

## EN ROUTE TO HIGH-PERFORMANCE DISCHARGES: INSIGHTS AND GUIDANCE FROM HIGH-REALISM GYROKINETICS

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### Abstract

Although remarkable progress in ab initio gyrokinetic plasma core turbulence studies has been seen in the last decade, some important open issues remain – e.g., in view of high performance discharges where magnetic fluctuations tend to reduce the turbulence levels and where the presence of fast ions may provide significant stabilization enhancements. This effect was shown to lead to a remarkable reduction of ion temperature profile stiffness in JET and was required to explain DIII-D quiescent H-modes as well as non-inductive ASDEX Upgrade (AUG) discharges. Several questions immediately arise in this context: Are these - mainly local flux-tube simulation based – results modified by nonlocal effects in steep-gradient regimes? Can fast ion populations be used to control turbulent transport in burning plasmas? All of these questions culminate into this one: To which degree is core gyrokinetics able to reproduce observations from present-day experiments and predict future devices? In order to address this crucial task, comprehensive state-of-the-art validation studies with AUG fluctuation measurements will be presented. Furthermore, nonlocal studies will be shown confirming that the level of stabilization and threshold values for transitions between electromagnetic micro-instabilities, like ion temperature gradient driven and kinetic ballooning modes, may be affected by nonlocal effects. In addition, light will be shed on the improvements that can be expected by considering fast ion effects in electrostatic and electromagnetic simulations. Employing the gyrokinetic code GENE, a wave-fast ion resonance mechanism was found to be critical in describing corresponding JET discharges. While irrelevant to fusion-generated alpha particles which just act as diluting particles, it can be shown that cleverly tailored fast ion temperature (gradient) profiles may still offer pathways towards optimized plasma scenarios with substantial turbulence reduction. The predictions are further improved by studying the impact of more realistic fast ion models than the often employed equivalent Maxwellian backgrounds.

## 1. INTRODUCTION – TOWARDS FULLY PREDICTIVE GYROKINETICS FOR CORE CONFINEMENT

The last decade has seen significant progress in *ab initio* plasma turbulence studies based on nonlinear gyrokinetics. Particularly in the core region of fusion devices, quantitative comparisons between simulations and experiments have become standard. Nevertheless, some important questions remain to be solved – e.g., in view of high performance discharges where high kinetic-to-magnetic pressure ratios (beta) are achieved. In such situations, magnetic fluctuations tend to reduce the turbulence and transport levels in a significant manner. Employing the gyrokinetic plasma turbulence code GENE [1], the strong ion temperature (Ti) peaking of non-inductive ASDEX Upgrade (AUG) discharges could, for instance, recently be attributed to a electromagnetically substantially reduced ion temperature gradient (ITG) driven turbulence regime close to the kinetic-ballooning mode (KBM) / beta-induced Alfvén eigenmode (BAE) threshold [2]. Similarly to gyrokinetic studies of neutral beam heated quiescent H-modes at DIII-D [3], fast ions are found to be another crucial ingredient to reproduce realistic heat flux levels in dedicated turbulence simulations. A particularly strong impact of the latter could be demonstrated for some JET discharges reporting a significant reduction of ion temperature profile stiffness [4]. Contrary to the above mentioned specific DIII-D and AUG examples, the impact of the fast ion dynamics substantially differed from simple dilution. Crucial questions are, therefore, how electromagnetic stabilization and fast ion effects can be further assessed and exploited, and why fast-ion impacts tend to be qualitatively different for various scenarios. Particularly the latter – with direct implication for ITER – will be addressed in Sec. 3, while a brief discussion of finite-gyroradius effects in electromagnetic simulations will be presented in Sec. 2 beforehand. Section 4 is then dedicated to state-of-the-art validation studies for core gyrokinetics which shall be extended to high-performance scenarios in the future. All results are briefly summarized in Sec. 5.

