# Coherent Beam-Ion Losses during Instabilities in DIII-D

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# Abstract

**A scintillator-based fast-ion loss detector (FILD) was installed on DIII-D in 2010[1] and successfully measured coherent losses produced by fast-ion driven instabilities. Loss signals at mode frequencies were observed for off-axis fishbones[2], toroidal Alfvén eigenmodes (TAE)[3], reversed-shear Alfvén eigenmodes (RSAE)[3], and energetic-particle driven geodesic acoustic modes. Modeling of the TAE and RSAE experiments indicate that the observed losses are predominately counter-passing ions that are scattered onto lost trapped-ion orbits by the Alfvén eigenmodes[4]. The original FILD detector is ~ 45° below the midplane. For the 2011 campaign, a second FILD detector is installed near the midplane. First results from the pair of FILD detectors are reported.**

* Supported by the DOE

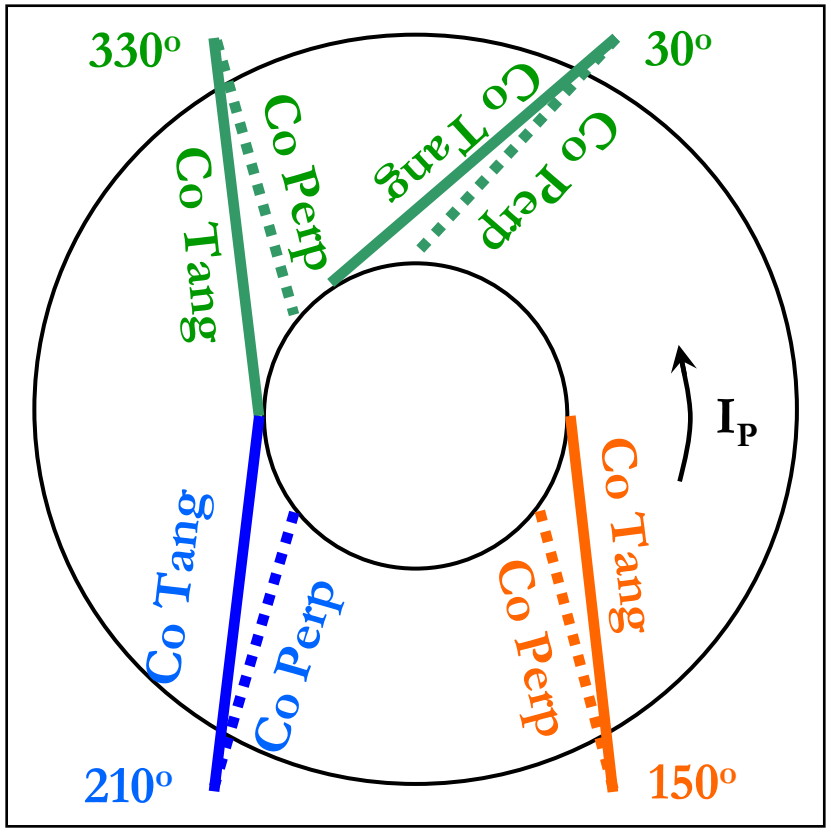
[1] R.K. Fisher *et al.*, Rev. Sci. Instrum. *81* (2010) 10D307
[2] W.W. Heidbrink *et al.*, Plasma Phys. Cont. Fusion *53* (2011) 085028
[3] D.C. Pace *et al.*, Plasma Phys. Cont. Fusion *53* (2011) 056114
[4] M.A. Van Zeeland *et al.*, Phys. Plasmas *18* (2011) 056114

# Motivation

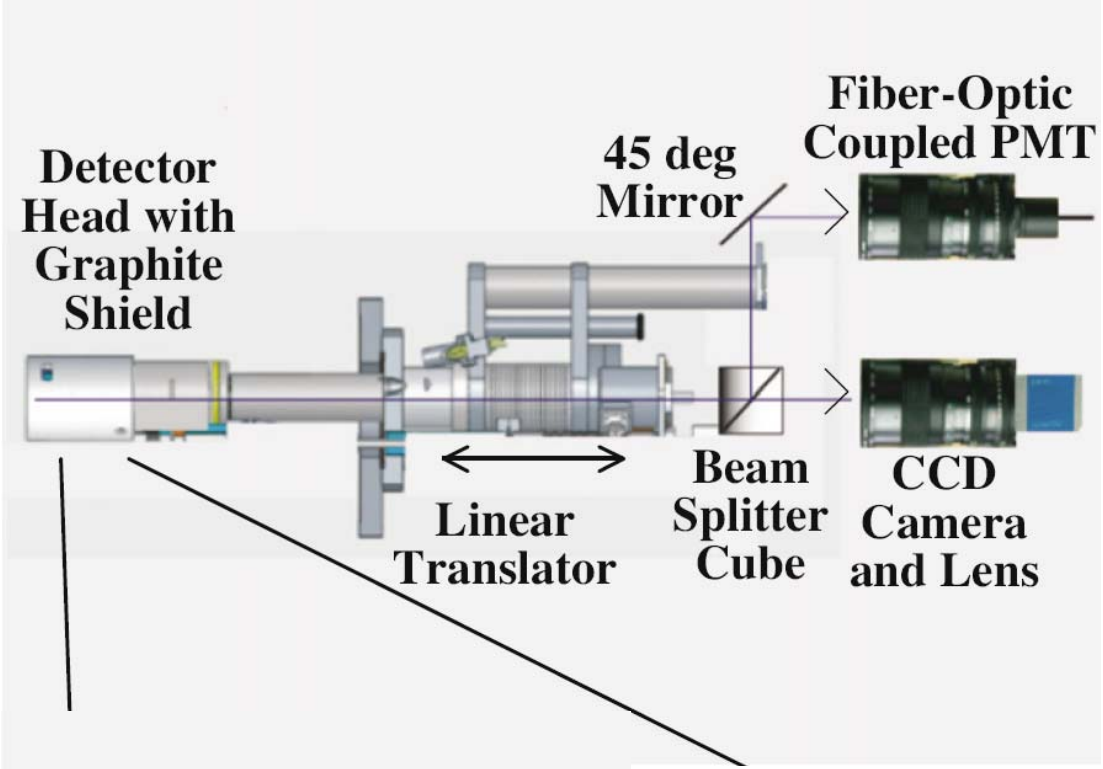
- **Transport of energetic particles (neutral beam injected ions, ion cyclotron heated tail ions and fusion born alpha particles) is of crucial importance for magnetically confined fusion plasmas.**
  - **Loss of beam injected ions on DIII-D impacts plasma performance, including plasma heating, neutron production, and current drive.**
  - **Losses of the $\alpha$-particles in ITER could cause excessive heat loads on the first wall, additional impurity sources, and might prevent achieving ignition.**
- **MHD instabilities have been shown to increase the radial transport of fast ions. Details of fast ion loss reveal aspects of the physical processes that induced the loss and help understand the loss mechanism and the properties of associated instabilities.**

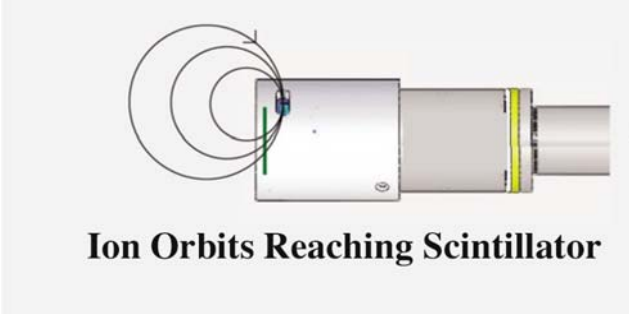
# Energetic Ion Population is Varied Using Different Neutral Beam Injection Geometries

