# Off-axis NB heated discharges at ASDEX Upgrade: EGAMs,TAE bursts, and RSAEs

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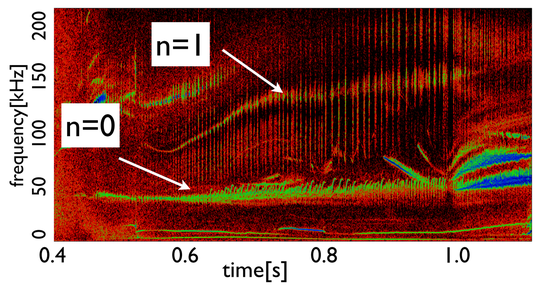
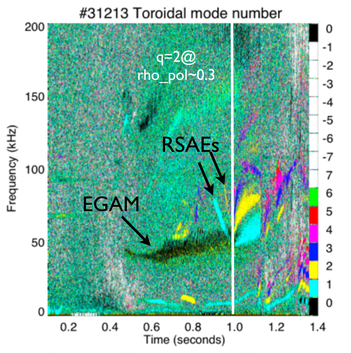
## Motivation

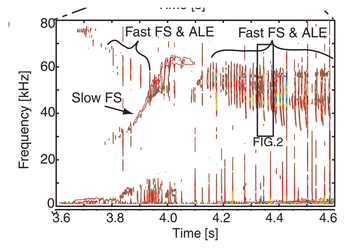
- how general is the experimental observation of many small-amplitude modes close to marginal stability in reversed shear plasmas with sub-Alfvénic beams? [Heidbrink, van Zeeland, et al 2006-2015]
- under which conditions can one reach a regime where strongly non-linear physics dominates the energetic particle (EP) transport like in spherical tokamaks [Fredrickson, 2007-2012] or in experiments with super-Alfvénic beams? [Shinohara 2002-2006]
- what are mode properties and transport mechanisms in this case?
- off-axis NB drive will be needed for scenarios with reversed shear resulting in an off-axis peaked (partial) EP -NB pressure
- at ASDEX Upgrade, off-axis NBI experiments were carried out showing strongly bursting toroidal Alfvén eigenmodes (TAEs) and velocity space coupling to co-NB-driven geodesic acoustic modes (EGAMs)
- also on-axis NBI cases with 93keV beam energy show strongly bursting behaviour

## Experimental Results




off-axis drive #31213: magnetic spectrogram

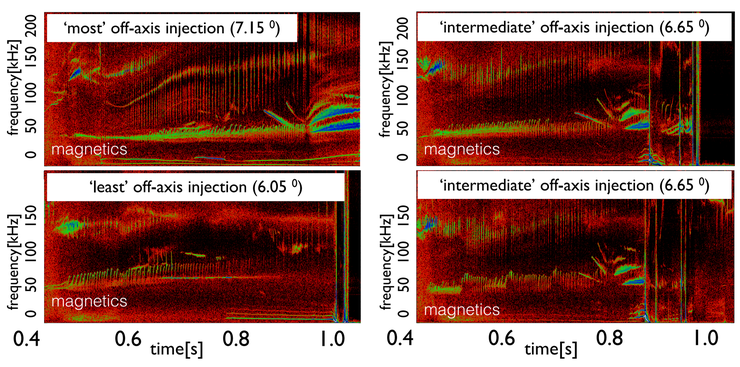


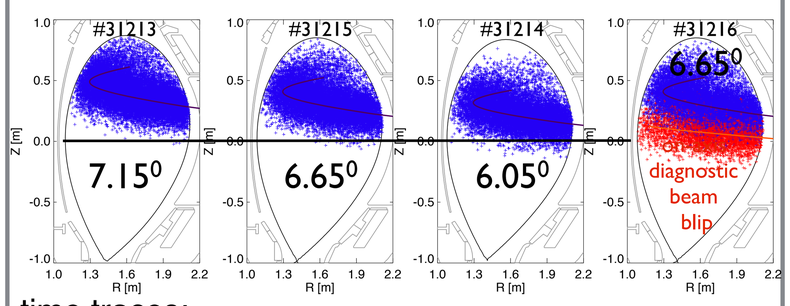

JT-60U: K. Shinohara et al, 2002-2004

JT-60U: $v_f/v_{A0}$~1.3 ; NB: 350keV
DIII-D: $v_f/v_{A0}$~0.4 ; NB: 80keV
AUG: $v_f/v_{A0}$~0.45; NB: 93keV

