Code: Kinezero	Version (date):
Responsible Officer: Clarisse Bourdelle	
Source Location: link to CVS page to be done.	
TF Use: (projects)	
Classification:	
Status:	

Contents:

Code Catalogue Entry: Kinezero

Author(Institution):
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Objective:
Calculate the linear growth rates of unstable modes to characterise the microturbulence. This code has been developed in order to have a very fast tool (1 hour on 1 processor for 150 growth rates) to analyse experimental plasmas extensively.

Physics basis:
Solves the linearized gyrokinetic equations for each species coupled to the quasi-neutrality condition. It includes passing and trapped electrons (i.e. Trapped Electron Modes and Electron Temperature Gradient modes) and passing and trapped ions (Ion Temperature Gradient modes) with the main ions and one impurity. It finds all the unstable eigenvalues.

Assumptions and limitations:
Linear, Collisionless, Gaussian trial eigenfunction, s-alpha equilibrium
No magnetic perturbations

Status:
Mature, with a group of about 10 users

References:
http://tokamak-profiledb.ukaea.org.uk/KZERO/KINEZERO.htm
C. Bourdelle, X. Garbet, G. T. Hoang, J. Ongena, R. V. Budny, Nuclear Fusion 42, 892 (2002)

Links to other codes:
Interfaced to the ITPA database and to the JETTO output, and soon to be included as a post-processing tool in the Jams interface at JET.

Language:
Code in Fortran 90, interfaces in Matlab

Libraries:
Nag, libmat

Computational power required:
About 1 hour on one processor for 150 growth rate calculations

Physics description

KINEZERO is an electrostatic linear gyrokinetic code. The code evaluates the growth rates (γ), which are the imaginary parts of the eigenmode pulsations (ω) together with the mode width w. The calculation is performed for each toroidal wavenumber (n) on a set of magnetic surfaces. The density perturbations, induced by the perturbed electrostatic potential, are computed by linearizing the Vlasov equation, and the coherence is expressed by the electroneutrality constraint. For a given magnetic surface (radial position r) and at n fixed, the poloidal wavenumber (m) is constrained by the safety factor: $q = -m/n$. Magnetic perturbations are neglected. This approximation is valid for very low values of beta: $\beta < m_e / m_i$ (m_e and m_i being the electron and ion masses). Here β is defined as the ratio of the total kinetic pressure P over the total magnetic pressure $B^2/2\mu$. The effect of collisions is also neglected. This approximation is not valid when the effective collision frequency becomes of the same order as the vertical drift frequency of trapped electrons. In order to reduce the computation time the ballooning representation at the lowest order is used to represent the perturbed electric field. The ballooning angle is restricted to $\theta_0 = 0$, which usually corresponds to the most unstable value with respect to the interchange instability. This procedure allows us to reduce the determination of the eigenmodes to a 1-D problem, instead of 2-D. The ballooning representation is valid if the gradient lengths of equilibrium quantities ($Ln = -n/\nabla n$, $L_T = -T/\nabla T$) are larger than the distance between two adjacent resonant surfaces ($d = |1/n\partial rq|$). This representation does not give access to the stabilizing effect of γ_E. To take this effect into account in our calculation, we have used a heuristic criterion. Moreover, the ballooning representation does not describe the zero s configuration correctly, since in this case d is infinite and cannot be smaller than the gradient lengths.
The electroneutrality constraint is cast into a variational form and a trial function is used for the fluctuating electrostatic potential. This trial function is chosen to be the most unstable exact solution obtained in the fluid limit.

Combining the perturbed Vlasov equation with the variational form of electroneutrality constraint, one obtains the following equation for ω:

$$D(\omega) = \sum_s \frac{n_s Z_s^2}{T_s} \left[1 - L_{ts}(\omega) - L_{ps}(\omega)\right] = 0$$

where n_s, Z_s and T_s are, respectively, the density, charge number and temperature of the species s. The species treated are electrons and two types of ion, typically the main ions and one kind of impurity. The functional expressions for the trapped (L_{ts}) and passing (L_{ps}) particles are multiple integrals of rapidly varying complex variable functions.

