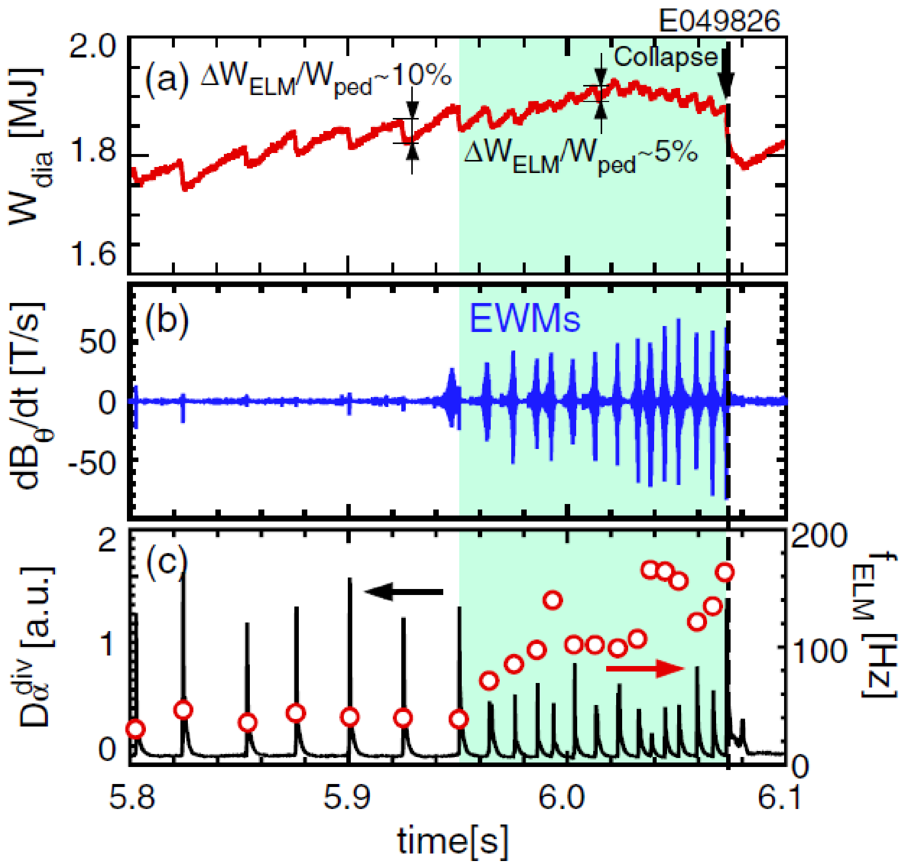

## ELM Induced Fast-Ion Losses

- **Important for machine safety in burning plasmas?**
- **Pedestal Transport mechanisms?**
- **Escaping fast-ions carry extra information on ELM cycle**

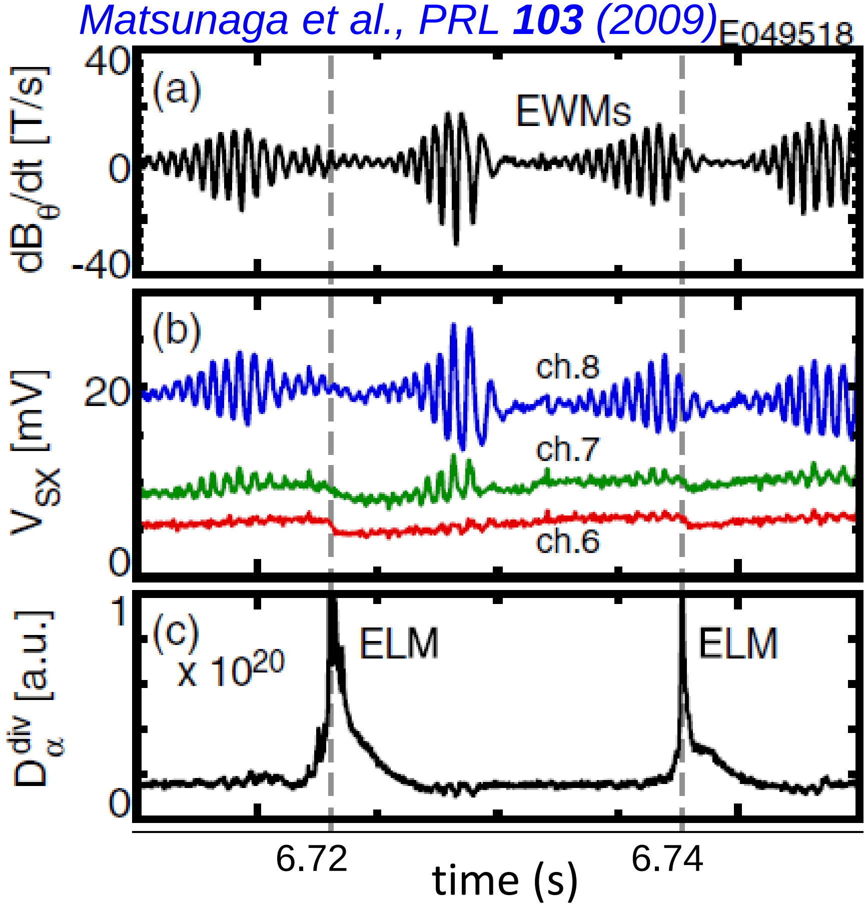
## ELM Stability

- **In Peeling-Ballooning model fast-ions could modify ELM stability through additional pedestal current, pressure and $E_r$**

## Smaller and more frequent ELMs in the presence of fast-ion driven ideal kink-ballooning mode




*Matsunaga et al., PRL **103** (2009)*




- EWM = 2 kHz (2,1) Global Mode

Ion-Diam Direction

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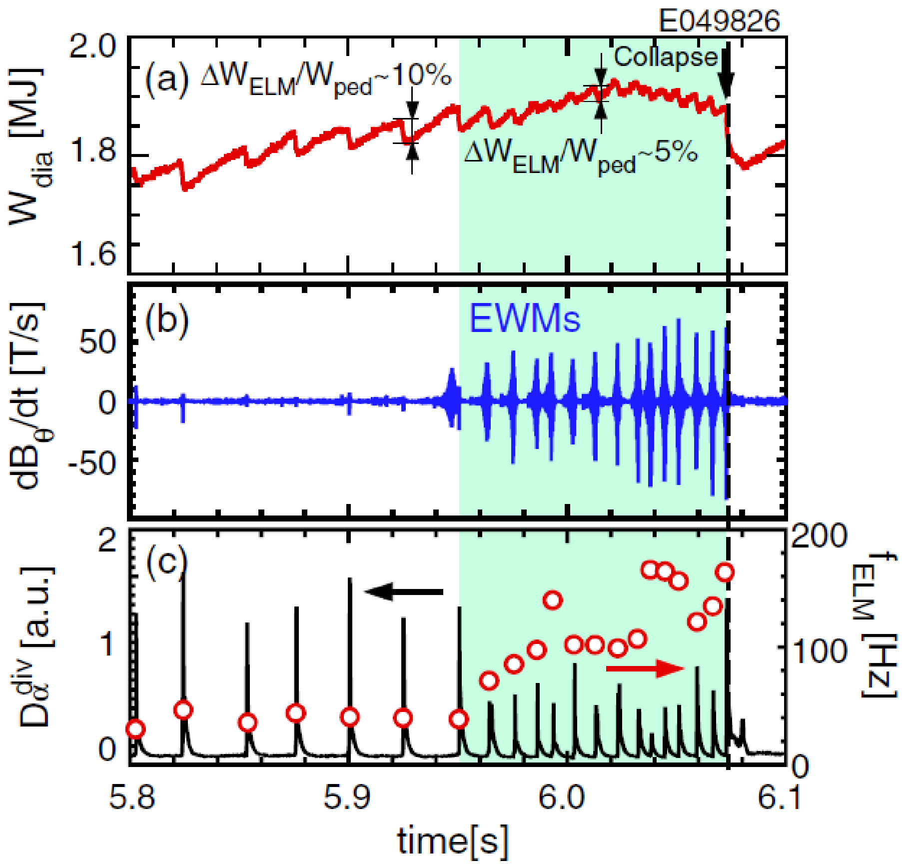