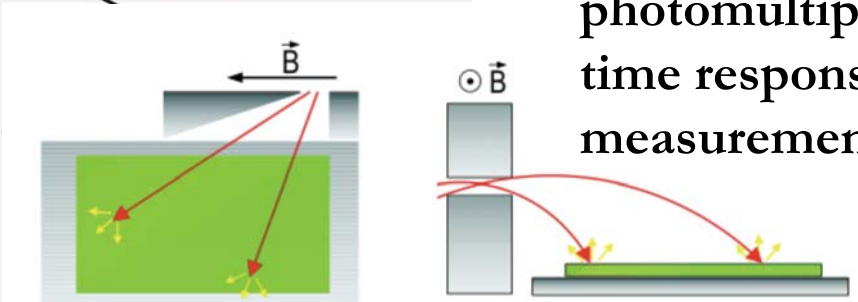
- **Neutral beam injection (NBI) possible in both co-current and counter-current directions**
- **Tangential/perpendicular injection**
  - prompt losses
  - beam-ion trapped/passing populations
- **150° Neutral Beam can be tilted vertically for off-axis injection**
- **Adjustable ion energy**
  - Varies from 60 to 80keV



# Fast-Ion Loss Detector (FILD) System



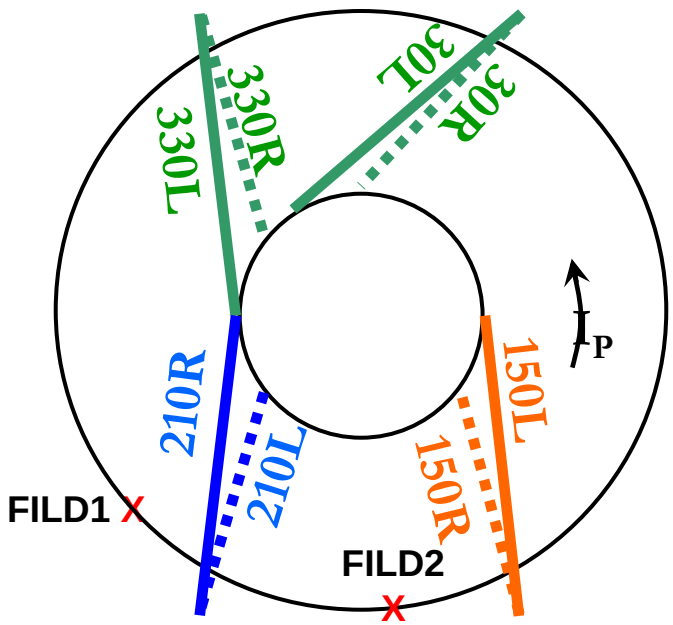

- Scintillator based detector
- ~1mm collimating aperture
- Adjustable insertion of the detector head
- Camera provides time resolved measurements of pitch angle and gyroradius (energy)
- Fiber-optic coupled photomultipliers provides fast time response (>100kHz) measurements.

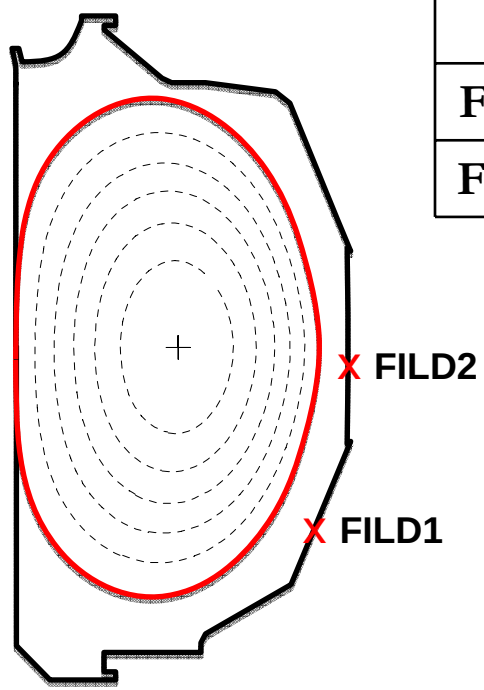
*R.K. Fisher, RSI(2010)*

# Locations of the Two FILDs on DIII-D

- FILD1 is at $\phi = 225^o$, $\theta = -45^o$ with one PMT and the newly installed FILD2 is at $\phi = 165^o$, $\theta \approx 0^o$ near midplane with nine PMTs.

- With these two FILDs, lost fast ions at different striking locations, pitch angles and gyro-radiuses (energies) can be detected.



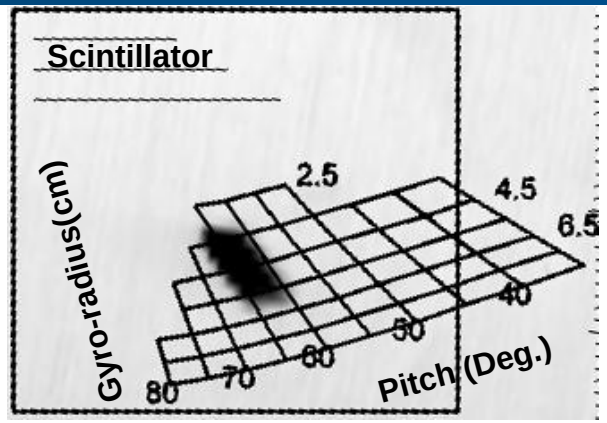



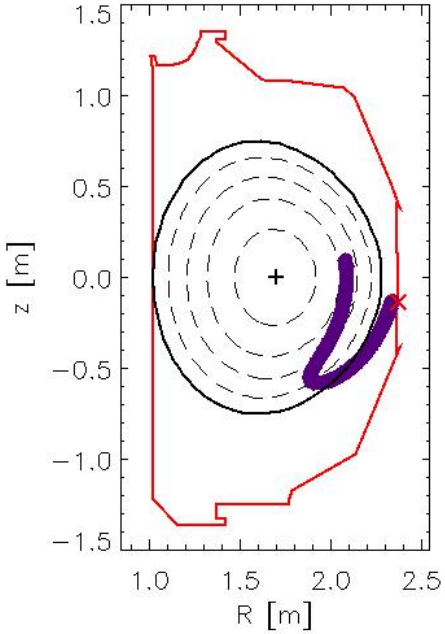

| | $r_L$ (cm) | $\alpha$ (°) |
|---|---|---|
| FILD1 | 1.5-5.0 | 30-75 |
| FILD2 | 2.5-8.0 | 35-85 |

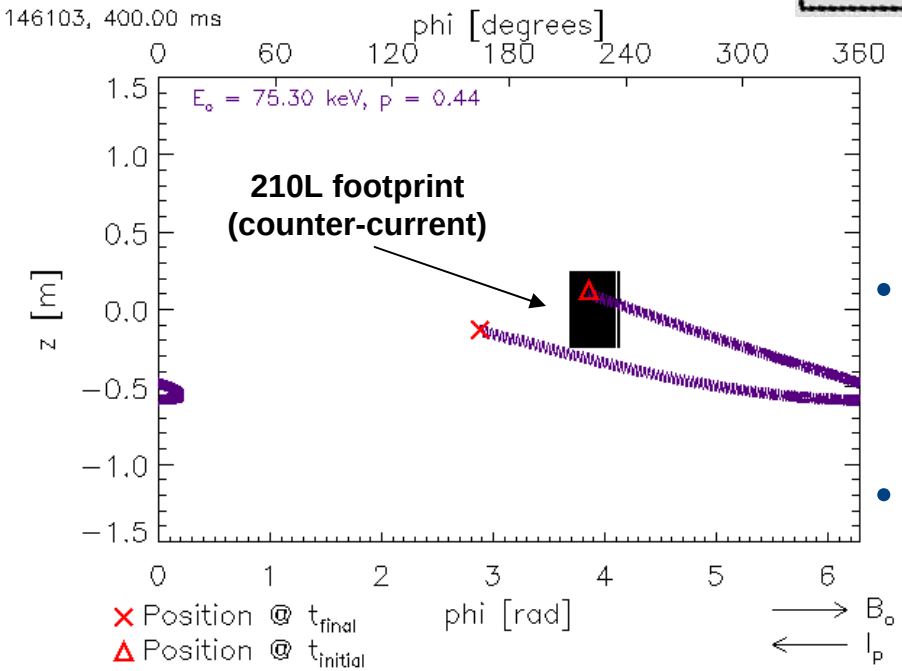
- Generally, FILD1 has stronger signal in oval shape plasmas while FILD2 is more suitable in circular shape plasmas.

