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

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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 mechanisms can cause FI transport and acceleration during ramp-up and disruptions.

**MHD interaction**

- Resonances
- FI ↔ Mode

**$E_{\parallel}$ acceleration**

- Balance between $E_{\parallel}$ 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 *, **

[* See H. Chen talk on Tuesday]
[** See J. Domínguez-Palacios talk on Monday]
Parallel electric field can accelerate ions if it overcomes friction force

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

[H. Dreicer, Phys. Rev. 115, 238]
[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

![Graph showing $E_r$ vs $\rho_{pol}$ with different modes: L-mode, I-mode, and H-mode.](image)

[E. Viezzer et al, Nucl. Fusion 53 (2013)]
Fast-Ion Loss Detector (FILD\textsuperscript{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)

[1 S. J. Zweben, Rev. Sci. Instrum. 57, 1774 (1986)]
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

\[ S_i = F_\alpha W_i^\alpha \]

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

- Early NBI injection
- $V_{\text{loop}} \sim 4V$ 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
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
- 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
- $5\text{cm} \sim (200 - 250)\text{keV}$
- Similar behaviour through the whole acceleration phase

![Graph showing accelerated ions with labels 1st, 2nd, and 3rd.](#39612 @ 0.35s)
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
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
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
- Similar for off-axis distribution
Electric field cannot accelerate NBI ions in the observed time scales

- Modest value of $E_{||} = 0.5 \text{ V/m}$ 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. Viezzer et al, Nucl. Fusion 53 (2013)]
Electric field cannot accelerate NBI ions in the observed time scales

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


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L-mode compatible $E_r$ introduced in ASCOT

- Full orbit simulation performed
- Peaks appearing at 125 keV

[E. Viezzer et al, Nucl. Fusion 53 (2013)]
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- Theoretical background
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- Losses during disruptions
Rich FIL phenomenology observed during disruptions

Before disruption

- Usual prompt losses
Rich FIL phenomenology observed during disruptions

- **Before disruption**
  - *Usual* prompt losses

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

![Graph showing FIL phenomenology](image)
Rich FIL phenomenology observed during disruptions

Before disruption

- *Usual* prompt losses

Minor disruptions

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

Major disruption & current quench

- Low signal level due to plasma shifting towards central column

[See talk by P. Heinrich tomorrow]

06/12/2021

Jose Rueda. IAEA 2021
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

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- At the mode locking: low pitch [$^\circ$] feature dominates
Rich variety of FIL structures observed during minor disruption events

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- At the mode locking: low pitch [°] feature dominates.
- 1 ms after the locking: prompt losses dominate again. Low pitch [°] feature *lost* from FILD due to changes in B.
Rich variety of FIL structures observed during minor disruption events

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- At the mode locking: low pitch [$^\circ$] feature dominates
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- 2 ms after locking: Low pitch [$^\circ$] feature is detected again
Rich variety of FIL structures observed during minor disruption events

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- At the mode locking: low pitch [$^{\circ}$] feature dominates
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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
- 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:
  - $37^\circ$ & $75^\circ$: FIL due to the mode locking
  - $50^\circ$: 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 $\lambda$[º] have $E > E_{\text{NBI}}$
- $r_i = 4.65$ cm $\sim$ 145 keV
- Acceleration ($\sim$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.