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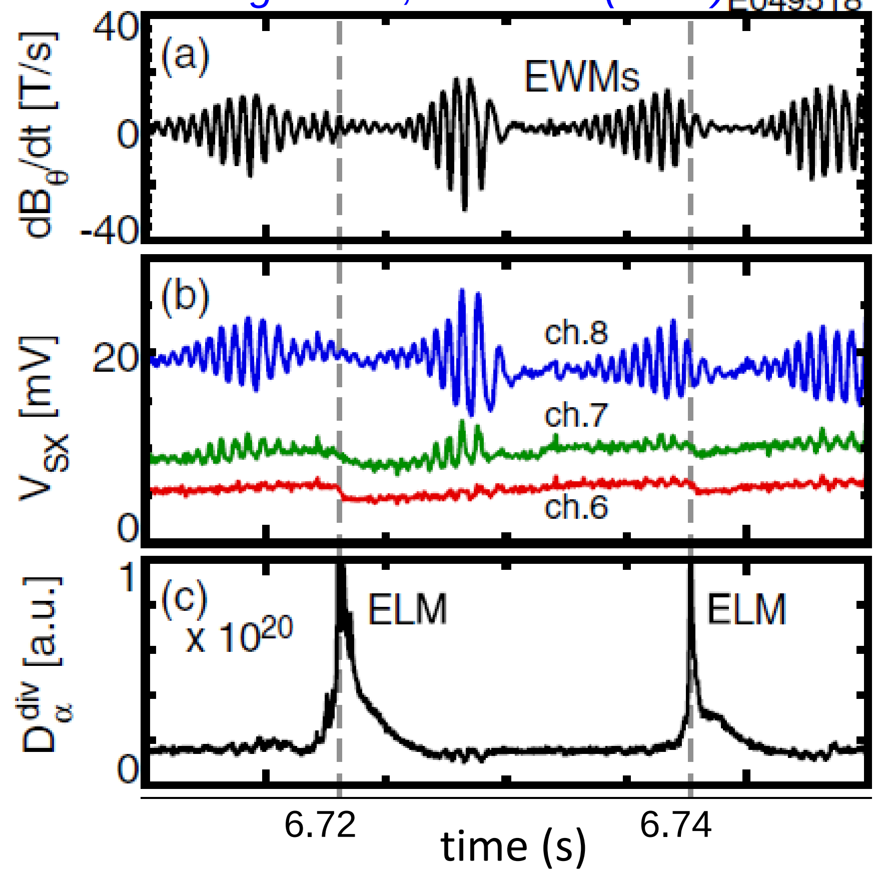



Lack of fast-ion measurement.
Can FILD / FIDA give extra information?

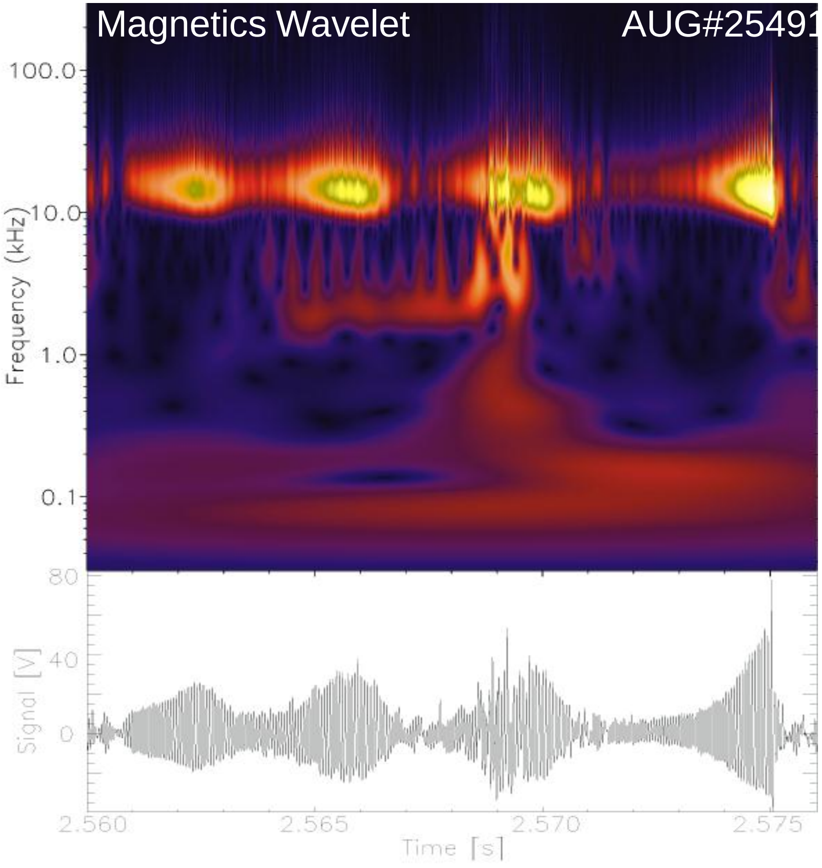
- EWM = 2 kHz (2,1) Global Mode

Ion-Diam Direction

# Global mode seems to trigger ELM but not always…



- Global (1,1) Kink in Ion-Diam Direction Doesn‘t Change Significantly with ELMs

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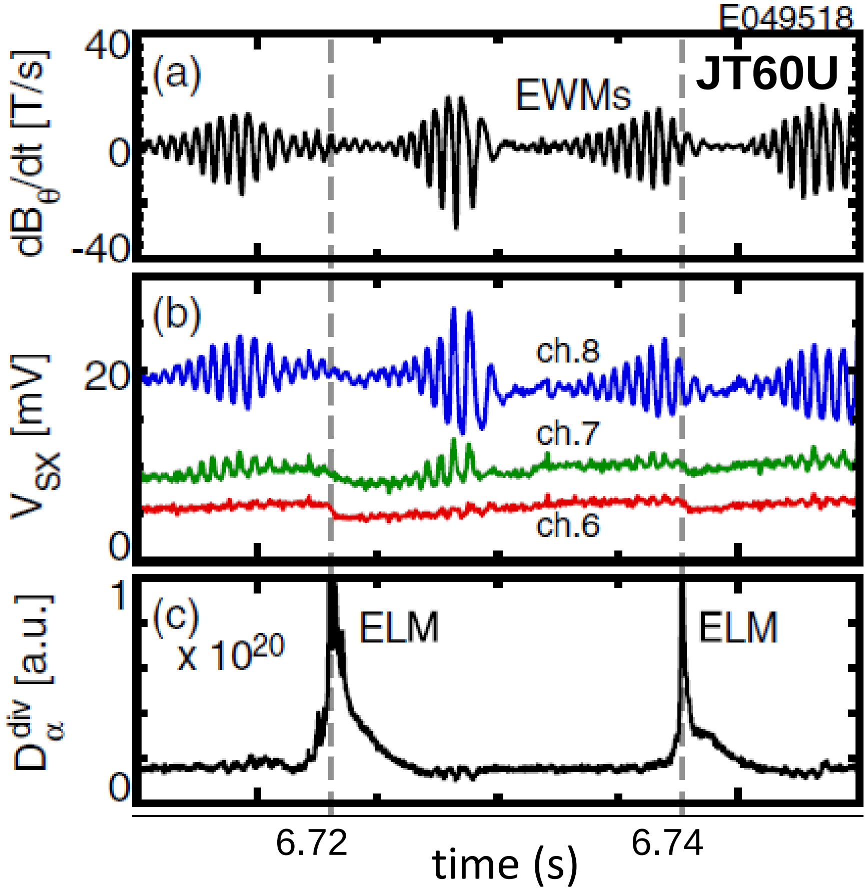