Kinezero solves the gyrokinetic equations in a toroidal geometry and include all the types of particles: main ion, electron and impurity; passing and trapped, covering large ($k_\theta \rho_i < 1$, ITG and TEM) and small scales ($k_\theta \rho_i > 1$, TEM and ETG) instabilities,

Linear codes do not provide the saturation levels of the turbulence, but they do provide the growth rates of the unstable modes, γ, and their mode widths, w. They give detailed and quantitative information about the threshold above which the instabilities are triggered. The parametric dependences of the threshold can be extensively studied, see for example [bou3]. The level of transport cannot be quantitatively compared with the measured fluxes. The saturation levels due to non-linear modes coupling determine indeed the turbulent transport.

Nevertheless, based on linear information such as the growth rates and the mode widths, a quasi-linear approach can be used ($\chi \propto w^2\gamma$) and one can compare qualitatively the quasi-linear transport coefficient with the measured one. In particular, the parametric dependences of quasi-linear and measured coefficients can be compared.

References:
C. Bourdelle et al , Nuclear Fusion **42**, 892 (2002)

Numerical Implementation

An efficient method to find the solutions is needed. A generalized Nyquist method developed by Davies and extended by Brunner *et al* is used here. The method consists in using the argument principle and the residues theorem. In this way, knowing the values of $D(\omega)$ over a contour C yields the zeros of D in the domain enclosed by C. In order to obtain all the unstable solutions, we scan the upper part of the ω complex plane with several contours. The maximum value along the imaginary axis is given by an estimate of the growth rate calculated using fluid equations. The minimum value has to be positive and can be chosen as small as needed. Once we have determined the eigenvalues using this method, werefine their localization using Newton's method. The solutions are classified in decreasing order of their imaginary part (γ). This is done for each pair $(n, r/a)$. The stability analyses are performed using the growth rate of the most unstable mode for each $(n, r/a)$: $\gamma\ max(n, r/a)$.

C. Bourdelle et al , Nuclear Fusion **42**, 892 (2002)
B. Davies, J. Comput. Phys **66**, 36 (1986)
S. Brunner et al, Phys Plasmas **5**, 3929 (1998)

Qualification

Limitations:

As in all gyrokinetic codes, the following assumptions are made:

$$\frac{V_{\tilde{E}xB}}{V_{th}} = \frac{\tilde{f}}{f} = \frac{\omega}{\omega_c} < 1$$

the mode length can be of the same order of the Larmor radius: $k_\perp \rho \approx 1$

In the local approach that Kinezero employ, we neglect all the second derivatives of all profiles, this means that L, the gradient length is such that
$\frac{w}{L} << 1$.
This approximation can be problematic in low magnetic field plasmas, such as in Spherical Tokamaks or in high gradient lengths plasmas; such has pedestals of transport barriers. But in all the Internal Transport Barriers analyzed so far, this approximation was not broken.
Both are using the ballooning representation which uses the fact that for the microinstabilities, $\frac{k_{//}}{k_\perp} << 1$. This means also that $\frac{d}{w} << 1$ where d is the distance between resonant modes and w is the mode width.

Domain of Validity:

Kinezero is mainly applicable to low collisionality, low beta discharges.

Verification

Static Analysis:

Performed with lahey source code analyzer. Code passes with some warnings and a possible type inconsistency. Under review of developer.

Dynamic Analysis :

For more detailed information on the verification exercise, see [bou4].
The generalized Nyquist method used to find the eigenvalues has been tested to find known polynomial roots in the complex plane.
The expected symmetry in the equations has also been tested. For example, the same results have been found with trapped particles only and with passing particles only with: the finite banana width effect neutralized for trapped particles, the transit frequency of the passing particles brought to zero and the vertical drifts multiplicative terms $f(\kappa)$ for trapped particles and $f(k^*)$ for passing particles forced to be equal to one. The same results where also found for electrons only and for ions only, where the mass of the ions was artificially set to the mass of the electrons. The exercise was also done for impurities only and main ions only. The last test was done with trapped electrons and trapped ions only, with $T_e = T_i$ and $n_e = n_i$. The finite Larmor radius effects were not included, such that the mass of each species does not come into play. In this case, the dispersion relation becomes symmetric such that if ω is solution then $-\omega^*$, its opposite complex conjugate, must also be solution. This is what was found. Therefore, the implementation of electrons, main ions and impurities has been checked with respect to each other, as well as passing versus trapped particles.

