Nonlinear dynamics of energetic-particle driven geodesic acoustic modes in ASDEX Upgrade.

I. Novikau,1, a) A. Biancalani,1 A. Bottino,1 Ph. Lauber,1 E. Poli,1 P. Manz,1 G. D. Conway,1 A. Di Siena,1 N. Ohana,2 E. Lanti,2 L. Villard,2 and ASDEX Upgrade Team1

1) Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
2) École Polytechnique Fédérale de Lausanne, Swiss Plasma Center, CH-1015 Lausanne, Switzerland

(Dated: 18 December 2019)

Turbulence in tokamaks generates radially sheared zonal flows (ZFs). Their oscillatory counterparts, geodesic acoustic modes (GAMs), appear due to the action of the magnetic field curvature. The GAMs can also be driven unstable by an anisotropic energetic particle (EP) population leading to the formation of global radial structures, called EGAMs. The EGAMs might play the role of an intermediate agent between the EPs and thermal plasma, by redistributing EP energy to the bulk plasma through collisionless wave-particle interaction. In such a way, the EGAMs might contribute to the plasma heating. Thus, investigation of EGAM properties, especially in the velocity space, is necessary for precise understanding of the transport phenomena in tokamak plasmas. In this work, the nonlinear dynamics of EGAMs is investigated with the help of a Mode-Particle-Resonance (MPR) diagnostic recently implemented in the global gyrokinetic (GK) particle-in-cell code ORB5. This enables to investigate the relative importance and the evolution of the resonances responsible for the ion and electron Landau damping, and of the EP drive. An ASDEX Upgrade discharge is chosen as a reference case for this investigation due to its rich EP nonlinear dynamics.

a) Electronic mail: ivan.novikau@ipp.mpg.de
I. INTRODUCTION

An energetic particle (EP) beam, injected in tokamak plasma, can excite a variety of modes. One of these modes, called energetic-particle-driven geodesic acoustic mode (EGAM)\textsuperscript{1,2}, can have a significant influence on the EP dynamics and on the plasma confinement. First of all, being excited, this mode provides an additional mechanism of the energy exchange between the energetic particles and the thermal plasma\textsuperscript{3–6} due to the wave-particle interaction. Moreover, because of its interaction with the turbulence\textsuperscript{7,8}, this mode might be used as an additional knob in the turbulence regulation. Significant progress has been made in the last decade in building a theoretical model which can explain the main nonlinear physics of the EGAM\textsuperscript{9–11}. Yet, when one wants to quantitatively compare with experimental measurements, some of the approximations in the previous models can be limiting. For example, due to the importance of the wave-particle resonances with the thermal and energetic species, a kinetic treatment should be used as in Ref.\textsuperscript{12–14}. Apart from that, effect of the magnetic surface shape\textsuperscript{15} can be considered by employing an experimental magnetic equilibrium. In this work, the importance of these effects on an experimental ASDEX-Upgrade (AUG) case by means of numerical simulations with the nonlinear gyrokinetic code ORB5\textsuperscript{16–18} is investigated. ORB5 has been previously used for nonlinear studies of EGAMs in simplified configurations\textsuperscript{19,20}, and it is used here to compare the nonlinear EGAM dynamics with experimental measurements.

In this work, only the EGAM dynamics, leaving aside its interaction with the turbulence is going to be considered. The nonlinear behaviour of this mode, such as the mode chirping\textsuperscript{21,22}, plasma heating by the EGAMs, and its dependence on the plasma parameters are of interest here. It should be noted here that in contrast to finite-\textit{n} modes (where \textit{n} is a toroidal number), which also can transfer energy from the EPs to the thermal plasma due to the wave-particle interaction, the EGAM dynamics is practically not associated with additional particle loss, at least if one does not consider the mode propagation and topological orbital changes\textsuperscript{23}.

The EGAM dynamics is going to be investigated in the plasma configuration of the ASDEX Upgrade (AUG) discharge \#31213@0.84 s (referred to as the NLED-AUG case\textsuperscript{24,25}, where a rich EP nonlinear dynamics is present\textsuperscript{26}. In this discharge, various types of EP-driven instabilities were identified, among which there are Alfvén instabilities (see, for example, Ref.\textsuperscript{27}) and EGAMs. In particular, a clear EGAM chirping was observed. More precisely, at the experimental EGAM frequency spectrogram (Fig.\textsuperscript{1a}) one can see at least two different branches of the EGAM evolution.
in time. A "short" one is with a $\sim 2.5$ ms period with the frequency rise from $\sim 45$ kHz till $\sim 55$ kHz. A "long" branch is characterised by an ascending frequency from $\sim 45$ kHz till $\sim 58$ kHz and frequency saturation with a period of change around 13 ms.

FIG. 1: Experimental EGAM spectrum$^{24,26}$ in the NLED AUG discharge #31213@0.84 s, obtained from Mirnov coils (Fig. 1a). Fig. 1b shows the magnetic field configuration, while Fig. 1c describes safety factor profile.