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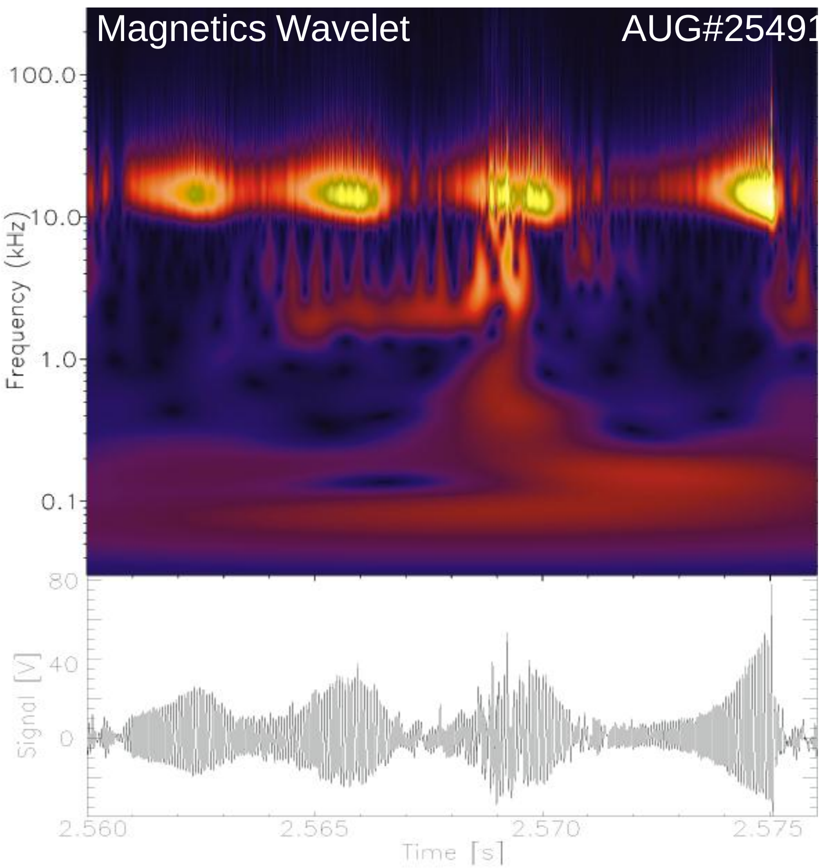


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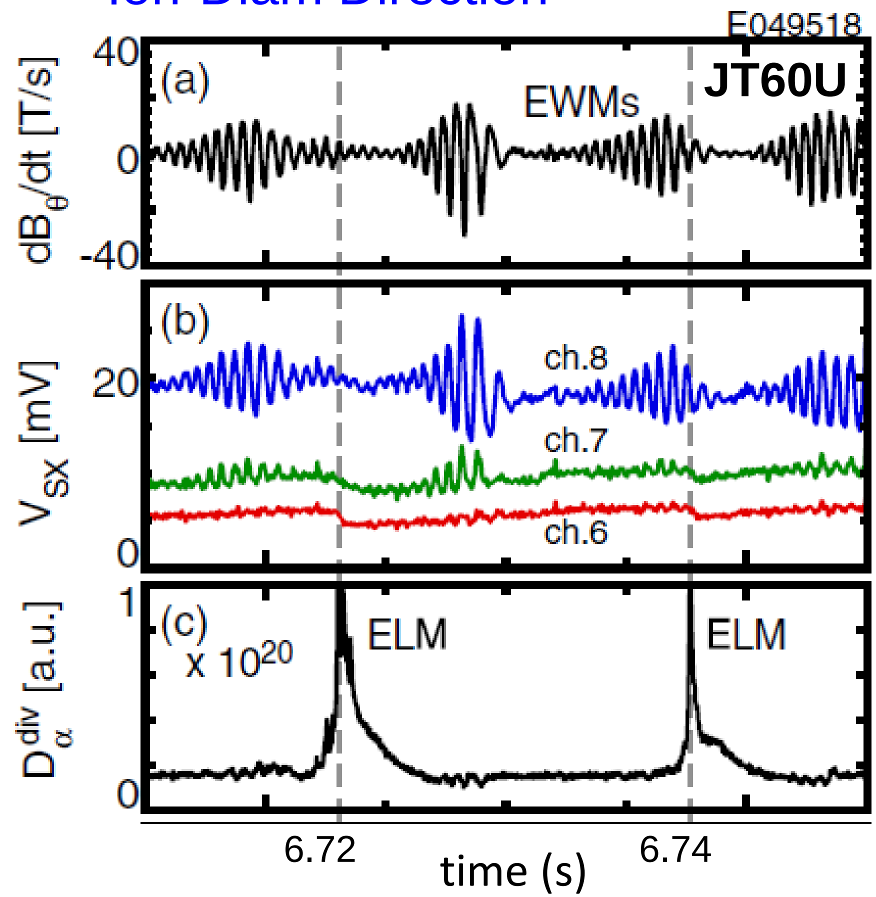


