Strongly non-linear energetic particle dynamics in ASDEX Upgrade scenarios with core impurity accumulation

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acknowledgements to the Eurofusion Enabling Research ’NLED’ Team

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This work was partly performed within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. Funding from the EUROfusion Enabling Research work-package AWP15-ENR-09/ENEA-03 (NLED) and AWP15-ENR-09/IPP-01 (NAT) are acknowledged. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
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new scenario with strong mode activity induced by energetic particles (EPs) was established at ASDEX Upgrade

I=800kA
B=-2.5T
q≥2 slightly reversed
new scenario with strong mode activity induced by energetic particles (EPs) was established at ASDEX Upgrade

investigation of strongly non-linear EP dynamics at ASDEX Upgrade is now possible:

- with sub-Alfvénic beams (2.5-5MW)
- in current flat top with stationary plasma conditions
- compatible with tungsten wall
- for EP physics relevant parameters:
  \[ \frac{\beta_{EP}}{\beta_{thermal}} \approx 1, \frac{E_{NBI}}{T_{i,e}} \approx 100 \]
motivation: predicting self-organisation of burning fusion plasmas

- one crucial physics element: transport properties of energetic particles (EPs) are determined by non-linear saturation level of EP-driven modes

- mechanism: mode-induced flattening of EP phase space gradients by non-linear wave-particle interaction vs. recovery of depleted gradients by collisional slowing down processes

- these ingredients lead to several non-linear saturation states: steady state, bifurcation, chaotic, bursting (typically super-Alfvénic drive \([JT-60SA,NSTX,MAST]\)) that are determined by linear drive, damping, effective collisionality \([O'Neill, Berk&Breizman]\) and radial non-uniformity of resonances \([Briguglio, X.Wang 2015; Duarte 2017]\)

- less studied: wave-wave coupling processes and formation of zonal structures (ZS) caused by EP-driven modes influence the saturation and the overall plasma state \([Hahm 1995; Todo 2010-12, 2015; Bierwage Nature 2018; Chen&Zonca 2012, Qui 2018]\)

- on long time scales: average EP profile close to -slightly upshifted - marginally stable state (stiff EP profiles, DIII-D \([Collins 2016]\)); on short and intermediate time scales: steady, intermittent (‘ALE’, \([Shinohara, JT-60U]\)) or even ballistic (EPM \([G. Vlad 2004]\)) transport possible

• the dynamics of EP-driven geodesic acoustic modes (EGAMs) and excitation conditions under various experimental conditions

• interaction EGAMs and Alfvén eigenmodes (AEs)

• discussion & conclusions
EGAM properties: radial location and mode numbers

- one the most prominent modes in this scenario: EP-driven geodesic acoustic mode [other exp. observations: Boswell, Berk Nazikian, Ido, Chen, Horvath,… ]
- visible in magnetics, soft-X ray: toroidal mode number \( n=0 \); dominant poloidal mode number \( n=2 \) [Wahlberg 2008]; global mode, peaked in core \( \rho_{\text{pol}} \sim 0.2-0.4 \)

![Images of magnetic spectrograms and X-ray spectrograms showing EGAM modes](image)

Also change of radial EGAM mode structure in non-linear phase was observed [Horvath et al., NF 2016]
EGAM properties: radial location and amplitude as measured by reflectometry

• one the most prominent modes: EP-driven geodesic acoustic mode
  \[\text{other exp. observations: Boswell, Berk Nazikian, Ido, Chen, Horvath,…}\]
• visible in magnetics, soft-X ray: toroidal mode number \(n=0\); dominant poloidal mode number \(n=2\) \[Wahlberg 2008\]; global mode, peaked in core \(\rho_{\text{pol}} \sim 0.2-0.4\)
• visible also in interferometer and reflectometry, confirming mode location and giving estimate about \(\delta n/n \sim 1-4\%\)
• EGAMs only found in frequency band between 40-70kHz
EGAM excitation conditions: comparison of discharges w/o EGAMs

- **Current**: \(34924/34925\)
- **NBI power**: \(34924/34925\)
- **Central el density**: \(34924/34925\)
- **Central Te**: \(34924/34925\)
- **Core radiation**
- **Edge radiation**
- **Da -ELMs**

