WORK PACKAGE ENABLING RESEARCH

2016 scientific/technical report

Deadline: 31 December 2016

<table>
<thead>
<tr>
<th>Project reference number (as in Task Agreement)</th>
<th>AWP15-ENR-01/ENEA-03</th>
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<tbody>
<tr>
<td>Project title (as in Task Agreement)</td>
<td>Theory and simulation of energetic particle dynamics and ensuing collective behaviors in fusion plasmas (NLED)</td>
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<tr>
<td>Principal Investigator</td>
<td>Fulvio Zonca</td>
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<td>Beneficiary of Principal Investigator</td>
<td>ENEA</td>
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Filename should be of the format: WPENR_AWP15_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

Summarise the main achievements of the project to date

The NLED Research Team [1] has consolidated the framework established for general theory and numerical simulation of energetic particle (EP) dynamics and ensuing collective behaviors in fusion plasmas introduced in 2014 and 2015, leveraging mutual positive feedbacks between general theory [2], numerical simulations and properly diagnosed experimental observations [3].

The ASDEX Upgrade based NLED reference case has been continuously updated to the needs of the experimental [4] and simulation community. Linear analyses with LIGKA, FLU-EUTERPE and EUTERPE, and preliminary non-linear simulations with EUTERPE were carried out. The data attract increasing interest from the broader community: 8 new AUG discharges will be performed in 2017 [3] and joint modelling efforts between the NLED group, the Max-Planck-Princeton Centre (MPPC, M. Schneller, GTS) and NIFS (H. Wang, MEGA) were started.

The recent LIGKA developments are also used within the MST1 EP modelling efforts, DEMO studies [5] and the WPSA project (Exploitation of JT-60SA) [6,7] for the collaboration with QST Japan on comparisons between MHD and gyrokinetics in high-β discharges [8].

The fast particle physics in W7-X will start in the next operational phases engaging NBI (OP 1.2a) and ICRH (OP 1.2b) [9]. Therefore, the focus in those phases will be on generation of fast particles and their equilibrium confinement. The theoretical aspects of wave-particle physics in stellarators have been addressed in a talk [10] on the “Workshop on Fast Particle Physics in W7-X”. Here, the potential of CKA-EUTERPE and FLU-EUTERPE developed in the NLED project has been demonstrated with examples.

Meanwhile, using CKA-EUTERPE, calculations for first W7-X mode observations from OP 1.1 have been done. This shows even more the impact of an enabling research project on the interpretation of experimental results [11,12,13]. In another activity, the observed sawtooth activity will be tackled using CKA and FLU-EUTERPE.

The non-linear version of the CKA-EUTERPE code [14,15] has been successfully applied to stellarators retaining the phase factor extraction of the dominant Fourier harmonic. Saturation levels of an NBI-driven TAE mode in Wendelstein 7-X and an alpha-driven HAE mode in the HELIAS reactor have been calculated. Due the more complicated particle motion, the time step necessary to converge the results is found to be smaller by more than an order of magnitude compared with a tokamak case.

The saturation levels found for relevant parameters are around $\delta B_{rad}/B_0=10^{-3}$.

The direct coupling of HAGIS and LIGKA has been partly finished in 2016. Linear mode properties can now be passed between the codes at any point of the non-linear simulation. The code interface has been generalized such that LIGKA can also serve as linear non-perturbative solver for an extended quasi-linear transport model to be completed in 2017. A hierarchy of different models can be requested when calling LIGKA: local kinetic, global ideal MHD, global analytical-kinetic zero-orbit width limit or the global kinetic version. Additionally, a generalized analytical finite orbit width model has been developed for LIGKA [16] and compared to the literature [Zonca, PoPs 1998]. This might be helpful also to improve the corresponding zero orbit width in 3D model implemented in STAE-K [17,18]. First simulations with HAGIS/LIGKA (local) where an update of the mode structure during the non-linear phase have been successful. Benchmarks with XHMGC, CKA-EUTERPE and FLUTERPE are on the way.

