WORK PACKAGE ENABLING RESEARCH

2017 scientific/technical report

Deadline: 31 December 2017

Project reference number *(as in Task Agreement)*	CfP-AWP17-ENR-MPG-01
Project title *(as in Task Agreement)*	Nonlinear interaction of Alfvénic and turbulent fluctuations in burning plasmas (NAT)
Principal Investigator	Philipp Lauber
Beneficiary of Principal Investigator	IPP Garching (MPG)

Filename should be of the format: ***WPENR_AWP17_interim_report_****Beneficiary-nn* *where* ***Beneficiary-nn*** *is, for example,* ***ENEA-01****.*

Purpose and use of report

This compact report is to report the progress on the deliverables, to justify payment. A brief summary of the scientific highlights is also requested. While the report will be available to STAC the performance will be assessed by the PMU unless there are issues which require the advice of STAC. The mid-term evaluation of the project, where relevant, is a separate activity but can refer to these reports.

The reports should be as brief and clear as possible, referring to publications and other information for details. However there should be enough information to support statements that deliverables have been achieved. As an indication **the full report should not exceed 4 pages excluding this title page**. Please keep to the report format and do not attach additional information. If there are one or two particularly significant figures that are needed to demonstrate the results, these can be included in the tables.

1. Main scientific output - summary

In 2017 the NAT team [1] started to explore the interaction of Alfvénic modes and turbulent spectra via the generation of zonal structures (ZS) in an integrated fashion: considerable progress concerning the analytical framework, the construction of simplified models, the hierarchical application of several non-linear codes in various geometries and the development of advanced diagnostics applicable to code output and experimental data is documented within this report. Most of the 6 work packages (WPs) are closely interlinked e.g. via common 'base cases' for numerical studies ('NLED [2] base case' [3]) in the view of the development of reduced models (beam-plasma model-HAGIS/LIGKA-ORB5), via common code (ORB5, EUTERPE) and via common diagnostics (NTI Wavelet Tools) developments. It is expected that these links will strengthen further, allowing the NAT team to reach all its envisaged milestones and deliverables by the end of 2018. In addition, several important results by NAT team members related to ZS and geodesic acoustic modes (GAMs/EGAMs) that do not correspond directly to pre-defined deliverables are summarised in this report.

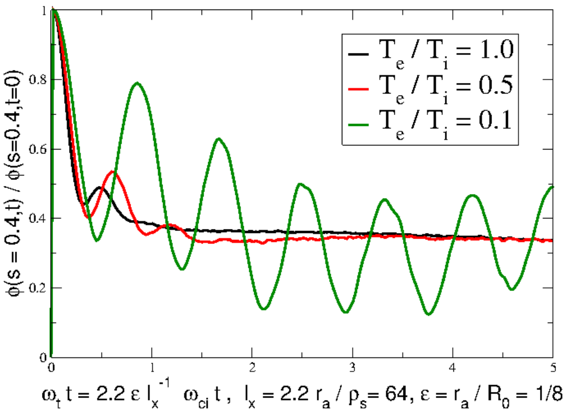
WP1: Based on the existing and well-established theoretical framework [L.Chen, F.Zonca, RMP **88**, (2016), F. Zonca et al., NJP **17** (2015)], we have systematically derived transport equations for phase space ZS [4,5], that is of structures in the particle phase space that are unaffected by fast collisionless dissipation processes. Consistent with the work-plan, we have adopted the "fishbone paradigm" in toroidal geometry, where the fluctuation frequency is assumed to be small enough that two constants of motion can be assumed for wave-particle interactions; i.e., the magnetic moment and the parallel invariant $J=\int v_{\|}dl$. Thus, particle motion is characterized by one degree of freedom as in the beam-plasma system case, while preserving the information of equilibrium geometry and plasma non-uniformity [F. Zonca et al., NJP **17** (2015)]. The theoretical formulation, generalizing the resonance broadening theory [Dupree, Phys. Fluids **9** (1966)] to non-uniform plasma, has been completed [6,7] and a journal paper is being submitted [7]. Anticipating part of the 2018 milestones, numerical simulations of the beam-plasma system, constructed by mapping from the Alfvén Eigenmode (AE) case [Schneller, PPCF **58**, (2016)] in ITER reference scenario is underway [8]. In order to facilitate the future analysis of a broad range of scenarios with this simplified model, the HAGIS/LIGKA code has been automated to deliver the relevant linear input quantities [9].