The paper structure is as follows. The ASDEX Upgrade configuration is presented in Section II. The Mode-Particle-Resonance (MPR) diagnostic$^{14}$, implemented in ORB5 to study field-particle interaction in velocity space, is briefly described in Section II A. The mode chirping and corresponding comparison with the AUG experiment is presented in Section III. Using two shifted Maxwellians as an EP distribution function, a nonlinear electrostatic (ES) gyrokinetic simulation with the code ORB5 produces a relative EGAM up-chirping close to the experimental one. In this simulation, EP parameters have been taken consistent with previous works (Refs. 14 and 15), where in the same AUG discharge the ordering of the EGAM frequency was reproduced in linear electrostatic and electromagnetic (EM) simulations, performed with the codes GENE$^{28}$ and ORB5. In Section IV the EGAM linear behaviour is investigated by varying EP parameters. This study is used later for the analysis of the plasma heating by the EPs through the EGAMs in Section V. Existence of an energy exchange between EPs and thermal particles are emphasized, and dominant resonant thermal species are indicated using the MPR diagnostic. Such kind of plasma heating has been recently demonstrated in Ref. 6 in a realistic 3D equilibrium of the LHD stellarator, using the hybrid code MEGA with kinetic treatment of both thermal and energetic ions.

By comparing ES simulations with adiabatic electrons and electromagnetic (EM) simulations with drift-kinetic electrons, it is shown how the inclusion of the electron dynamics affects the EGAM formation and the plasma heating by this mode in Section VI. Although even in the pres-
ence of drift-kinetic electrons the EGAM transfers most of its energy to the thermal ions, electron
dynamics still clearly decreases the mode level in the considered AUG discharge, and in such a
way reduces the energy flow from the EPs to the thermal ions.

II. NUMERICAL AUG CONFIGURATION

The AUG plasma is simulated in the gyrokinetic (GK) particle-in-cell (PIC) global code
ORB5\textsuperscript{16–18}, where a realistic magnetic configuration up to the last closed flux surface, constructed
by the Grad-Shafranov solver code CHEASE\textsuperscript{29} from experimental data, is used (Fig. 1b). The
magnetic field at the magnetic axis is \(B_0 = 2.2\) T. The major radius at the axis is \(R_0 = 1.67\) m.
The geometrical major and minor radii are \(R_0 = 1.62\) m and \(a_0 = 0.482\) m respectively. Realistic
temperature and density profiles of the thermal species (deuterium and electrons) are used as well
(Figs. 2a-2b). Under "energetic particles" we understand here a deuterium beam, which actually
drives EGAMs in a plasma system. This species is described by a two-bumps-on-tail distribution
function in velocity space (Fig. 2c)

\[
F_{0,EP}(p_z, \mu) = A_{EP}(\psi) \exp \left[ -\frac{m_{EP}}{T_{EP}} \left( \frac{1}{2} \left( \frac{p_z}{m_{EP}} \right)^2 + \frac{\mu B}{m_{EP}} \right) - \frac{v_{\|,EP}^2}{2T_{EP}} \right] \cosh \left( \frac{p_z}{m_{EP}} \frac{v_{\|,EP}}{T_{EP}} \right),
\]

which leads to the EGAM formation through the wave-particle interaction (due to the mechanism
of the inverse Landau damping). Here, \(p_z\) is the canonical parallel momentum, \(\mu\) is the magnetic
moment, \(B\) is the background magnetic field, while \(v_{\|,EP}, T_{EP}\) being constant input parameters,
which specify a shift and width of the bumps respectively. It means, that the EPs are described by
a flat temperature profile and a constant in space parallel velocity shift. From Fig. 2b one can see
that the EPs have relatively low temperature, which just indicates the fact that the width of the EP
bumps is smaller in comparison to that of the thermal ion Maxwellian. A typical shift of the EP
bumps in the parallel velocity is \(v_{\|,EP}[c_s] = 8.0\), while typical EP temperature is \(T_{EP}[T_e(s = 0)] = 1.0\) or
\(T_{EP}[keV] = 0.70\). Here, \(c_s = \sqrt{T_{e,\text{max}}/m_d}\) is the sound speed with \(m_d\) being the deuterium
mass, \(T_{e,\text{max}} = 1.15\) keV. Such kind of normalization for \(v_{\|,EP}\) and \(T_{EP}\) is used further in this work.
The EPs are modelled by means of the two shifted Maxwellians to qualitatively investigate the
EGAM behaviour in the AUG plasma configuration. The presence of two bumps in the velocity

4
FIG. 2: Thermal species density (Fig. 2a) and temperature (Fig. 2b) profiles (blue and red lines), and corresponding typical EP profiles (green lines). Distribution functions of the thermal and energetic ions in velocity space are shown in Fig. 2c.

space is explained by the necessity to avoid the input of an additional momentum into the plasma system, which might have some effect on the EGAM dynamics.

In the nonlinear (NL) electrostatic simulation, performed in Section III to study the EGAM up-chirping, the EPs have a realistic density profile, shown in Fig. 2a. In other sections, the EPs
are described by an axisymmetric Gaussian distribution function:

\[ F_{0,EP}(s) \sim \exp \left( \frac{(s - s_{EP})^2}{2\sigma_{EP}^2} \right), \]  

and are localised at a radial point \( s_{EP} = 0.50 \), with \( s = \sqrt{\psi/\psi_{edge}} \) being a radial coordinate, where \( \psi \) is the poloidal flux coordinate. Such a simplification has been done to have more freedom in the variation of the EP parameters. The radial width of the EP Gaussian \( \sigma_{EP} \), used in this work, is equal to 0.10 to have a localised EP beam. An EP concentration is defined as \( n_{EP}/n_e \), where \( n_{EP} \), \( n_e \) are the EP and electron densities, averaged in volume, respectively.