A benchmark of XHMGC and LIGKA-HAGIS has been completed for single-$n$ (toroidal mode number) by means of Hamiltonian mapping techniques [19]; the transition from a quadratic (resonance detuning) to a linear (radial decoupling) growth-rate scaling for the saturation amplitude has been observed and explained in terms of a simplified pendulum model. It has been shown that the radial width of the single poloidal harmonic sets an upper limit to the radial displacement of circulating fast ions produced by a single-$n$ gap mode in the large $n$ limit, irrespectively of the possible existence of an extended global mode structure formed by many harmonics.

The benchmark of HYMAGYC and XHMGC is also continuing [20]. Phase space diagnostics have been fully implemented in HYMAGYC along with the test particle Hamiltonian method (TPHM) package [S.
Briguglio et al, PoP 21, 112301, (2014)], which has been successfully tested. Finite Larmor radius (FLR) effects, with \( k \cdot \rho_i = O(1) \) and the effects of magnetic compression \( \delta A_i = O(0) \) is under testing for a reference test TAE case. More realistic scenarios, such as the AUG based NLED reference case [4] are also being analysed with HYMAGYC, including the reconstruction of fully shaped equilibrium by CHEASE, the calculation of the Alfvén continuous spectra for \( n=1, 2, 3 \); and analysis of the global ideal MHD modes (TAEs, EAEs, etc.) by MARS. In particular, the analyses retain finite magnetic field compression. Implications of FLR effects are currently being analysed.

The saturation mechanism of BAEs driven unstable by anisotropic fast-ion populations (co-passing or counter-passing ions) has been investigated, for different single-\( n \) modes by means of XHMGC simulations [21,22,23,24]. Multi-\( n \) simulations, retaining only wave-particle nonlinearities, have also been performed in order to investigate the synergistic effect of different \( n \) numbers on fast-ion transport. Phase-space diagnostics have been developed in order to check whether EPs driving a certain mode in the linear phase are able to drive a different \( n \) mode after they have been displaced by the nonlinear interaction with the former mode. Finally, chirping frequency EPMs have been investigated. It has been shown that, for specific resonant EPs, a radial displacement larger than both linear-phase mode and resonance widths is possible, but this does not necessarily imply a large fast-ion density flattening [25,26].

The FLU-EUTERPE code has been extended to work non-linearly and applied to the ITPA benchmark case. With finite resistivity, a saturation of the mode amplitude close to the saturation level of the non-linear kinetic-MHD perturbative hybrid model CKA-EUTERPE, and the similar non-perturbative hybrid code HMG is has been found. The scaling of saturated amplitude with changing linear growth is also comparable [27]. The importance of mode structure modification remains to be investigated. Proof of principle simulations within a limited range of numerical parameters have been performed in W7-AS, LHD, and W7-X stellarator geometries, while studies of cases of experimental relevance are in progress. Global modes driven by an EP population have been found in W7-X geometry. For a complex kinetic mode in a closed TAE gap, non-linear calculations have been performed using the MHD bulk model and a fluid-electron model with kinetic ions.

With the fully gyro-kinetic model implemented in the EUTERPE code, the destabilization of drift Alfvén modes has been investigated in LHD. It has been found that a TAE-like mode could be destabilized by the bulk plasma gradients without EPs. Similar modes have also been found in W7-X. The newly developed “pull-back scheme” for the solution of the electromagnetic gyro-kinetic Vlasov Poisson system has been used for these calculations [11,12,13,15,28]. Using CKA-EUTERPE, it has been found that EAE can be driven unstable by the gradients of thermal electrons. This may explain observed high frequency mode activity in W7-X, but more experimental evidence is needed.