## 2. NONLOCAL EFFECTS AT HIGH BETA

High-performance plasmas are intrinsically linked to high beta, which poses a challenge for theoretical models since additional effects and field equations need to be considered. In steep gradient regimes, however, even machines like ITER may furthermore be subject to radially nonlocal effects. Due to the high complexity, only few direct comparisons exist between global electromagnetic and corresponding flux-tube simulations. Here, one such dedicated microinstability study which has been a by-product of a global electromagnetic multi-code benchmark [5] shall be highlighted. For a detailed discussion of the Cyclone Base Case inspired input parameters, the reader may refer to Ref. [5]. Here, the focus will be on Fig. 1a, where linear growth rates of a global parameter scan at  $\rho^*=1/180$  and corresponding flux-tube results averaged over radius and ballooning angle are shown as functions of beta, or the reference density, respectively. The magnetic equilibrium is kept constant for simplicity. While the real frequencies agree well and confirm that the same microinstabilities – ITG

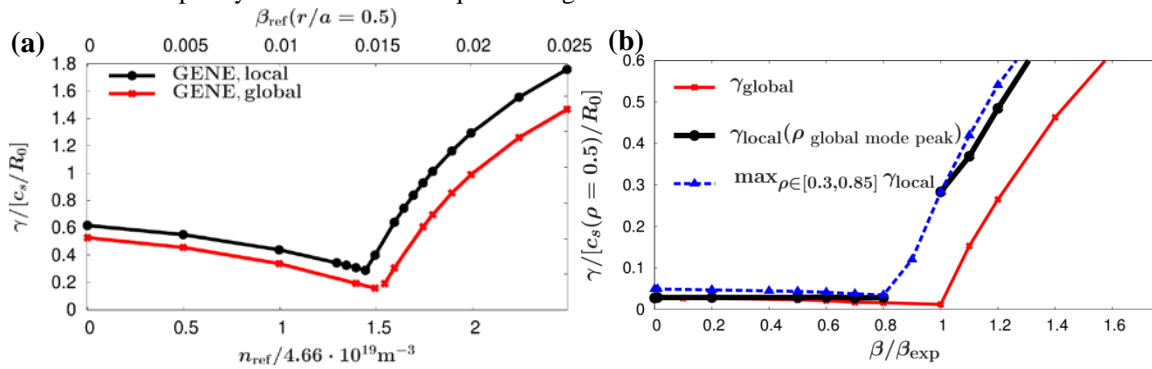


FIG. 1: Linear growth rates from local and global simulations as function of  $\beta$  for (a) a simplified CBC-like scenario and (b) an actual non-inductive ASDEX Upgrade discharge [2]. While the ITG growth rates are found to be relatively close in both cases, the difference between fluxtube results maximized over radius and radially global results is more pronounced in the KBM/BAE regime and the threshold value is visibly shifted.

at low beta and KBM at high  $\beta$  – are found in both simulation types, the growth rates differ significantly. As expected from the smaller effective drive, which is quite pronounced due to the chosen peaked gradient profiles, the global code results are below the fluxtube ones. The difference in amplitude seems to be roughly aligned with the character of the mode. This also affects the threshold value at which the dominant mode changes. The upshift observed in the case at hand may very well have implications in cases where the profiles are determined by the KBM onset.

That experimental conditions can be close to such thresholds may be observed in Fig. 1b where a corresponding parameter scan has been performed with input profiles from a high-beta AUG discharge [2]. The difference between the modes is, however, more pronounced in Fig. 1b. The figure furthermore demonstrates the complexity of applying similar studies to experiments. With temperature and density profiles being much less well determined near the magnetic axis (with normalized square root of the toroidal flux  $\rho < 0.3$ ), the corresponding flux-tube results are highly uncertain and may even be found deep in the KBM regime at  $\beta/\beta_{\text{exp}} \sim 0.5$  and  $\rho \sim 0.25$ . The global mode structures obtained in the radial range  $\rho = [0.1, 0.9]$  on the other hand seem to always peak at values  $\rho \geq 0.3$ . This can to some degree be explained by the Dirichlet (zero fluctuation) boundary condition considered at  $\rho < 0.1$  which penetrates inside the simulation domain via gyro-averaging and other finite orbit effects and therefore attributes less weight to the radial range under question.