Benchmark of Kinezero versus GS2

GS2 has been widely successfully benchmarked with other gyrokinetic codes including collisions, magnetic perturbations effects and geometry effects. In particular it has been widely tested against the FULL code [kot], [bou2] and [bel]. The FULL codes solves the same equation as GS2 but uses a very different numerical scheme, therefore the fact that the same results are obtained with both codes is very comforting. GS2 took also part of the large benchmarking exercise using the cyclone base case [cyc]. Therefore GS2 is a very trustable code that can be used to compare Kinezero's results.
Before showing any benchmarking results, it is to notice here that the choices made in Kinezero to have a fast code are not compatible with a perfect quantitative agreement with respect to a gyrokinetic code that is solving the eigenfunctions self-consistently. GS2 has a wider range of validity than Kinezero, so for the benchmark exercise, GS2 is restricted to the Kinezero validity domain, i.e.: collisionless, s-α equilibrium, electrostatic. This benchmark exercise is published in [rom]. It has been done using two open source codes (GS2 and Kinezero) interfaced to an open database (the ITPA profile database) using open source interfacing tools (mdskize.m and gs2get.pro). So in principle anyone from the community can easily reproduce the exercise with the information given in appendix A1. A comparison of the difference in implementation between GS2 and Kinezero is given in Appendix A2,

Benchmark tests: See appendix A3 for details

- The impact of collisions on trapped electrons on the growth rates
- Initial test of the new collisionality model in Kinezero
- the impact of triangularity, δ, and elongation, κ: ongoing
- the impact of the magnetic shear on the mode widths (ongoing)

In summary: ….

Experimental Validation

Both Kinezero and GS2 have been extensively used to analyze experimental data. Both codes have a group of users, which are often experimentalists.
For GS2 see: Alcator C-mod [ern], NSTX [red] [bou2], JET [bud1] [bud2], DIII-D [ros], MAST [app]
For Kinezero see: Tore Supra [hoa], [bou1], [fen], JET [baa], [kir], TEXTOR [bou1], DIII-D, JT-60 U [bou5], FTU [rom].

References:

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Appendix A1: Input data

GS2 and Kinezero are directly interfaced with the ITPA database [db] through 2 tools that can be downloaded on the ITPA website: gs2get.pro for GS2 (C. Roach, [roa]) and mdskize.m for Kinezero (C. Bourdelle [bou6]).

The benchmark is based on data easily downloadable from the ITPA database by any member of the fusion community. The case chosen for the benchmark is the jet discharge #46664 at 45.1 s and r/a = 0.4.

Caveat:

The normalization has to be checked very carefully to be consistent between the two codes, in order to properly compare the results. In GS2, the normalization rules are chosen in the input file and they can vary widely. For example, k_θ can be normalized to

$$\rho_i = \frac{\sqrt{2T_i m_i}}{eB} \text{ or to } \rho s = \frac{\sqrt{T_i m_p}}{eB},$$

and the growth rates are or normalized to

$$V_i = \sqrt{\frac{2T_i}{m_i}} \text{ or to } c_s = \sqrt{\frac{T_i}{m_p}}.$$

The final results are given as growth rates in s^{-1} versus $k_\theta \rho_i$. In order to simplify the input data used, we have set Z_{eff} =1.

