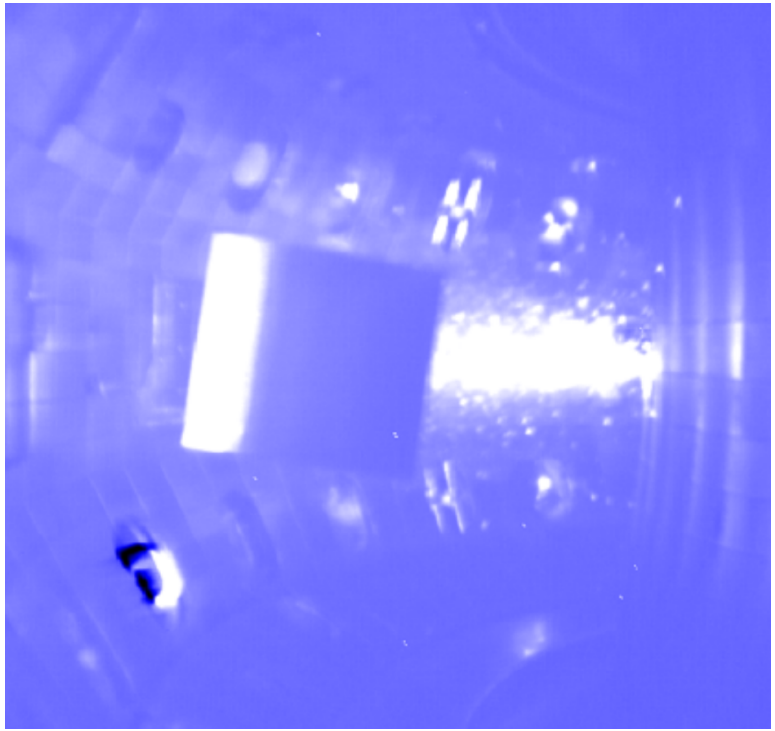
Fast-ion losses during ramp-up phase and disruptions of the ASDEX Upgrade tokamak

J. Rueda-Rueda, J. Galdón-Quiroga, M. García-Muñoz, L. Velarde-Gallardo, B. Simmendefeldt-Schmidt, M. Salewski, P. Schneider, P. Oyola, E. Viezzer, and the AUG and PSFT teams

Large changes in plasma current brings attractive features to understand fast-ion dynamics

- Fast changes in plasma current:
  - Large parallel electric fields
  - Changes in *q*-profile
- Low densities



[C. Paz-Soldan Journal of Plasma Physics Colloquium]

Outline

- **Theoretical background**
- **Losses during ramp-up phase**
- **Losses during disruptions**

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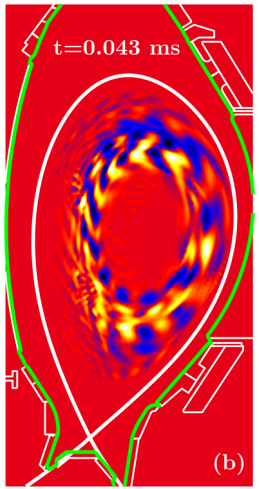
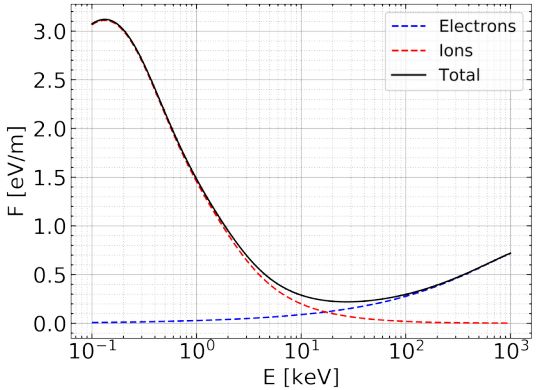
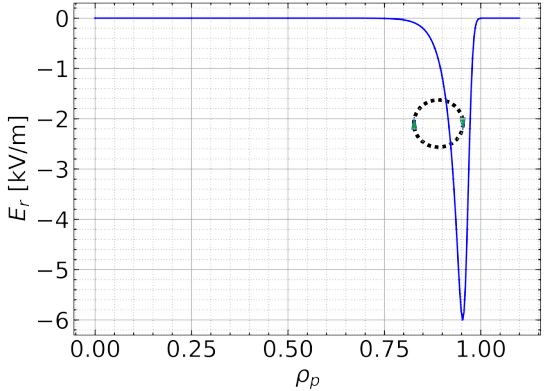
Several mechanism can cause FI transport and acceleration during ramp-up and disruptions







MHD interaction

Resonances
FI $\longleftrightarrow$ Mode

$E_{//}$ acceleration

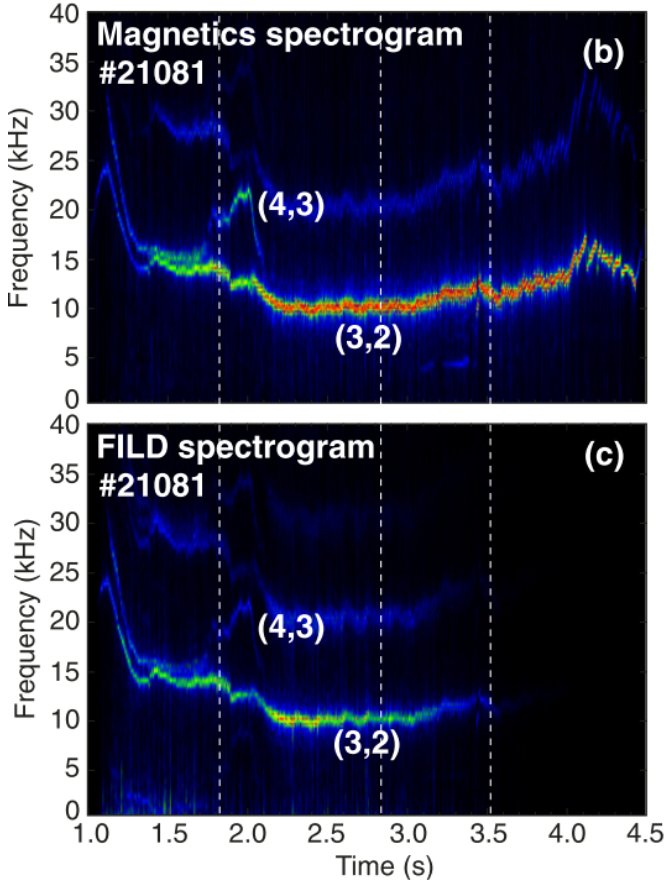
Balance between $E_{//}$ and drag force

$E_{\perp}$ acceleration

Caused by FLR effect

Fast-ions strongly interact with MHD activity

- Possible resonant interaction:
  - Single resonance: Coherent (frequency correlated) FIL losses are expected in FILD
  - Overlapping resonances: Convective FIL. No dominant frequency expected in FILD
- For full information *, **

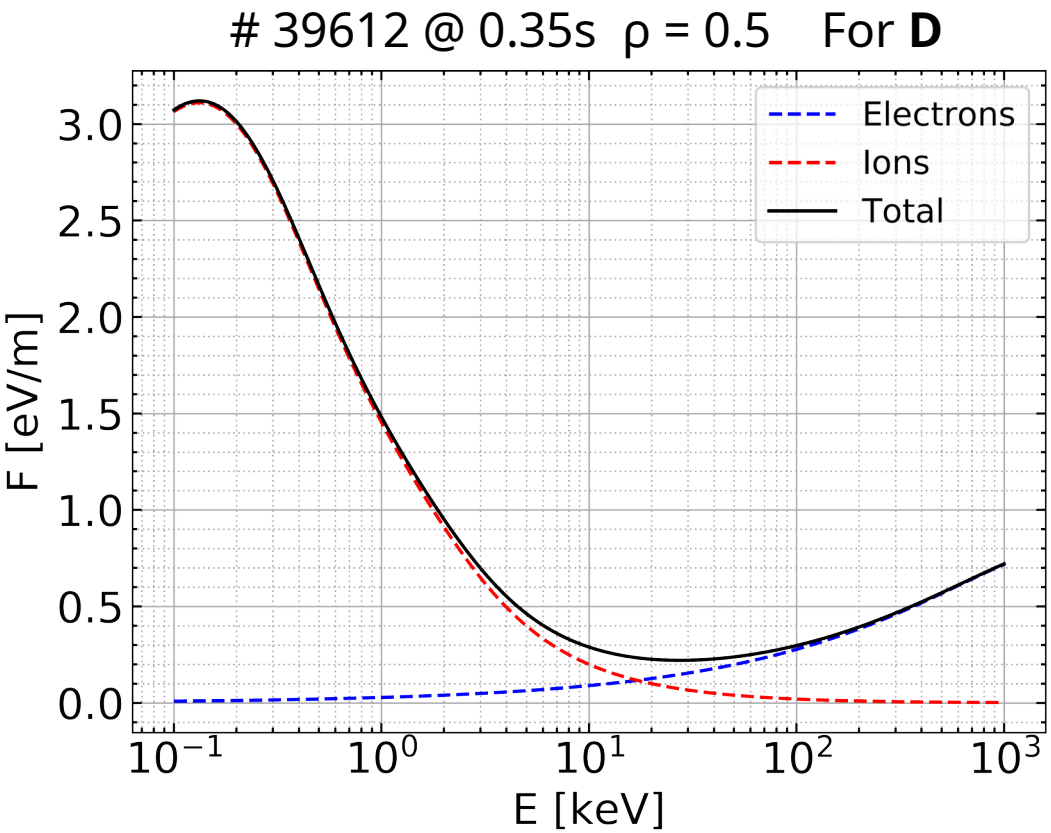


[M. García-Munoz et al. Nucl. Fusion 49 (2009)]

[* See H. Chen talk on Tuesday]
[** See J. Domínguez-Palacios talk on Monday]