# FILD2 is Working Properly and Prompt Losses from Several Neutral Beams are Detected

- The dark spot (negative image of camera frame) at ($r_L$~4cm, $\alpha$ ~64°) corresponds to prompt losses with full energy (75.3keV) from 210°-L source beam.



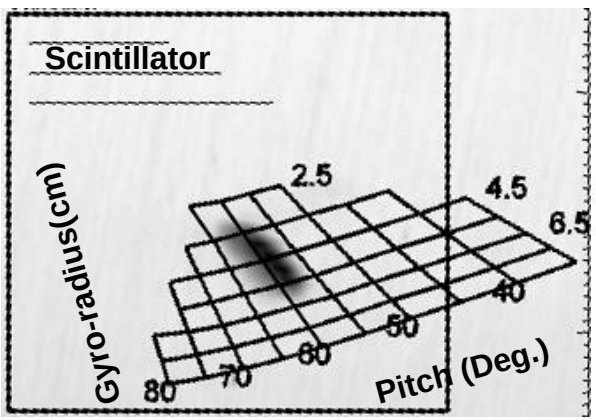



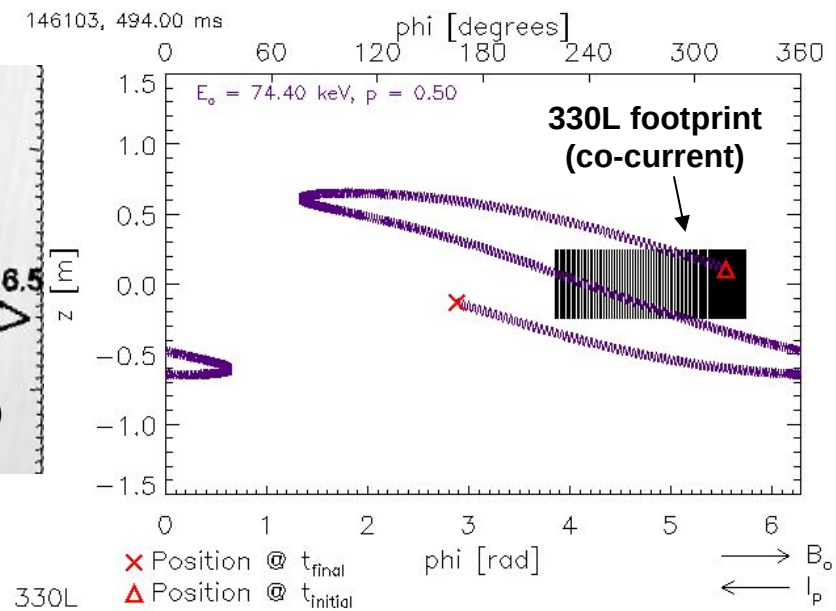



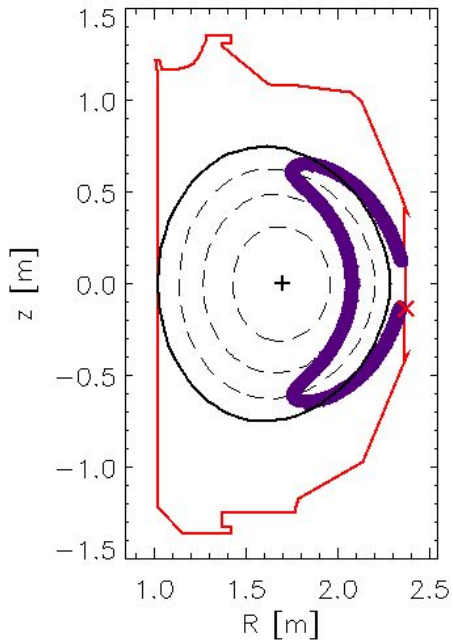

- The ion trajectory can be calculated using reverse-time orbit code with this given gyroradius and pitch angle.
- The overlay with source beam footprint also indicates the possible birth location of the lost ions.

# Prompt Losses from Several Neutral Beams are Detected at FILD2

- **Prompt losses with full energy (74.4keV) from 330°-L source beam are detected on the FILD2 scintillator ($r_L$~4cm, $\alpha$ ~60°).**
- **Reverse orbit shows these losses are produced by deposition in the far plasma edge.**

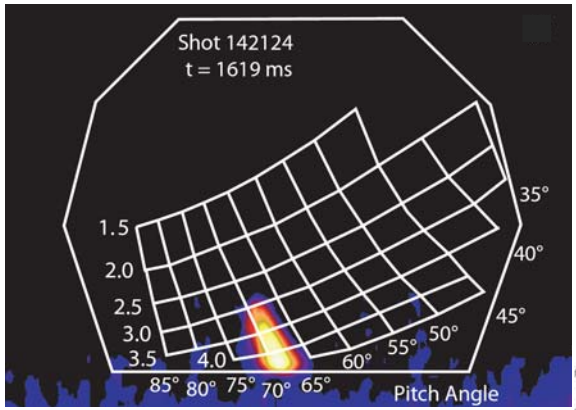


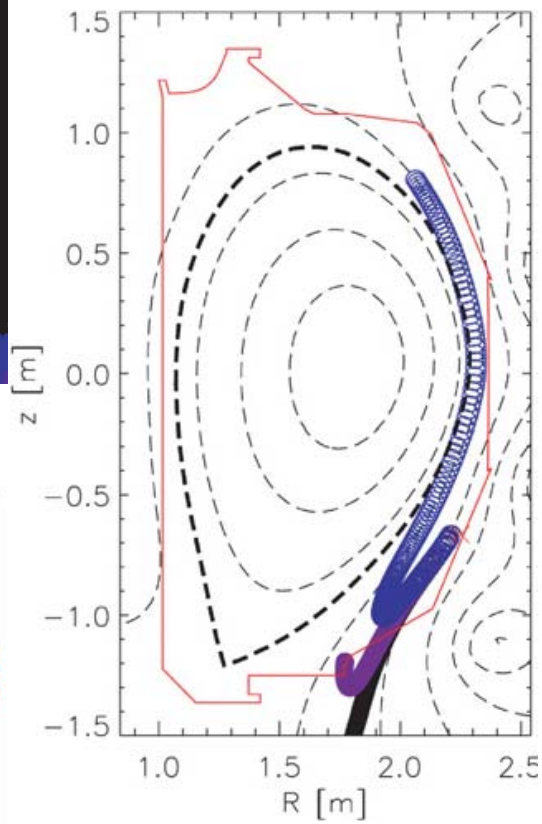



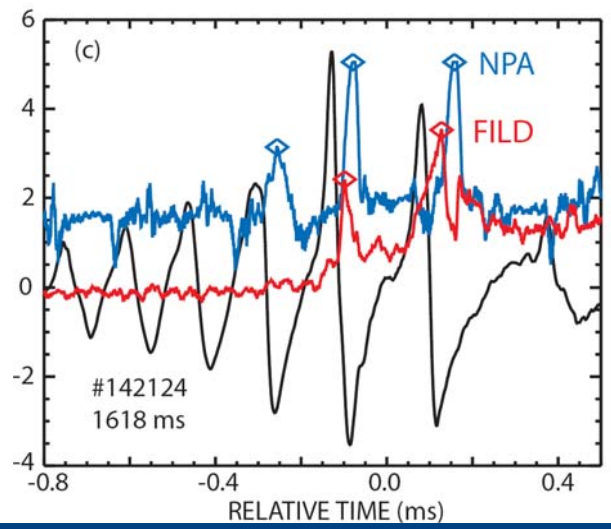




- **Prompt losses measurements also serve for validation of FILD operation, strike map calibration, and transit time calculation.**

# FILD1 observed Off-axis Fishbones induced Losses




- During fishbone activity, bright spot was produced by ejected trapped particles on the FILD scintillator.
- The gyro-radius and pitch angle corresponds to the loss of full-energy, trapped fast ions.
- Fishbone mode cause a decrease in $P_\phi$ on the inner leg of the banana that moves barely confined trapped particles onto the loss orbit detected by FILD.
- FILD PMT detect bursts in conjunction with the fishbone activity (fixed phase relative to the mode).