Considering both results, two conclusions can be drawn. For mid-sized and larger machines, finite gyro-radius effects may not dramatically alter results obtained from typically much cheaper and faster flux-tube simulations in the low-beta regime. Approaching the onset of kinetic-ballooning modes, on the other hand, may trigger the necessity for global simulations in order to establish a more realistic mode transition and threshold values. Unfortunately, it was found particularly that a high radial resolution is crucial in order to obtain physically meaningful results [5] such that global simulations become even more challenging. New numerical approaches such as block-structured grids [6] have therefore recently been added to GENE in order to optimize the runtime for the results displayed in Fig. 1b.

### 3. TURBULENCE REDUCTION BY FAST IONS

A fast ion related though varying turbulence stabilization could recently be identified in a number of advanced scenarios in DIII-D, JET, and AUG, see Refs. [2-4], for instance. With observed electromagnetic turbulence reductions by factors of up to ten, previous projections not accounting for these effects for reactor type plasmas with inherently large fast ion fractions could be too pessimistic.

While developing a full understanding involves studying rather complex nonlinear interactions and is still a subject to on-going research, some pieces of the puzzle could already be found and connected. Among these is a new resonance stabilization which has recently been identified as a relevant ingredient in some JET plasmas with strongly reduced ion temperature stiffness and which could possibly be exploited to further optimize advanced plasma scenarios [7]. While extending previous studies of the NBI and ICRH heated JET L-mode shot 73224 [4], nonlinear GENE simulations could clearly find a fast ion related turbulence reduction in the electrostatic limit. This was to some degree surprising since such stabilizing effects would usually be highlighted in the electromagnetic framework and motivated further investigations along these lines which will be briefly summarized in the paper.

First of all, the parameter set at hand had to be simplified to allow for comprehensive parameter scans. Keeping just one fast ion species ( $^3\text{He}$ ) and scanning over its temperature, it became obvious that a sweet spot can be found in the linear growth rate amplitude at fast helium temperatures about 12 times larger than the electron temperature. Going to even higher values results in the growth rates slowly approaching the dilution limit, i.e. the limit where the main fast ion effect is a reduction of the bulk ion density. Being furthermore interested in identifying the parameter dependence of the “sweet spot”, an analytic model has been derived which allows for even faster scans and thus helped to develop a detailed understanding of this even electrostatically relevant reduction. Neglecting trapping, radial-curvature and parallel-dynamic contributions which are here rather irrelevant and by employing a plane wave ansatz, it can be observed that a resonance occurs if the fast ion magnetic-drift velocity matches the propagation of the mode. While this immediately allows to attribute a particular dominant contribution to bad curvature regions, it is at this stage not clear whether a mode destabilization or stabilization is achieved. A necessary but not sufficient condition for the latter is that the logarithmic fast ion density gradient is smaller than  $3/2$  times the logarithmic fast ion temperature

gradient, i.e. a rather flat fast ion density profile should be beneficial. The exact conditions at which a wave-fast ion turbulence reduction can be expected depend on the velocity space structure of the background drive term, i.e. where the velocity-dependent resonance condition overlaps with regions where this term is negative. However, the above criterion already helps to understand why active fast ion stabilization is particularly relevant in the aforementioned JET scenario [4] but, for instance, absent in recent ASDEX Upgrade advanced scenarios [2] where fast ions mainly affect the plasma via dilution and geometric effects.

Given that the above examples are all present-day devices with rather low fast ion temperatures compared to future burning plasmas with large alpha particle densities, it is obvious to question the relevance of the wave-fast ion resonance for ITER and beyond. In such conditions, only dilution effects are expected. The situation, however, changes with consideration of auxiliary heating, e.g., during a reactor ramp-up phase. Another study is therefore dedicated to a time slice of the planned ITER standard scenario with  $^3\text{He}$  ICRH minority heating which is chosen just before the L-H transition. At this stage, where ion and electron temperatures are still sufficiently low, ICRF waves will be mostly absorbed by the  $^3\text{He}$  minority (here, 3%) and corresponding energetic  $^3\text{He}$  can be expected. The input parameters for GENE at  $\rho=0.32$  are based on the (fixed) thermal species kinetic profiles and magnetic equilibrium obtained from the JINTRAC code [8] and on the consistent fast helium profiles computed with the ICRF full-wave TORIC code interfaced with the SSFPQL Fokker-Planck solver [9,10].