In the simulations, presented in this work, three species are taken into account: gyro-kinetic thermal deuterium, gyro-kinetic energetic deuterium (EP), and electrons, either adiabatic (AE) or drift-kinetic (KE). Simulations with AE have been performed electrostatically, while the ones with KE have been made electromagnetically. The experimental pressure ratio at the reference magnetic surface has been adopted:

\[ \beta_e = \frac{n_e T_e(s = 0)}{B_0^2/(2\mu_0)} = 2.7 \cdot 10^{-4}. \]  

Electromagnetic simulations have the advantage of the absence of the unstable \( \omega_H \)-mode, observed in ES simulations with KEs. The KEs have a realistic deuterium/electron mass ratio \( m_D/m_e = 3672 \). The pullback scheme has been used for the mitigation of the cancellation problem. Real space in ES simulations has been discretized using the following grid parameters: \( n_s = 128, n_X = 64, n_\phi = 32 \), - for the radial, poloidal and toroidal directions respectively. Only \( n = 0 \) toroidal and \( |m| = [0, \ldots, 3] \) poloidal mode numbers have been taken into account, since generally the geodesic acoustic modes have mainly low \( m \) numbers. The ES cases have been simulated in a radial domain \( s = [0.0, 0.95] \) with a time step \( dt[\omega_{ci}^{-1}] = 20 \) (where \( \omega_{ci} = eB_0/m_d \) and \( e \) being the absolute value of the electron charge). The number of numerical markers for the thermal deuterium \( (N_d) \) and for the EPs \( (N_{EP}) \) in these cases are \( N_d = N_{EP} = 6 \cdot 10^7 \). The EM cases have been simulated with \( n_s = 256, dt[\omega_{ci}^{-1}] = 5 \) in a radial domain \( s = [0.0, 0.90] \), taking \( N_e = 1.2 \cdot 10^8 \) with the same \( N_d \) and \( N_{EP} \). The radial domain has been reduced to make the EM simulations more stable by avoiding the abrupt increase of the safety factor at the edge, reducing in such a way the restriction on the numerical time step. Since EGAMs are localised mainly in the core, this reduction of the radial domain has a negligible influence on the EGAM dynamics.
A. Mode-Particle-Resonance diagnostic

To localise velocity domains of the most intensive EGAM-particle interaction, the power balance diagnostic, implemented in ORB5\textsuperscript{33}, has been recently extended\textsuperscript{14} by keeping information about the wave-plasma interaction in velocity space. Using this diagnostic, a damping/growth rate $\gamma$ of an ES wave can be calculated as\textsuperscript{14,33}

$$\gamma = -\frac{1}{2} \frac{1}{n_w T_w} \int_0^{n_w T_w} \mathcal{P} \, dr,$$

(5)

$$\mathcal{P} = \sum_{sp} \mathcal{P}_{sp} = - \sum_{sp} Z_{sp} e \int dV \, dW_{sp} f_{sp} \dot{R}_{0,sp} \cdot \nabla (J_{0,sp} \Phi),$$

(6)

$$\mathcal{E}_f = \sum_{sp} \frac{1}{2} Z_{sp} e \int dV \, dW_{sp} f_{sp} \Phi,$$

(7)

where $\mathcal{P}$ is the energy transfer signal (heat rate), $\mathcal{E}_f$ is the field energy, $f_{sp}(r, p_z, \mu, t) = F_{0,sp}(r, p_z, \mu) + \delta f_{sp}(r, p_z, \mu, t)$ is the species distribution function, $\Phi, J_{0,sp} \Phi$ are the ES potential perturbation and the gyroaveraged one, $\dot{R}_{0,sp}$ is the species equations of motion, unperturbed by the field perturbations, $Z_{sp} e$ is the species charge. The time integration in Eq. 5 is performed on several wave periods $n_w T_w$. Finally, the integration in Eq. 6 and Eq. 7 is performed over the real $V$ and species velocity $W_{sp}$ domains. For the equilibrium distribution functions $F_{0,sp}$, considered in this work, the part of $\mathcal{P}$ related to $F_{0,sp}$ is negligible. The energy transfer is normalized in the following way:

$$\mathcal{P} = \frac{\mathcal{P}[W]}{T_e(s = 0)[J][\omega_e][s^{-1}]}.$$

(8)

III. GK SIMULATION OF EGAM CHIRPING IN THE AUG DISCHARGE

To model the nonlinear evolution of the EGAM frequency, the EP parameters are taken consistent with previous works (Refs. \textsuperscript{14} and \textsuperscript{15}), where the order of the mode frequency has been reproduced in linear GK simulations. The following EP velocity $v_{\parallel, EP} = 8.0$, temperature $T_{EP} = 1.0$ and concentration $n_{EP}/n_e = 0.095$ are applied. In Fig. 3a, one can see a zoom of the ‘long’ branch, described previously, of the experimental EGAM up-chirping. In Fig. 3b experimental and numerical spectrograms normalized to an initial EGAM frequency are indicated. The blue curve shows the mode up-chirping, obtained from a NL ES simulation with adiabatic electrons. The numerical spectrogram has been measured by nonlinear fitting of zonal electric field in different time windows at the radial point of the mode localisation $s = 0.70$. In the experimental discharge, the
FIG. 3: A zoom of a 'long' branch of the EGAM up-chirping from the experimental AUG spectrogram is shown in Fig. 3a. Experimental and numerical EGAM spectrograms, normalized to the initial EGAM frequency, are indicated in Fig. 3b. The numerical chirping is calculated by nonlinear fitting of zonal electric field $\bar{E}$ at a radial point of the EGAM localisation.