Parallel electric field can accelerate ions if overcomes friction force

- Friction force in AUG typically present a minimum around NBI injection energy
- FI will accumulate when $F = eE_{eff}$
- *Similar* to e-runaway * phenomena
- Several tens of milliseconds needed to achieve E > 200 keV



[H. Dreicer, Phys. Rev. 115, 238]
[Embréus O., et al. Phys. Plasmas 22 (2015)]

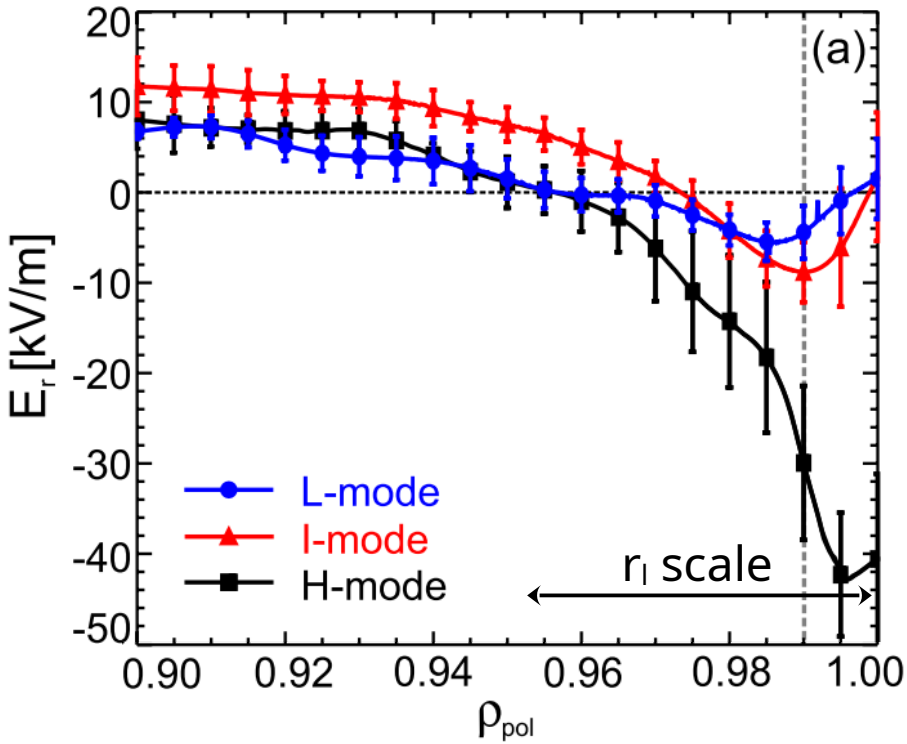
[* Boris N. Breizman et al, Nucl. Fusion 59 (2019)]

Radial electric field can accelerate FI due to finite Larmor radius effects

- FI Larmor radius (~2.5 cm) comparable to E_r well width
- FI feel different values of E_r along its gyro-motion

↓

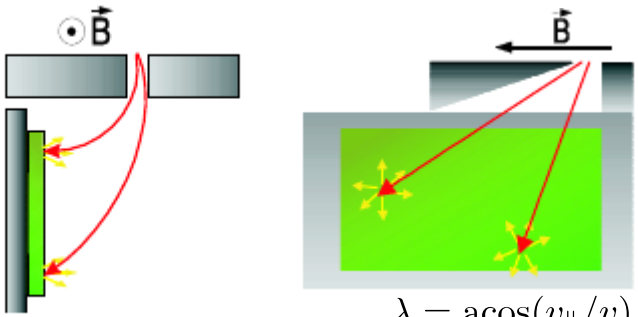
- Acceleration due to not cancellation



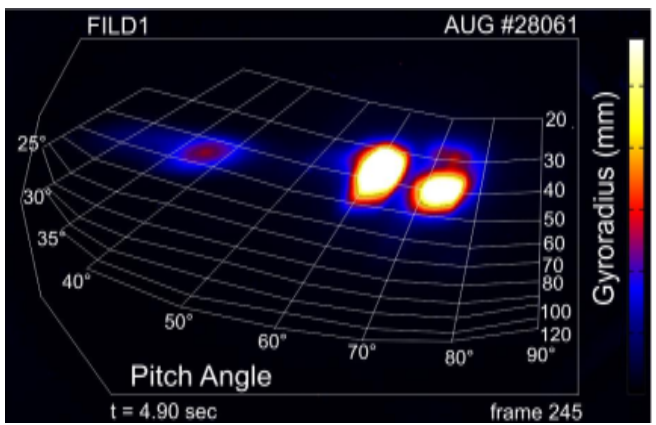
[E. Viezzer et al, Nucl. Fusion 53 (2013)]

Fast-Ion Loss Detector (FILD[1,2]) provide time resolved information on velocity space of escaping ions

- Uses the local magnetic field and a scintillator as a spectrometer
- Measure pitch-angle and energy of escaping FI
- Large bandwidth allows measurements at Alfvén Eigenmode frequencies (~100kHz)

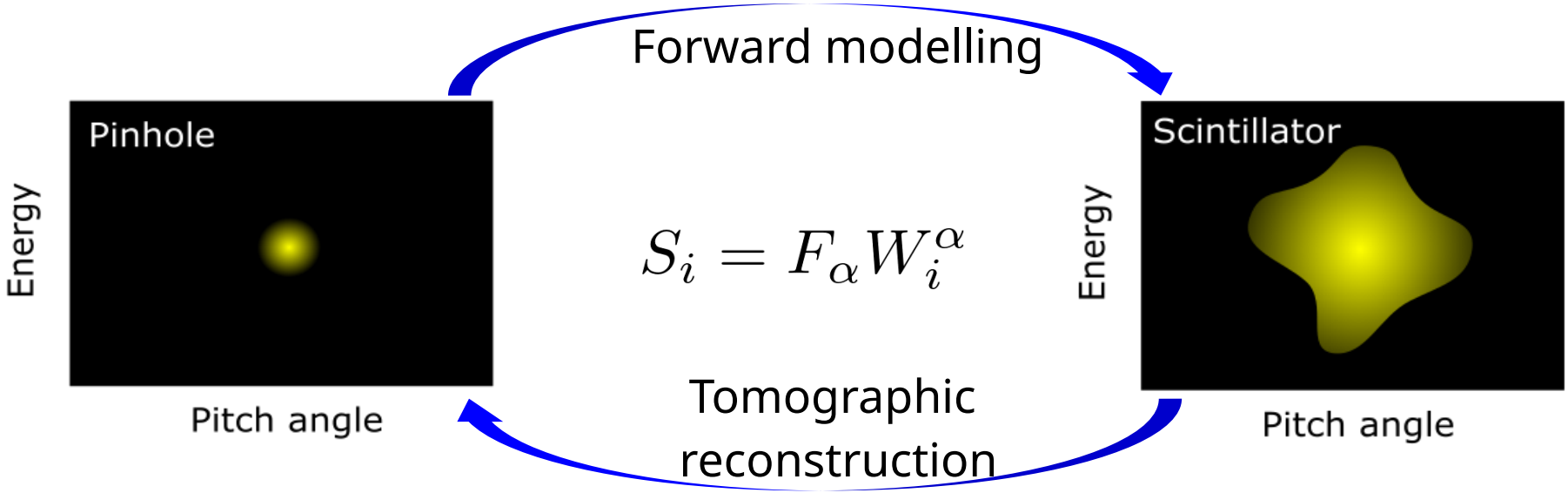


$$\lambda = \mathrm{acos}(v_{\parallel}/v)$$



[1 S. J. Zweben, Rev. Sci. Instrum. 57, 1774 (1986)]
[2 M. Garcia-Munoz et al, Rev. Sci. Instrum. 80 053003 (2009)]

Velocity space measurement is distorted due to finite resolution of the system

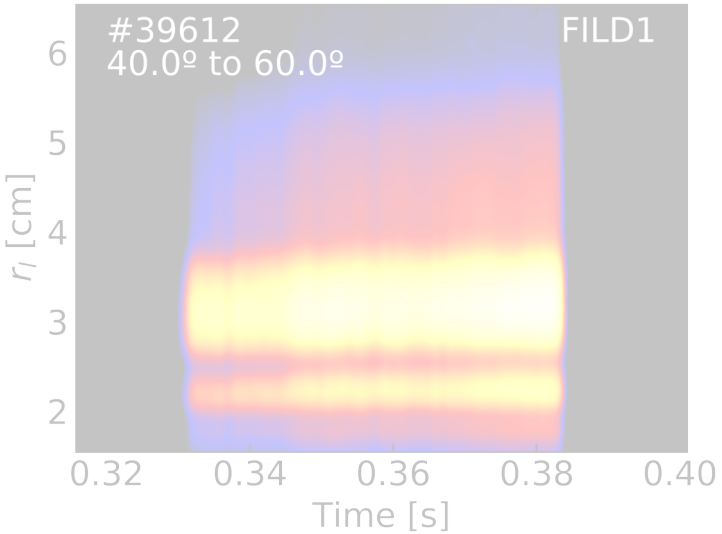


- Weight function calculated via forward modelling (FILDSIM):
  - Consider 3D geometry and scintillator yield
  - Same model used in FILD signal analysis

[*M.Salewski et al, Nucl. Fusion 52 (2012)* // *J. Galdon-Quiroga et al, PPCF 60 (2018)* // *J. Galdon-Quiroga et al, Nucl. Fusion 58 (2018)*]