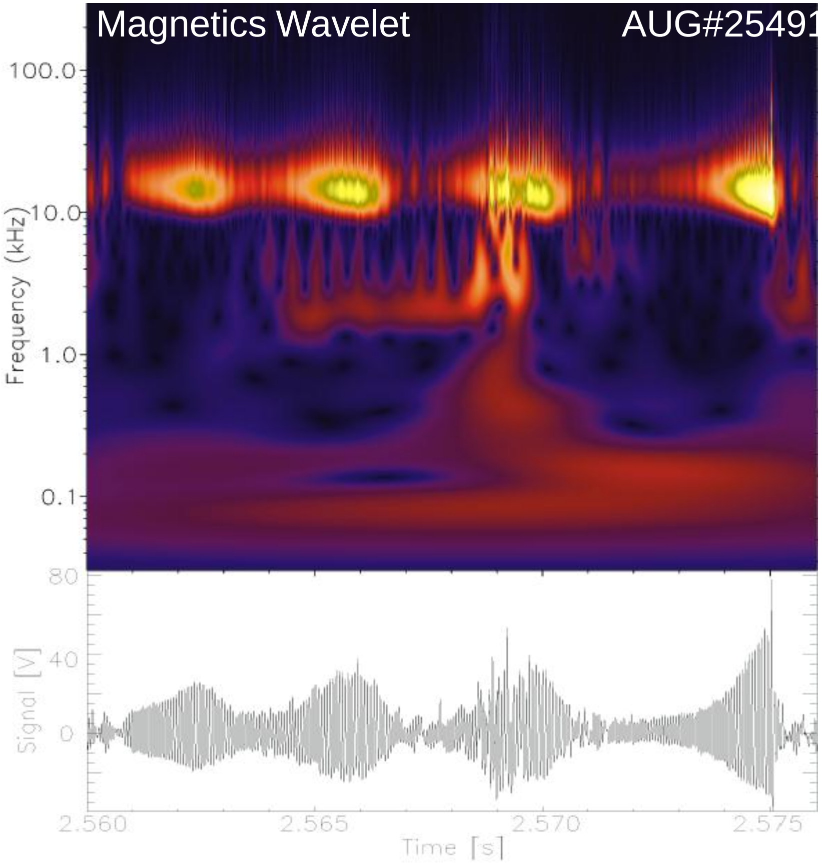

- Edge Localized n=2.5-3 & m=12, e-Diam Direction. Only Visible Before ELM

# Fast-Ion Losses Observed Mainly with Low-f Edge Mode & ONLY Before ELM

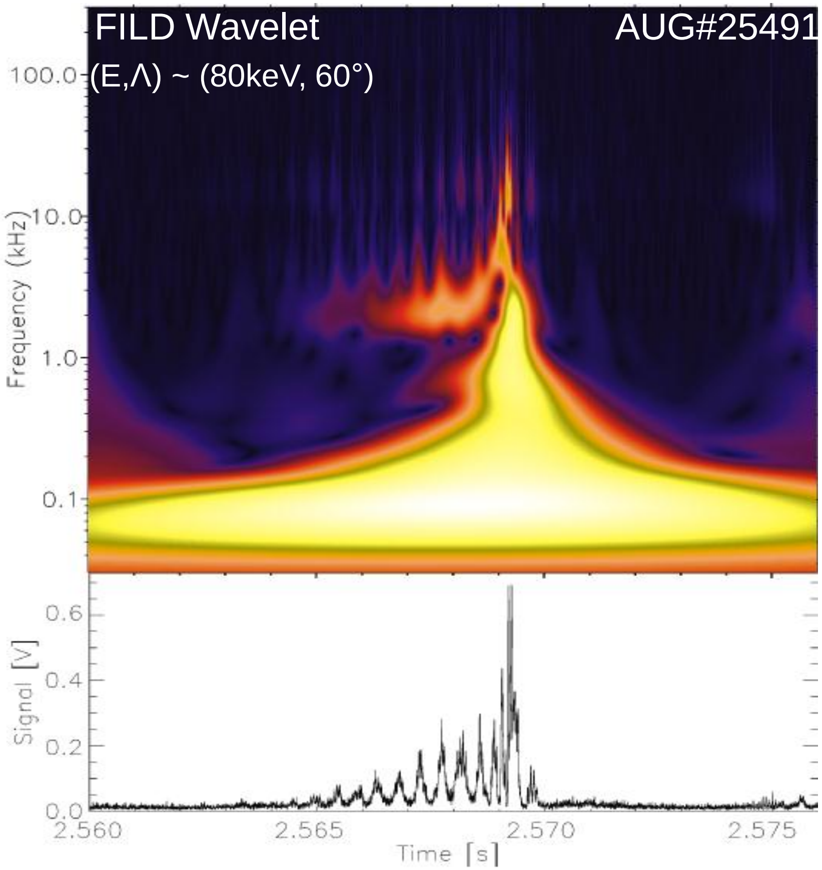


- Global (1,1) Kink in Ion-Diam Direction

Doesn‘t Change Significantly with ELMs




- Fast-Ion Losses Increasing Towards ELM Crash

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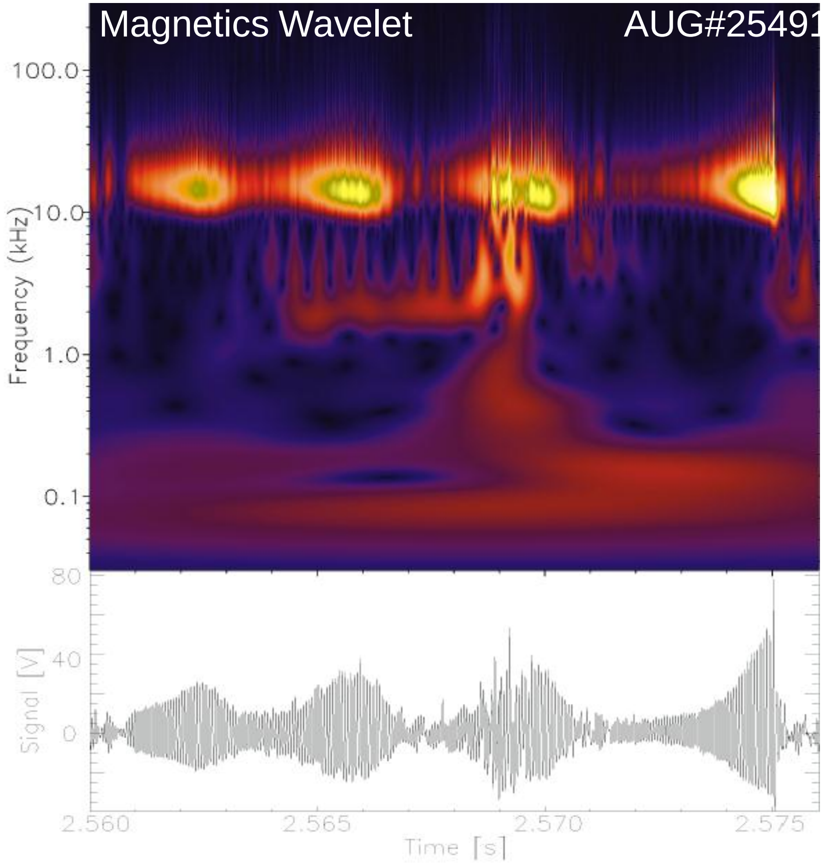
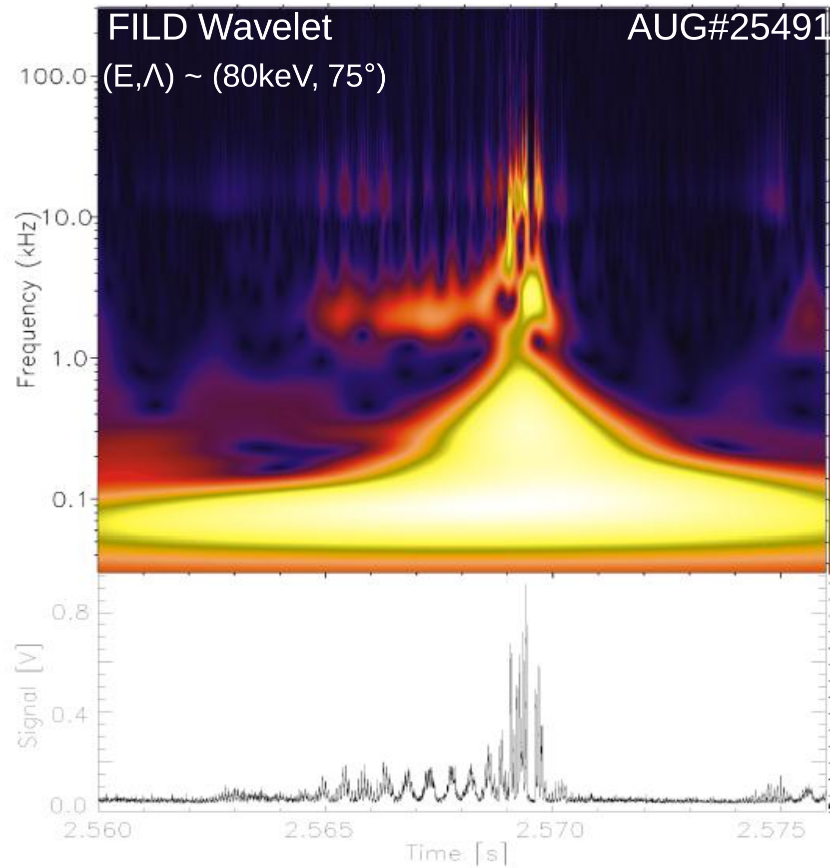