A mode was found in a radial domain $s \sim [0.50, 0.67]$ according to soft X-ray emission data. The red curve corresponds to the experimental EGAM spectrogram, but with a squeezed time scale, since the characteristic time of the numerical frequency change is shorter than the experimental one. As one can see from Fig. 3b, despite the two shifted Maxwellians, which are used as a distribution function of the EPs, the GK model is able to simulate the EGAM relative up-chirping in this AUG discharge. On the other hand, to perform quantitative comparison with the experiment of absolute chirping and of the time scales, one should use an EP distribution function closer to the experimental one such as a slow-down distribution function with a pitch-angle dependence. Since the EGAM is a strongly driven mode, it significantly depends on EP parameters. Moreover, the considered simulation is performed electrostatically without taking into account the dynamics of the drift-kinetic electrons. As it is shown in Section VI, electrons can significantly modify the EGAM behaviour and, as a result, might have some effect on the mode chirping as well.
IV. INFLUENCE OF EP PARAMETERS ON THE EGAM DYNAMICS

To investigate the plasma heating by the EGAMs, we start from the study of the mode behaviour dependence on EP parameters. First of all, the linear growth rate is strongly modified by EP temperature variations, as one can see in Fig. 4b while the EGAM frequency remains practically the same and does not depend on \( T_{EP} \). As it was already shown in different works (Refs. 34 and 35), the EPs can excite an EGAM corresponding to a damped mode in the absence of the EPs. By reducing the EP parallel velocity by a factor around of two, an EGAM with half the frequency of the original is excited (compare blue points and green crosses in Fig. 4a). It should be noted that since the mode excited by a smaller EP velocity is less unstable, it was necessary to increase the EP concentration from \( n_{EP}/n_e \approx 0.01 \) to \( n_{EP}/n_e \approx 0.09 \).

The localisation of the GAM-particle resonances of order \( m \) can be analytically estimated from the equation

\[
v_{\parallel, res}^{(m)} = \frac{qR_0 \omega_{GAM}}{m}.
\]

By reducing the EP velocity \( v_{\parallel, EP} \) one can excite an EGAM which is driven by higher order GAM-EP resonances. In Fig. 5a, one can see that by injecting an EP beam with \( v_{\parallel, EP} = 8.0 \) (blue dashed line), one obtains an EGAM driven by the low order resonance \( m = 1 \) (blue solid line). On the other hand, injection of an EP beam with \( v_{\parallel, EP} = 3.5 \) (red dashed line) leads to the EGAM drive on the \( m = 2 \) resonance (red solid line). The time evolution of the zonal electric field in these two cases with low and high EP velocities is shown in Fig. 6. The high velocity energetic beam (Fig. 6b) drives an EGAM through a low order \( m = 1 \) resonance, and the resulting mode has a
FIG. 5: Localisation of the EGAM interaction with the EPs (Fig. 5a) and with thermal deuterium (Fig. 5b). Here, two simulations are considered: with $v_{\parallel,EP} = 8.0$, $T_{EP} = 1.0$ (blue lines), and with $v_{\parallel,EP} = 3.5$, $T_{EP} = 0.25$ (red ones). The solid lines indicate the mode-species energy transfer $P_{sp}$, summed on the perpendicular velocity and averaged on several EGAM periods in time. The dashed lines depict the localisation of the species initial distribution functions.

frequency close to the original GAM frequency. The low velocity energetic beam (Fig. 6a), which interacts with the geodesic mode through a high order $m = 2$ resonance, drives an EGAM with a frequency close to half the GAM frequency.

As it was mentioned in Refs. 6 and 23, interactions between the EPs and thermal species significantly benefit from the existence of high order resonances, which is confirmed here as well. The EGAM-thermal ion energy exchange occurs at the higher order ($m = 2$) resonance in both cases, independently of the EP parallel velocity (Fig. 5b). In other words, even when the EGAM is driven by an EP beam with a high parallel speed, the EGAM is still damped by the thermal deuterium through resonances at higher order. This can be simply explained by the fact that the position of these resonances are closer to the bulk of the thermal ion distribution function. Since the thermal ion energy transfer signal (Fig. 5b) is positive, and the EP energy transfer signal (Fig. 5a) is mostly
FIG. 6: Time evolution of zonal electric field $\vec{E}$ in two cases with low (Fig. 6a) and high (Fig. 6b) EP velocities.

negative, there is an energy flow from the EPs to the thermal ions establishing bulk plasma heating.
FIG. 7: Time evolution of the heat rate (solid blue line), and the amount of energy transferred from the EGAM to the bulk deuterium plasma (red points). A case with $n_{EP}/n_e = 0.09$, $v_{EP} = 3.5$, $T_{EP} = 0.25$ is considered here. The heat rate $\mathcal{P}_D$ is normalized according to Eq. 8.

V. PLASMA HEATING BY EGAMS

As it has been already discussed previously in Refs. 3–6, the EGAMs might provide an additional route for plasma heating by EPs. The thermal species can obtain energy from the EGAM due to the Landau damping of the mode, which in turn is driven by the energetic particles through the inverse Landau damping. Note that this is also true for Alfvén modes, with the substantial difference that the EP radial redistribution due to EGAMs is negligible with respect to Alfvén modes. Therefore, EGAMs represent a privileged mode for this plasma heating mechanism. This process is investigated here by varying the EP parameters in the AUG plasma configuration by performing nonlinear GK simulations firstly in the ES limit with adiabatic electrons.

To calculate the amount of energy transferred from the mode to the thermal ions, the EGAM-species energy exchange signal $\mathcal{P}_{sp}$ is integrated in time. As it is shown in Fig. 7 at the beginning,
a rise of the heat rate due to the growth of the mode is observed. After a while, the mode saturates, the heat rate level decreases due to the relaxation of the EP distribution function, and in the deep saturated domain the energy transfer from the mode to the thermal ions is practically suppressed. It means that the total energy transferred to the bulk plasma (red points in Fig. 7) remains practically unchanged after the mode saturation. The amount of this energy depends on the EP parameters (Fig. 8a), which is directly reflected in the bulk ion temperature evolution (Fig. 8b).