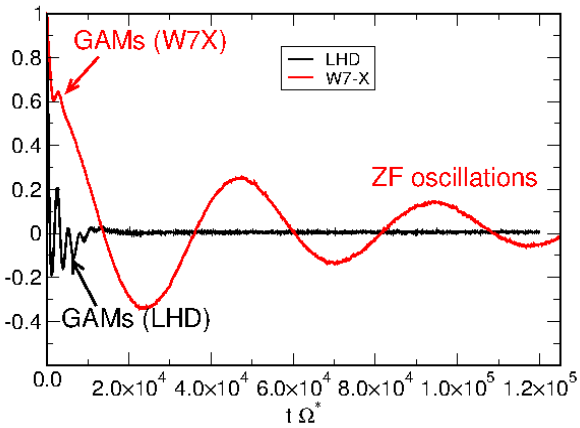
WP2 : The development of a zonal flow (ZF) model for the HAGIS/LIGKA code has been started. The due to the hybrid nature of the model, the n=0 GAM/EGAM physics of LIGKA had to be developed, tested and benchmarked as a first step. LIGKA's FLR/FOW model has been verified with respect to theory, and the influence of a finite radial wavelength on radial propagation has been compared to other work [10,18]. Analytical expressions for anisotropic distribution functions to be implemented in LIGKA have been derived [11]. The HAGIS Lagrangian has been extended to include 3-wave interaction terms, and a system of coupled wave equations with analytically given scattering cross sections has been derived [12]. The publication of the model together with the implementation into the HAGIS code is delayed due to other unforeseen obligations and opportunities (AUG experiments, see Outreach) related to the NAT project.

WP3: The hybrid MHD/gyrokinetic code XHMGC has been used previously to study AEs driven by EPs whereby the zonal component has been kept in the equilibrium without time evolution. This constraint has been relaxed now and the capability of describing the ZS dynamics by XHMGC has been demonstrated. The residual states of a damped GAM with different parameters have been successfully achieved. The ZS driven by AEs are currently investigated. In order to extract the zonal current dynamics from resistivity effects, radially dependent resistivity profiles are used to control the possible numerical instability driven by resistivity. In order to compare the results with the MEGA code [Todo, NF 2010], where only the ZF is taken into account and thermal ions are treated as a fluid, current XHMGC simulations are keeping the zonal current component in the equilibrium. Meanwhile, XHMGC allows for the study of the kinetic thermal ion effects on the ZFs, which is absent in other hybrid codes such as MEGA. It is clearly demonstrated how kinetic thermal ion effects modify the dynamics of GAMs and ZFs. A reference BAE case was used to study the amplitude of forced driven ZFs with and without kinetic thermal ion effects. Such a reference BAE case has been recently studied with respect to symmetry breaking properties by energetic particles [13-16]. The first results obtained are the 'double growth rate' of the forced driven ZF and the modification of the saturation amplitude of the pump wave [17]. The radial structure and the amplitude of the ZF will be analysed and compared with both theory and other simulation codes in 2018.

WP4: The linear and nonlinear dynamics of ZS in the absence and in the presence of energetic particles (EP) has been investigated analytically and in comparison with ORB5. The radial propagation of GAMs has been studied in the presence of temperature gradients, in simulations with circular flux surfaces, and neglecting the effect of kinetic electrons. By using the first principle of the phase mixing energy cascade in the presence of a continuum spectrum, it was demonstrated that the GAM frequency is not constant but can evolve in time. A direct consequence of this is a strong radial propagation of these structures. In this way, it is possible to reduce the gap between the GAM velocity observed in the experiments/simulations and that one predicted by linear and quasi-linear theories [18-20]. These strong velocities can have important implications on the ZF dynamics and on the energy transport. GAM propagation could be responsible of a nonlocal contribution to the turbulence via a radiative dissipation mechanism. An estimate of phase and group velocities has been given for simulations performed with experimental parameters. Moreover, through a comparison of the GAM acceleration between simulation and theory, this work allows to select between several perturbative methods present in literature [20]. The GAM Landau damping and the phase mixing have been also investigated in realistic configurations, i.e. in non-circular equilibria and with the inclusion of kinetic electrons with realistic mass [21]. Regarding the nonlinear dynamics of GAMs in the presence of EPs, the saturation of EP-driven GAM (EGAM) due to wave-particle nonlinearity has been investigated. In particular, quadratic scalings of the saturated electric field on the linear growth rate have been found, and the dependence of the scaling coefficient on the bulk temperature has been studied [22]. The redistribution of the EP population in phase space is under investigation with ORB5 and with a 1D model for the beam-plasma instability. Both the excitations of ZSs by turbulence and by Alfvén modes have been investigated with ORB5. Regarding the excitation of ZSs by turbulence, a dedicated PhD projected has started at the end of 2016 (I. Novikau). The implementation of diagnostics for the study of the power exchange of GAMs with the plasma particles and with the turbulence has started, together with the analysis of reduced models [23]. Regarding the excitation of ZSs by Alfvén modes, the force-driven excitation of ZSs has been investigated more in detail, and the modified EP radial redistribution has been quantified in simplified configurations with locally zero shear [24].