34924: EGAMs

34925: no EGAMs

Time (s)
EGAM excitation conditions: comparison of discharges w/o EGAMs

Current: #34924/#34925
NBI power: #34924/#34925
Central el density: #34924/#34925
Central Te: #34924/#34925
Core radiation

SXR #34924: EGAMs
Emissivity profile

SXR #34925: no EGAMs
Emissivity profile
EGAM excitation conditions: comparison of discharges w/o EGAMs

Interpretative TRANSP analysis: fast particle pressure contribution dominates in phase with one beam; in 2-beam phase ~ 30-50% of total $\beta$
EGAMs: linear theory

1. $\omega_{\text{GAM}}$ depends mainly on $T_i, T_e$, local curvature ($R$); damping strongly on $q$; simplest local formula underpredicts damping by orders of magnitude:

$$\omega_{\text{GAM}} = \frac{v_{\text{th},i}^2}{R^2} \left\{ \frac{7}{4} + \frac{T_e}{T_i} \right\} - i \pi \left( \frac{\omega}{\omega_{\text{ti}}} \right)^5 \exp\left(-\frac{\omega}{\omega_{\text{ti}}}\right)^2 \left[ 1 + \frac{1 + 2 \frac{T_e}{T_i}}{\left( \frac{\omega}{\omega_{\text{ti}}} \right)^2} \right]$$

any deviation of the geodesic curvature drift from $\sin(\theta)$ dependence introduces $\exp\left(-\frac{\omega}{(2\omega_{\text{ti}})^2}\right)$ terms that dominate the damping:

- plasma shaping in particular elongation [Gao, NF 2009] changes both $\omega$ and $\gamma$
- finite orbit width and finite Larmor radius effects [Sugama 2006, Zonca 2008]

trapped electrons increase the damping considerably [Zhang 2010, Biancalani & Novikau 2017, Garbet, Varenna 2018]

2. EGAMs are driven by the anisotropy in velocity space [Fu 2008]; realistic $F_{\text{NBI}}$ has to be included:

$$\gamma \sim \frac{\omega}{\omega_{\text{ti}}} \cdot \frac{\partial F}{\partial E} - n \frac{\partial F}{\partial P_{\phi}}$$

3. modes are global, have electromagnetic halo [Wahlberg 2008]

global, electromagnetic calculations in realistic geometry with a realistic EP distribution function are needed

modeling has been started with ORB5, GENE [di Siena, Biancalani 2018], HYMAGYC [G. Vlad] MEGA [H Wang]
EGAM modeling: linear gyrokinetic eigenvalue solver LIGKA

- LIGKA library comprises several local and global models for kinetic Alfvén mode (AE) physics and low frequency global modes based on the same linear gyro-kinetic model [Qin 1998, Lauber 2007, 2013, 2018]

- various dispersion relations in literature (e.g. BAE, GAM, KGAM dispersion relation including FLR and FOW effects [Lauber, Varenna 2018] were directly derived from model equations

- fully numerical (based on HAGIS [S.D. Pinches, 1996] particle orbit information) and analytical evaluation of resonance integrals possible

- local and global solvers using either analytical or numerical v-space integrals

- in combination with non-linear HAGIS code, fast and automated stability and non-linear saturation evaluations for AE physics possible [Hayward-Schneider & Lauber 2017/18]
GAM continuum: local calculations

at each radial position, solve linear dispersion relation:

- analytical, circular equilibrium
- numerical, circular eq., all ion resonances
- numerical, shaped equilibrium $\kappa \approx 1.6$; $\omega \approx \sqrt{2/(1+\kappa^2)}$
- numerical, add trapped electrons
- numerical, trapped + circulating electrons

profiles $(q,T_i,T_e)$ create (flat) minimum in GAM damping rate
control cases: lower q, set $T_e=T_i$

- reference parameters (last slide)
- lower $q_0$ from 2.4 to 1.99 (so far EGAMs were never observed for $q<2$)
- set $T_e=T_i$: increases $f_{GAM}$, reduces damping! $T_e$ inversion not a necessary ingredient for EGAM excitation (as experimentally confirmed)

Damping analysis alone does not explain EGAM excitation conditions
EP phase space analysis

- As expected, T^{-3/2} dependence of slowing down processes leads to higher EP pressure for case with higher background temperatures (and without EGAMs).

