WORK PACKAGE ENABLING RESEARCH
2015 scientific/technical report
Deadline: 31 December 2015

<table>
<thead>
<tr>
<th>Project title (as in Task Agreement)</th>
<th>Theory and simulation of energetic particle dynamics and ensuing collective behaviors in fusion plasmas</th>
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<tr>
<td>Principal Investigator</td>
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<td>Beneficiary of Principal Investigator</td>
<td>ENEA</td>
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<tr>
<td>Project reference number (as in Task Agreement)</td>
<td>AWP15-ENR-01/ENEA-03</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. It will also be uploaded to the Enabling Research Wiki pages [https://www2.euro-fusion.org/ERwiki/index.php?title=Main_Page](https://www2.euro-fusion.org/ERwiki/index.php?title=Main_Page), and thereby be available to the PMU and the relevant Work Package and Task Force Leaders.

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 Research Team of the 2015 ER Project ENEA-03, NonLinear Energetic particle Dynamics (NLED), has consolidated the general framework established for general theory and numerical simulation of energetic particle (EP) dynamics and ensuing collective behaviors in fusion plasmas introduced in 2014 [1]. In fact, with the aim not to provide a modeling support to experimental activities, but rather to adopt experimental "cases" to "extract" the underlying physics processes, mutual positive feedbacks have been achieved between general theory, numerical simulations and properly diagnosed experimental observations, as new element of the 2015 w.r.t. the 2014 NLED Project activities [1]. Based on the plasma conditions in the ASDEX Upgrade discharge 31213@0.84s, a set of equilibria and profiles were collected, parameterized and made available to the NLED project team [2]. In order to satisfy the limitations of some numerical codes, the equilibrium was chosen to be circular, which is a reasonable approximation for the core region in this discharge. Several stages and profiles for code-comparison purposes are defined. Linear local LIGKA results are given for reference. The most important feature of the equilibrium is its large ratio of $\beta_{ep}/\beta_{thermal}=1$, which shows the onset of strongly non-linear Toroidal/Reversed-Shear Alfvén Eigenmodes (TAE/RSAE) dynamics in the presence of EP-driven Geodesic Acoustic Modes (EGAMs). The interest in these findings triggered further experiments at ASDEX Upgrade that confirmed previous findings and added new data. Theoretical predictions of mode onset conditions in these new experiments were confirmed. A key element of this NLED reference scenario is the model parametric distribution function for EPs in the space of constants of motion, based on probabilistic assumptions and capable of rendering realistic experimental conditions [3]. This is crucial for the V&V of various codes involved in the project. The reference scenario is kept up to date and routinely used by project participants. In the future, it will be made available to all researchers interested in V&V of EP physics.

The Beta-induced AE (BAE) dynamics excited by anisotropic EPs at low magnetic shear has been investigated by the XHMGC code. Linear dynamics in similar for co-passing and counter-passing EPs, while nonlinear behaviour is different in the two cases [4]. Nonlinear saturation amplitude is much larger for the co-passing than the counter-passing EP. Moreover, in the former case the scaling of saturation amplitude with growth rate is linear, different from the usual quadratic scaling observed in the low growth rate limit and for counter-passing ions. Linear scaling is obtained also for the counter-passing ions at sufficiently large growth rates. These differences are due to different radial structures of resonance frequencies, yielding distinct saturation mechanisms and confirming the crucial role predicted theoretically for radial non-uniformity and equilibrium geometry [5,6,7]. For co-passing ions case, saturation is reached when EP density-flattening region is limited by the mode width (radial decoupling). For counter-passing ions, saturation occurs when the flattening region is set by the resonance width (resonance detuning). These two different processes cause the observed differences in terms of saturation amplitude and its scaling with the mode growth rate [8]. Nonlinear dynamics of chirping EP Modes (EPMs) driven unstable by transit resonance has been also investigated. It has been shown that it is due to the succession of resonant excitations from different phase-space regions [4,9,10].

The benchmark between HYMAGYC and HMGC codes has been performed for the ITPA-TAE test case [A. Könies et al., IAEA-FEC, Vienna, ITR/P1-34 (2012)]. At low values of the EP drive, the frequencies and growth-rates, obtained by the two codes, are very similar, and correspond to the same mode (TAE). For higher values of the EP drive, the differences observed between HYMAGYC and HMGC are mainly due to the different response of the MHD modules; in particular, to the smaller continuum damping observed in HYMAGYC w.r.t. HMGC. A scan w.r.t. EP temperature (T=200 - 800 keV) has been performed, with good agreement between HYMAGYC and HMGC computed EP drive, once the damping is subtracted [11,12]. A newly developed scheme for |
computing shear Alfvén continuum damping in both tokamak and stellarator geometries has been proposed [13,14].

A detailed linear analysis of Alfvén modes has been carried out with NEMORB [15]. Linear benchmarks with EUTERPE and HMGC on the ITPA-TAE case have been successfully completed finding good agreement. Radial mode structure ("boomerang shape") has been found to be due to the coupling effect of the EP drive and the radial variation of the continuous spectrum. Nonlinear investigations of the ITPA-TAE case (with wave-particle nonlinearities only) suggest nonlinear structure modification due to EPs [16], consistent with [R. Ma et al., PoP 22, 092501 (2015)]. A comparison of the nonlinear saturation levels with EUTERPE has also started.