Both linear and nonlinear results displayed in Fig. 2 perfectly confirm the relevance of the wave-fast ion resonance in such conditions. While virtually no fast ion resonance effect (beyond dilution) can be seen at the lowest heating power and even a minor destabilization is observed at 10 MW ICRH power where the resonance is still boosting corresponding background drive velocity space regions, this picture changes dramatically at higher heating power. Here, predominantly negative background drive regions are amplified by the resonance condition. Both, the linear micro-instability and the fully developed nonlinear turbulence are finally found to be reduced by a factor of 5 at 20 MW ICRH input. Needless to say that this would dramatically improve the performance of the ramp-up phase. However, it should be noted that these studies need to be embedded in a larger transport framework where the kinetic profiles and fast ion distributions develop self-consistently with the turbulence. Here, everything besides the fast ion properties as functions of the heating power is kept constant and evaluated at a single radial location. Nevertheless, the above results may serve as a strong encouragement to further study advanced scenario improvements by optimally tailored heating schemes which exploit the wave-fast ion resonance turbulence reduction.

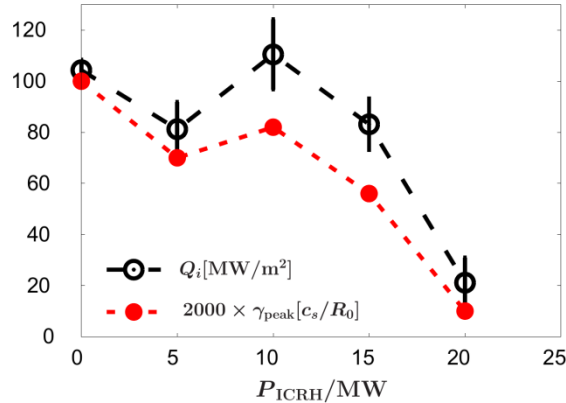


FIG. 2: Linear and nonlinear flux-tube results as function of the fast ion power deposition in the ramp-up phase of the ITER standard scenario. See Ref. [7] for details.

So far, the above investigations have been restricted to the electrostatic limit – on the one hand for cheaper simulations and on the other to disentangle the resonance effect from the electromagnetic stabilization. A prime question, therefore, is whether both effects are compatible and provide additive beneficial impact. This could indeed be shown for the JET discharge #73224 as is detailed in Ref. [7]. Linearly, both seem to simply superimpose. Nonlinearly, a synergetic effect can be observed where, similarly to the nonlinear electromagnetic stabilization, which is a subject of active research itself (see, e.g. Ref. [11]), the addition seems to be stronger through nonlinear interaction. This is good news, but also calls for further theoretical efforts along these lines.

Another crucial task is a better fast ion physics integration or representation in gyrokinetic codes. Almost all publications describing fast ion effects on plasma turbulence employ equivalent Maxwellian distributions or other analytic expressions such as a slowing-down distribution at most. In reality, such distributions may be highly anisotropic and should ideally be taken from specialized codes like TORIC-SSFPQL. The GENE code has therefore recently been equipped with the capability to consider arbitrary background distributions including numerical ones from external codes [12]. Simulations with such improved fast ion models – a fast (NBI) deuterium slowing-down distribution approximating a coarse-grid distribution from NEMO/SPOT [13] and a fast (ICRH) helium distribution from TORIC-SSFPQL or SELFO [14] - indeed seem to significantly increase the realism of the results as can be observed in Fig. 3. The transport levels are now found within the error bars