- Edge Localized n=2.5-3 & m=12, e-Diam Direction. Only Visible Before ELM

- Deeply trapped particles are more strongly affected

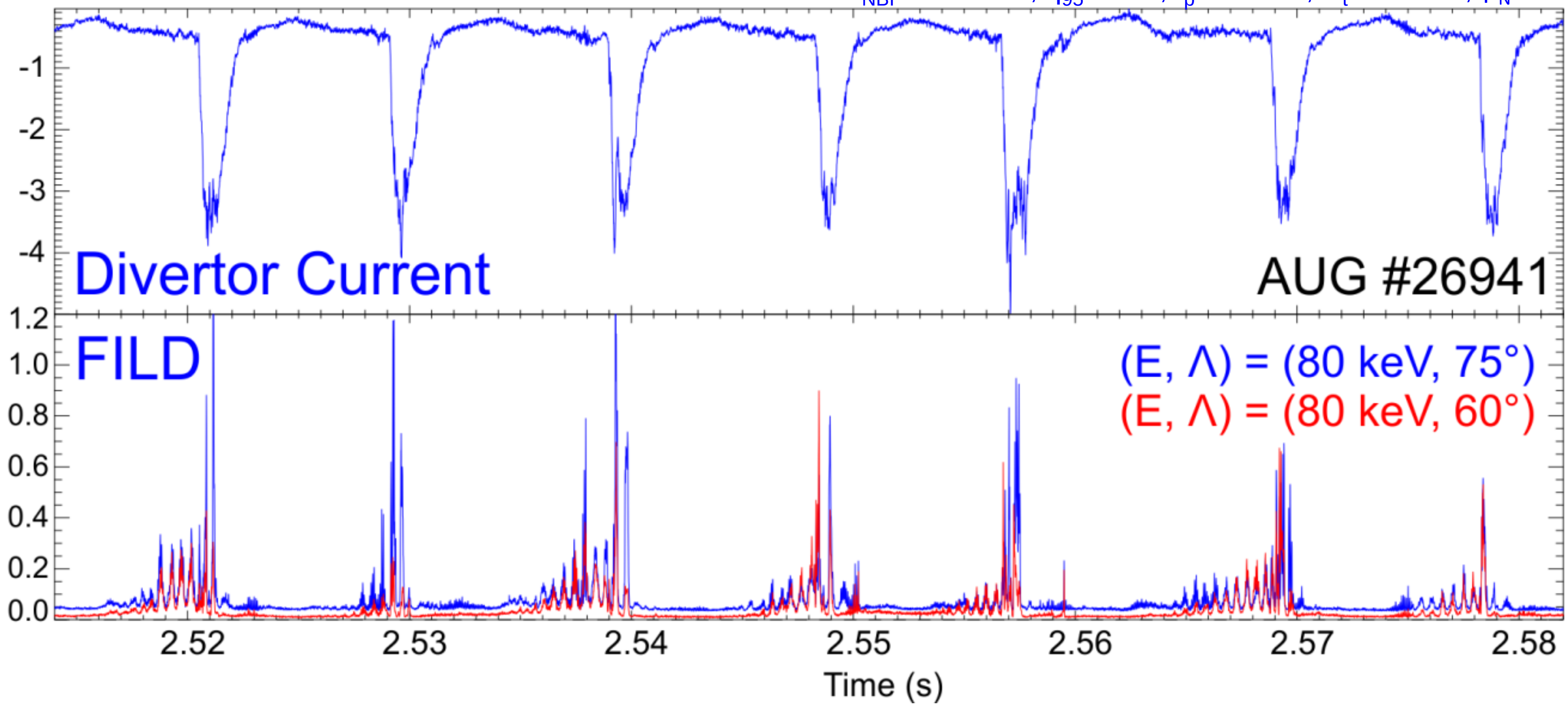
# Fast-Ions Seem To Contribute To ELM Stability



Low-freq pedestal fluct. prior ELM crash leads to an increasing fast-ion loss flux which seems to contribute to the ELM triggering

- Frequent, small ELMs are often accompanied by large fluxes of fast-ion losses during and pre-ELM crash

$P_{NBI}$ = 7.5 MW, $q_{95}$ = 3.3, $I_p$=1.0 MA, $B_t$ = -1.75T, $\beta_N$ ~ 3



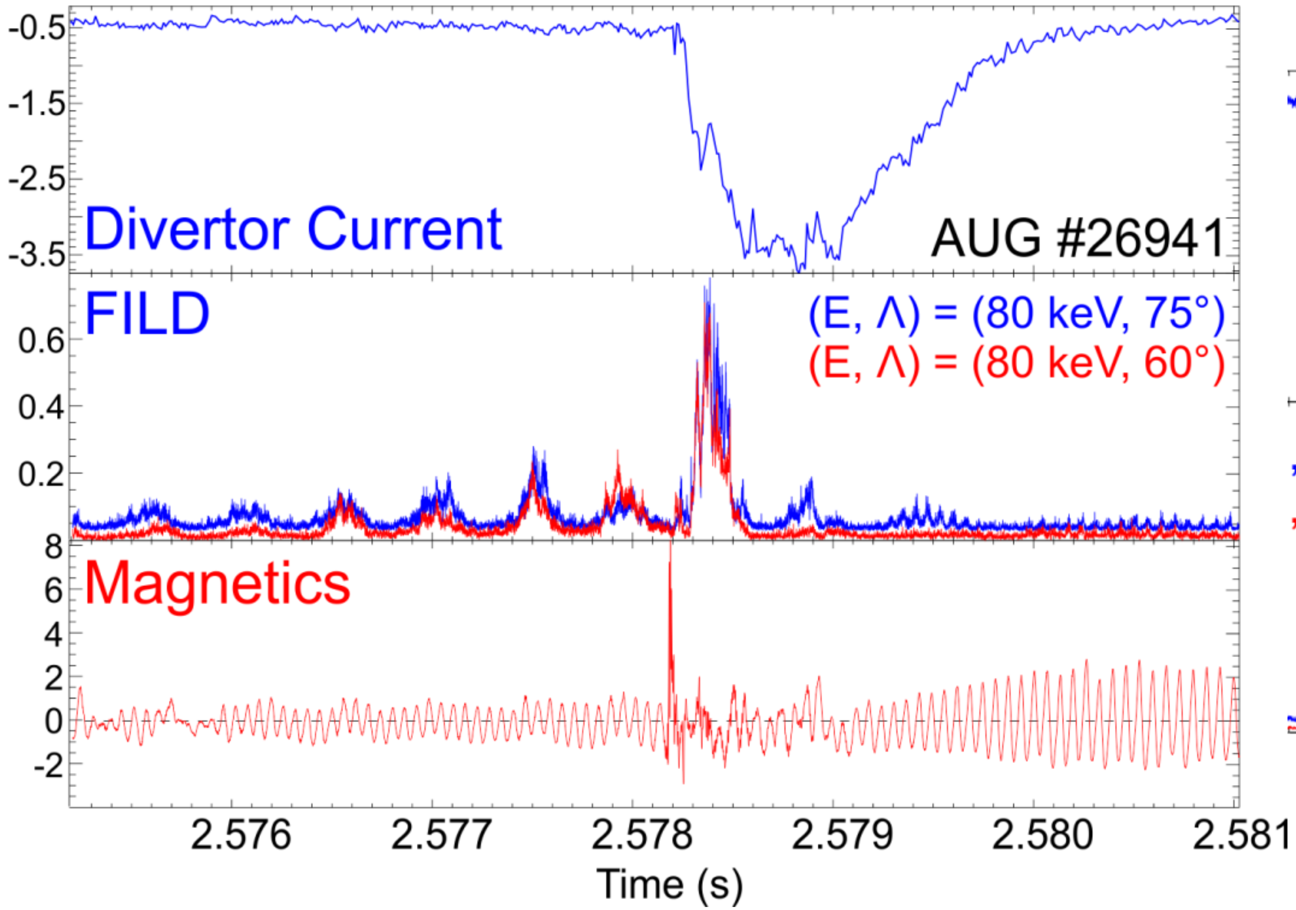

Pre-ELM Divertor current (ELM Monitor) Rise Correlated with FILD

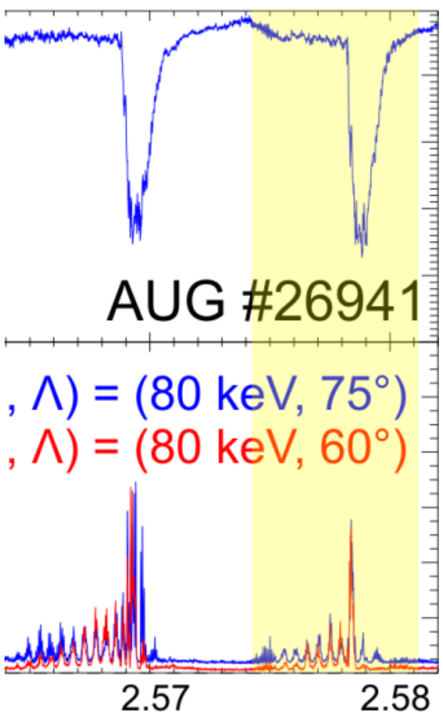
# Magnetic Fluctuation of Edge Mode Is Not Sinusoidal