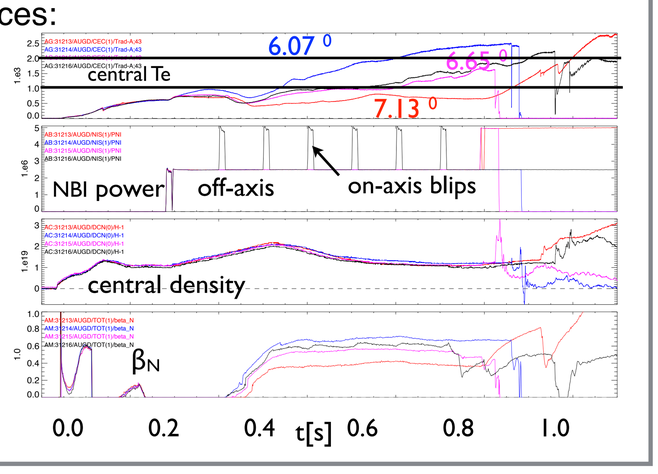
- $B_0$=2.2T, I=0.6-1.0MA
- $P_{beam}$=2.5MW, $E_{beam}$=93keV
- rather well reproducible scenario
- no 'sea' of Alfvénic modes (TAEs/RSAEs)
- but strongly chirping n=0 modes and n=1 'bursts'



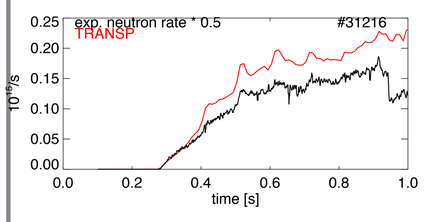

NBI deposition [FIDASIM]:



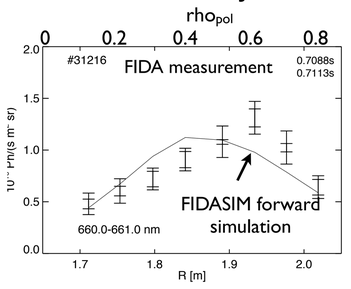

time traces:



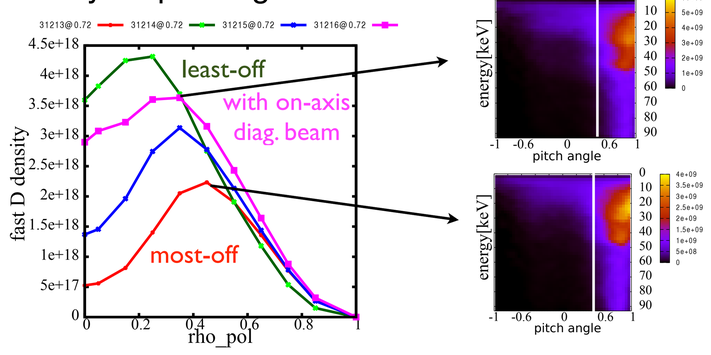

neutron rate: experiment vs. TRANSP



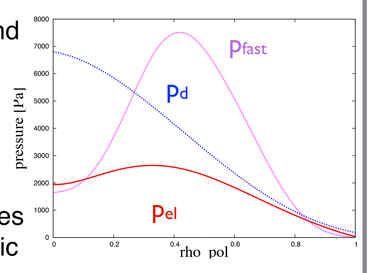

measured fast ion density

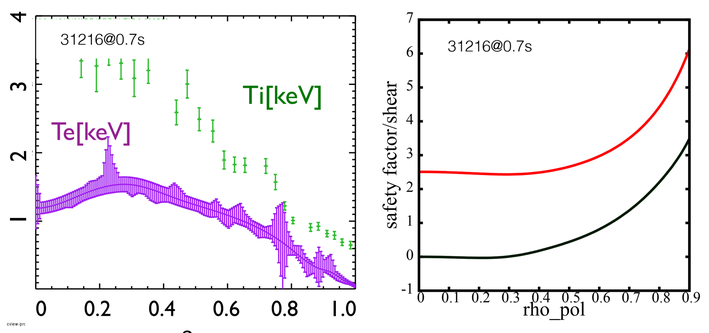



NB distribution function: mainly co-passing ions



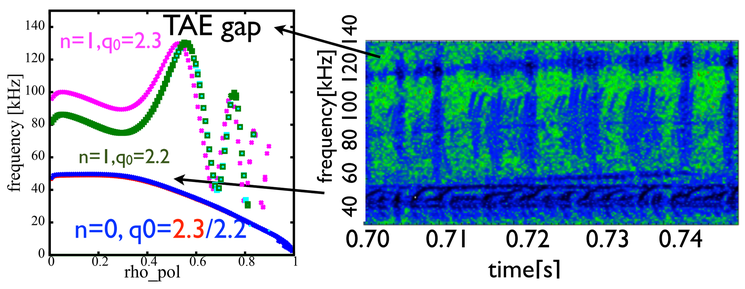

- from ECE, SXR, interferometry and reflectometry:
- EGAMs more core localised (0.15-0.5 $\rho_{pol}$),
- TAEs more outside (0.2-0.6 $\rho_{pol}$)
- weak RSAE activity
- inverted gradient also drives modes rotating in the electron diamagnetic direction



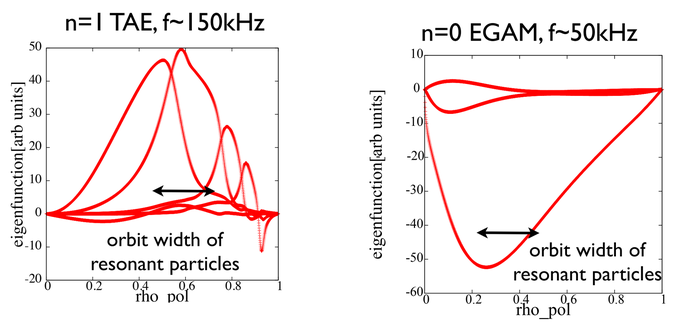




## Gyrokinetic Modeling

Use the linear GK eigenvalue solver LIGKA to investigate linear onset conditions

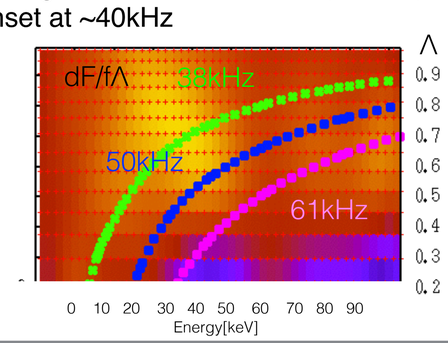



global eigenfunctions: both TAE and EGAMs are above stability threshold for nominal EP pressure

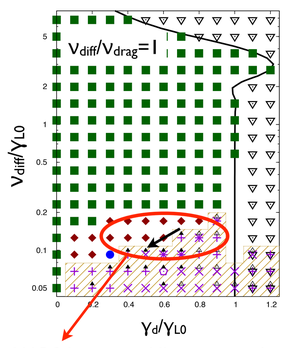


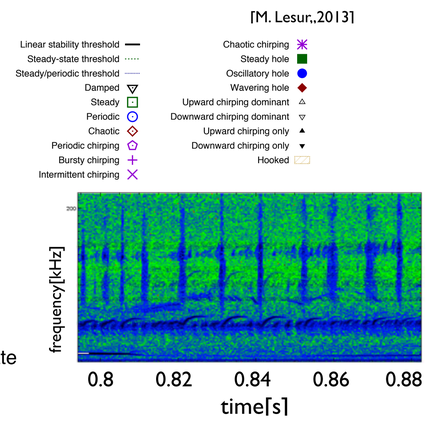

relatively large orbit width (flat q ~2) favours low mode numbers to be understood: the condition should be fulfilled for n=2, n=3 as well