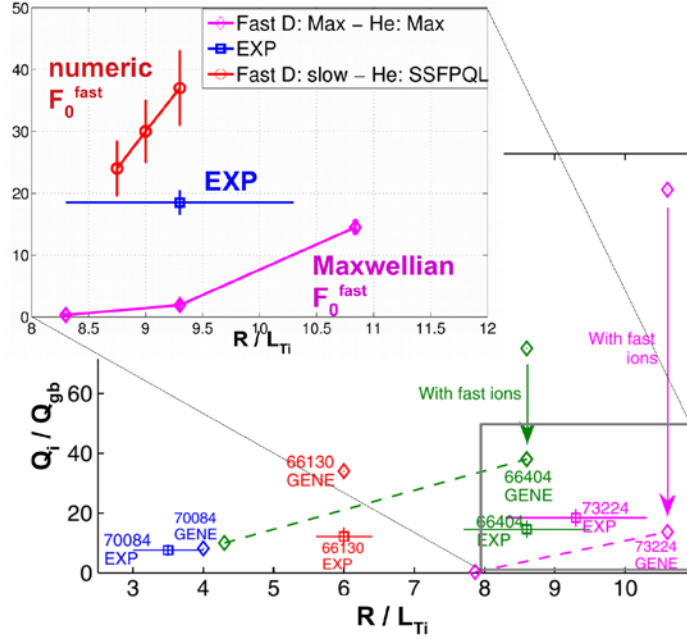


FIG. 3: Nonlinear GENE results with slowing-down distributed fast D and fast  $^3\text{He}$  from TORIC-SSFPQL compared to previous results [2] using equivalent Maxwellian fast ion distributions.

of the experimentally determined heat fluxes in JET discharge 73224 while still reproducing the significant fast ion stabilization. This new capability should be taken into account in future simulation campaigns for discharges with strong auxiliary beam or ICRH heating.

#### 4. SOPHISTICATED STATE-OF-THE-ART CODE VALIDATION

After the rather predictive statements in the previous sections, one may ask how gyrokinetics in general – and the GENE code in detail – compare to actual measurements in current experiments. For the aforementioned advanced scenarios, transport levels could already be successfully reproduced within the error bars of the physics inputs. Given a finite chance for a coincidental agreement, it is important to reach out for as many observables from experiment as possible. In the following, two such examples shall be highlighted which are not yet actual representatives of advanced scenarios – this disadvantage is, however, balanced by the high quality of the experimental data and shall be rectified as soon as similar turbulence fluctuation data is accessible for high-performance discharges. The first example is the result of a multi-year project where scale-resolved Doppler reflectometry data has been compared to density fluctuation spectra obtained from gyrokinetic simulations. This is particularly interesting since similar spectral properties would imply that measurements and numerical tools largely agree on the underlying cascades and nonlinear couplings. First attempts, however, could only find roughly similar spectral power laws at high wave numbers but would disagree on low- $k$  spectral breaks. This result was particularly puzzling as one would expect the low- $k$  spectral roll-over between the approximated injection scale and inertial range. This long-standing issue could finally be resolved by applying two-dimensional full-wave simulations with the IPF-FD3D [15] code on top of the GENE density fluctuations [16]. This sophisticated synthetic diagnostic emulating the scattering of the waves on the turbulence background revealed that a highly nonlinear mechanism may occur which – depending on the density fluctuation level and

the employed microwave probing frequency – may result in a spectral flattening of the Doppler signal at low- $k$  and an enhanced response at high- $k$  [17] and thus modify the spectral break. As can be seen in Fig. 4a, the combined gyrokinetic and full wave codes agree qualitatively very well with the Doppler reflectometry measurements in X- and O-mode and clearly represent similar physics. Besides validation of GENE and the