The collisional damping of Alfvén waves in slab geometry has been investigated using the pull-back scheme [29]. It has been rigorously benchmarked against a numerical solution of the Vlasov-Maxwell system. An application to more complex geometry has started and an extended collision operator keeping the conserved quantities has been implemented. Furthermore, sinks and sources for temperature and density control have been installed. For the ITPA benchmark case, the changes of the mode structure in the non-linear phase (becoming larger with the drive) and the flattening of the EP profile by wave-particle nonlinear interaction has been investigated with ORB5 and EUTERPE [13,14,30,31,32,33] following previous linear stability analyses [34]. Nonlinear wave-wave coupling of AE with zonal structures have been investigated in greater detail, in particular in relation to the measurement of the ratio of the growth rates of zonal and non-zonal structures [35,36]. Nonlinear wave-particle and wave-wave interactions of AE and zonal structures have also been studied analytically, with emphasis on the crucial role played by fine radial fluctuation structures on nonlinear dynamics [37,38].

It is shown that long-term particle-in-cell simulations of stable AEs in tokamaks can be done with the codes GYGLES and EUTERPE. Using advanced signal processing techniques, a radially resolved spectrum can be calculated, resembling the shear Alfvén continuum [39,40]. A quantitative study of the phase mixing has been made [41,42,43], which will be adopted for
studying the balance with EP drive for electromagnetic modes. The dynamics of global modes in the presence of background temperature gradients has been investigated in the electrostatic limit, with adiabatic electrons and circular magnetic flux surfaces [41,42,43,44,45]. The extension to more realistic configurations is presently under investigation.

The nonlinear saturation levels of EGAMs due to wave-particle interaction have been studied in dependence on the EP concentration [33], and the comparison with GYSELA has started (following the linear comparison published in 2012-14). The development of a velocity space diagnostics giving quantitative results about the energy lost by the particles during the linear and nonlinear phase of the EGAM drive has been started. EGAM saturation levels were studied with ORB5 (NEMORB) for wave-particle nonlinearity only and for the fully nonlinear system.

EGAM studies have been further pursued by CEA and Aix-Marseille University (AMU). For this, the EP description capabilities of the GYSELA code have been exploited in two separate fashions: 1) either the distribution function is set up as an initial condition, which implies that it must be a function of the invariants of motion (initial value mode); or 2) the upgraded fast particle source which has been recently implemented in the code is used and determines the distribution function and the kinetic profiles self-consistently (flux-driven mode). As to 1), a particular situation was studied, in which the thermal population is modeled by a Maxwellian distribution function and the fast population is modeled by a shifted Maxwellian in parallel velocity. Different scenarios have been analyzed, changing the mass, charge and fraction of fast particles. In all scenarios, the linear excitation of the m=1 EGAM is consistent with the analytic theory. During the early stage of the nonlinear saturation, an m=1 island forms around the resonant velocity. Later, additional islands characterized by m=1 and m>1 around the different possible resonant velocities also appear. Even for a relatively small drive, those islands may interact or even overlap if the drive is large enough. This translates into a transfer of energy from the mode to the particles that can extent to thermal particles for higher values of m. Also, interactions between the EGAM island and the magnetically trapped particles island have been observed. Further quantifications of the radial transport due to the interaction between the different islands are required. As to 2), the intensity of the EP source has been varied at fixed fast ion energy. It was found that at high power, EGAMs appear and turbulence reaches a higher level than in the phase without EPs, consistently with past results. This result points again to a direct interaction between EGAM and ITG. A careful analysis of the EGAM and ITG spectra shows that the excited EGAM couples to an ITG at frequency close to the EGAM frequency, and another one at very low frequency. The respective spectra in terms of m and n numbers are such that the conditions of the non-linear 3-wave coupling are fulfilled. The respective role of both instabilities is now being assessed [46].

Similarity and differences of EP transport by multiple modes, and multi-beam interaction [N. Carlevaro et al, JPP 81, 495810515 (2015)] with plasma waves in 1D uniform system has been addressed. The applicability of the single-mode approximation has been investigated by considering harmonics excitation and dense spectra [47]. In the multi-mode scenario, both theoretical and numerical analyses have pointed out non-diffusive behaviors beyond “quasi-linear” paradigm [48]. This is qualitatively consistent with EP transport by multi-modes in fusion plasmas and the case of a single resonance has been successfully tested [49,50] for scaling of the saturation amplitude and relaxation of the distribution function. This analysis has been generalized for multiple resonances and several cases of interest (close to the standard ITER 15MA case) have been set up. The comparison of HAGIS/LIGKA results vs. multi-mode bump-on-tail simulations has been addressed and several tests have been performed to understand the correct damping response. The issue related to a proper 1D representation of the fully 3D case is under investigation.