By varying the EP parameters in NL electrostatic simulations, one can observe a general correlation between the EGAM saturation levels and the amount of energy transferred from the mode to the bulk deuterium plasma (Fig. 9). However, for example, the case with $v_{EP} = 3.5$, $T_{EP} = 0.4$, $n_{EP}/n_e = 0.01$ (the most right red star) has practically the same saturation level as the case with $v_{EP} = 3.5$, $T_{EP} = 0.15$, $n_{EP}/n_e = 0.09$ (the most right blue point). Having said that, we should notice that the corresponding EGAM-bulk ion energy exchange for these cases is significantly different. This means, that having the same mode level, one can achieve higher plasma heating by varying EP parameters. A possible explanation is that the EP beam with a lower velocity $v_{EP} = 3.5$ drives the EGAM through the resonances of the same order as those responsible for the mode interaction with the thermal ions (Fig. 5). In other words, the plasma heating by the EGAMs might be enhanced if the EGAM drive and damping occur through the resonances of the same order. It is another indication of the importance of the higher order mode-plasma resonances in the EGAM nonlinear dynamics.
FIG. 9: Dependence of the EGAM-thermal deuterium energy exchange on the EGAM saturation level in nonlinear ES simulations with adiabatic electrons. The saturation levels are calculated as a maximum value in time of r.m.s in space of the zonal electric field $\overline{E}$. The electric field is normalized to $T_e(s = 0.0) [eV] \omega_{ci}[s^{-1}] / c_s[m/s]$. Here, $m_{res}^{sp}$ indicates an order of a resonance, where the mode-species energy exchange occurs. The blue points correspond to the cases with $v_{\parallel,EP} = 3.5, n_{EP}/n_e = 0.09, T_{EP} = [0.25, 0.22, 0.20, 0.15]$, while the red stars correspond to the cases with $v_{\parallel,EP} = 6.0, n_{EP}/n_e = 0.01, T_{EP} = [1.0, 0.8, 0.6, 0.4]$.

VI. INFLUENCE OF ELECTRON DYNAMICS

In this section, the effect of the drift-kinetic electrons on the EGAM dynamics is examined, by considering electrons with a realistic mass $m_d/m_e = 3672$. In Fig. 10a, one can observe the EGAM growth rate significantly decreases when drift-kinetic electrons are included. The interaction between the EGAMs and the electrons is investigated by the wave-particle energy transfer signal in the velocity space. In Fig. 10b, one can see the EGAM-electron resonances, where the horizontal dashed lines indicate the analytical estimation of the resonance positions (Eq. 9).
FIG. 10: Influence of electron dynamics on the EGAM linear growth rate for different EP concentrations (Fig. 10a). "AE" indicates ES simulations with adiabatic electrons, "KE" indicates EM simulations with drift-kinetic electrons. Localisation of the EGAM interaction with the electrons (case with $n_{EP}/n_e = 0.01$, Fig. 10b). The black cone indicates the approximate position of the boundary between the passing and trapped electrons of Eq. [10]. The horizontal lines are the analytical estimation of the EGAM-plasma resonances, calculated in Eq. [9] (for $m = 1$). Here, all simulations have been performed linearly with $v_{\parallel,EP} = 8.0, T_{EP} = 1.0$.

guide the eye, the passing-trapped boundary for electrons is shown as well:

$$v_{\parallel}^{p-tr} = \sqrt{2\epsilon \mu},$$

where $\epsilon$ is an inverse aspect ratio, the parallel velocity $v_{\parallel}$ is normalized to the sound speed $c_s$, and the magnetic moment $\mu$ is normalised to $m_d c_s^2 / (2B_0)$. The energy exchange between the EGAM and trapped electrons occurs inside of this cone. The fact that the energy transfer resonances are close to the passing-trapped boundary, means that the mode interacts mainly with the barely trapped electrons with a bounce frequency close to that of the mode.

The inclusion of the electron dynamics influences the nonlinear EGAM behaviour as well. Consistently with the decrease of the EGAM linear growth rate, the mode saturation levels are also reduced in NL simulations (Fig. 11a) that leads to the lowering of the bulk plasma heating by the mode. This reduction is clearly observed in the time evolution of the thermal ion temperature (Fig. 12b). However, even in the case with the drift-kinetic electrons, the EGAM transfers most of its energy to the thermal ions, and not to the electrons, that can be seen in Fig. 12a. In other words, it is the ion plasma heating, which mainly benefits due to the presence of the EGAM dynamics. Having said that, we should emphasize, that the electron contribution is still not negligible in
FIG. 11: Comparison between an electrostatic NL simulation assuming adiabatic electrons and an electromagnetic NL simulation with the drift-kinetic electrons. In both cases \( n_{EP}/n_e = 0.01, v_{||,EP} = 8.0, T_{EP} = 1.0 \) are taken. EGAM saturation levels (Fig. 11a). Evolution of the thermal deuterium temperature (Fig. 11b).