Appendix A2: Comparison of GS2 and Kinezero

Overview

Kinezero, [bou1] http://tokamak-profiledb.ukaea.org.uk/KZERO/KINEZERO.htm	GS2, [kot] http://gs2.sourceforge.net/
Electrostatic	Electromagnetic: $\delta\Phi$, $\delta A_{//}$, δA_{perp}
Linear	Linear and non-linear
Ions and electrons trapped and passing	ions and electrons trapped and passing
local (flux tube)	local : field-line following (Clebsch) coordinates
Vlasov + Maxwell	Vlasov + Maxwell
no collisions, soon collisions on trapped electrons	collisions on all species
analytic magnetic equilibrium of 's-α' type	Flexible Simulation Geometry: analytic 's-α' and Miller [mil] equilibria or numeric equilibrium from EFIT, TRANSP, JSOLVER, etc
use a trial gaussian eigenfunction with a width deduced from gyrofluid calculations similar to [big]	calculate the eigenfunction
finds all the eigenmodes	finds fastest growing (or least damped) eigenmode
~ 15 min on 1 processor for 50 modes	~ 30 min on ~ 200 processors for 10 modes
developed by Clarisse Bourdelle, Xavier Garbet, Claude Fourment, Chantal Passeron Association Euratom-CEA, Cadarache France	developed by Bill Dorland and Mike Kotschenreuther University of Maryland, University of Texas, USA
Analysis of data from : Tore Supra [hoa], [bou1], [fen], JET [baa], [kir], TEXTOR [bou1], DIII-D, JT-60 U [bou5], FTU [rom]	Analysis of data from: Alcator C-mod [ern], NSTX [red] [bou2], JET [bud1] [bud2], DIII-D [ros], MAST [app]

The main differences of Kinezero with respect to GS2 are further detailed below:

- Kinezero is an eigenvalue code; therefore it can find coexisting unstable modes. GS2 calculates only the fastest growing mode. The draw back of Kinezero's approach is that it cannot be extended to perform non-linear calculations contrarily to GS2.

- In Kinezero, the electrostatic potential eigenfunctions (no magnetic perturbation included) are approximated by trial Gaussian functions, whereas, in GS2, the eigenfunctions are solved. This Kinezero's approximation speeds up the code

substantially. Indeed, a run of about one hour on one CPU provides 150 values of the growth rates, approximately 380 times faster than a calculation performed with the code GS2 [kot] in the Kinezero validity limits. The computational efficiency of Kinezero allows extensive testing of the impact of various parameters on the microturbulence growth rates and on the thresholds.

- Kinezero uses only simplified circular shifted cross section s-α equilibrium. GS2 can handle any kind of magnetic equilibria. Therefore, the impact of the triangularity and elongation is correctly taken into account by GS2 but not by Kinezero.

- The collisionless approximation used so far in Kinezero is valid if the effective collisionality on trapped electrons, ν_{eff}, does not exceed the curvature drift frequency of the trapped electrons, $n\omega_K$ as defined in eq. (2). ν_{eff} is defined as the ratio ν_{ei} / ε, where ν_{ei} is the electron-ion collision frequency and $\varepsilon = r/R$. This approximation is valid in the scans presented in this section where ν_{eff} is at most equal to $1/10^{th}$ of $n\omega_K$. But we are now developing a version of Kinezero including the collisions on trapped electrons.

- In GS2 and Kinezero, the ballooning representation is used. The use of the ballooning representation implies that the distance between 2 resonating surfaces ($d = \nabla q / n$, q being rational) must be smaller than the width of the eigenfunction of the unstable modes, w : $d/w < 1$. The mode widths differ between the 2 codes. The width of the Kinezero Gaussian trial functions is calculated in a limit where the mode frequency, ω, is larger than any transit frequency along the field lines. This leads to w proportional to $1/\sqrt{s}$, see for example ref. [big]. So when s is low, since the ratio d/w scales like $1/\sqrt{s}$, the ballooning representation is not valid anymore. But the scaling of the mode width as $1/\sqrt{s}$ chosen in Kinezero is controversial. Indeed, recently, Connor and Hastie [con] have shown that in the limit, as s tends to zero, the lowest order ballooning equation does correctly describe stability. They show that extended ballooning modes do persist down to very low but finite values of constant magnetic shear, and in the case where there is a minimum q surface, except at the longest wavelengths. This observation is consistent with the findings of Waltz and Candy in [can] using a global, non-linear simulation. Therefore, contrarily to the findings in gyro-fluid calculations [gar], they do not predict any divergence of d/w when going to low s. So the choice of w made in Kinezero scaling like $1/\sqrt{s}$ could not be the most appropriate one. Indeed, in GLF23, a choice for d/w is such that at s=0, d/w does not diverge. C. Angioni says that this scaling is determined by GKS which is basically the same code as GS2. On the JAC, in cronos/Cronos/zineb/v2.2/coef/glf23/glf23_v1.61/glf2d.F line 440, one finds:

$$\frac{d}{w} \approx rms\_theta = \frac{\pi}{3}\left(\frac{T_e}{T_i}\right)^{1/4} \frac{1}{0.15\left(\frac{q}{2}-1\right)+1} \frac{1}{\left[1+0.4\left((s-\alpha)^2-\frac{1}{2}\right)+0.25\left(s-\alpha-\frac{1}{2}\right)^2\right]^{1/2}}.$$

So at s = 0, α=0, $T_i = T_e$ and q =2: $\frac{d}{w} \approx \frac{\pi}{3}$ which is still of order 1 but does not tend to infinity. This means that the choice made in Kinezero for the mode width based on gyrofluid calculations (equation (17) of [big]) and detailed in [bou1] might not be correct for a gyrokinetic calculation. This point has to be further studied.

Appendix A3: Results of the benchmark

In order to simplify the input data used, we have set Z_{eff} =1.

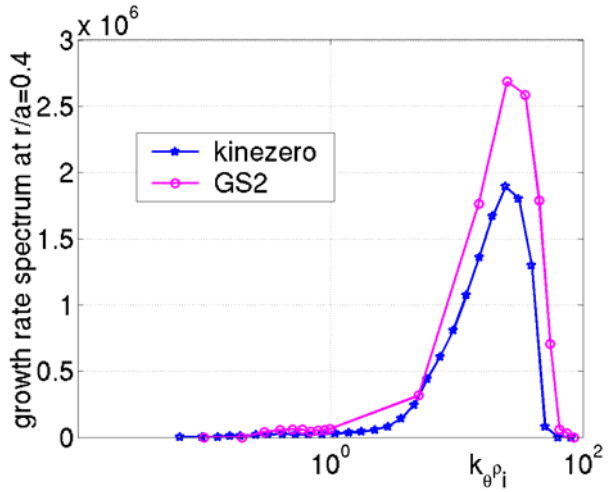

Fig. 1: Benchmark of two growth rates spectra for $k_\theta\rho_i$ up to 100, including therefore ITG-TEM and ETG modes, between Kinezero and GS2 on JET shot #46664 at 45.1 s and r/a = 0.4, with a Z_{eff} forced to 1.

The main differences between GS2 and Kinezero listed above: collisonless or not, mode width scaling with s, impact of triangularity and elongation, have to be tested. So that the users of these codes will know when one code is more appropriate than the other. Since Kinezero is faster, one would like to use it as often as possible, until the validity limits are hit.

The impact of collisions on trapped electrons on the growth rates

To test the impact of collisions, we are using high density FTU discharge, [rom]. This FTU discharge is available on the ITPA database web site, the input files are made using the same tools as for the benchmark case presented in Figure1.

Since Kinezero does not include collisions yet, we can only treat either non collisional cases where both Ion Temperature Gradient and Trapped Electron Modes are resonating or highly collisional cases which are equivalent to cases where the Trapped Electron Modes are off. In the FTU plasma, the collisions frequencies are so high, see Fig.2, that one can consider that the TEM are not active.

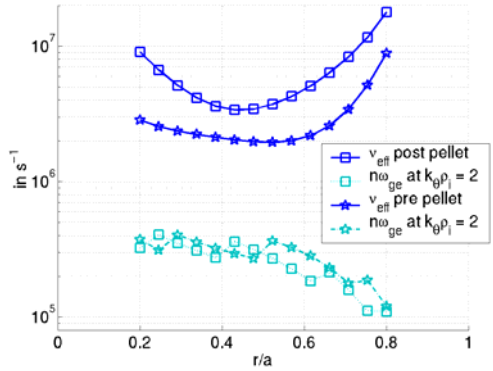

Fig. 2:Effective collision frequency, $\nu_{eff} = \nu_e / (r/R)$, figure 11, for FTU shot #12744 at 0.58 s, pre-pellet, and 0.85 s, post-pellet, compared to the electron vertical drift, $n\omega_{ge}$, at $k_\theta\rho_i = 2$, typical wave number of the TEM range.