- At first glance: similar distribution in phase space structure.
EP phase space analysis: $\partial F/\partial E$

- EGAM drive is determined by integral along resonance line $\omega - \omega t = 0$
- no drive due to mismatch of drive region and local GAM frequency
EP phase space analysis: $\partial F/\partial E$

- EGAM drive is determined by integral along resonance line $\omega - \omega t = 0$
- no drive due to mismatch of drive region and local GAM frequency
- 2nd resonance $\omega - 2\omega t = 0$ suffers from damping of thermal background - ‘anomalous ion heating’ [LHD, Ido 2014, H. Wang 2018]
global EGAM structure [LIGKA]

- global EGAM frequency stays roughly constant with increasing $n_{EP}$, and close to flat part of the GAM continuum
- change in mode structure is observed with increasing $n_{EP}$
• mode is destabilised with increasing $n_{EP}$

• asymmetries of poloidal sidebands observed when anisotropic EP drive is present [Z. Lu, Varenna 2018]

• mode stays in flat continuum region - avoid continuum damping $\sim \partial \omega_{GAM}/\partial r$ [Biancalani, Palermo, 2016,17]
• the dynamics of EP-driven geodesic acoustic modes (EGAMs) and excitation conditions under various experimental conditions

• interaction of EGAMs and Alfvén eigenmodes (AEs)

• discussion & conclusions
interaction with Alfvén modes

3 types:

1. nearly simultaneous mode onset - but no phase correlation between different frequency bands, i.e. no significant bicoherence: triggering via non-linear phase space relaxation
interaction with Alfvén modes

3 types:

1. simultaneous mode onset, no phase correlation: triggering
2. phase correlation between different frequency bands: significant bicoherence indicating wave-wave non-linear coupling
interaction with Alfvén modes

3 types:

1. simultaneous mode onset, no phase correlation: triggering
2. phase correlation between different frequency bands: significant bicoherence indicating nonlinear wave-wave coupling
3. both mechanism can be observed together

[P Poloskei et al, IAEA TCM 2017]
local and global LIGKA analysis

1st type:

core SXR and magnetic fluctuation spectrogram in 2 beam (5 MW) phase
local and global LIGKA analysis

1st type:

calculate kinetic shear Alfvén and kinetic GAM spectrum for n=0 and n=-1 (LIGKA):
local and global LIGKA analysis

1st type:

**global mode structures:**
[arb units for amplitudes]

resonance analysis shows that:

- BAEs can tap energy from gradient both in velocity space and real space: most unstable mode

\[ \gamma \sim \frac{\omega \frac{\partial F}{\partial E} - n \frac{\partial F}{\partial P}}{\omega - \omega_t} \]

- BAE redistributes mainly in radial direction and thus triggers the EGAM (increased EP density) and TAE (higher order resonances)
local and global LIGKA analysis
1st type: phase space analysis (@ $\rho_{pol}=0.35$)
bicoherence measures phase coherence between the frequency bands that indicates a **non-linear (i.e. quadratic) interaction**: \( n=-2 \) TAE and \( n=4 \) TAE bands
2nd type:
calculate kinetic shear Alfvén and GAM spectrum for n=4 and n=-2 (LIGKA):
LIGKA: unstable modes, 3 wave coupling analysis

- after subtracting/adding rotation (7kHz): \( \omega_{TAE-2} - \omega_{TAE+4} = 0 \)
- also: \( k_{TAE-2} + k_{TAE+4} = \frac{1}{2 q_{TAE-2}} - \frac{1}{2 q_{TAE+4}} R \approx 0.222 - 0.211 \approx 0 \)
- fulfil matching conditions with zero frequency zonal structure: modified parametric decay constellation

[Biancalani FEC 2016, TH/P2-9 2018]
radial flattening of EP gradient observed - inwards transport

TAE and BAE redistribute particles radially: FIDA measurements in comparison to neoclassical TRANSP/NUBEAM calculations

control case, where no strong Alfvénic mode activity is observed (#34921): strongly inverted EP gradient, small EP transport
discussion (I)