EGAM n=0 resonance condition:$\omega-\omega_t=0$
$dF/f\Lambda$ in pitch angle is maximal at 40keV, $\Lambda$=0.6, consistent with mode onset at ~40kHz

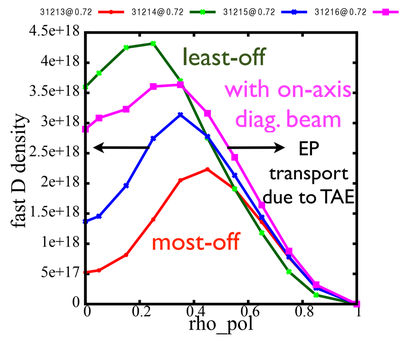



## Non-linear observations: TAE bursts trigger EGAMs

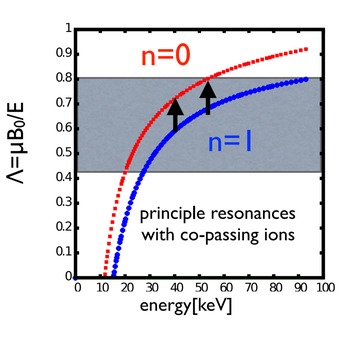



AUG? increased linear growth rate would explain transition from 'wavering hole' to hooked up-chirping

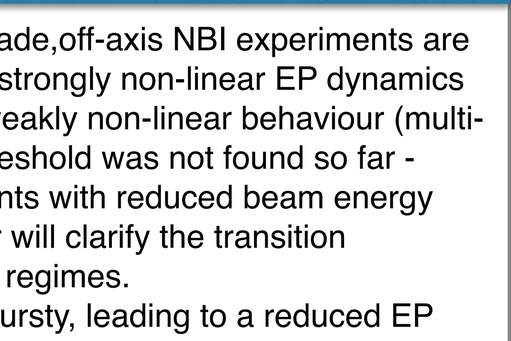



radial transport due to TAE reduces EP density at EGAM position (0.4) - no increased EGAM drive

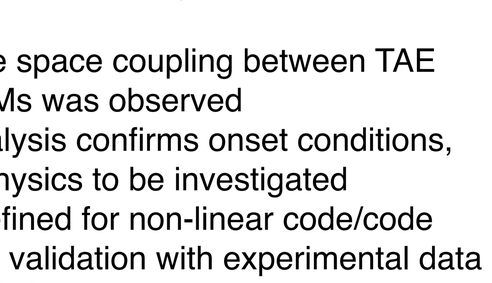



(small) transport due to TAE in μ and E moves particles into EGAM resonance - increased EGAM drive

different timing of the beams (longer on-axis phase (0.2-0.3s): weak EGAMs, but n=1 BAE bursts




on-axis cases: off-axis 93keV source replaced by 93keV on-axis source: no EGAMs, but n=2 BAE bursts




⇒ strong q-profile and distribution function dependence

## Conclusions

- At ASDEX Upgrade,off-axis NBI experiments are in a regime with strongly non-linear EP dynamics
- the regime for weakly non-linear behaviour (multi-mode) above threshold was not found so far - further experiments with reduced beam energy and beam power will clarify the transition between the two regimes.
- EP transport is bursty, leading to a reduced EP density.
- interesting phase space coupling between TAE bursts and EGAMs was observed
- linear kinetic analysis confirms onset conditions, rich non-linear physics to be investigated
- test case was defined for non-linear code/code benchmarks and validation with experimental data within EUROFUSION NLED project

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