Low-freq pedestal fluct. prior ELM crash leads to an increasing fast-ion loss flux which seems to contribute to the ELM triggering

- Magnetic fluctuation of Low-f (12,3) Edge Mode is not sinusoidal



# Fast-Ion Losses Are in Phase with Pre-ELM Edge Fluctuation



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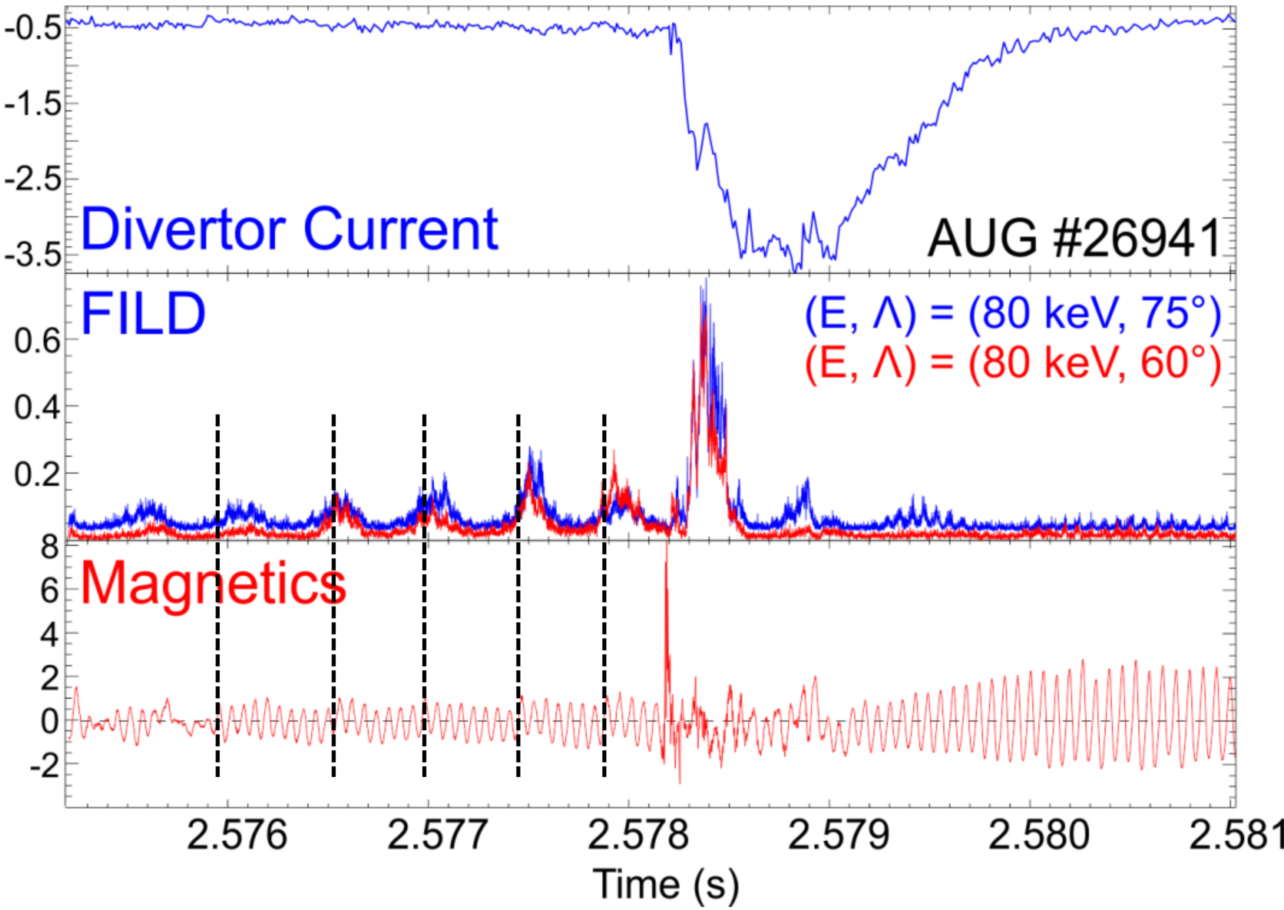
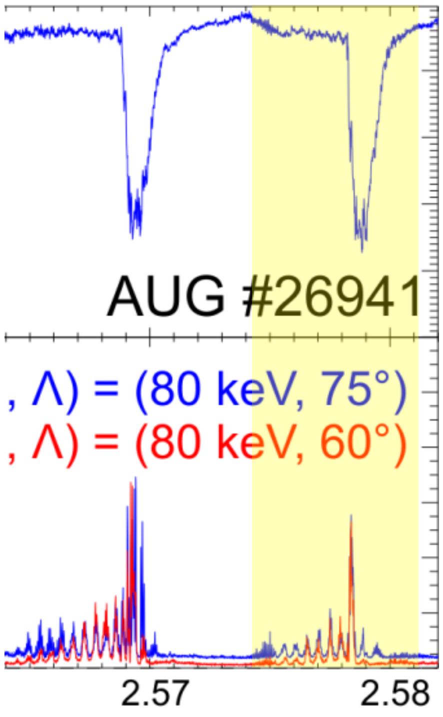
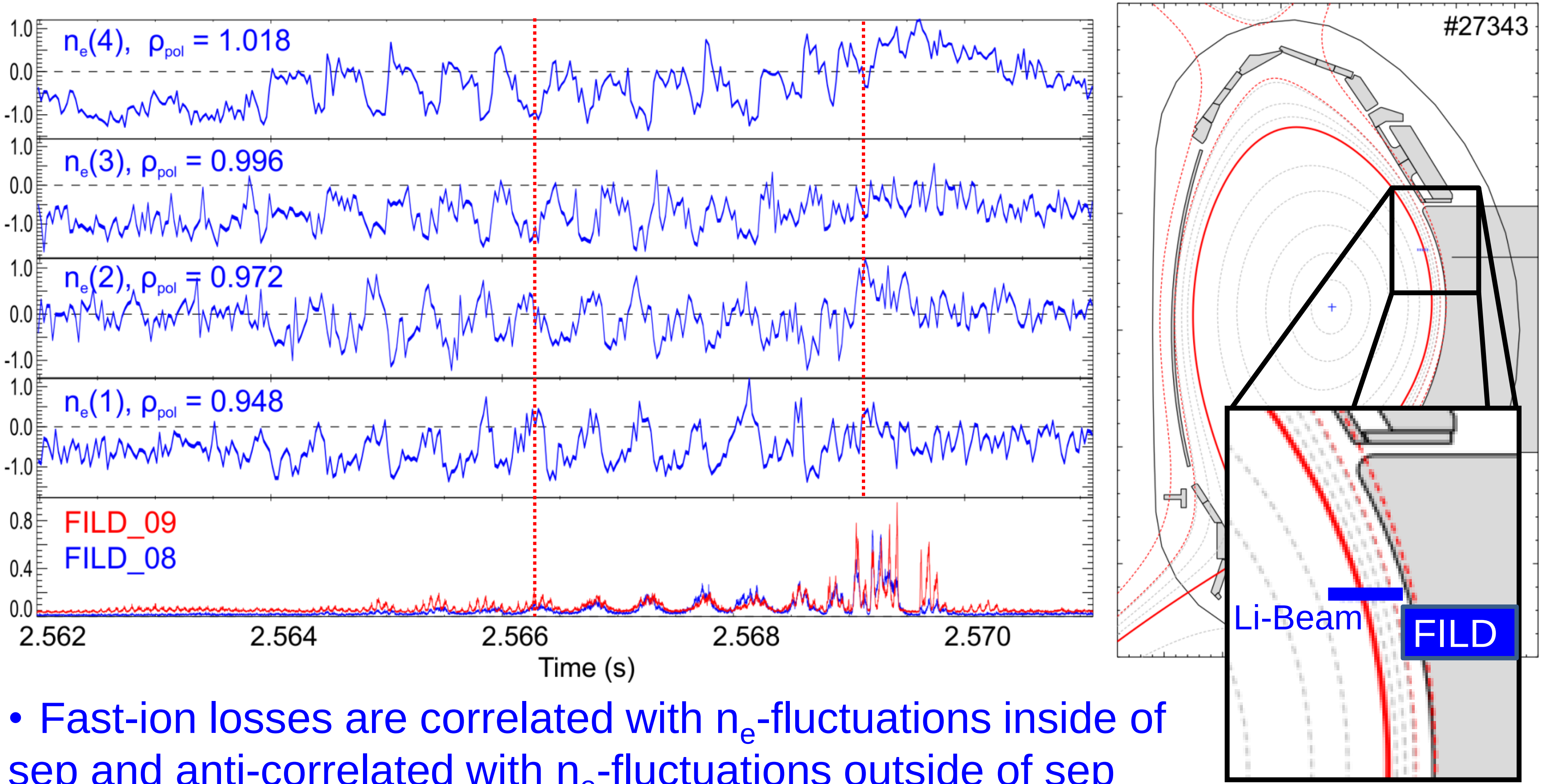