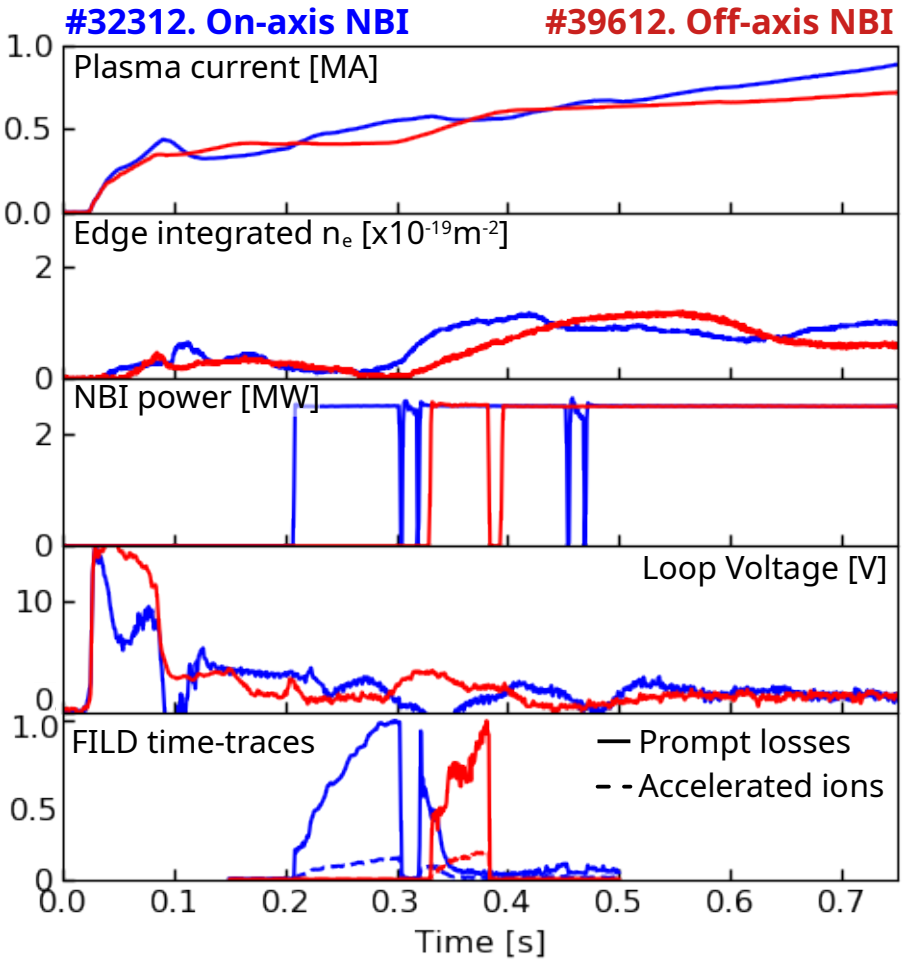
Outline

- Theoretical background
- **Losses during ramp-up phase**
- Losses during disruptions



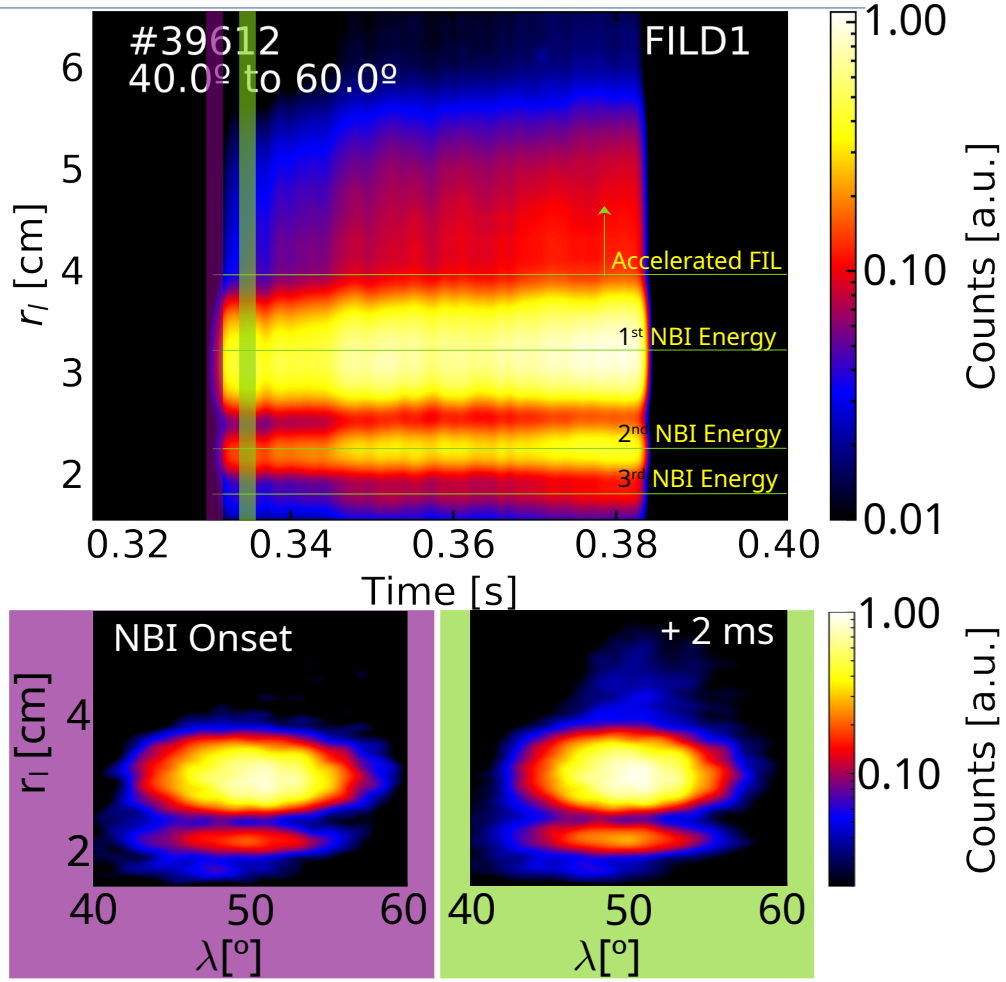
FI acceleration seen in the ramp-up phase of *low* density with early NBI injection

- Early NBI injection
- V_{loop} ~ 4V while the acceleration is observed place
- Acceleration seen in FILD:
  - During the early NBI injection phase
  - With on- and off-axis NBI heating



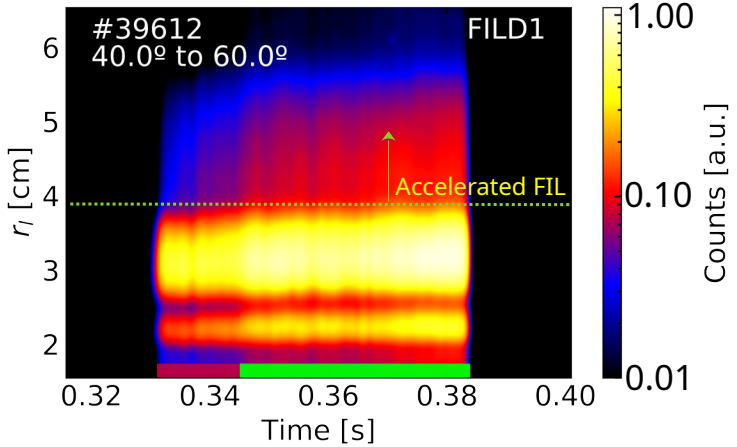
Accelerated FIL seen in FILD right after NBI onset

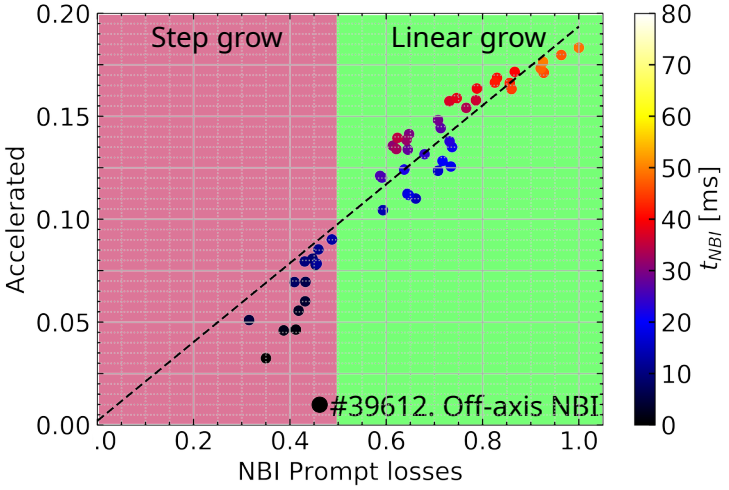
- Prompt losses at the NBI onset do not show acceleration
- High energy feature appear in FILD 2 ms after the NBI onset
- Intensity of the high energy feature grows with the prompt losses
- Pitch of the accelerated FIL similar to the prompt losses



Accelerated FIL grows linearly with prompt losses after some ms of NBI injection

- Two clear phases seen in the grow of accelerated FIL:
  - Sudden grow→ First ms of NBI
  - Linear phase→ Accelerated FIL grows together with NBI prompt losses