*W.W. Heidbrink, PPCF (2011)*

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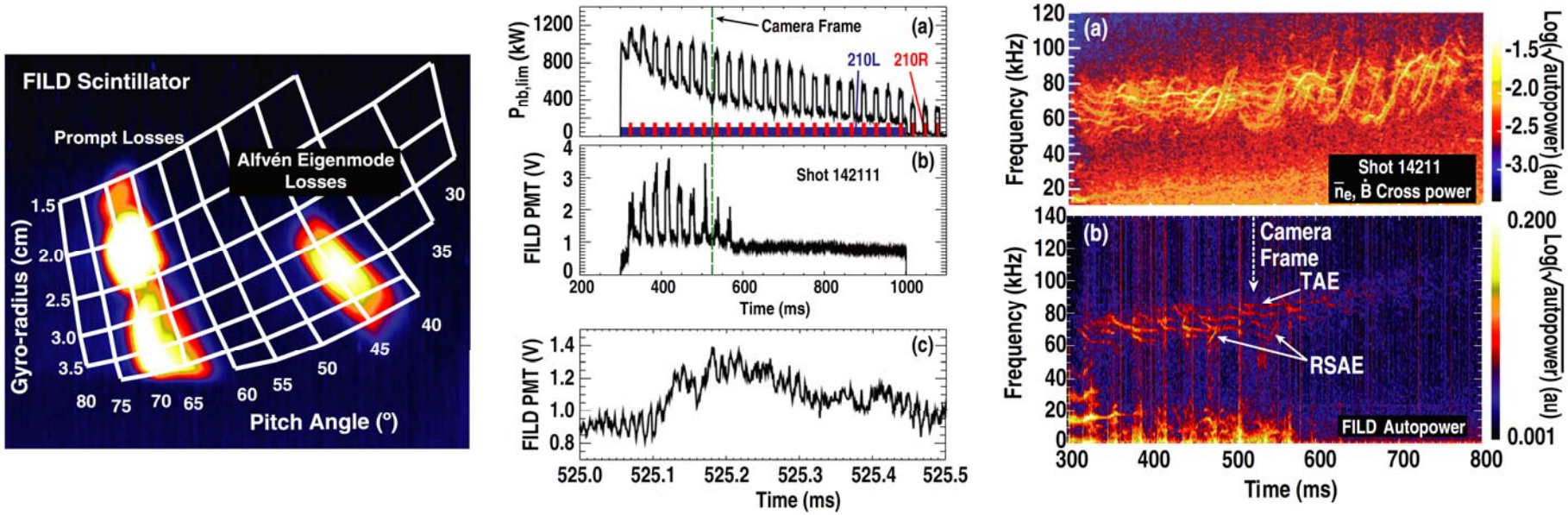
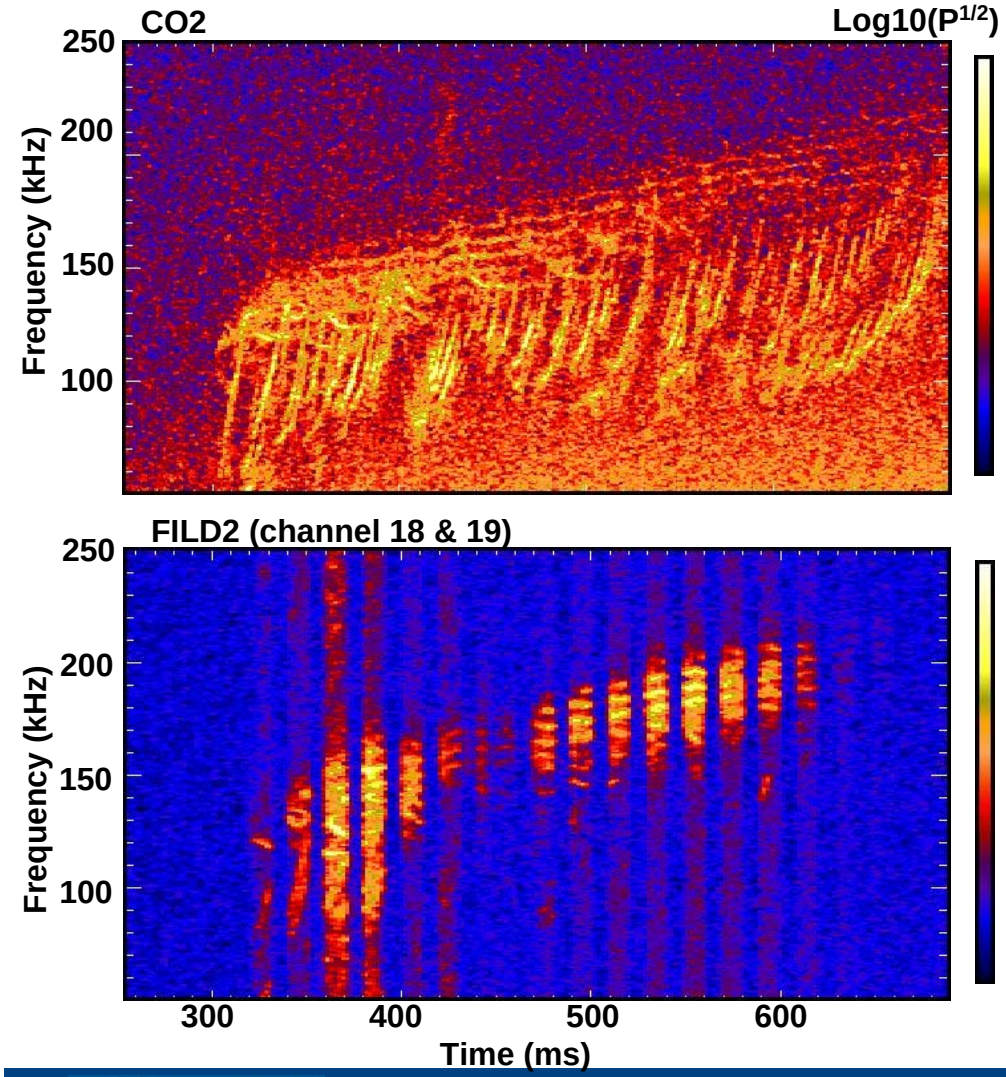
# Coherent Losses driven by TAEs and RSAEs are detected at FILD1

- The bright spot on the scintillator ($2.7 \leq r_L \leq 4.5$cm, $42^o \leq \alpha \leq 47^o$) is produced by ions lost due to Alfvén eigenmode activity.
- Loss of beam ions modulated at frequencies corresponding to toroidal (TAEs) and reversed-shear Alfvén eigenmodes (RSAEs) were resolved from FILD1 PMT measurements.