A qualitative comparison between GS2 with and without collisions and Kinezero without and with TEM for the FTU shot 12747 is shown on figure 3. The maximum values over each growth rate spectra are similar in both codes, and a qualitative agreement between the codes is found. Indeed, both sets of results exhibit a destabilization due to density peaking, for the case without collision in GS2 and for the case treating both ITG modes and TEM in Kinezero. On the contrary, as expected, both sets of results exhibit a stabilization due to density peaking, for the highly collisional case in GS2, and for the case with TEM off in Kinezero.

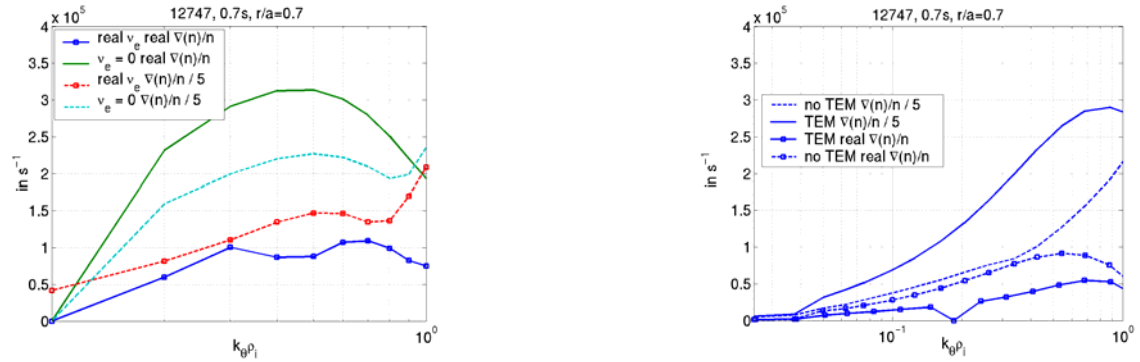

Fig. 3: Comparison of growth rates spectra for $k_\theta\rho_i < 1$ calculated by GS2, left figure, and Kinezero, right figure, on shot FTU #12747 at 0.7 s and r/a = 0.7. The impact of density peaking and collisionality are tested and compared with both codes.

Now we show the impact of collisions on TEM for collisionalities, ν_e, varying from 0 to twice the FTU level in the post-pellet phase using GS2, Fig. 4. For each ν_e, the impact of density peaking is tested by varying the actual normalized density gradient A_n from its real value to this value divided by 5. So, on Fig. 4, both impacts: density peaking and collisionality are tested. We see in this example that taking or not into account for collisions can change the conclusion on the impact of density peaking on the microstability, since for $\nu_e = 0$ density peaking is destabilizing whereas it is stabilizing at the real ν_e.