WP5: In this project, GAMs have been studied in W7-X, HSX and LHD geometries. It has been found that they are strongly damped in W7-X and HSX geometries where the mode disappears within a single oscillation. In LHD geometry, however, the GAM oscillations are well pronounced over several oscillation periods.





This striking difference of GAM dynamics in different stellarator and heliotron geometries can be attributed to the rotational transform and its role in the damping of those modes. Due to the higher shear in LHD, its rotational transform changes stronger than that in W7-X and HSX where iota is around one for all flux surfaces. Therefore, the Landau damping is expected to be very high for such profiles of the rotational transform as has been confirmed by the EUTERPE simulations [25] (left figure for HSX and right figure for LHD and W7-X).

The damping of the GAMs can be decreased at a smaller ion-to-electron temperature ratio. For this regime, GAM oscillations have been observed also in the low-shear HSX geometry (left figure). This temperature regime is of experimental relevance W7-X plasmas under OP1 conditions in which the electrons are much hotter than the ions. In the future one can compare different types of W7-X geometry with respect to the GAM oscillations, in particular those geometries which have smaller rotational transform, where GAM damping shall be reduced. It has been observed that the both GAMs and zonal flows are affected by the radial electric field in stellarator geometry. This can be addressed in more details in the next stage of the project.

WP6: In 2017 a standard set of signal processing tools was developed, and integrated into the already available NTI Wavelet Tools, to investigate the linear and non-linear behavior of chirping plasma waves. NTI Wavelet Tools were prepared to be able to carry out 3D spatial structure analysis of plasma transients, using newly available calibration data and diagnostics. Details of the methods are being published [26]. Besides the linear characterization of chirping modes, nonlinear properties of wave-wave interactions were investigated as well. A higher order spectral analysis method (bicoherence) was generalized to chirping signals [27], and was successfully applied to experimental measurements on ASDEX Upgrade. Significant interaction of fast ion driven modes was found [28,29].

Outreach: Inspired by the overall research goal of this project and by the analysis of previous ASDEX Upgrade data within the NAT [1] and NLED [2] project ('NLED base case' [3]), a new stable high-radiation scenario has been developed on ASDEX Upgrade (Oct 2017) that is dominated by NBI-driven AEs and EGAMs. Due to the large ratio of $\beta_{EP}/\beta_{thermal}$, the modes exhibit large amplitudes and non-linear dynamics. This is an excellent (and to our knowledge presently the only) opportunity to validate codes for non-linear EP dynamics in NBI-driven, conventional tokamak scenarios. The discharges also attracted interest from other groups such as PPPL

(M. Schneller, GTS code), NIFS (H. Wang, MEGA code) and QST (A. Bierwage). Also future modelling with respect to JT-60SA scenarios with strong off-axis beam drive will be connected to these results.