• the combination of low background temperatures caused by core radiation and large EP pressure allows one to excite modes that are usually not accessible by sub-Alfvénic beam excitation: new experimental data facilitates the understanding cross scale and cross-frequency coupling mechanisms also in cases when modes are not present

• for EGAM excitation the beam anisotropy characteristics has to match the frequency range of the GAM continuum

• other regimes with lower beam energy are accessible for EGAM destabilisation and the influence of on-axis beam blips can be understood:

![Graphs showing frequency vs. time for #32386 (65kV, 1.27MW) and #31216 (93kV, 2.5MW) with on-axis blips and TAE and EGAM features.]
discussion(II)

• influence of EGAMs on turbulence [Zarzoso 2013-18] and presence of ‘anomalous ion heating’ [Osakabe, Ido 2014] could not be clarified yet: although there are clear differences in turbulent spectra between phases with and w/o EGAMs, this cannot be straightforwardly attributed to the EGAMs, since also overall plasma conditions change considerably

• co- and counter propagating AEs open possibility for non-linear wave-wave coupling studies

• scenario can be seen as complement to recent studies of ECRH influence on AE stability [Van Zeeland 2014, Sharapov 2017]: ECRH in NB heated discharges usually stabilises AEs - our scenario demonstrates opposite effect when ‘cooling’ the background

• scenario can be seen as a close relative to fully non-inductive scenarios [J. Stober FEC 2016, A Bock 2017, D Rittich EX/P8-25] with central ECCD (800kA) and current hole discharges (600keV) with [B Geiger, EX 2-3]

• these scenarios facilitate the physics understanding, preparation of tools and (advanced) scenarios for future devices such as JT-60SA, DTT, ITER, DEMO
other slides
EGAM properties: non-linear amplitude evolution observed

- one the most prominent modes: EP-driven geodesic acoustic mode
  [other exp. observations: Boswell, Berk Nazikian, Ido, Chen, Horvath,... ]
- visible in magnetics, soft-X ray: toroidal mode number $n=0$; dominant poloidal mode number $n=2$ [Wahlberg 2008]; global mode, peaked in core $\rho_{pol} \sim 0.2-0.4$

[Hovrath et al, NF 2016]
control cases: lower $q$, set $T_e = T_i$, $T_i = T_i/2$

- reference parameters (last slide)
- lower $q_0$ from 2.4 to 1.99 (so far EGAMs were never observed for $q<2$)
- set $T_e = T_i$: increases $f_{GAM}$, reduces damping! Te inversion not a necessary ingredient for EGAM excitation (as experimentally confirmed)
- lower $T_i$ by factor 2, $T_e = T_{e,\text{ref}}$

damping analysis does not explain alone EGAM excitation conditions
advanced bicoherence analysis [P Poloskei et al IAEA TCM 2017]

phase randomized bicoherence probability density function calculation

- High bicoherence around at (55, 55) kHz indicates strongly nonlinear EGAMs. (see spectrogram at ~110 kHz)
- Without filtering interaction with TAEs is not clear

- Filtering shows high, significant bicoherence around (155, 55) kHz
- Indicates the nonlinear interaction between EGAMs and TAEs
LIGKA: FLR/FOW validation with analytical theory

[Lauber, Varenna JPCS 2018]
strong core radiation confirmed by SXR tomography

tungsten concentration:
\( c_W = 3 \times 10^{-4} - 2 \times 10^{-3} \)

neutron deficit larger in 5MW (2 beam phase)
linear gyrokinetic eigenvalue solver LIGKA

- LIGKA library comprises several local and global models for kinetic Alfvén mode (AE) physics and low frequency global modes
- various dispersion relations in literature (e.g. BAE, GAM, KGAM dispersion relation including FLR and FOW effects [Lauber, Varenna 2018] were directly derived from model equations
- fully numerical (based on HAGIS particle orbit information) and analytical evaluation of resonance integrals possible
- local and global solvers using either analytical or numerical v-space integrals
- in combination with non-linear HAGIS code, fast and automated stability and non-linear saturation evaluations for AE physics possible [Hayward-Schneider & Lauber 2017/18]

15MA ITER scenario:
linear TAE-α driven stability overview
linear gyrokinetic eigenvalue solver LIGKA: reduced models

Perform broad search for potentially unstable modes ($s < 0.55$)