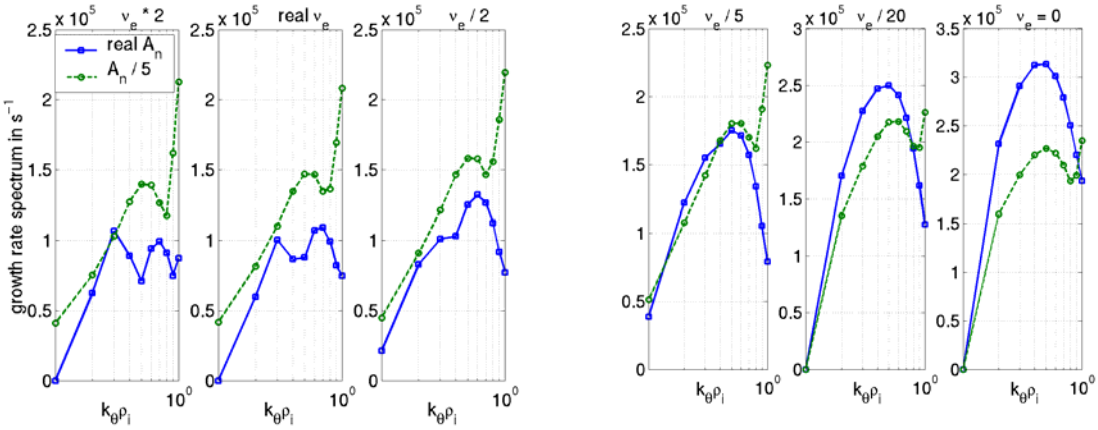

Fig. 4: GS2 growth rate of instabilities varying $k_\theta\rho_i$ from 0.1 to 1 at r/a = 0.7 of FTU #12747. From left to right, the electron collisionality goes from twice its experimental value to 0. On each graph, the full line with open squares is the spectrum for the experimental value of the density peaking, A_n, and the dashed line with open circles stands for the same case but with $A_n/5$.

Initial test of the new collisionality model in Kinezero

So having studied the important impact of collisions on the microstability analysis, we (G. Regnoli, M. Romanelli and myself) have included the collisions on trapped electrons in Kinezero. The first results are convincing, since the impact of collisions on the growth rates given by Kinezero is very similar to the one observed with GS2, as shown on figure 5.

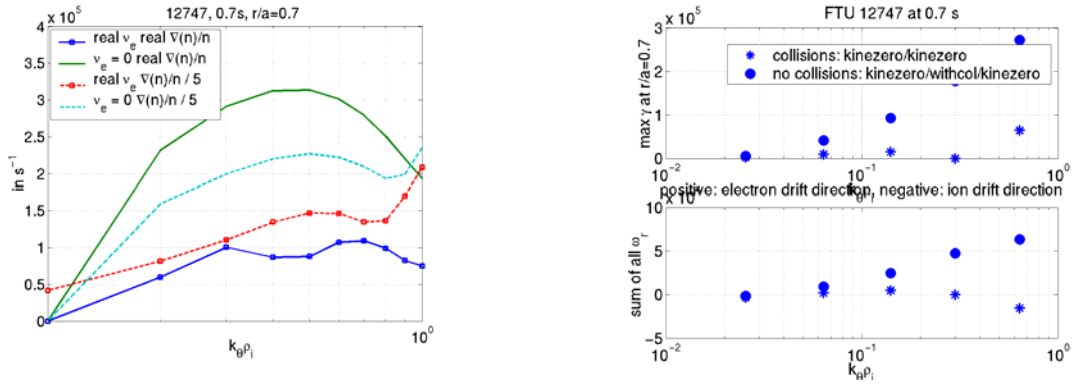

Fig. 5: Comparison of growth rates spectra for $k_\theta\rho_i < 1$ calculated by GS2, left figure, and Kinezero with collisions for the real density gradient only, right figure, on shot FTU #12747 at 0.7 s and r/a = 0.7.

The impact of triangularity, δ, and elongation, κ:

Plan: test the limits of the s-alpha equilibrium on a JET case, getting from s-alpha to Miller [mil] equilibrium in GS2 and see how much the growth rates change. This will allow to discuss the δ and κ impact on a given test case.
Status: GS2 jobs submitted for the JET ELMy H mode discharge 57987 at 22s with $Z_{eff} = 1$. The Miller equilibrium is used and δ and κ are varied from their real values to these values divided and multiplied by 2, the case with δ = 0 and κ = 1 is also ran for comparison with Kinezero.

The impact of the magnetic shear on the mode widths

Plan: to compare the eigenfunction of GS2 that is consistently solved, with the trial functions used in kinezero. In particular, I would like to see how the width of these functions changes with the magnetic shear. This might be a crucial point in the validity of the local approach. As discussed above some contradictory results have been recently published ([gar], [can], [con]). I would like to understand and discuss that open issue more carefully looking at GS2 eigenfunctions while changing s, and eventually proposing some improvements for Kinezero gaussian trial eigenfunctions width.
Status: GS2 jobs submitted for the JET ELMy H mode discharge 57987 at 22s with $Z_{eff} = 1$, using the Miller equilibrium. I am then changing s from s/16, s/4, s*4, s*16. So that I will see the impact on the eigenfunctions widths due to s and compare with the scaling proposed in GLF23.