2. Project deliverables

Deliverable *(2017 deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement**
Derivation of nonlinear model equations for the self-consistent evolution of SAW/DAW and ZS/PSZS for the "fishbone paradigm"; generalization of resonance broadening theory.	fully/partly	Theoretical framework is complete [6,7], based on the "fishbone paradigm"; a journal paper is being submitted [7] (full achievement of milestone slightly delayed). Numerical simulations of the beam-plasma system, constructed by mapping from the AE case in ITER reference scenario is completed and a paper is underway [8] (anticipating part of 2018 milestone).
Formulation of the extension of HAGIS model for three-wave interaction; implementation into the existing code	partly	n=0 GAM/EGAM physics of HAGIS/LIGKA (FLR,FOW) developed, tested and benchmarked[10]; 3-wave equations derived [10], not yet implemented into HAGIS/LIGKA due to unforeseen AUG experimental opportunities (see 'Outreach')
Develop and implement scheme to extract zonal current dynamics from resistivity effects	fully	Extraction scheme and simulations have been successfully implemented and carried out [17].
Study three-wave interaction of a non-zonal instability with a ZF (ITG, Alfvén mode) with ORB5, compare to analytical and simpler models	fully/partly	Force-driven excitation of ZSs via AEs has been investigated [24]; progress concerning linear & non-linear GAM/EGAM physics [18-22]; comparison to simpler models [23]
Compare linear GAM physics in W7X and LHD geometries without the fast particles	fully	EUTERPE simulations for W7X, HSX and LHD carried out [25]. Results to be submitted.
Develop a standard set of tools for the linear characterization of chirping modes, comparison to simulations; linear characterization of chirping modes demonstrated on EGAMs, BAEs and bursting TAEs at the ASDEX Upgrade tokamak	partly	Tools developed [26,27], results for selected AUG discharges presented [28,29] and prepared to be published; application of tools to simulation output ongoing

3. Publications/presentations

Below the most relevant publications and talks within the ENR NAT project. The complete list can be found on the ENR NAT web page, see [1]. Publications with dominant NAT support are underlined.

[1] ENR NAT Team: http://www2.ipp.mpg.de/~pwl/NAT/ENR_NAT.html
[2] ENR NLED Team: https://www2.euro-fusion.org/erwiki/index.php?title=ER15-ENEA-03
[3] NLED/NAT *AUG base case description*, Ph. Lauber (2015-2017) http://www2.ipp.mpg.de/~pwl/NLED_AUG/data.html
[4] M. V. Falessi, arXiv preprint arXiv:1701.02202 (2017)
[5] M. V. Falessi and F. Zonca, submitted to Phys. Plasmas (2017)
[6] F. Zonca and L. Chen, *On the nonlinear dynamics of phase space zonal structures.* Invited Talk at the 11th West Lake International Symposium on Energetic Particle Physics and Microturbulence in Magnetic Fusion, Hangzhou, China, April 24-26, (2017)
[7] F. Zonca et al., *Physics of Energetic Particles and Alfvén Waves.* Tutorial Invited Talk at the 17th European Fusion Theory Conference, Athens, October 9-12, (2017). To be submitted to J. Plasma Phys
[8] N. Carlevaro et al., *Avalanches in multi-mode simulations of the beam-plasma system: applications to fusion plasmas and its criticalities*. To be submitted to J. Plasma Phys
[9] T Hayward-Schneider and Ph. Lauber, Poster at the 15th IAEA TCM on EP, PPPL September 2017

