Investigating fast-ion transport due to sawtooth crashes using collective Thomson scattering

Jesper Rasmussen¹, S. K. Nielsen¹, M. Stejner¹, B. Geiger², A. S. Jacobsen¹, F. Jaulmes³, S. B. Korsholm¹, F. Leipold¹, F. Ryter², M. Salewski¹, M. Schubert², J. Stober², D. Wagner², the ASDEX Upgrade Team² and the EUROFusion MST1 Team

¹Technical University of Denmark       ²IPP Garching                    ³FOM-DIFFER
Impact of sawteeth on fast ions

- Magnetic reconnection when $q_{\text{core}} < 1$
- Redistribute particles and can cause NTMs $\rightarrow$ disruptions

Periodic crash in electron $T_e + N_e$:

![Graph showing periodic crash in electron temperature and density over time](image)
Impact of sawteeth on fast ions

Significant redistribution of fast ions due to

• Ion movement along evolving field lines (Kadomtsev model)
• $\mathbf{E} \times \mathbf{B}$ drifts caused by E-fields arising during reconnection

...but still unclear how redistribution depends in detail on fast-ion orbit topology

• Magnetic reconnection when $q_{core} < 1$
• Redistribute particles + can cause NTMs $\rightarrow$ disruptions
Dependence on fast-ion orbits observed

Collective Thomson scattering (CTS) at TEXTOR: 50% reduction for passing ions

Electron temperature

Fast-ion density

Passing fast ions

Trapped fast ions

S. K. Nielsen et al 2010, PPCF, 52, 092001
Fast-ion D-alpha spectroscopy (FIDA) at ASDEX Upgrade:

Dependence on fast-ion orbits observed

FIDA: Good agreement with Kadomtsev model
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Fast-ion D-alpha spectroscopy (FIDA) at ASDEX Upgrade:

FIDA: Good agreement with Kadomtsev model

Previously: Measurements at different machines
Now: Multiple diagnostics on one machine = AUG
Collective Thomson scattering (CTS) at ASDEX Upgrade

• 105 GHz probe beam \( (k^i) \) injected into plasma (\( \sim 600 \text{ kW, unabsorbed} \))

• Beam scatters off plasma fluctuations \( (k^\delta) \)

• Scattered signal \( (k^s = k^i + k^\delta) \) contains information on fast-ion distribution function \( f \) along \( k^\delta \):

\[
g(u) = \int dv f \delta \left( \frac{v \cdot k^\delta}{k^\delta} - u \right)
\]

S. K. Nielsen et al 2015, PPCF, 57, 035009
Interpreting CTS fast-ion data

CTS spectra fitted with a scattering model to obtain the 1D projection of $f$:

$$g(u) = \int dv f \delta \left( \frac{\mathbf{v} \cdot \mathbf{k}^\delta}{k^\delta} - u \right)$$
Interpreting CTS fast-ion data

CTS spectra fitted with a scattering model to obtain the 1D projection of $f$:

$$g(u) = \int dv f \delta \left( \frac{\mathbf{v} \cdot \mathbf{k}^\delta}{k^\delta} - u \right)$$

Each $u$ related to energy-pitch space through weight functions $w$:

$$g(u) = \int w f(E, p) \, dE \, dp$$
Sawtooth experiments with CTS at AUG

CTS volume: \((R,z) = (1.62, 0.06)\)m
\(\rho_p = 0.15, \angle(k^\delta, B) = 101^\circ\)

\(\rho_p = 0.4 \approx\) sawtooth inversion radius from soft X-rays
Sawtooth experiments with CTS at AUG

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"Crash 1"  "Crash 2"
Spectra respond to sawtooth crashes

Crash 1

$\text{t} = 2.29 \text{ s}$

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Crash 2

$\text{t} = 2.51 \text{ s}$
Spectra respond to sawtooth crashes in agreement with forward model