Linear and nonlinear studies of electron fishbone instability have been performed with the HMGC code. Standard (peaked on-axis) [G. Vlad et al., NF 53, 083008 (2013)] and inverted (peaked off-axis) [V. Fusco et al., 7th IAEA TM on PI and 14th IAEA TM on EP, 2015] supra-thermal electron density profiles with moderately hollow q-profile have been studied. The two situations are different in terms of the characteristic resonance frequency as well as the fraction of supra-thermal particles
involved in the destabilization of the mode, confirming theoretical expectations [51,52]. In particular, centrally peaked energetic electron profiles are characterized by resonant excitation and nonlinear response of deeply trapped energetic electrons. On the other side, off-axis peaked energetic electron profiles are characterized by resonant excitation and nonlinear response of barely circulating energetic electrons, which experience toroidal precession reversal of their motion. The study of e-fishbone nonlinear saturation mechanisms adopted the TPHM package [S. Briguglio et al., op. cit.]. It has been shown that for the on-axis peaked profile, the nonlinear saturation is characterized by a pronounced downward (in absolute value) frequency chirping, and evident phase locking, causing a large radial transport up to the q=1 radius; the off-axis profile one, on the other hand, is characterized nonlinearly by a double resonance structure in the kinetic Poincaré plot, and nonlinear saturation occurs causing energetic particle transport within the two resonance radii. The scaling of the saturation amplitude vs. the ratio of the linear growth rate to the frequency of the mode $\gamma / \omega_0$, for both cases considered, has been shown to compare favourably with theoretical analyses [2].

A reduced model for precessional fishbones has been developed. It consists of 1) a core region which combines deeply trapped EPs described by a non-linear kinetic model, with a linearized MHD response, 2) an annular region surrounding this core with no EPs, and in which a semi-spectral code solves the MHD equations. This conceptual simplicity allows for an exact solution of the linear evolution, and for an easier, compared to more complete models, detailed studies of phase space processes. Numerical and analytical results are in good agreement during the linear phase [53] (frequency and damping rate). Interesting observations can be made in the non-linear phase: firstly, the frequency chirping effect, typical of fishbones, is recovered, and is associated with the ejection of particles from the core region. The early non-linear phase shows particles that are successively trapped and de-trapped in the mode well while its amplitude oscillates, allowing for a continuous transfer of energy from the particles to the mode and to their ejection. An effort is now ongoing for investigating this mechanism and clarifying if it is, or not, a common behavior of EPMs close to the threshold.