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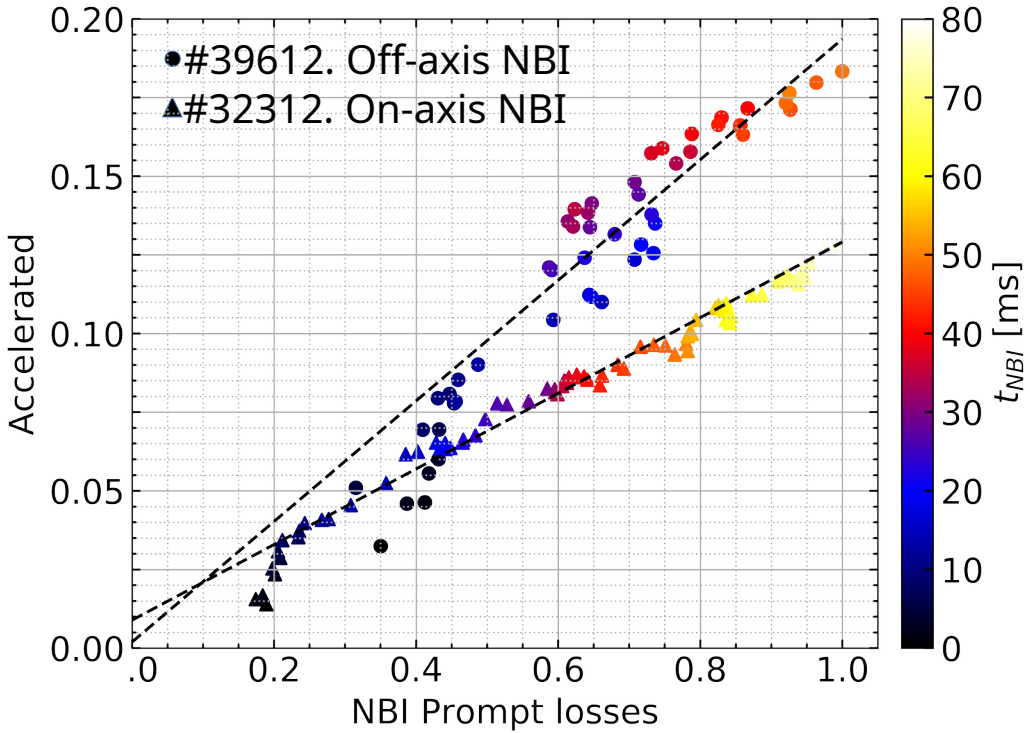
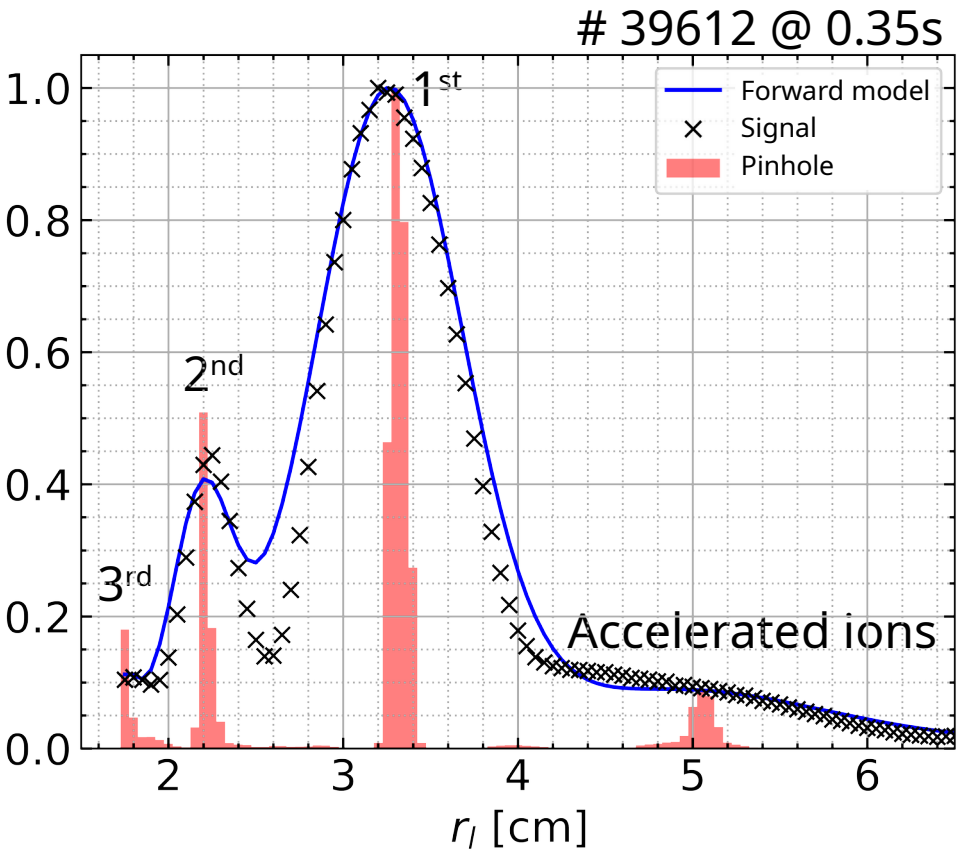
  - Linear phase→ Accelerated FIL grows together with NBI prompt losses
- Similar trend observed for the on-axis NBI-heating



Tomographic reconstruction reveals that high energy feature is due to a single energy component

- Prompt losses formed by three NBI energy components
- Accelerated feature corresponding to a single energy component
- 5cm ~ (200 - 250) keV
- Similar behaviour through the whole acceleration phase



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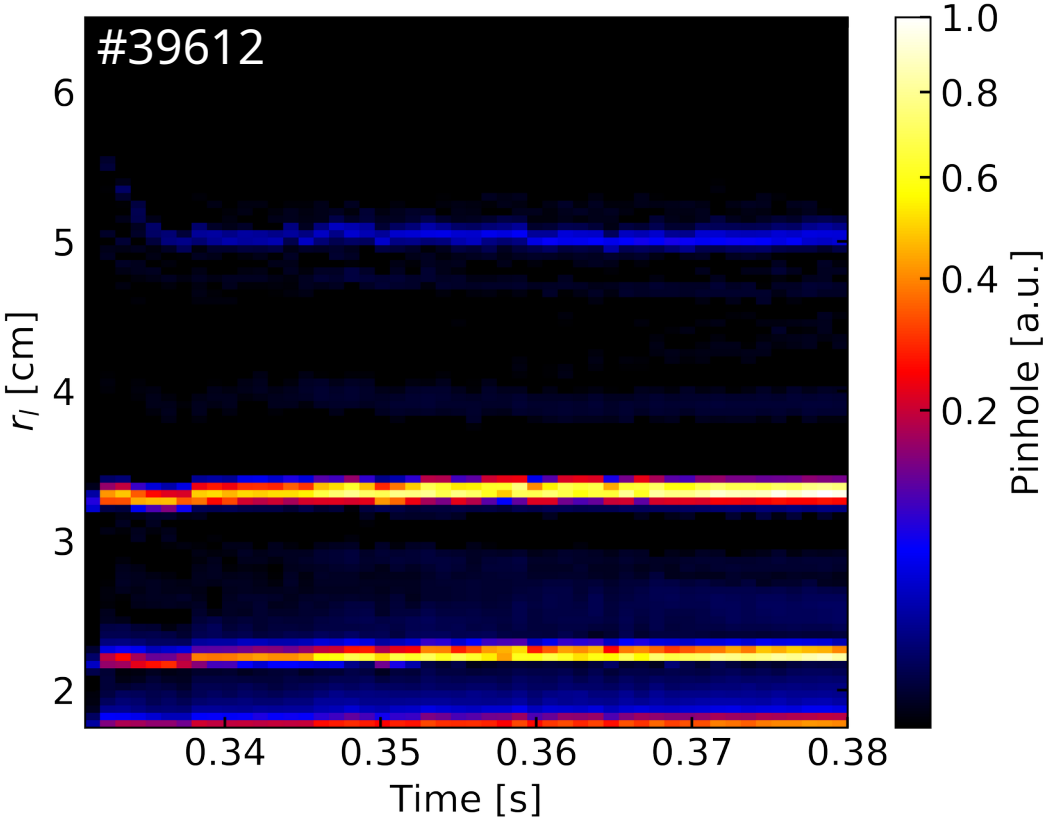
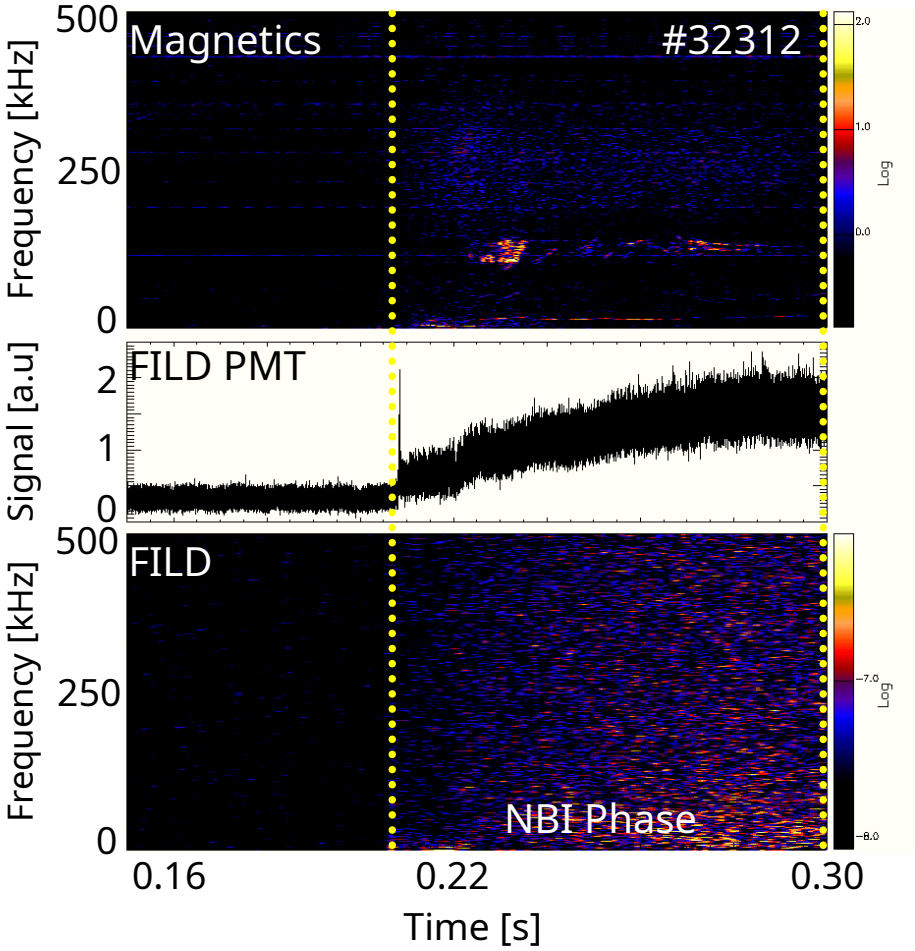