FIG. 12: Nonlinear ES and EM cases with \( n_{EP}/n_e = 0.01, v_{||,EP} = 8.0, T_{EP} = 1.0 \) are considered. Energy transferred from the mode to the thermal species (Fig. 12a, blue line - thermal ions, red line - electrons) in the nonlinear EM case with drift-kinetic electrons. Total energy balance between the EGAM and all kinetic species in the ES case (Fig. 12b, blue line), and the electron contribution in the EM simulation (red line).

comparison to the total energy, obtained by the EGAM due to the wave-particle interaction with all kinetic species in the considered plasma system. More precisely, in Fig. 12b, one can see that the amount of energy that the mode stores in the ES simulation (blue line) and the energy that the mode transfers to the electrons (red line) in the EM simulation are of the same order. Negative blue line indicates the fact that the EGAM interaction with the EPs and the thermal ions result in
the increase of the mode energy. The red curve is positive that demonstrates the energy flow from
the mode to the electrons. Although this flow is significantly smaller than that to the thermal ions,
it is still comparable to the total mode energy. Therefore, the electron dynamics can noticeably
decrease the amount of energy, stored in the mode, and in such a way reduce the plasma heating
by the EGAM.

VII. CONCLUSIONS

Energetic-particle-driven geodesic acoustic modes (EGAMs) have a significant influence on
the EP dynamics and on the plasma confinement. These modes provide an additional mechanism
of the energy exchange between the energetic particles and the thermal plasma, enhancing direct
heating of the bulk ions. The significant progress done in the last decade in studying the EGAM
nonlinear physics has been expanded here, by including kinetic electrons and the geometrical
effects of a realistic magnetic shape in the GK simulations.

In this work, linear and nonlinear global GK simulations of the EGAMs in an ASDEX Up-
grade discharge have been presented. While a corresponding tokamak configuration and thermal
species profiles have been used here, the EPs have been represented by two shifted Maxwellians
in velocity space. Using such a model, an EGAM relative up-chirping close to the experimental
one has been obtained. It has demonstrated that the GK code is able to handle zonal structures
and anisotropic distribution functions properly in experimentally relevant cases which is a crucial
ingredient before going onto more complex plasma systems. On the other hand, to compare abso-
lute mode chirping and characteristic time scales of the mode frequency evolution, it is necessary
to use an EP distribution function as close as possible to the experimental one.

By varying the EP parameters, general correlation between the mode level and the EP-thermal
plasma energy flow had been revealed. Apart from that, it has been emphasized that the plasma
heating by EGAMs benefits from the presence of high order mode-particle resonances which are
often responsible for the EGAM-thermal species interaction. More precisely, it has been shown
that having the same mode levels, one can have higher energy transfer from the EPs to the bulk
plasma if the EGAM drive and damping occur through the resonances of the same order.

Finally, it was indicated that although the EGAM transfers most of its energy to the thermal
ions, and not to the electrons, the electron dynamics might significantly reduce the plasma heating
by EGAMs by lowering the mode amplitude.
Since the nonlinear GK simulations with drift-kinetic electrons have shown a significant influence of the electron dynamics on the EGAM behaviour, it would be reasonable to study effect of the kinetic electrons on the mode chirping. The results obtained here will be useful in a future work to perform investigation of the EGAM influence on the turbulent dynamics in the ASDEX Upgrade, that will be a next step in the code validation and an interesting example of a complex plasma system.

ACKNOWLEDGMENTS

The authors would like to acknowledge stimulating discussions with the Multi-scale Energetic particle Transport in fusion devices (MET) team, and especially with Prof. Fulvio Zonca. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014-2018 and 2019-2020 under grant agreement N° 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Simulations, presented in this work, have been performed on the CINECA Marconi supercomputer within the framework of the OrbZONE and ORBFAST projects.

REFERENCES

1. C. Boswell, H. Berk, D. Borba, T. Johnson, S. Pinches, S. Sharapov, Observation and explanation of the jet n=0 chirping mode, Physics Letters A 358 (2) (2006) 154 – 158 (2006). doi:https://doi.org/10.1016/j.physleta.2006.05.030
   URL http://www.sciencedirect.com/science/article/pii/S0375960106007031
2. G. Y. Fu, Energetic-particle-induced geodesic acoustic mode, Phys. Rev. Lett. 101 (2008) 185002 (Oct 2008). doi:10.1103/PhysRevLett.101.185002
   URL https://link.aps.org/doi/10.1103/PhysRevLett.101.185002
3. M. Sasaki, K. Itoh, S.-I. Itoh, Energy channeling from energetic particles to bulk ions via beam-driven geodesic
   Plasma Physics and Controlled Fusion 53 (8) (2011) 085017 (jun 2011). doi:10.1088/0741-3335/53/8/085017
   URL https://doi.org/10.1088%2F0741-3335%2F53%2F8%2F085017
4. M. Osakabe, T. Ido, K. Ogawa, A. Shimizu, M. Yokoyama, R. Seki, C. Suzuki, M. Isobe, K. Toi, D. A. Spong, K. Nagaoka, Y. Takeiri, H. Igami, T. Seki, K. Nagasaki, LHD experiment group,
Indication of bulk-ion heating by energetic particle drive on LHD, in: 25th IAEA fusion energy conference, 2014 (2014). URL https://inis.iaea.org/search/search.aspx?orig_q=RN:47070985

K. Toi, K. Ogawa, T. Ido, S. Morito, S. Ohdachi, N.A. Pablant, K. Tanaka, H. Funaba, T. Oishi, M. Osakabe, A. Shmizu, H. Tsuchiya, K.Y. Watanabe, LHD Experiment Group, Observation of non-collisional bulk ion heating by energetic ion driven geodesic acoustic modes in LHD in: Proc. 16th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems — Theory of Plasma Instabilities, Shizuoka, Japan, 2019 (2019). URL https://nucleus.iaea.org/sites/fusionportal/Shared%20Documents/EPPI%202019%20Materials.pdf