### 2. Project deliverables

<table>
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<tr>
<th>Deliverable (2016 deliverables as specified in the Task Agreement)</th>
<th>Achieved: Fully/Partly/Not</th>
<th>Evidence for achievement, brief reason for partial or non-achievement</th>
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<tr>
<td>Study EPM thresholds (LIGKA, XHMGC, NEMORB); complete LIGKA/HAGIS coupling. Full Larmor radius and magnetic compression effects in HYMAGYC.</td>
<td>Fully/Partly</td>
<td>Systematic numerical studies have been carried out and results are published [19,26]. LIGKA/HAGIS coupling is partly finished. Generalized analytical FOW model for LIGKA derived [16]. HYMAGYC benchmarks including FLR and magnetic compression are in progress and partly completed [20].</td>
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<tr>
<td>Characterization of EP transport in the presence of many modes with different numerical codes and models: 1D vs. 3D and analytical vs. numerical.</td>
<td>Partly/Fully</td>
<td>Multi-n simulations, retaining only wave-particle nonlinearities, have been performed with HMGC. First successful tests with non-perturbative version of HAGIS/LIGKA were carried out. Multi-mode simulations with reduced 1D model are ongoing [49,50]. Coupling of Alfvén mode and zonal structures studied with</td>
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<tr>
<td>Deliverable</td>
<td>Achieved: Fully/Partly/Not</td>
<td>Evidence for achievement, brief reason for partial or non-achievement</td>
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<td>Attempt first analysis of TAE and BAE saturation in the presence of turbulence (NEMORB), multi-n studies.</td>
<td>Partly</td>
<td>ORBS(NEMORB) [35].</td>
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<tr>
<td>Apply nonlinear kinetic MHD hybrid model to and develop nonlinear electron fluid model in stellarators.</td>
<td>Fully</td>
<td>CKA-EUTERPE (kin. MHD): non-linear calculations for W7-X, Helias reactor, fluid-hybrid model: several tokamak examples, W7-X [11,12,13,28].</td>
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<td>Compute interaction between DAW modes and fast particles in stellarators.</td>
<td>Partly</td>
<td>DAW modes have been computed in stellarator geometry. In spite of the pull-back scheme [15] used, these calculations still suffer from numerical instabilities [11,12,13,28].</td>
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<tr>
<td>Implement source/sink and collisions in 3D gyrokinetic EUTERPE code.</td>
<td>Fully</td>
<td>The collisional damping of Alfven waves in EUTERPE has been successfully benchmarked in slab geometry. The application to Alfven waves in more complex geometry is in progress [29].</td>
</tr>
<tr>
<td>Analysis of nonlinear dynamics of EGAMs in different collisionality regimes and characterization of nonlinear dynamics by means of velocity space diagnostics. Turbulence regulation by EGAM. Comparison with experiments in ASDEX Upgrade.</td>
<td>Fully/Partly</td>
<td>Upgraded version of GYSELA code has been implemented and tested; and is being used for analyzing turbulence regulation by EGAM [46]. EGAM saturation levels studied with ORBS (NEMORB) for wave-particle nonlinearity only or fully nonlinear [33]. ORBS (NEMORB) code is presently addressing EGAM in NLED-AUG reference case [4].</td>
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### 3. Publications/presentations

Those which have had a substantial component from the work of the project, marking those which are entirely from the work of the project.

Give title, first author, journal/conference/other venue


[8] A. Bierwage and Ph. Lauber, Shear Alfvén and ion sound waves in high-beta tokamak plasmas (two papers, advanced drafts: local and global analysis).


[16] Ph. Lauber et al, Analytical finite orbit width model for LIGKA, (‘technical’ draft finished).


Some applications of the fully gyro-kinetic EUTERPE and GYGLES codes to tokamaks and comparison with MHD (talk), IPP Theory Meeting, Schloss Ringberg, 2016.

A. Könies, R. Kleiber, M. Borchardt, Some applications of the fully gyro-kinetic EUTERPE and GYGLES codes to tokamaks and comparison with MHD (talk), IPP Theory Meeting, Schloss Ringberg, 2016.

A. Könies, R. Kleiber, M. Borchardt, Some applications of the fully gyro-kinetic EUTERPE and GYGLES codes to tokamaks and comparison with MHD (talk), IPP Theory Meeting, Schloss Ringberg, 2016.


A. Könies, R. Kleiber, A. Mishchenko, R. Hatzky, M. Borchardt, Some applications of the fully gyro-kinetic EUTERPE and GYGLES codes to tokamaks and comparison with MHD (talk), IPP Theory Meeting, Schloss Ringberg, 2016.

A. Könies, R. Kleiber, M. Borchardt, Some applications of the fully gyro-kinetic EUTERPE and GYGLES codes to tokamaks and comparison with MHD (talk), IPP Theory Meeting, Schloss Ringberg, 2016.


N. Carlevaro et al., Mixed diffusive-convective relaxation of a broad beam of energetic particles in cold plasma, Entropy 18, 143 (2016).


F. Zonca et al., Nonlinear dynamics and transport processes in the beam-plasma system. Invited talk at the 10th West Lake International Symposium on Magnetic Fusion, and 12th Asia Pacific Plasma Theory Conference,
Hangzhou, China, May 9-13, 2016.