No mode is seen during the whole time window when acceleration is observed

- Clear activity in magnetics around 125 kHz
- Not present during whole window when acceleration is seen
- No coherent losses observed in FILD spectrogram



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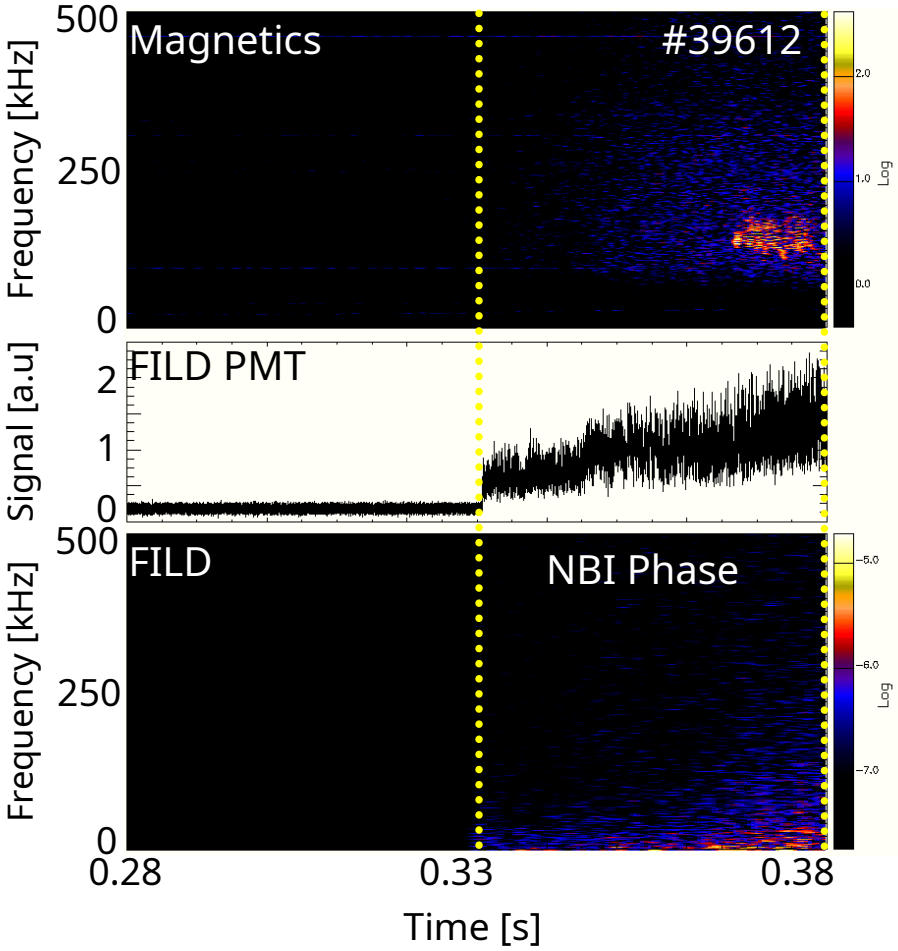
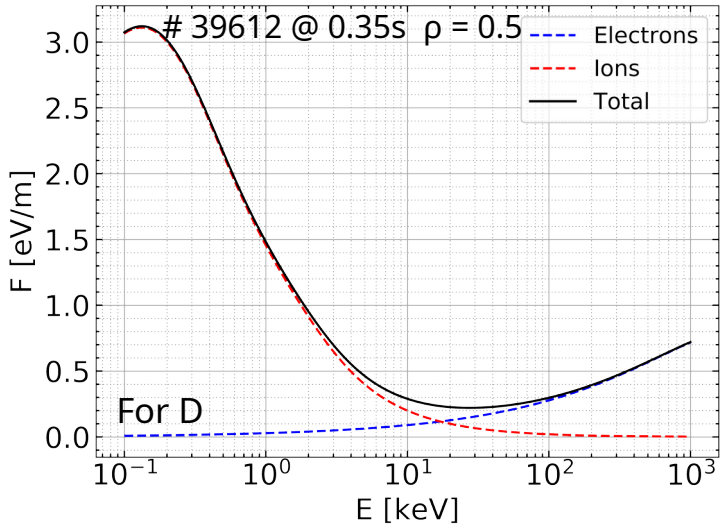
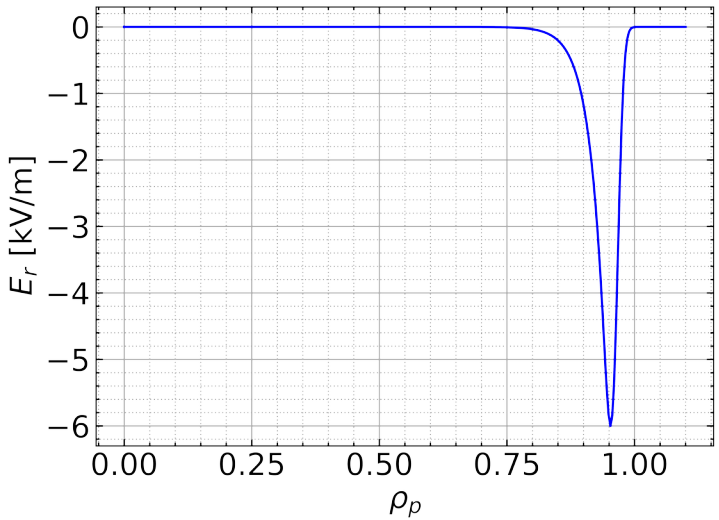
- Similar for off-axis distribution



Electric field cannot accelerate NBI ions in the observed time scales





- Modest value of $E_{//}$ = 0.5 V/m could accelerate FI up to 200 keV
- More than 50 ms needed
- L-mode compatible E_r introduced in ASCOT
- Full orbit simulation performed

[E.Hirvijoki et al. Computer Phys Comm. 185 (2014)]
[E. Viezzer et al, Nucl. Fusion 53 (2013)]

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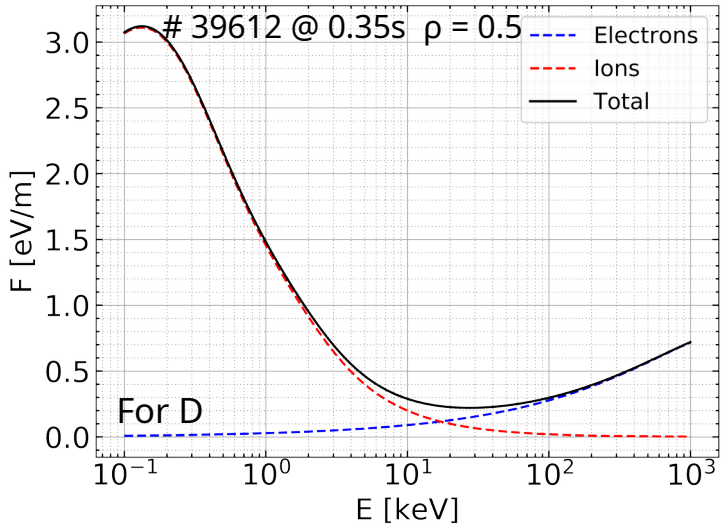

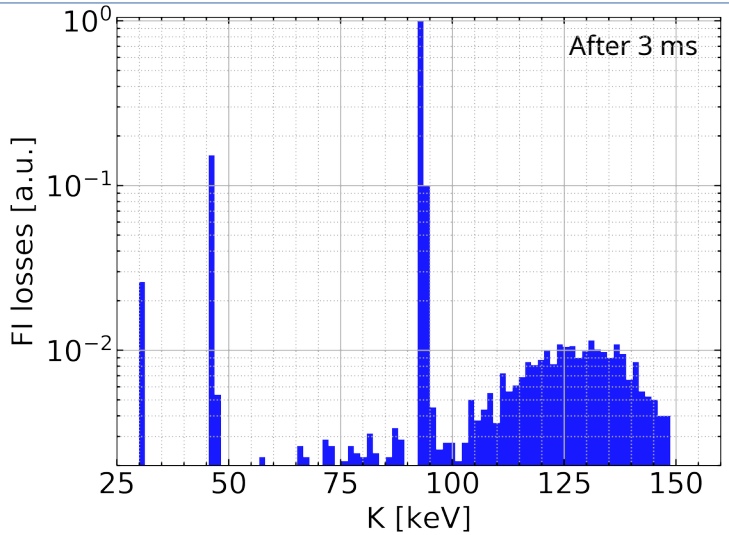

- Modest value of $E_{//}$ = 0.5 V/m could accelerate FI up to 200 keV
- More than 50ms needed

- L-mode compatible E_r introduced in ASCOT
- Full orbit simulation performed
- Peaks appearing at 125 keV

[E.Hirvijoki et al. Computer Phys Comm. 185 (2014)]