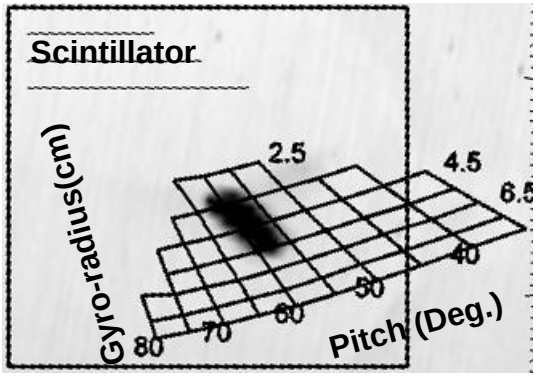



*D.C Pace, PPCF (2011)*

# AEs Induced Losses are Observed at FILD2 in Small Circular Plasmas

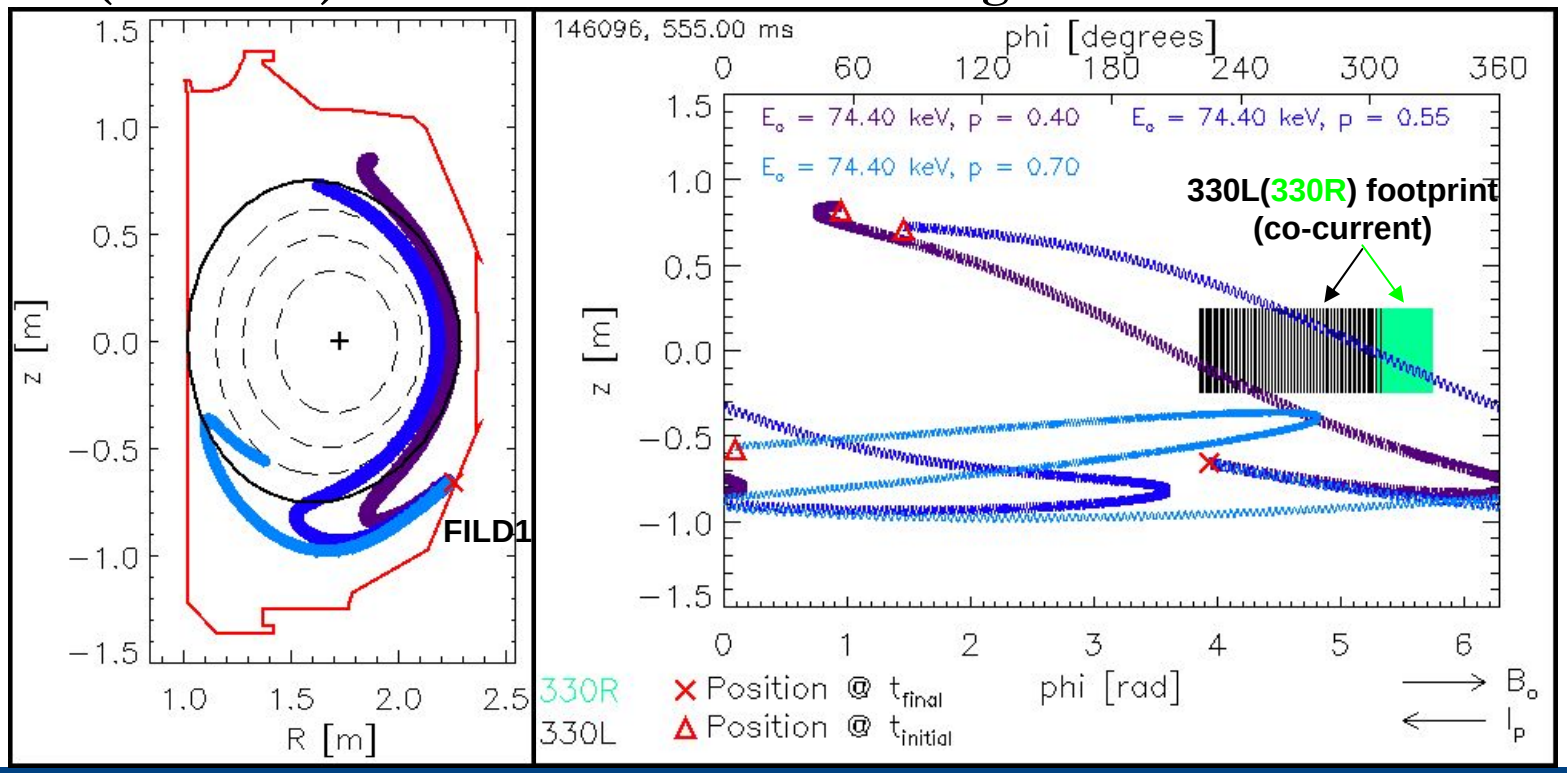



- TAEs and RSAEs in small circular plasma (shot 146096) are resolved from $CO_2$ interferometer data. Coherent losses are observed at FILD2 but not at FILD1.
- The black spot (negative image of camera frame) on the scintillator is due to a combination of prompt losses (330L) and AEs driven losses.

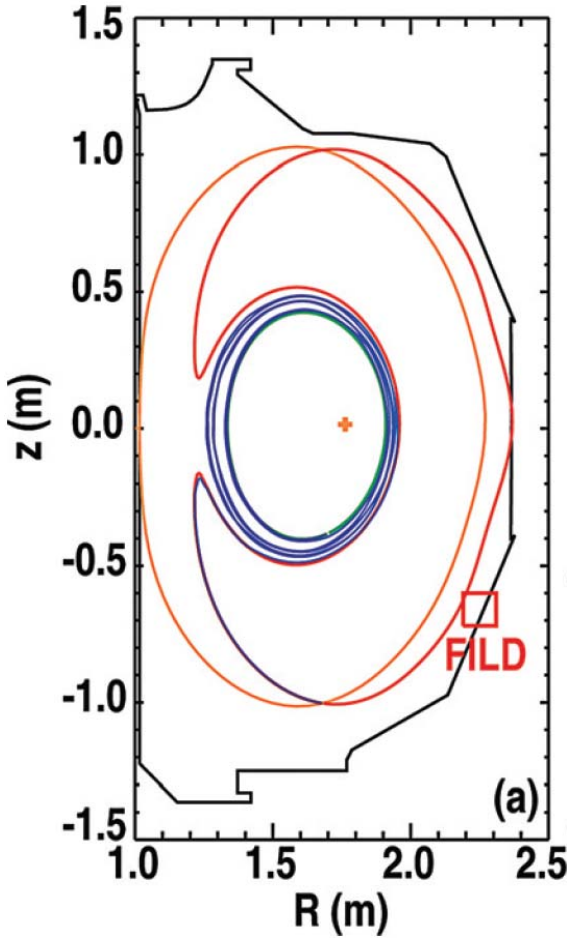


# FILD2 increase the Diagnosing Range of FILD system

- The lack of detected prompt losses and coherent losses at FILD1 in the same shot (146096) might be due to the "Circular" shape of the plasma.
- Three example ion orbits, with $E$ ~ full injection power of the two operated beams and $\alpha$ ~ $\cos^{-1}$(0.4, 0.55 and 0.7) overlay with the beam footprints show no deposition (to FILD1) from these two beams during this shot.