H. Wang, Y. Todo, M. Osakabe, T. Ido, Y. Suzuki, Simulation of energetic particle driven geodesic acoustic modes and the energy channeling in the large helical device, Nuclear Fusion 59 (9) (2019) 096041 (Aug 2019). doi:10.1088/1741-4326/ab26e5 URL https://doi.org/10.1088%2F1741-4326%2Fab26e5

D. Zarzoso, P. Migliano, V. Grandgirard, G. Latu, C. Passeron, Nonlinear interaction between energetic particles and turbulence in gyro-kinetic simulations and impact on turbulence properties, Nuclear Fusion 57 (7) (2017) 072011 (Jun 2017). doi:10.1088/1741-4326/aa7351 URL https://doi.org/10.1088%2F1741-4326%2Faa7351

M. Sasaki, K. Itoh, K. Hallatschek, N. Kasuya, M. Lesur, Y. Kosuga, S.-I. Itoh, Enhancement and suppression of turbulence by energetic-particle-driven geodesic acoustic modes, Scientific Reports 7 (2017) 16767 (2017). doi:10.1038/s41598-017-17011-y URL https://doi.org/10.1038/s41598-017-17011-y

Z. Qiu, I. Chavdarovski, A. Biancalani, J. Cao, On zero frequency zonal flow and second harmonic generation by finite amplitude energetic particle induced geodesic acoustic mode, Physics of Plasmas 24 (7) (2017) 072509 (2017). arXiv:https://doi.org/10.1063/1.4993053, doi:10.1063/1.4993053 URL https://doi.org/10.1063/1.4993053

Z. Qiu, L. Chen, F. Zonca, Kinetic theory of geodesic acoustic modes in toroidal plasmas: a brief review, Plasma Science and Technology 20 (9) (2018) 094004 (Jul 2018). doi:10.1088/2058-6272/aab4f0 URL https://doi.org/10.1088%2F2058-6272%2Faab4f0

L. Chen, Z. Qiu, F. Zonca, Short wavelength geodesic acoustic mode excitation by energetic particles, Physics of Plasmas 25 (1) (2018) 014505 (2018). arXiv:https://doi.org/10.1063/1.5003142, doi:10.1063/1.5003142
12. H. S. Zhang, Z. Lin, Trapped electron damping of geodesic acoustic mode, Physics of Plasmas 17 (7) (2010) 072502 (2010). [arXiv:https://doi.org/10.1063/1.3447879](https://doi.org/10.1063/1.3447879).

13. G. Merlo, S. Brunner, Z. Huang, S. Coda, T. Görler, L. Villard, A. B. Navarro, J. Dominski, M. Fontana, F. Jenko, L. Porte, D. Told, Investigating the radial structure of axisymmetric fluctuations in the TCV tokamak with local and global gyrokinetic GE NE simulations, Plasma Physics and Controlled Fusion 60 (3) (2018) 034003 (jan 2018). [doi:10.1088/1361-6587/aaa2dc](https://doi.org/10.1088%2F1361-6587%2Faaa2dc).

14. I. Novikau, A. Biancalani, A. Bottino, A. Di Siena, P. Lauber, E. Poli, L. Villard, N. Ohana, S. Briguglio, Implementation of energy transfer technique in orb5 to study collisionless wave-particle interactions in phase-space, Comp. Phys. Comm. (2019). [doi:10.1016/j.cpc.2019.107032](https://doi.org/10.1016/j.cpc.2019.107032).

15. A. Di Siena, A. Biancalani, T. Görler, H. Doerk, I. Novikau, P. Lauber, A. Bottino, E. Poli, The ASDEX Upgrade Team, Effect of elongation on energetic particle-induced geodesic acoustic mode, Nucl. Fusion 58 (2018) 106014 (2018). [doi:10.1088/1741-4326/aad51d](https://doi.org/10.1088/1741-4326/aad51d).

16. S. Jolliet, A. Bottino, P. Angelino, R. Hatzky, T. Tran, B. Mcmillan, O. Sauter, K. Appert, Y. Idomura, L. Villard, A global collisionless pic code in magnetic coordinates, Computer Physics Communications 177 (5) (2007) 409 – 425 (2007). [doi:https://doi.org/10.1016/j.cpc.2007.04.006](https://doi.org/10.1016/j.cpc.2007.04.006).

17. A. Bottino, E. Sonnendruecker, Monte carlo particle-in-cell methods for the simulation of the vlasov–maxwell gyrokinetic equations, Journal of Plasma Physics 81 (5) (2015) 435810501 (2015). [doi:10.1017/S0022377815000574](https://doi.org/10.1017/S0022377815000574).

18. E. Lanti, N. Ohana, N. Tronko, T. Hayward-Schneider, A. Bottino, B. McMillan, A. Mishchenko, A. Scheinberg, A. Biancalani, P. Angelino, S. Brunner, J. Dominski, P. Donnel, C. Gheller, R. Hatzky, A. Jocksch, S. Jolliet, Z. Lu, J. M. Collar, I. Novikau, E. Sonnendrucker, T. Vernay, L. Villard, Orb5: A global electromagnetic gyrokinetic code using the pic approach in toroidal geometry.
A. Biancalani, I. Chavdarovski, Z. Qiu, A. Bottino, D. Del Sarto, A. Ghizzo, Ö. D. Gür- can, P. Morel, I. Novikau, Saturation of energetic-particle-driven geodesic acoustic modes due to wave–particle nonlinearity, Journal of Plasma Physics 83 (6) (2017) 725830602 (2017). doi:10.1017/S0022377817000976

A. Biancalani, N. Carlevaro, A. Bottino, G. Montani, Z. Qiu, Nonlinear velocity redistribution caused by energetic-particle-driven geodesic acoustic modes, mapped with the beam-plasma system, Journal of Plasma Physics 84 (6) (2018) 725840602 (2018). doi:10.1017/S002237781800123X