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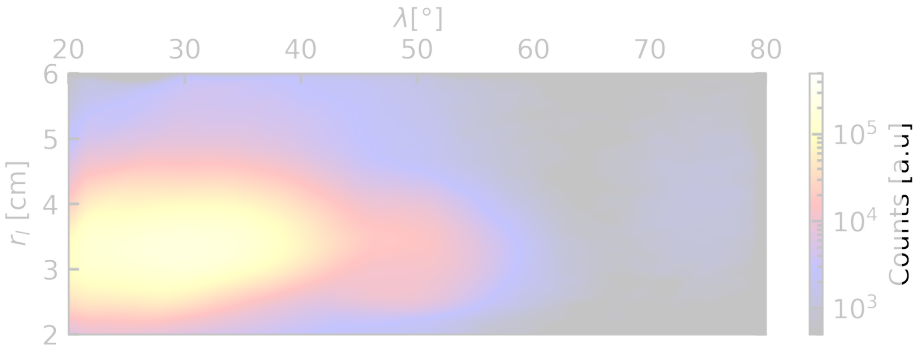
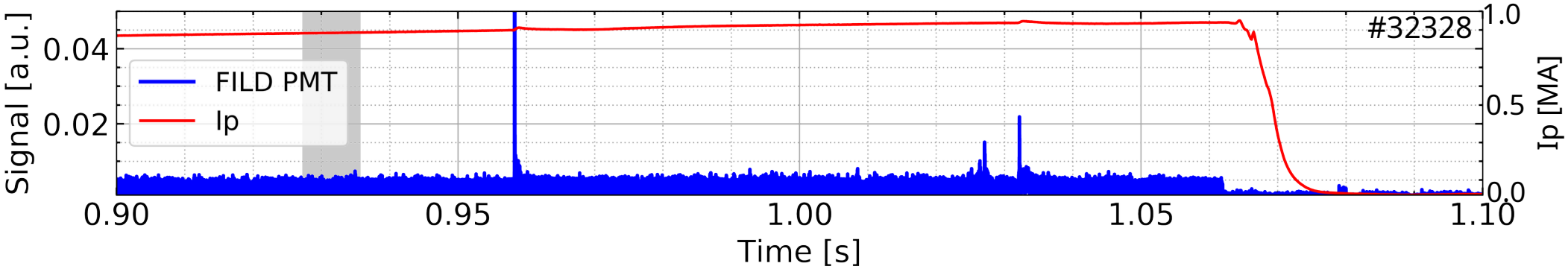
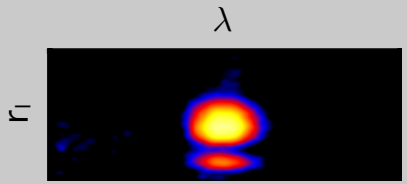


Rich FIL phenomenology observed during disruptions

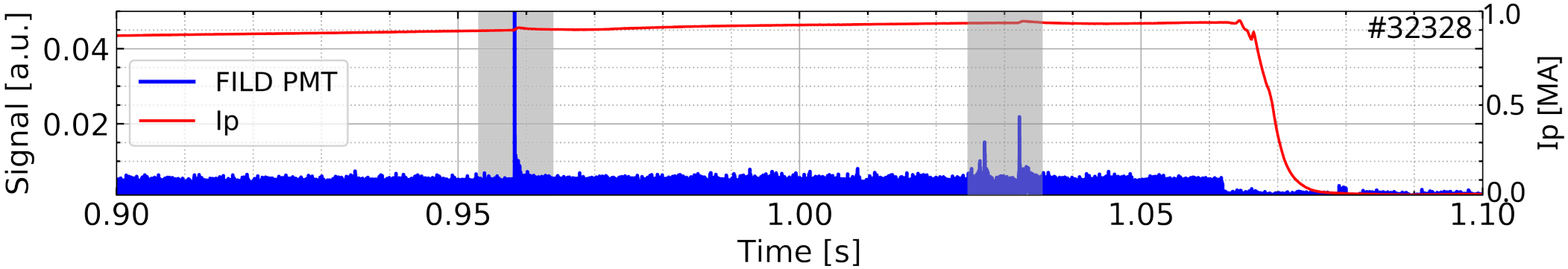


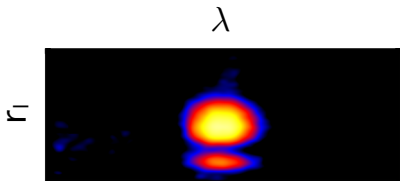


<u>Before disruption</u>

- *Usual* prompt losses

Rich FIL phenomenology observed during disruptions





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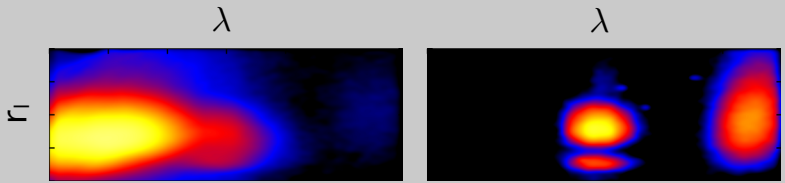

Minor disruptions

- Correlated with mode locking
- Rich zoo: deeply passing and accelerated trapped FIL

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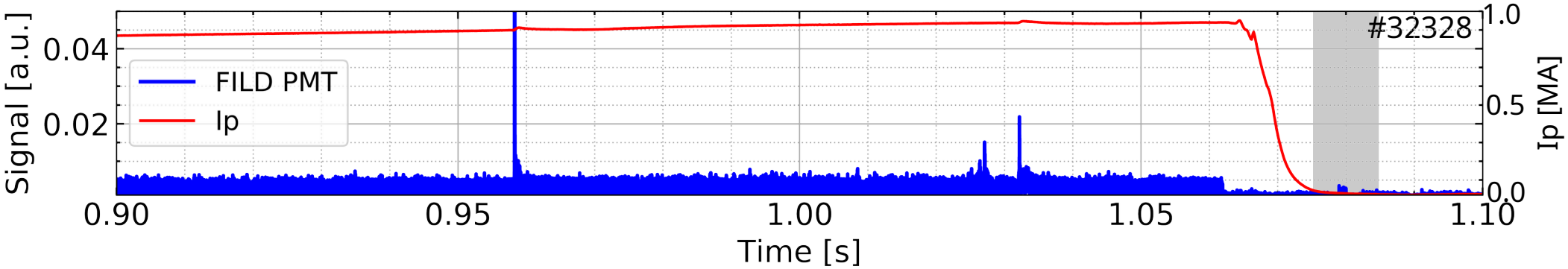

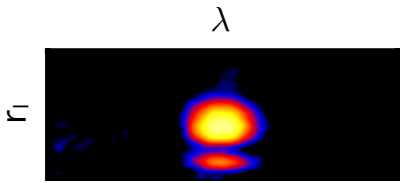

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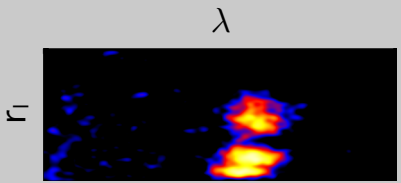


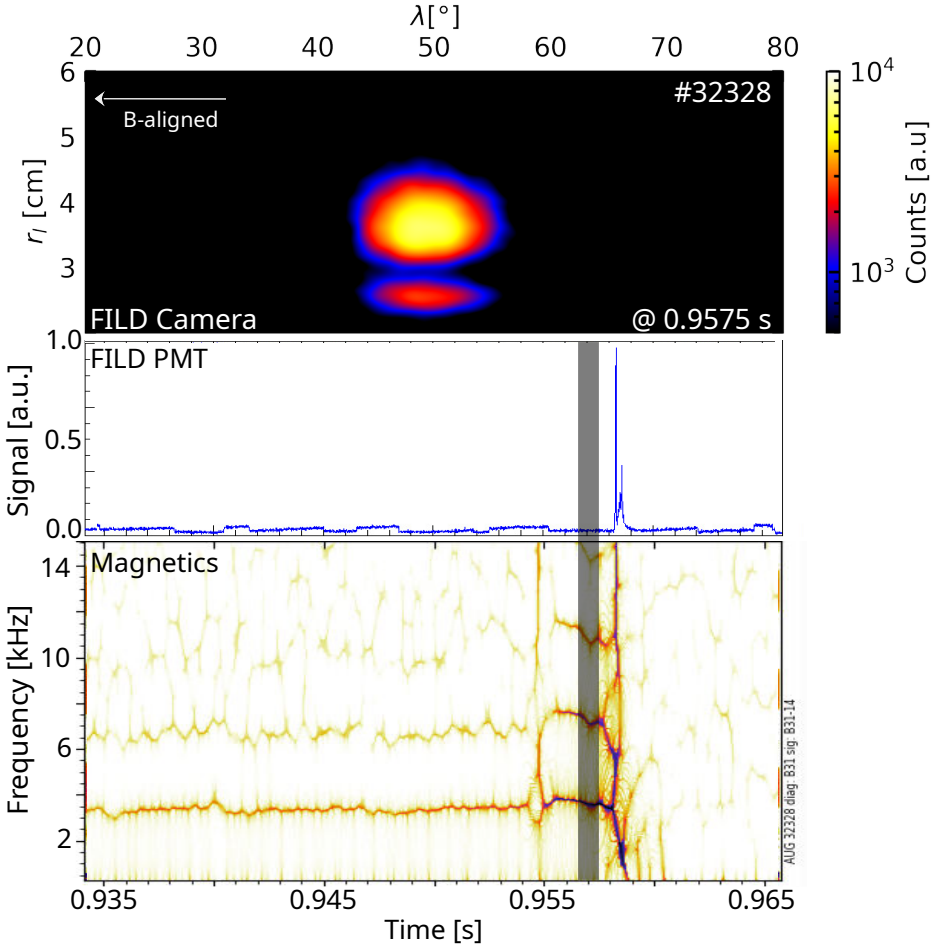
Major disruption & current quench

- Low signal level due to plasma shifting towards central column

[See talk by P. Heinrich tomorrow]