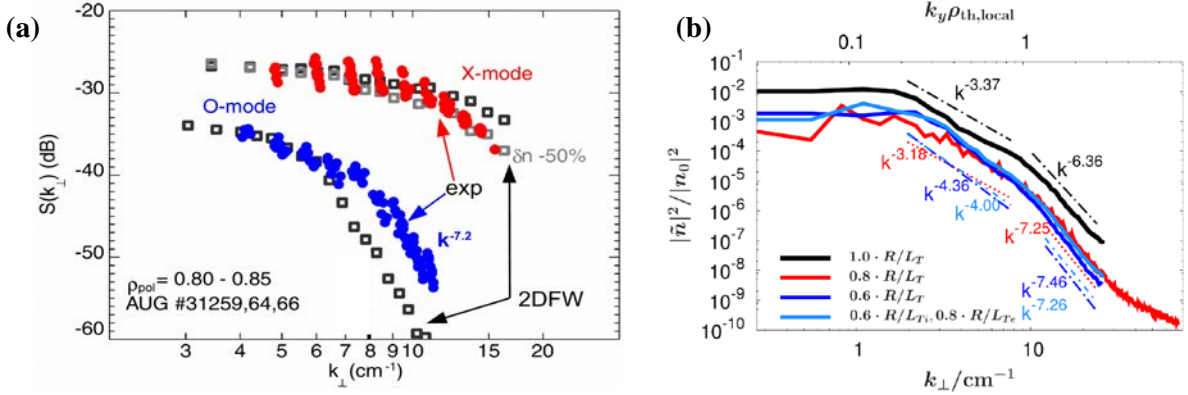


FIG. 4: Density fluctuation spectra obtained (a) from Doppler reflectometry and GENE+2DFW simulations and (b) from raw GENE data for various temperature gradient settings.

precious information for diagnosticians to avoid parameter regimes with strong nonlinear scattering if possible, the gyrokinetic simulations can also be used to predict measurements at currently inaccessible scales. Fig. 4b displays the raw gyrokinetic data up to almost electron scales. Clearly, another high- $k$  spectral break can be identified at  $k_y \rho_{th,local} \sim 3$  which can be related to linear unstable small-scale electron temperature gradient (ETG) driven turbulence. The figure furthermore contains gradient sensitivity study results which confirm a rather robust position of the spectral roll-over while the power laws are mildly varied in response to the different drive.

Another example of a fruitful interaction between gyrokinetic simulations and experiment can be found in the recent installation of a correlation electron cyclotron emission (CECE) diagnostic at AUG whose design had been inspired by estimates being based on AUG dedicated GENE simulations. The new diagnostic offers a whole range of new observables for code validation and insights into plasma turbulence physics. Besides electron temperature fluctuations, it can also be employed to compare corresponding frequency spectra and radial correlation lengths – and if coupled to reflectometry – electron density and temperature cross phase relations. Again, a synthetic diagnostic must be applied to the gyrokinetic data which mimics the spatio-temporal filters inherently set by the diagnostic hardware. Accordingly post-processed ion-scale GENE simulations matching both the ion and the electron heat fluxes are compared to the various observables offered by the CECE system in Fig. 5.

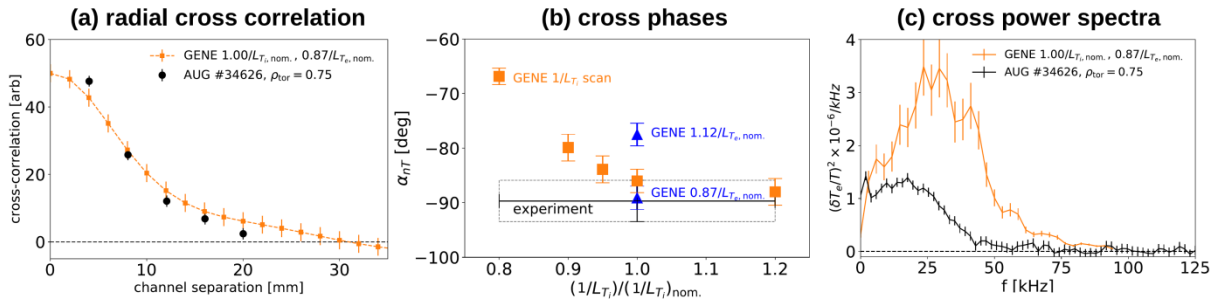


FIG. 5: Comparison of CECE measurements (black) and post-processed GENE simulations (orange, blue) for (a) the radial cross correlation, (b) electron density-temperature cross phases and (c) electron temperature fluctuation cross power spectra.