(https://nucleus.iaea.org/sites/fusionportal/Shared%20Documents/EP%2017th/Posters/P-10.pdf)
[10] Ph. Lauber, MPPC meeting Greifswald, September 20th (talk)
http://www2.ipp.mpg.de/~pwl/NAT/NATfiles/2017_9_MPPC_Lauber.pdf
[11] Ilija Chavdarovski, Mirjam Schneller, Zhiyong Qiu, Jintao Cao, and Alessandro Biancalani, Poster at the 15th IAEA TCM on EP, PPPL September 2017
https://nucleus.iaea.org/sites/fusionportal/Shared%20Documents/EP%2017th/Posters/P-3.pdf
[12] Ph. Lauber et al, 3rd NAT Meeting, Dec 6th 2017
http://www2.ipp.mpg.de/~pwl/NAT/NATfiles/06Dec2017.channel21/2017_12_NAT_pwl.pdf
[13] Z. Lu et al *Mode structure symmetry breaking of energetic particle driven Beta-induced Alfvén Eigenmode*, submitted to Phys. Plasmas
[14] Z. Lu et al, *Kinetic effects of thermal ions and energetic particles on discrete kinetic BAE mode generation and symmetry breaking*, submitted to Nucl. Fusion
[15] Z. Lu et al, *Local and global analysis of symmetry breaking for ITG and BAE modes*, 17thEuropean Fusion Theory Conference 9-12 October 2017, Athens, Greece
[16] Z. Lu et al, *Symmetry breaking of Beta induced Alfvén eigenmode driven by energetic particles*, 15th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems 5-8 Sep 2017, Princeton, USA
[17] X Wang, 3rd NAT Meeting, Dec 6th 2017,
http://www2.ipp.mpg.de/~pwl/NAT/NATfiles/06Dec2017.channel21/wang_06_12_2017_NAT.pdf
[18] F. Palermo, E. Poli, A. Bottino, A. Biancalani, G. Conway, B. Scott, *Radial acceleration of Geodesic Acoustic Modes in the presence of a temperature gradient*, Physics of Plasmas, Volume 24, 072503 (2017)
[19] F. Palermo, E. Poli, A. Bottino, A. Biancalani, C. Angioni, G. D. Conway, B. Scott, F. Zonca, *Enhanced radial velocity and damping rate of Geodesic Acoustic Modes in the presence of a temperature gradient*, 44th EPS Conference on Plasma Physics (2017)
[20] F. Palermo 17th European Fusion Theory Conference, Athens, October 9-12, (2017), paper in preparation
[21] I. Novikau, A. Biancalani, A. Bottino, G. D. Conway, O. D. Gurcan, P. Manz, P. Morel, E. Poli, A. Di Siena, the ASDEX Upgrade Team, *Linear gyrokinetic investigation of the geodesic acoustic modes in realistic tokamak configurations*, accepted for publication in Physics of Plasmas (2017)
[22] A. Biancalani, I. Chavdarovski, Z. Qiu, A. Bottino, D. Del Sarto, A. Ghizzo, O. Gurcan, P. Morel, I. Novikau, *Saturation of energetic-particle-driven geodesic acoustic modes due to wave-particle nonlinearity*, Journal of Plasma Physics, 83, 6, 725830602 (2017)
[23] I. Novikau, A. Biancalani, A. Bottino, G. D. Conway, P. Manz, P. Morel, O. D. Gurcan, E. Poli, *Power balance analysis of the geodesic acoustic modes*, to be presented at the Deutsche Physikalische Gesellschaft conference, Bochum, 26.02. - 02.03.2018
[24] A. Biancalani, A. Bottino, A. Mishchenko, et al, proposed as a contribution at the 27th IAEA Fusion Energy Conference, Ahmedabad, India, 22-27 October 2018
[25] A. Mischchenko et al , 2nd NAT Meeting, May 17th 2017,
http://www2.ipp.mpg.de/~pwl/NAT/NATfiles/mishchenko.pdf
[26] L. Horvath, G. Papp and G. I. Pokol: *Reconstruction of rapidly changing amplitude of chirping signals using time-frequency analysis*, JOURNAL OF IEEE TRANSACTIONS ON SIGNAL PROCESSING, to be submitted (2017)
[27] P. Zs. Poloskei, G. Papp, L. Horvath, G. Por, and G. I. Pokol: *Bicoherence analysis of nonstat. nonlinear processes*, JOURNAL OF IEEE TRANSACTIONS ON SIGNAL PROCESSING, to be submitted (2017)
[28] P. Zs. Poloskei, G. Papp, G. I. Pokol, Ph. W. Lauber, X. Wang, L. Horvath and the ASDEX Upgrade team: *Bicoherence analysis of fast ion driven transient plasma waves*, 44th EPS Conference on Plasma Physics, P5.179, (2017)
[29] P. Zs. Poloskei, G. Papp, G. I. Pokol, Ph. W. Lauber, X. Wang, L. Horvath and the ASDEX Upgrade team: *Analysis of the nonlinear interaction of fast ion driven plasma waves*, poster at15th IAEA TCM on EPs (2017)

4. Managerial aspects (optional)

Peter Poloskei will leave the official NAT team by January 2018; he will start his PhD within the AUG team. Thus, he will stay connected to NAT project as an external collaborator. On his behalf, Gabor Por (Wigner RCP, Budapest) has joined the team. His long-time experience with respect to signal processing and interpretation of experimental/numerical data will give important new input to the NAT project (0.3ppy). He will take over some of Gergo Pokol's responsibilities, so Gergo Pokol's contribution will decrease to 0.1ppy. The overall budget for Wigner RCP will stay constant in 2018. The use of EUROfusion Mobility in 2017 was less than expected, essentially due to the availability of mobility due to other resources (MST, NLED). Nonetheless, Mobility support was of crucial importance to facilitate and promote collaborative research activities. It is expected that EUROfusion Mobility in 2018 will used more extensively.