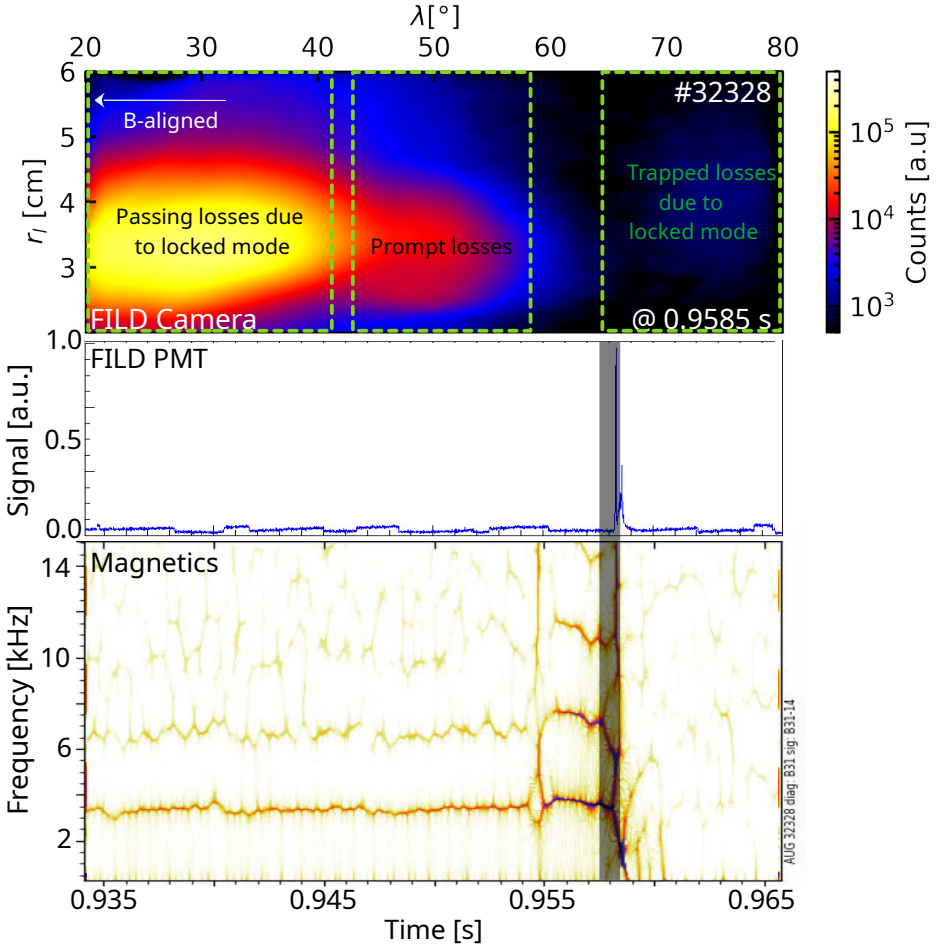
Rich variety of FIL structures observed during minor disruption events

- *Usual* prompt losses registered before the locking of the mode



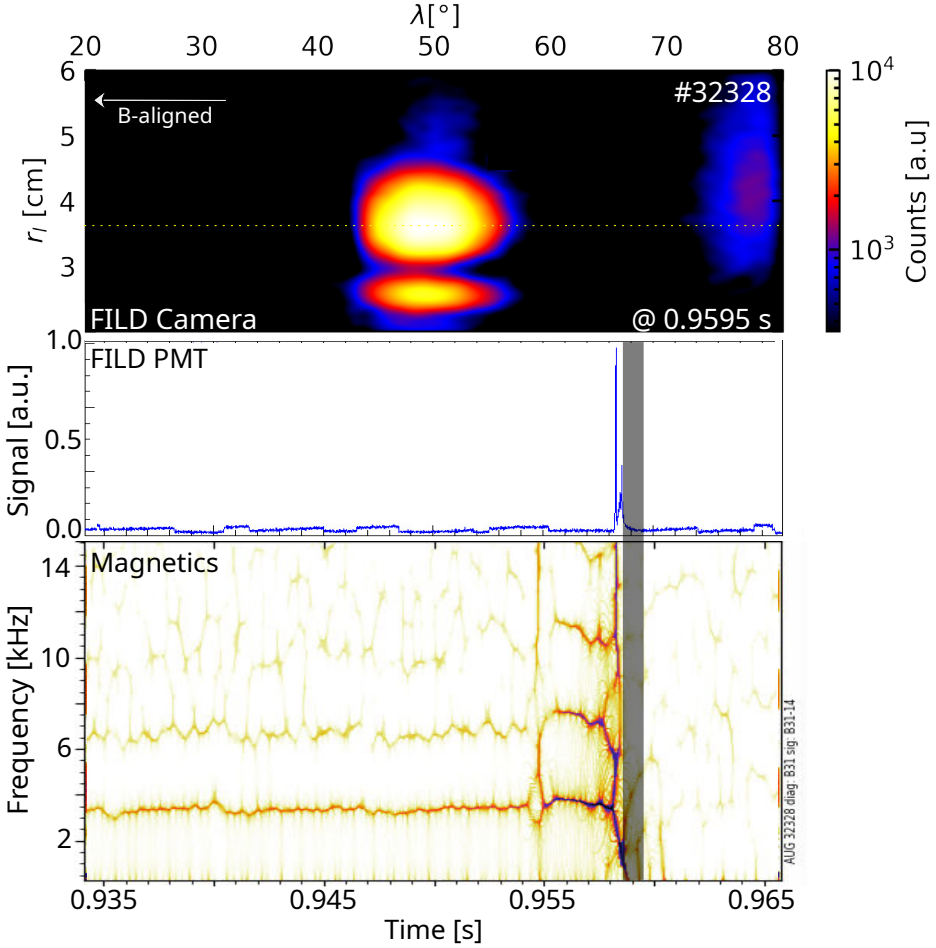
Rich variety of FIL structures observed during minor disruption events

- *Usual* prompt losses registered before the locking of the mode
- At the mode locking: low pitch [º] feature dominates



Rich variety of FIL structures observed during minor disruption events

- *Usual* prompt losses registered before the locking of the mode
- At the mode locking: low pitch [º] feature dominates
- 1 ms after the locking: prompt losses dominate again. Low pitch [º] feature *lost* from FILD due to changes in B



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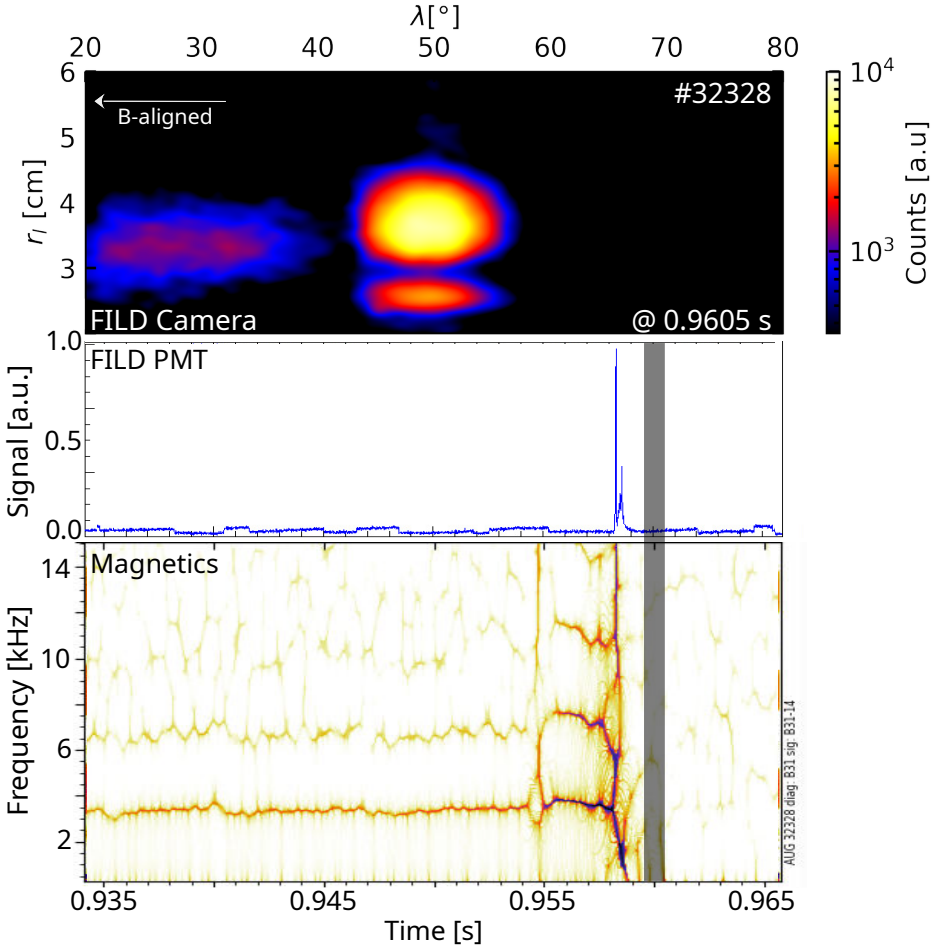
- 2 ms after locking: Low pitch [º] feature is detected again



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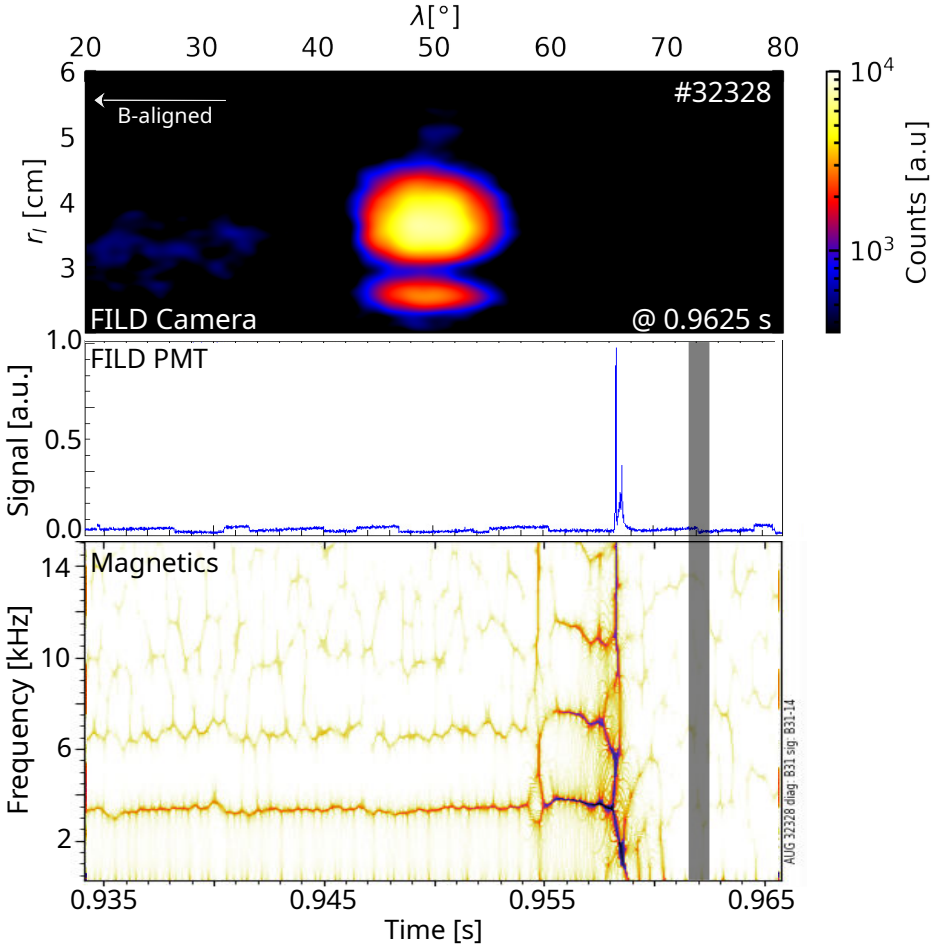