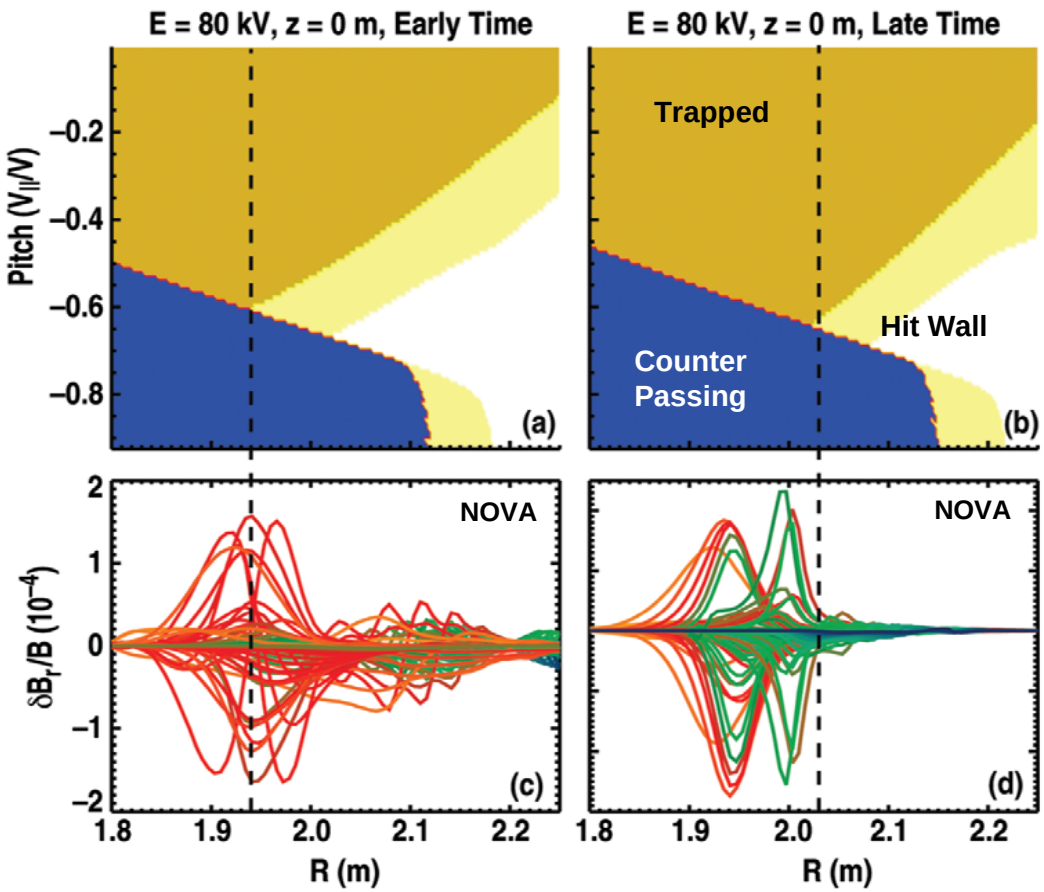
# Modeling of AE induced Fast Loss to FILD




- Loss measurements are modeled in steps:
  - Fit equilibrium profiles
  - Calculate the linear eigenmodes with NOVA and the expected beam ion deposition with TRANSP
  - Identify a subset of AE structures by comparison to experiment
  - Track ions using guiding center following code (ORBIT) in the plasma with these AEs
  - Follow lost ions from last closed flux surface (LCFS) to FILD using constants of motion (COM) based code
- Simulations show the dominant loss mechanism observed is AE modes induced transition of counter-passing fast ions to lost trapped orbits.

*M.A. VanZeeland, PoP (2011)*

# Modeling of AE induced Fast Ions Loss to FILD



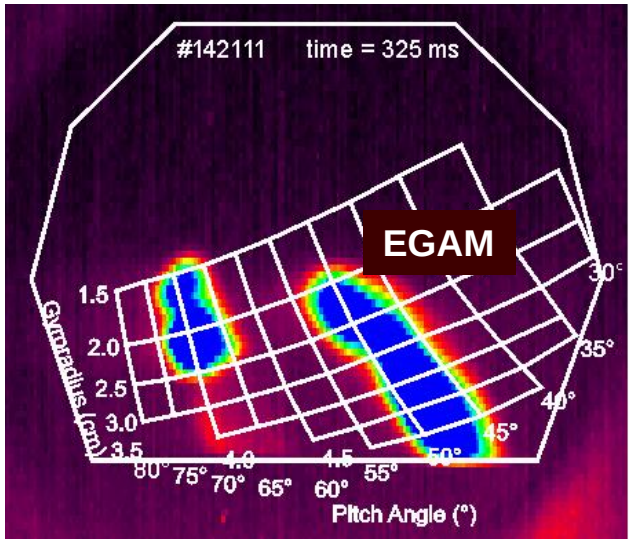

- Loss flux signals decreasing in time is due to
  - Plasma current increases, moves the loss boundaries outward
  - AE modes become more core localized
- Modeling also shows
  - Coherent losses scale proportionally with the amplitude (as expected for convective processes)
  - Additional incoherent contribution scales quadratically with the mode amplitude