# Pedestal $n_e$ fluctuation prior to ELM

Pre-ELM low freq, 1-2 kHz, density fluctuation measured around separatrix with Li-Beam diagnostic (close to FILD)




- Fast-ion losses are correlated with $n_e$-fluctuations inside of sep and anti-correlated with $n_e$-fluctuations outside of sep

- During ELM crash fast-ion losses are not correlated with any $n_e$ change

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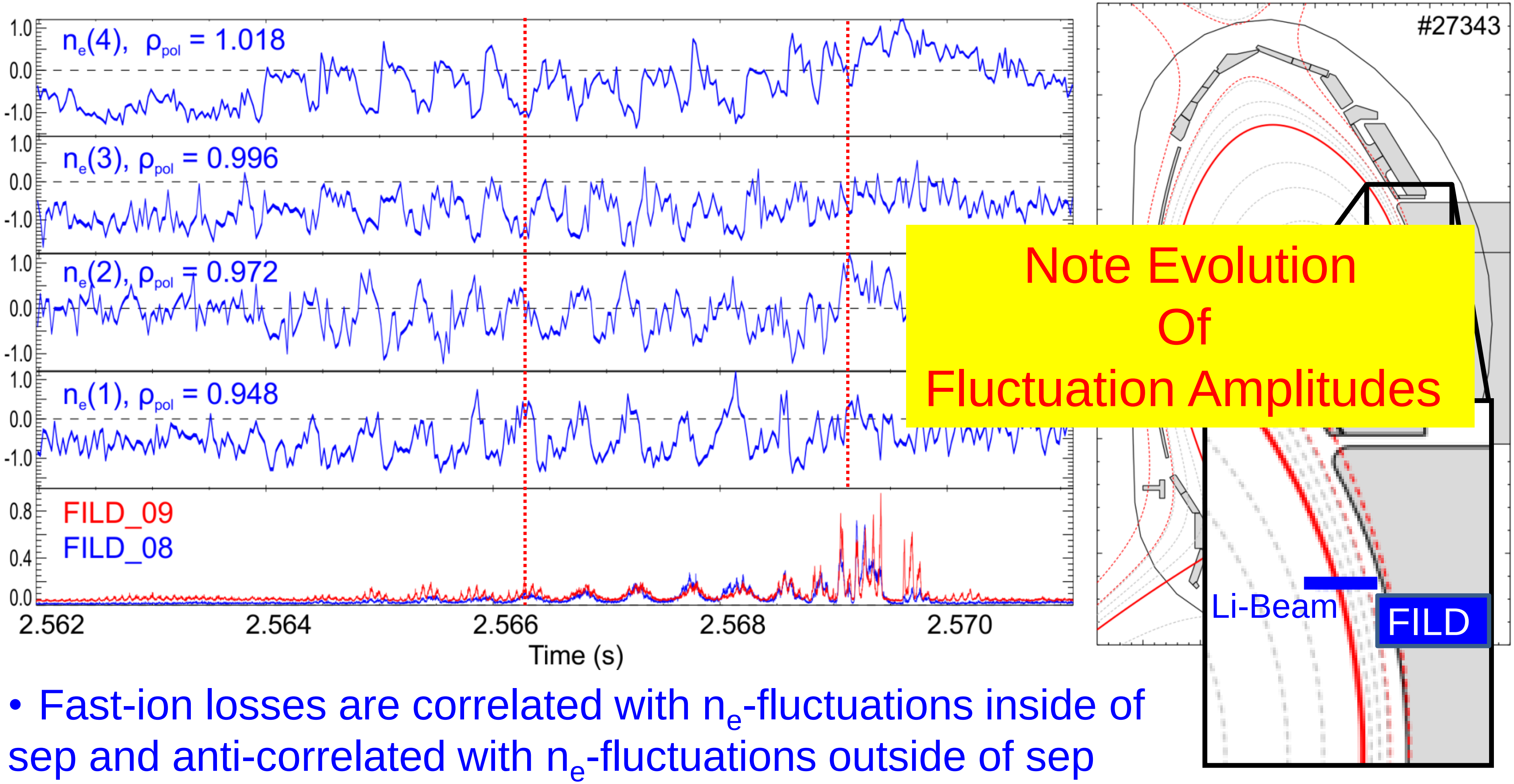