Very good agreement can be stated for the radial correlation function of the perpendicular electron temperature fluctuations and the cross phase between the latter and the density fluctuations [18]. The cross-power spectra bear similarities but the gyrokinetic data appears to be shifted to higher frequencies and is found at higher amplitudes. The last signal also depends much more on details of the synthetic diagnostics compared to the previous observables. The discrepancy still remains to be solved as all relevant parameters – foremost the

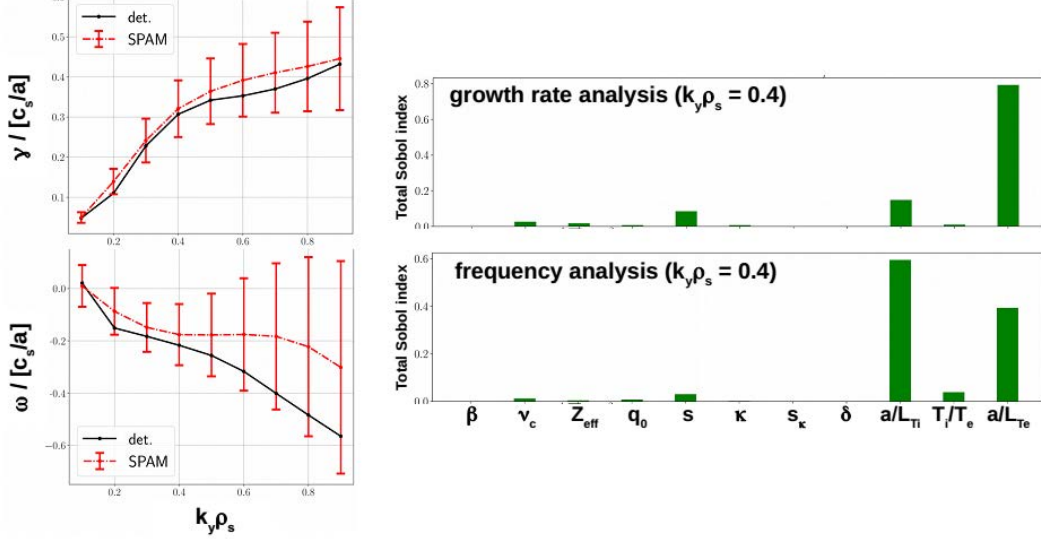


FIG. 6: Example of forward-UQ analysis with SPAM [19] for linear simulations for AUG #33585. Linear growth rates and real frequencies with error bars considering uncertainties in 11 input values are displayed on the left. Their individual impact at fixed wave number can be assessed by the total Sobol indices which are shown on the right.

background rotation velocity – have been revised carefully already. It should be noted that the plasma at hand is a particularly complex TEM and ITG mixture where dominant mode transitions can be found for relatively small changes in several physics inputs. A comprehensive analysis would therefore include high-dimensional parameter scans which unfortunately represent an enormous computational challenge. As a first step to tackle this quest, a forward uncertainty quantification (UQ) – namely, the sparse pseudo-spectral approximation method (SPAM) – has been implemented and applied with linear GENE simulations for the parameters at hand [19]. Such methods allow for much cheaper scanning of the hyper-dimensional parameter space spanned by more than 10 physics inputs as they select and refine the grids in an optimized fashion. As a result, error bars based on the physics input uncertainties can be derived and the individual impact of a physics input can be visualized by means of the total Sobol index, see Fig. 6. Here, cross-interaction between inputs are found to be significant if the sum of the latter exceeds one, as these interactions are added multiple times in the total Sobol' indices computation.

## 5. CONCLUSION

Nonlinear gyrokinetics is closing in on some outstanding plasma core turbulence challenges. Comprehensive validation studies performed with the GENE code are already able to demonstrate the maturity of gyrokinetics for a number of observables and scenarios. Significant progress is furthermore reported regarding the understanding of electromagnetic nonlocal effects and turbulence reduction by fast ions in high-performance discharges. These findings may very well open new opportunities for optimization of reactor-type plasmas with auxiliary heating, e.g., during a ramp-up phase. They furthermore emphasize the need for minimal plasma turbulence transport models to ensure a proper coverage of these physics effects in high-fidelity reactor predictions.

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