Forward model based on
- scattering geometry (raytracing)
- measured thermal-ion parameters (other diagnostics)
- Fast-ion distrib. function \( f(E,p) \) (TRANSP)
CTS fast-ion distribution functions: Suggest 50% redistribution across crashes
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At $1.5 \times 10^6 \text{ m/s} < |u| < 3.5 \times 10^6 \text{ m/s}$: Fast-ion reduction of

- **Crash 1**: $40 \pm 24\%$
- **Crash 2**: $60 \pm 22\%$
At $1.5 \times 10^6 \text{ m/s} < |u| < 3.5 \times 10^6 \text{ m/s}$: Fast-ion reduction of:

$40 \pm 24\%$

$60 \pm 22\%$

• Compare to **TRANSP** + Kadomtsev (guiding center)

• **EBdyna_go**: Kadomtsev + full orbits in evolving $E, B$ fields
  (F. Jaulmes et al. 2014, NF, 54, 104013) - see poster **P11** by F. Jaulmes
Vast majority of fast ions in CTS volume are passing (volume located centrally just on HFS)

Simulated distribution functions: TRANSPP vs. EBdyna_go

Crash 1

Crash 2

Vast majority of fast ions in CTS volume are passing (volume located centrally just on HFS)
1D fast-ion distribution functions: CTS vs. TRANSP

At $1.5 \times 10^6$ m/s < $|u|$ < $3.5 \times 10^6$ m/s: Fast-ion reduction of

- **CTS**: $40 \pm 24\%$
- **TRANSP**: $44 \pm 11\%$
- **CTS**: $60 \pm 22\%$
- **TRANSP**: $56 \pm 14\%$
1D fast-ion distribution functions: CTS vs. EBdyna_go

At $1.5\times10^6$ m/s < $|u|$ < $3.5\times10^6$ m/s: Fast-ion reduction of

- CTS: $40 \pm 24\%$
- EBdyna: $59 \pm 15\%$

- CTS: $60 \pm 22\%$
- EBdyna: $49 \pm 12\%$
Comparison of post-crash predictions

Crash 1

Crash 2

$g(u) [10^{12} \text{ s}^{-4}]$

$u [10^6 \text{ m/s}]$

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$g(u) [10^{12} \text{ s}^{-4}]$

$u [10^6 \text{ m/s}]$
FIDA signal also reduced by ~50% for passing ions

Similar results for comparable discharges:

- AUG #30809: Geiger et al. 2015, PPCF 57, 014018
- AUG #30815: Geiger et al. 2015, NF 55, 083001
Preliminary FIDA + CTS tomography (4+1 views) revealing redistribution in (E,p) space

Tomography, Crash 1

TRANSP

A. S. Jacobsen et al, in prep.  See also poster P36 by L. Stagner
Conclusions & outlook

First CTS study of sawtooth redistribution of fast ions at AUG:

- 50% fast-ion reduction in CTS volume (passing ions only)
- Good agreement with FIDA measurements and with TRANSP/Kadomtsev + EBdyna_go

CTS can discriminate between sawtooth models:

- Forthcoming experiments with other scattering geometries
- Tomographies using FIDA + CTS data (+ NPA, neutrons etc.)
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Relative change in distribution function predicted with TRANSP

Illustrates redistribution in (E,p) at a given (R,z)
Fast-ion loss detectors show ~10% increase in signal at sawteeth

M. Garcia-Munoz, J. Galdon, N. Lazányi
Raw neutron rates:  
Also only very modest variations

No strong drops across crashes →
Most redistributed fast ions remain confined
Calibrated neutron rates + plasma stored energy

Measured neutron rates from neutron counters at the dt = 10 ms time res. of TRANSP.

Offset subtracted + scaled to match TRANSP.

(measured rates are >> 0 even when no NBI/ECRH is on)
Contributions to CTS spectra

105 GHz gyrotron
Comparison of post-crash predictions

Crash 1

\[ T \cdot E \cdot f(E,p) \]

CTS weight function, \( u = +2e6 \text{ m/s} \)
Preliminary FIDA + CTS tomography (4+1 views) revealing redistribution in (E,p) space

A. S. Jacobsen et al, in prep.  See also poster by Luke Stagner

Detailed comparison in progress