Comparison between the wave-particle nonlinear dynamics predicted by CKA-EUTERPE, HAGIS/LIGKA and XHMG has been further carried out with reference to the n=6 ITPA-TAE benchmark. It has been shown that both CKA-EUTERPE and HAGIS/LIGKA exhibit a quadratic scaling of the saturation amplitude with the growth rate of the mode in the weak-mode regime (saturation due to resonance detuning), along with a transition to a linear scaling for strongly driven modes (saturation due to radial decoupling) [17]. These results are consistent with those obtained by XHMG for the same TAE case and in BAE studies [4,8,10]. They also fit with the predictions of a toy-model, developed for interpreting simulation results [8]. The fluid electron hybrid model FLU-EUTERPE code has been extended to work nonlinearly and has been applied to the ITPA-TAE benchmark case for a tokamak. With finite resistivity, a saturation of the mode amplitude close to that of CKA-EUTERPE and HMGC has been found. The scaling of saturated amplitude with changing linear growth is also comparable.

A Fourier representation in the toroidal direction has been introduced into the CKA code (reduced MHD) to speed up MHD calculation for stellarators. Convergence speed can be improved further, but CKA solver now works for large resolution. Furthermore, the gyrokinetic EUTERPE code has been improved and different models (e.g., fluid-hybrid, CKA-EUTERPE) have been merged [18]. This improvement provides flexibility and allows computing drift Alfvén wave (DAW) fluctuations in stellarators [18-23]. In particular, DAW have been investigated in LHD, showing that a TAE-like mode with a frequency lying in the TAE gap could be destabilized by the gradients of the bulk plasma without EPs. Similar modes have also been found in W7-X. The newly developed "pull-back scheme" for the solution of the electromagnetic gyrokinetic Vlasov Poisson system has been used for these calculations [24-27].

The nonlinear version of the CKA-EUTERPE code has been successfully applied to stellarators [28,29]. To allow computations, phase factor extraction of the dominant Fourier harmonic has been retained. Saturation levels of an NBI-driven TAE mode in W7-X and a β-driven HAE mode in the HELIAS reactor have been calculated. 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 \( \delta B_{rad}/B_0 = 10^{-3} \). Proof of principle FLU-EUTERPE simulations within a limited range of numerical parameters have been performed in W7-AS, LHD, and W7-X stellarator geometries. Global modes driven by EPs have been found in W7-X geometry. Work to expand the working parameter range to experimentally relevant values is in progress.

Nonlinear simulations of Alfvén modes with wave-particle and wave-wave nonlinearities have also been performed with NEMORB, in particular for the coupling with zonal structures [16]. With flat q-profile, wave-wave coupling has been found to dominate the saturation mechanism, preventing the Alfvén mode to reach the amplitudes necessary for appreciable EP radial redistribution. Linear simulations of GAMs with the realistic equilibrium of the NLED-AUG reference case have also been investigated. Nonlinear EGAMs have also been studied with wave-particle nonlinearities only, and with the EP distribution function suggested in [C. Di Troia, PPCF 54, 105017 (2012)] [see also [3]].

Numerical simulations of electrostatic turbulence have shown that instead of the expected moderating effect, EGAMs could on the contrary enhance ITG turbulence [Zarzoso et al., PRL 110, 125002 (2013); Dumont et al. PPCF 55, 124012 (2013)]. An analytical, non-linear three-wave parametric interaction
model has been developed to better understand the interaction between these instabilities observed in the simulations. A local dispersion relation shows that the non-linear excitation of two linearly stable ITG modes by an EGAM is only possible under stringent conditions, in line with expectations and the mitigating impact of GAMs on turbulence. Meanwhile, a three-wave interaction propagative model predicts that, if ITG modes are linearly unstable in the core region and linearly stable in the outer region, the EGAM can act as a pump to non-linearly destabilize ITG modes in the outer region.

The link between GAMs and EGAMs has been clarified by detailed analyses of the linear dispersion relation, as well as extensive gyrokinetic simulations [J.-B. Girardo et al., PoP 21, 092507 (2014); D. Zarzoso et al., NF 54, 103006 (2014)]. These findings may have impact on turbulence control. The validity of these results has been checked using the new 2-ion species version of the GYSELA code [30]. Good agreement of the EGAM frequency and linear growth rate was found. This motivates new simulations to be conducted, with a focus on identifying potentially different effects on ITG turbulence.