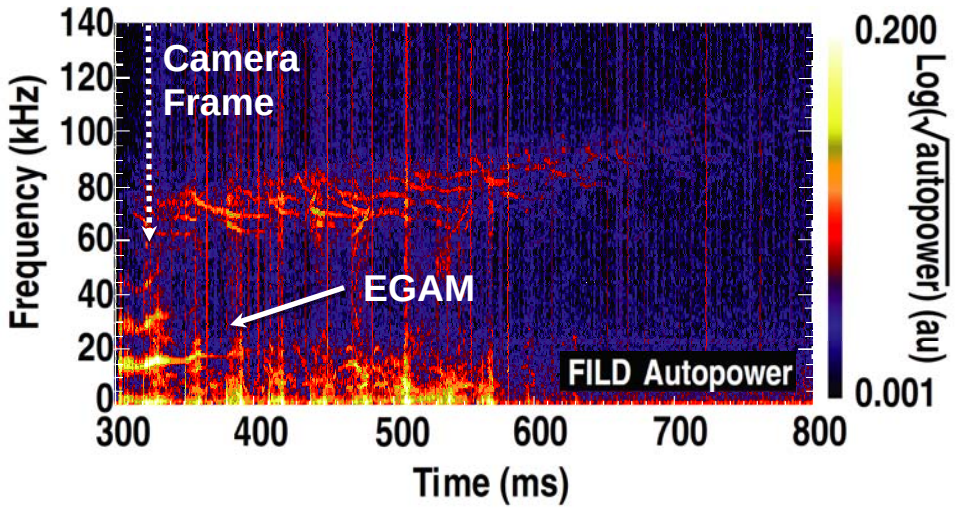
*M.A. VanZeeland, PoP (2011)*

# FILD1 observed Losses driven by EGAMs

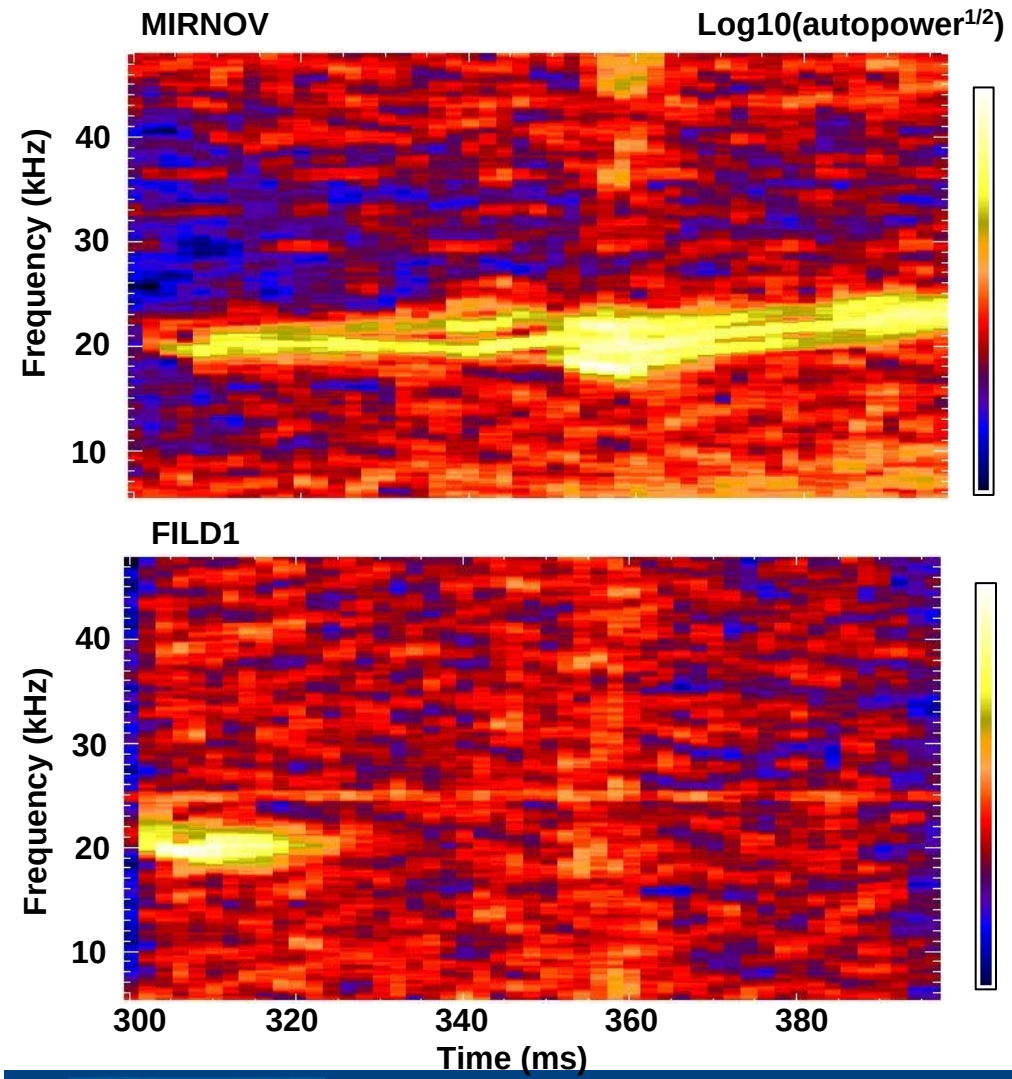
- Ions lost during energetic particle induced geodesic acoustic mode (EGAM) strike the scintillator near $1.9 \leq r_L \leq 3.8$cm, $45^o \leq \alpha \leq 55^o$ region.

- The EGAM and its harmonics are below approximately 50kHz as shown in the autopower spectrogram from FILD1 PMT.



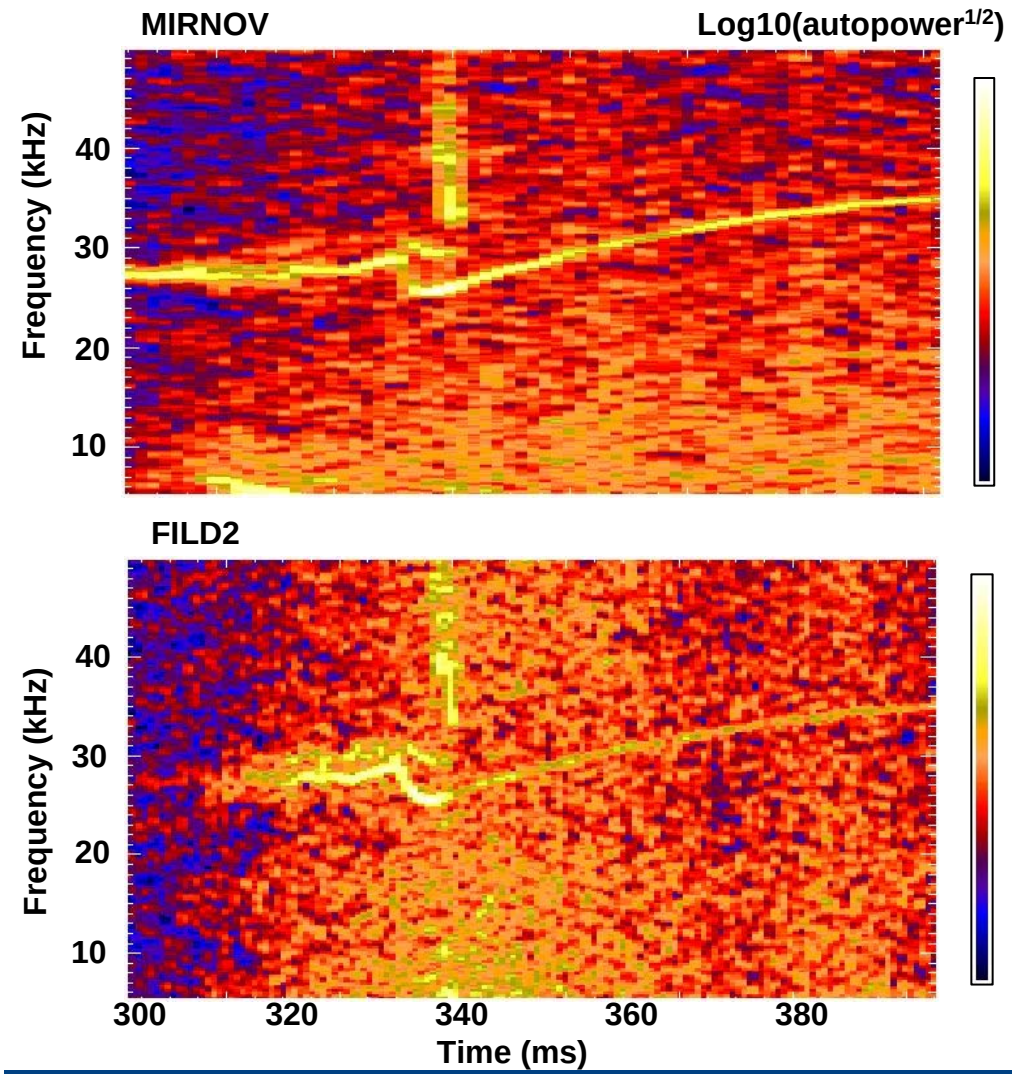



# Losses by EGAMs are detected with Counter-current Beam Injection at FILD1



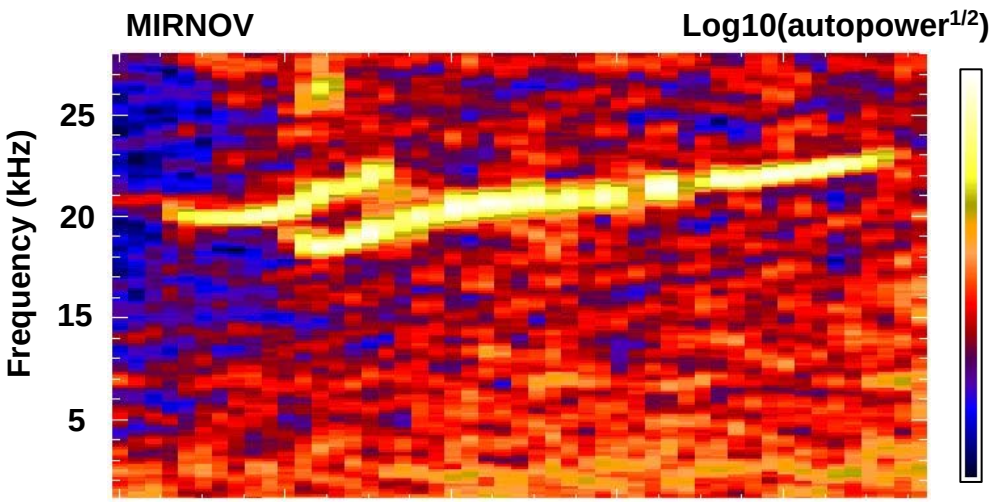

- EGAMs driven losses are detected at FILD1 in plasma(shot146119, oval) with only counter-current neutral beam injection.
- The observed losses are at frequency ~ 20kHz.