H. Berk, C. Boswell, D. Borba, A. Figueiredo, T. Johnson, M. Nave, S. Pinches, S. Sharapov, JET EFDA contributors, Explanation of the JETn= 0 chirping mode, Nuclear Fusion 46 (10) (2006) S888–S897 (sep 2006). doi:10.1088/0029-5515/46/10/s04

H. Berk, C. Boswell, D. Borba, A. Figueiredo, T. Johnson, M. Nave, S. Pinches, S. Sharapov, JET EFDA contributors, Explanation of the JETn= 0 chirping mode, erratum, Nuclear Fusion 50 (4) (2010) 049802 (apr 2010). doi:10.1088/0029-5515/50/4/049802

D. Zarzoso, D. del Castillo-Negrete, D. Escande, Y. Sarazin, X. Garbet, V. Grandgirard, C. Passeron, G. Latu, S. Benkadda, Particle transport due to energetic-particle-driven geodesic acoustic modes, Nuclear Fusion 58 (10) (2018) 106030 (aug 2018). doi:10.1088/1741-4326/aad785

P. Lauber, AUG test case description (2015).

P. Lauber, B. Geiger, G. Papp, G. Por, L. Guimarais, P.ZS. Poloskei, V. Igochine, M. Maraschek, G. Pokol, T. Hayward-SCHNEIDER, Z. Lu, X. Wang, A. Bottino, F. Palermo, I. Novikau, A. Biancalani, G. Conway, THE ASDEX UPGRADE TEAM, THE EUROFUSION ENABLING RESEARCH 'NAT' and 'NLED' TEAMS, Strongly non-linear energetic particle dynamics in asdex upgrade scenarios with core impurity accumulation, in: Proc. 27th IAEA Fusion Energy Conference - IAEA, Gandhinagar, India, 2018 (2018).
26 L. Horváth, G. Papp, P. Lauber, G. Por, A. Gude, V. Igochine, B. Geiger, M. Maraschek, L. Guimarais, V. Nikolaeva, G. Pokol, The ASDEX Upgrade Team, Experimental investigation of the radial structure of energetic particle driven modes, Nuclear Fusion 56 (11) (2016) 112003 (jul 2016). doi:10.1088/0029-5515/56/11/112003.
URL https://doi.org/10.1088%2F0029-5515%2F56%2F11%2F112003

27 F. Vannini, A. Biancalani, T. Hayward-Schneider, P. Lauber, A. Mishchenko, I. Novikau, E. Poli, the ASDEX Upgrade team., submitted to Physics of Plasmas (2019). [link].
URL https://arxiv.org/abs/1910.14489

28 F. Jenko, W. Dorland, M. Kotschenreuther, B. N. Rogers, Electron temperature gradient driven turbulence, Phys. Plasmas 7 (2000) 1904–1910 (May 2000). doi:10.1063/1.874014.

29 H. Luetjens, A. Bondeson, O. Sauter, The chease code for toroidal mhd equilibria, Computer Physics Communications 97 (3) (1996) 219 – 260 (1996). doi:https://doi.org/10.1016/0010-4655(96)00046-X.
URL http://www.sciencedirect.com/science/article/pii/001046559600046X

30 W. Lee, Gyrokinetic particle simulation model, Journal of Computational Physics 72 (1) (1987) 243 – 269 (1987). doi:https://doi.org/10.1016/0021-9991(87)90080-5
URL http://www.sciencedirect.com/science/article/pii/0021999187900805

31 A. Mishchenko, A. Bottino, R. Hatzky, E. Sonnendruecker, R. Kleiber, A. Koenies, Mitigation of the cancellation problem in the gyrokinetic particle-in-cell simulations of global electromagnetic modes, Physics of Plasmas 24 (8) (2017) 081206 (2017). arXiv:https://doi.org/10.1063/1.4997540, doi:10.1063/1.4997540.
URL https://doi.org/10.1063/1.4997540

32 R. Hatzky, A. Koenies, A. Mishchenko, Electromagnetic gyrokinetic pic simulation with an adjustable control variates method, Journal of Computational Physics 225 (1) (2007) 568 – 590 (2007). doi:https://doi.org/10.1016/j.jcp.2006.12.019
URL http://www.sciencedirect.com/science/article/pii/S0021999106006085

33 N. Tronko, A. Bottino, E. Sonnendruecker, Second order gyrokinetic theory for particle-in-cell codes, Physics of Plasmas 23 (8) (2016) 082505 (2016). arXiv:https://doi.org/10.1063/1.4960039, doi:10.1063/1.4960039.
URL https://doi.org/10.1063/1.4960039

34 J.-B. Girardo, D. Zarzoso, R. Dumont, X. Garbet, Y. Sarazin, S. Sharapov,
Relation between energetic and standard geodesic acoustic modes, Physics of Plasmas 21 (9) (2014) 092507 (2014). arXiv:https://doi.org/10.1063/1.4895479. doi:10.1063/1.4895479.
URL https://doi.org/10.1063/1.4895479

D. Zarzoso, A. Biancalani, A. Bottino, P. Lauber, E. Poli, J.-B. Girardo, X. Garbet, R. Dumont, Analytic dispersion relation of energetic particle driven geodesic acoustic modes and simulations with NEMORB, Nuclear Fusion 54 (10) (2014) 103006 (sep 2014). doi:10.1088/0029-5515/54/10/103006. URL https://doi.org/10.1088%2F0029-5515%2F54%2F10%2F103006