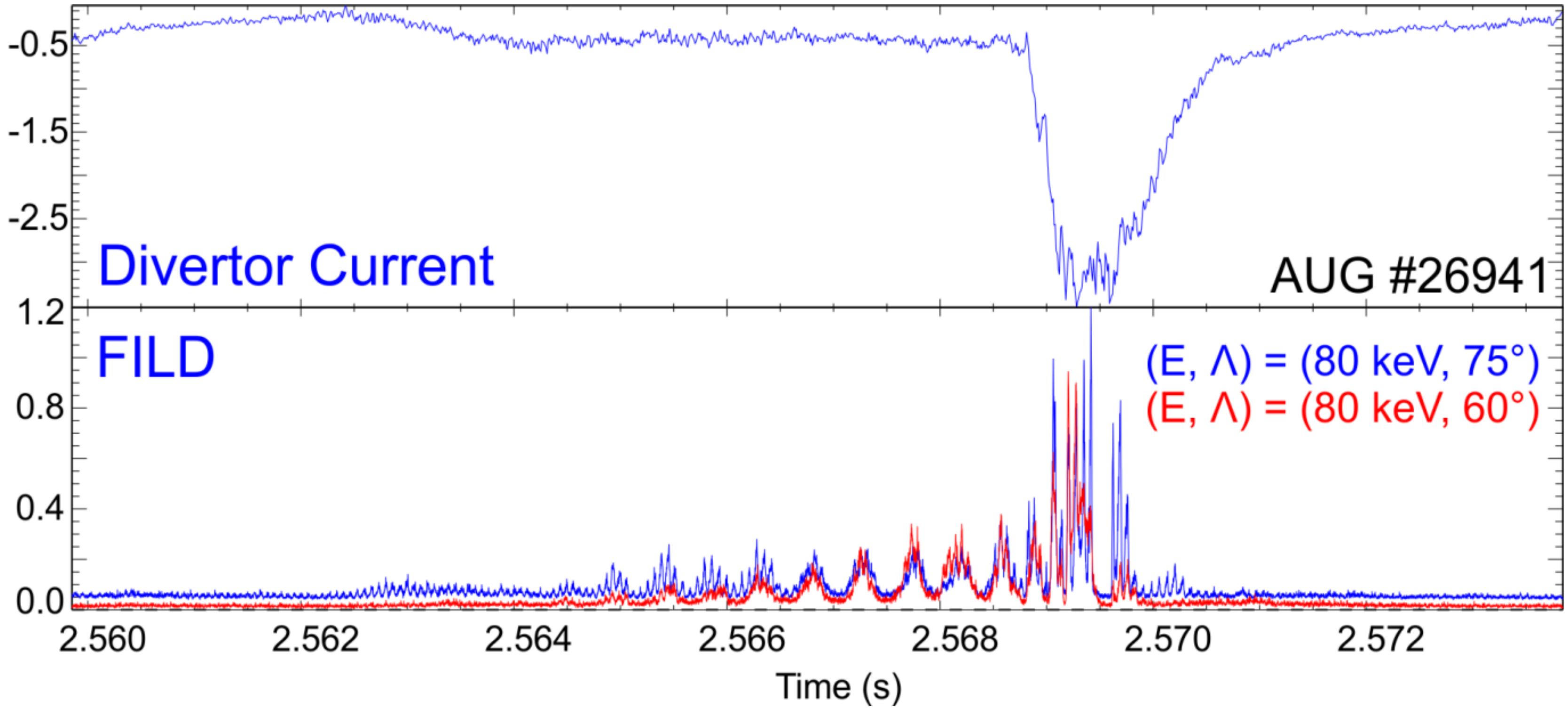

- Fast-ion losses are correlated with $n_e$-fluctuations inside of sep and anti-correlated with $n_e$-fluctuations outside of sep
- During ELM crash fast-ion losses are not correlated with any $n_e$ change

# Different Loss Mechanisms in ELM Cycle



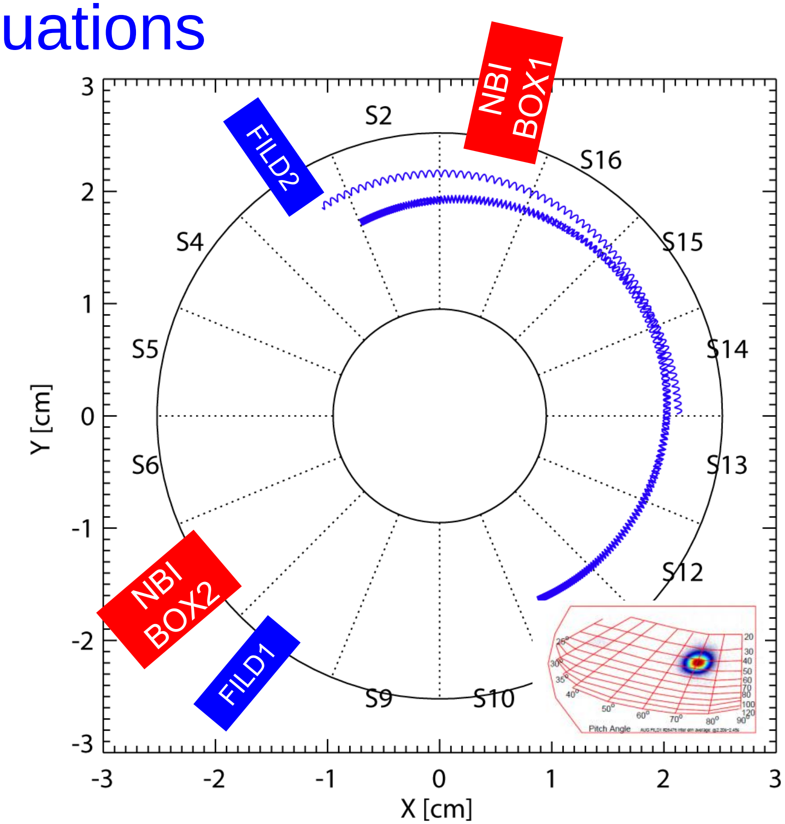
At least 3 different loss mechanisms (time scales) are observed during the ELM cycle.  Pitch-angle dependency

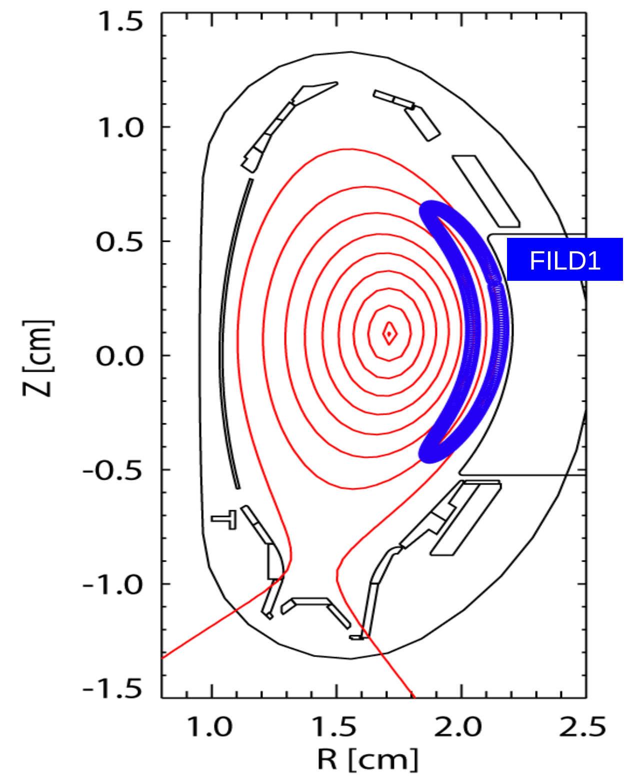
- Fast-ion losses due to pre-ELM fluctuations are coherent
- Amplitude evolution of pre-ELM edge $n_e$-fluctuation and fast-ion losses are NOT correlated
- During ELM crash fast-ion losses appear in bursting fashion



# Banana Orbits Are Most Affected

Measured fast-ion losses are on banana orbits that explore entire pedestal / SOL. Contribution to Stability. Sensitive to Most Pedestal Fluctuations




Both FILD1 and FILD2 observe similar behavior not correlated with any variation in $n_e$ profile. Not surprising but important to rule out first order effects such as prompt losses (DC signal)

# Summary

- AEs have been driven unstable with NBI in AUG
- AE induced fast-ion redistribution & loss measured with FIDA & FILD
  - Drop in central fast-ion population as $q_{min}$ passes through an integer with multiple RSAEs
  - Fast-ion losses mainly due to TAEs. Mostly on passing orbits
  - Possible wave-particle resonances only with passing ions. Consistent with experimental data
- Large bursts of fast-ion losses during ELMs
- Core kink mode causes fast-ion losses correlated with smaller & more frequent ELMs
  - Fast-ion losses due to pre-ELM edge fluctuation are dominant. Significant contribution to ELM triggering
  - Deeply trapped particles strongly affected. Several loss mechanisms in ELM cycle