Nonlinear EP interaction with multiple TAEs has been studied for the ITER 15 MA baseline scenario ($q_0=0.986$) using the HAGIS code [31-34]. Similar to earlier studies of ASDEX Upgrade [M. Schneller et al., NF 53, 123003 (2013)], it was found that global, nonlinear effects are crucial for the evolution of the multi mode scenario. Taking into account all weakly damped modes that can be identified linearly with the gyrokinetic, non-perturbative LIGKA solver, simulations with HAGIS demonstrated that the nonlinear excitation of linearly sub-dominant modes can be crucial to the relaxed EP profile. Whereas the most unstable, mid-radius localized TAEs lead only to a moderate EP redistribution that is rather close to quasi-linear estimates, in a certain parameter regime, the slowly growing low-n TAEs eventually lead to a substantial EP relaxation in the outer core region via domino-effect [H. Berk et al., NF 35, 1661 (1995)]. Similarity and differences of EP transport by multiple modes, and multi-beam interaction with plasma waves in 1D uniform system has been addressed. In particular, the general problem of n cold beams self-consistently evolving in the presence of m (greater or equal to n) Langmuir modes at the plasma frequency has been formulated in Hamiltonian form [35]. A theoretical analysis combined with numerical simulations has demonstrated non-diffusive behavior beyond the quasi-linear paradigm, as well as the necessity of accounting for modes of the linear stable spectrum for proper description of EP transport [36]. This is qualitatively consistent with EP transport by multi modes in fusion plasmas. A quantitative comparison is underway.

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) [37,38] supra-thermal electron density profiles with moderately hollow q-profile have been studied. The linear analysis demonstrated that the two situations are different in terms of the characteristic resonance frequency of the mode, as well as the fraction of supra-thermal particles involved in the destabilization of the mode, confirming theoretical expectations. The study of e-fishbone nonlinear saturation mechanisms adopted the test particle Hamiltonian method (TPHM) package [S. Briguglio et al., PoP 21, 112301 (2014)] and it has been performed for both the on axis profile as well as for the off axis density profile. The two cases show a different behaviour of phase-space resonant structures, which yield mode saturation via reduction of the free energy source by energetic electron density flattening.

A minimal model was developed for the nonlinear analysis of precessional fishbones. In this framework, only deeply trapped particles are retained in order to deal with a single, and relatively simple, mode-particle resonance. The bulk of the plasma it is described in the cold plasma approximation by the Reduced-MHD equations in a cylindrical geometry. An hybrid numerical code, based on this approach, was developed adopting a semi-lagrangian scheme for the evolution of the particle distribution function and a semi-spectral scheme for the MHD part. At the same time the growth rate and the real frequency of the Fishbone instability have been determined using a standard analytic approach. The numerical code has been benchmarked with the analytical results and it is able to correctly recover them, during the linear phase of the instability [39]. The non-linear phase is under investigation.
### 2. Project deliverables

<table>
<thead>
<tr>
<th>Deliverable</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>Definition of “reference cases” for linear and nonlinear physics studies of EP driven fluctuations, adopting ASDEX Upgrade “cases” to “extract the underlying physics”. Extrapolation of “reference cases” to burning plasmas by similarity scaling.</td>
<td>Fully</td>
<td>Based on an ASDEX Upgrade scenario a set of reference cases with different complexity [2] and a model parametric distribution function for EPs were defined [3].</td>
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<td>Linear and nonlinear BAE/TAE benchmarks and simulations with NEMORB, XHMGC, LIGKA and HYMAGYC.</td>
<td>Fully/Partly</td>
<td>TAE benchmarks completed [11,12,15-17]. BAE benchmarks in progress (XHMGC simulations completed) [4,8,10].</td>
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<tr>
<td>Upgrade CKA-EUTERPE to speed up MHD calculation for stellarators. Merge EUTERPE code versions to gain flexibility and compute DAW modes in stellarators.</td>
<td>Fully/Partly</td>
<td>Large resolution achieved in CKA [29]. Fourier version of EUTERPE to be done. EUTERPE versions merged and mode saturation for W7-X with CKA-EUTERPE [28,29].</td>
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<tr>
<td>Compare AE saturation mechanisms predicted by CKA-EUTERPE, HAGIS/LIGKA and XHMGC. Investigate importance of mode number and drive strength.</td>
<td>Fully/Partly</td>
<td>ITPA benchmark successfully completed for [4,8,10,17,28,29]. FLU-EUTERPE analysis in progress.</td>
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<tr>
<td>Analytic and numerical study of the interaction between EGAMs and turbulence in electromagnetic simulations. Improve EP source in NEMORB and GYSELA.</td>
<td>Fully</td>
<td>A three-wave interaction model has been developed. The EP source in both the NEMORB and GYSELA codes has been improved [30].</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

[2] Ph. Lauber et al., NLED-AUG reference case. [Link]
[17] A. Könies et al., The influence of FLR effects on tokamak saturation amplitude, 15th Meeting of the ITPA Energetic Particle Topical Group, Sep. 7-9, 2015, Vienna.


[34] M. Schneller et al., Nonlinear Energetic Particle Transport in the Presence of Multiple Alfvénic Waves in ASDEX Upgrade and ITER. Invited talk at the European Fusion Theory Conference 2015 (10/2015, Lisbon, Portugal).


[37] V. Fusco et al., Analysis of the electron fishbone instability with the XHMGC code, 7th IAEA Technical Meeting on Plasma Instabilities, Frascati, Italy, March 4-6, 2015

[38] V. Fusco et al., Electron fishbone dynamics studies in tokamaks using the XHMGC code, 14th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems, Vienna 1-4 Sep. 2015.