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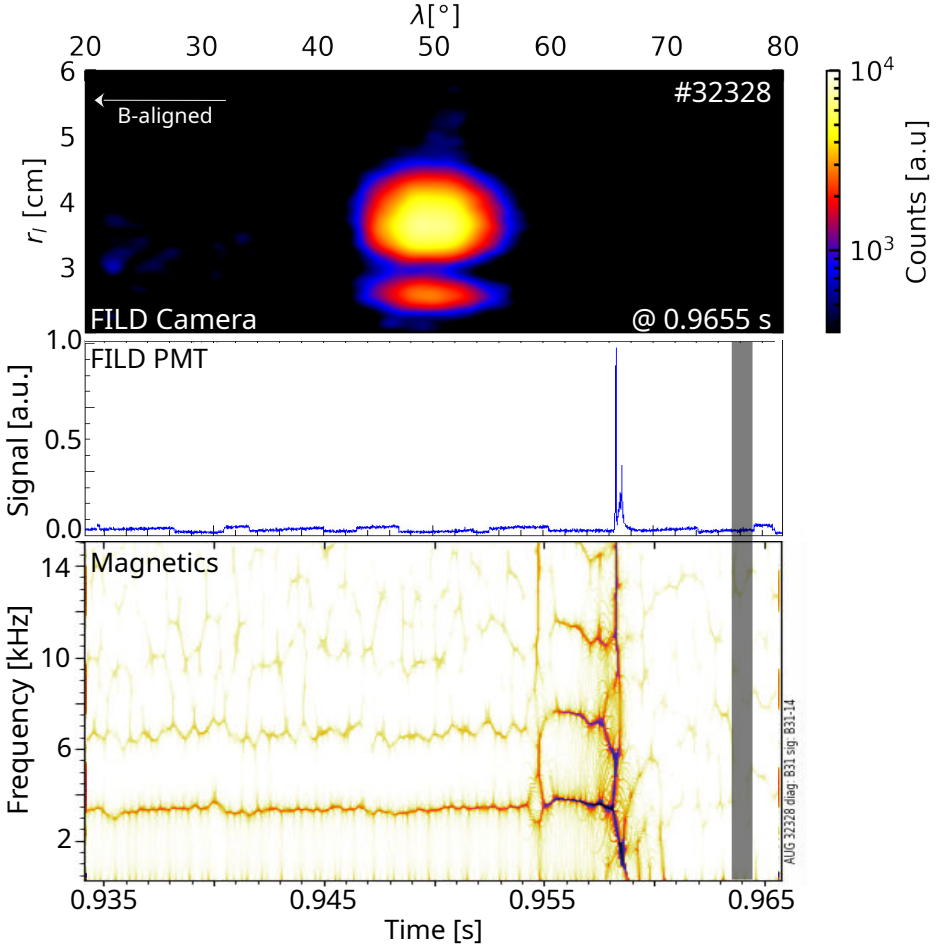
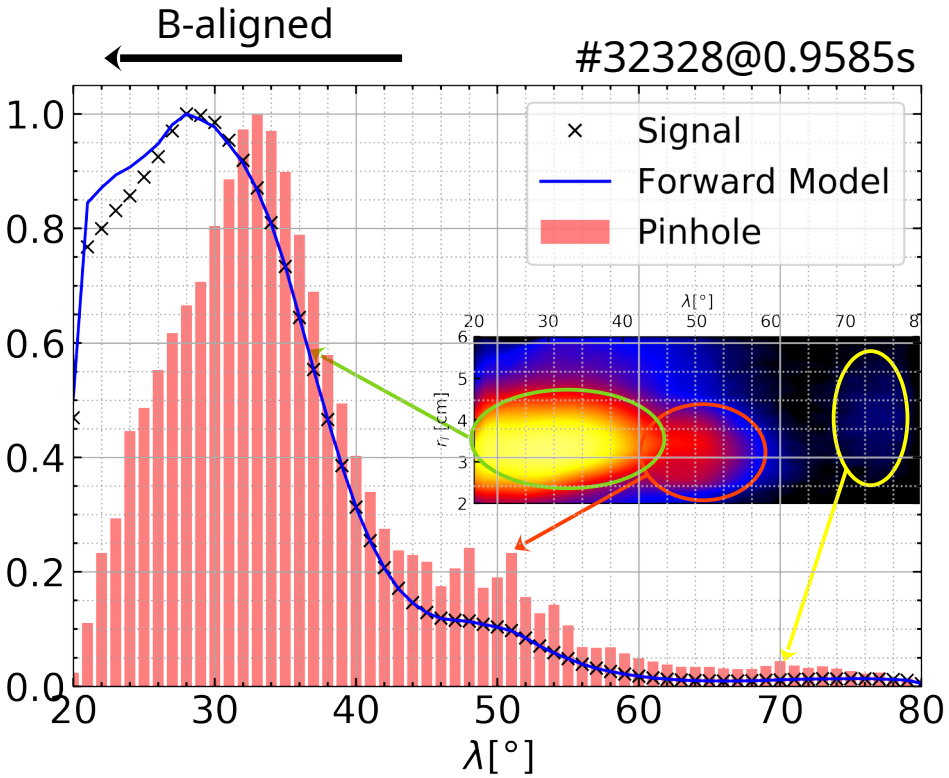
- *Usual* prompt losses registered before the locking of the mode
- At the mode locking: low pitch [º] feature dominates
- 1 ms after the locking: prompt losses dominate again. Low pitch [º] feature *lost* from FILD due to changes in B
- 2 ms after locking: Low pitch [º] feature is detected again
- Some ms after: only prompt losses again



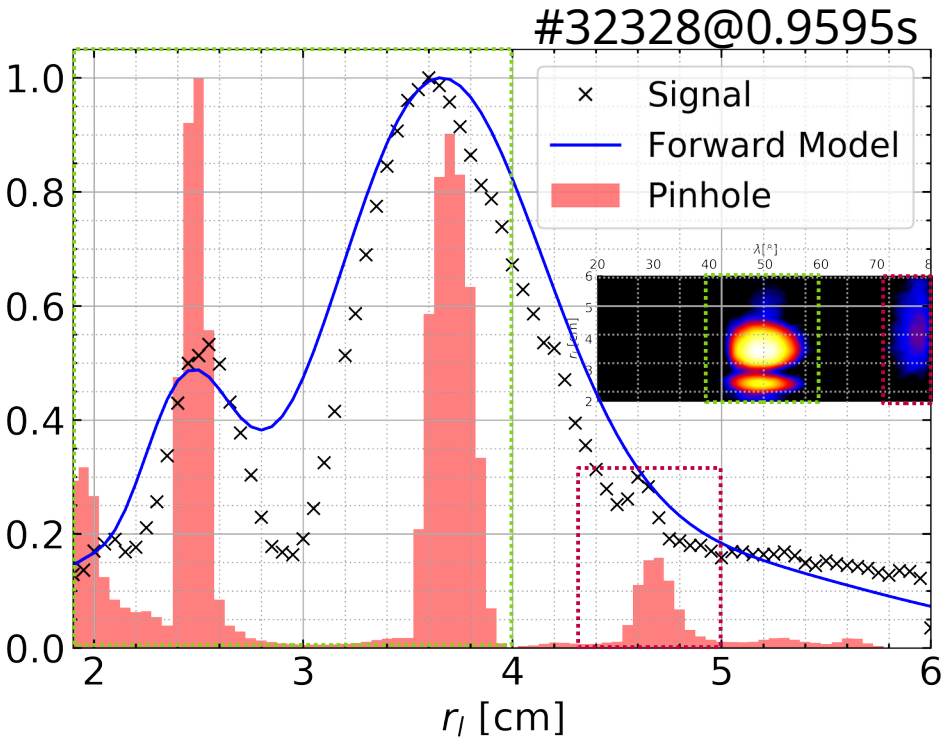
Pitch extended feature seems to be continuous in pitch angle. No single-pitch components are found

- Three peaks observed:
  - 37º & 75º: FIL due to the mode locking
  - 50º: Prompt losses
- Extended pitch feature:
  - Wide and continuous peak
  - No discrete peaks found (inside FILD resolution)



Trapped particle around 75º present energies larger than the NBI injection one

- Prompt losses formed by three NBI energy components
- Signal at large λ[º] have E > E_{NBI}
- r_l = 4.65 cm ~ 145 keV
- Acceleration (~50 keV) compatible with MHD interaction* or E_r mechanism



[* J. Galdón-Quiroga Phys. Rev. Lett. 121 (2018)]

Conclusions and outlook

- FI acceleration during the ramp-up phase has been observed
- Wide variety of FIL are observed in disruption events
- Accelerated features are due to single energy component
- Find the physical mechanism driving the acceleration