# Losses by EGAMs are detected with Counter-current Beam Injection at FILD2




- EGAMs driven losses are detected at FILD2 in plasma(shot146121, circular) with only counter-current neutral beam injection.
- Reverse orbit also shows these coherent losses do not necessarily originate from the prompt loss region of the counter-current neutral beam.

# No Losses are detected with Co-current Beam Injection with EGAM activities




- **Although similar EGAMs present in plasma(146118) with only Co-current neutral beam injection. No coherent losses are detected at either FILD.**

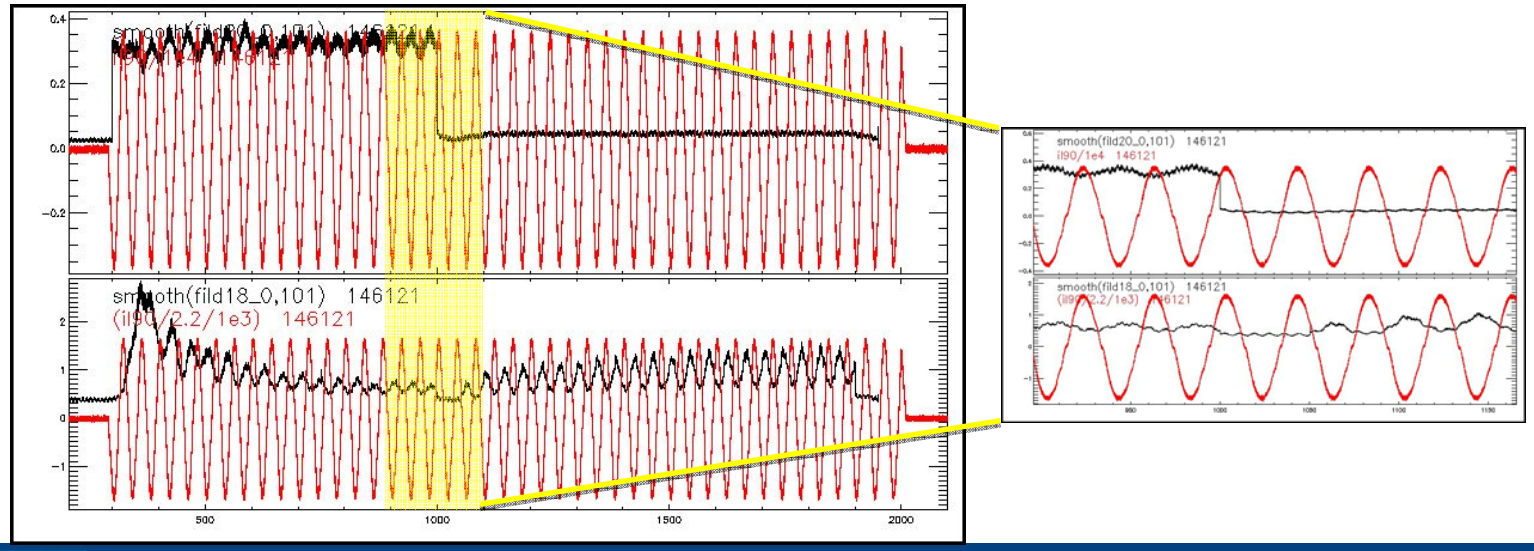
# Both FILD1 and FILD2 See Losses Modulation Caused by RMP

- **Resonant magnetic perturbations (RMPs) are used to control Edge-localized modes (ELMs) in magnetic fusion devices such as DIII-D. Its impact on fast ion losses is also studied.**

- **The DC signal in the detected loss (black traces) is from prompt losses and the fluctuation signal varies in phase with a rotating (f=25Hz) n=2 perturbation (red trace: coil current; black trace: FILD signal).**

**FILD1**

**FILD2**

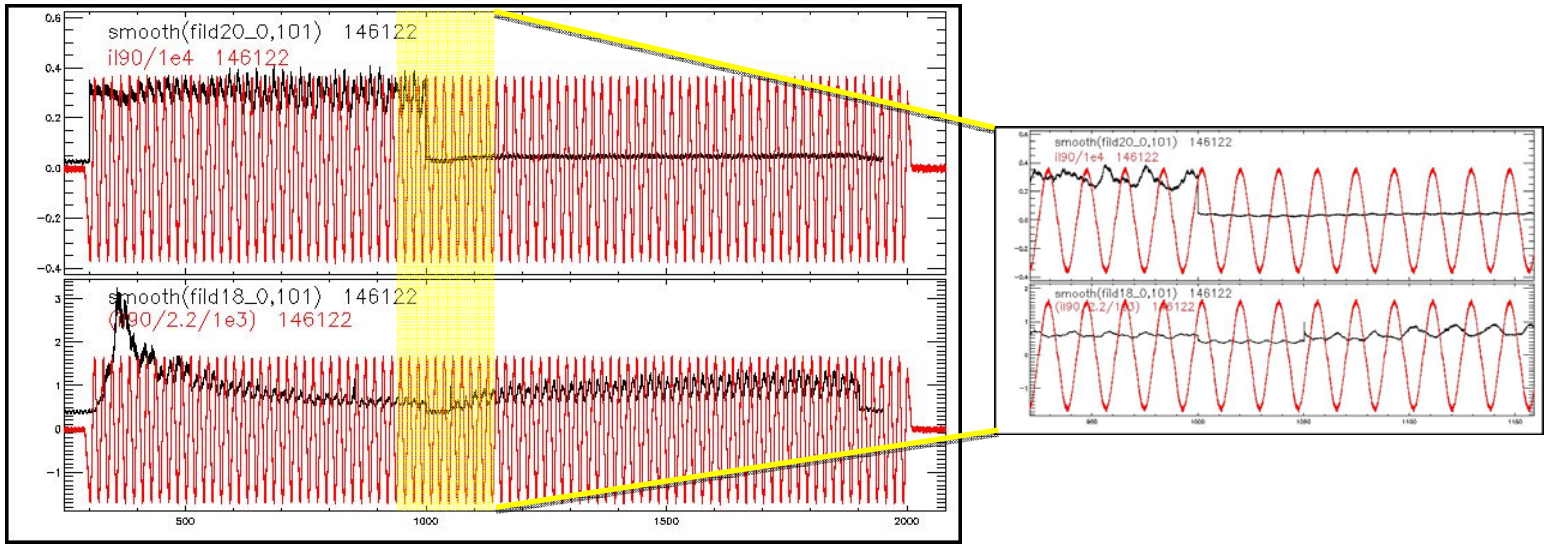


# Both FILD1 and FILD2 See Losses Modulation Caused by RMP

- **Both FILD1 and FILD2 detected loss signals (black traces) vary in phase with a rotating (f=55Hz) n=2 perturbation .**

**FILD1**

**FILD2**



# Summary and Future Work

- **FILD1 has successfully measured coherent losses during off-axis fishbone, TAEs, RSAEs and E-GAMs activities.**
- **The newly installed midplane FILD2 starts acquiring data in the 2011 Campaign and has observed prompt losses, losses driven by AEs and EGAMs.**
- **FILD1 has higher signals in oval plasmas while FILD2 in circular plasmas. With these pair of FILDs, a wider range of lost fast ions are detected and will benefit the total fast ions loss study.**
- **Fast ion losses signal have been observed modulation by RMP, the physics behind this will be studied further.**
- **Further analysis of multi-fiber-channel signals will be processed and relevant hardware development and improvement will be conducted.**