A linear benchmark between HYMAGYC, MEGA and ORB5 codes using the NLED-AUG test case to study Alfvénic modes driven by energetic particles

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(MET Enabling Research Project 2019-2020 (https://afs.enea.it/ zonca/METproject/index.html) and more...**)**

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ABSTRACT

- In the frame of the EUROfusion ENR project MET [1](Multi-scale Energetic particle Transport in fusion devices), a detailed benchmark activity has been undertaken among few of the state-of-the-art codes available to study the self-consistent interaction of an EP population with the shear Alfvén waves, in real magnetic equilibria and in regimes of interest for the forthcoming generation devices
- The codes considered are HYMAGYC [2], MEGA [3], and ORB5 [4], the first two being hybrid MHD-Gyrokinetic codes (bulk plasma is represented by MHD equations, while the EP species is treated using the gyrokinetic formalism), the third being a global electromagnetic gyrokinetic code (both bulk and EP species are treated using the gyrokinetic formalism)
- Here we decided to use a realistic, shaped cross section, equilibrium from AUG proposed by Philipp Lauber (so-called NLED-AUG [5] test case), considering both peaked on-axis and off-axis EP density profiles

Characterization of Alfvénic spectra ($|\varphi(s,\omega)|^2$) in MHD limit

- Toroidal mode number n=1, no EP drive • MEGA (left) and HYMAGYC (right) show very similar

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B_0 = 2

R_0/a =

n_{e0} = (

n_{H0} =

n_{i0} = (

ω_{A0} =

Benchmark equilibrium and code parameters

- the same input equilibrium file (EQDSK) has been considered for all the codes
- ion density profile has been obtained by imposing quasi-neutrality ($n_i + n_H = n_e$), as required by ORB5 (n_i, n_e, n_H being the bulk ions, electrons, and EP densities, respectively, both bulk ions and EPs are assumed to be Deuterons)
- finite resistivity $\eta/(\mu_0 R_0 v_{A0})=5\times10^{-7}$, and adiabatic index $\Gamma=5/3$ have been assumed for both the hybrid codes (HYMAGYC and MEGA); MEGA also consider finite viscosity $\nu/(R_0 v_{A0})=5\times10^{-7}$
- only Finite orbit width (FOW) effects has been retained and isotropic Maxwellian EP distribution function of Deuterons with T_H =93 keV, constant in radius
- Other typical parameters for the two scenarios considered (AUG peaked on-axis, and AUG peaked off-axis EP density profiles) are ("0" pedix means on-axis values):

B_0 = 2.208 [T], $I_p = 8.1434\times10^5$ [A],
R_0/a =1.666 [m]/0.483 [m],
n_{e0} = 0.171587 [$10^{20}/m^3$],
n_{H0} = (0.03552, 0.00458182) [$10^{20}/m^3$],
n_{i0} = (0.136067, 0.16700518) [$10^{20}/m^3$],
ω_{A0} = (5.53876, 4.99947) [10^6 rad/s],

$v_{H,th0}$ = 2.1111 [10^6 m/s],
ϱ_{H0} = 0.0199221 [m],
n_{H0}/n_{i0} = (0.261048, 0.0274352),
$v_{H,th0}/v_{A0}$ = (0.228782, 0.253461),
ϱ_{H0}/a = 0.041279.

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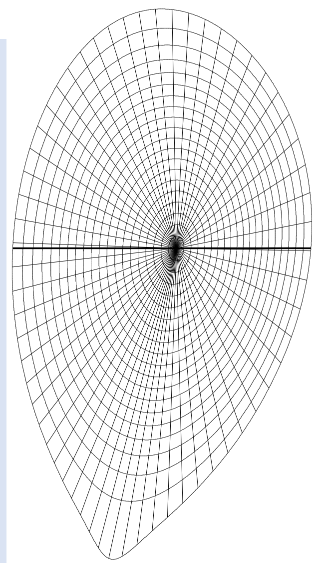
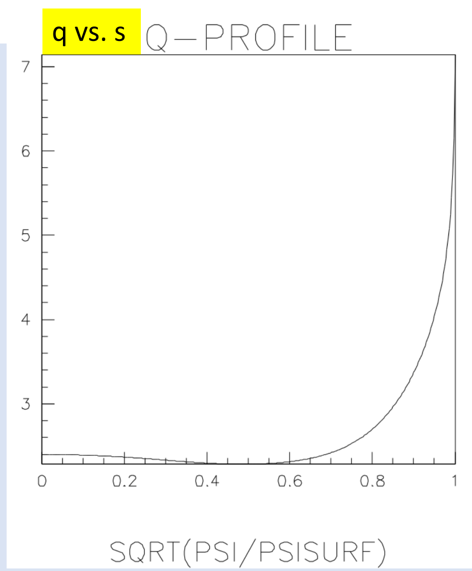
ng.

A ORB5

ω_{MEGA} [kHz]	$\gamma^{\dagger}_{ORB5}$ $[s^{-1}]$	$\omega^{\dagger}_{ORB5}$ [kHz]
-171.9	$\approx -10000.$	-146.
-185.2	$\approx -6000.$	-206.
-304.2		





Characterization of Alfvénic spectra ($|\varphi(s,\omega)|^2$) in MHD limit-1

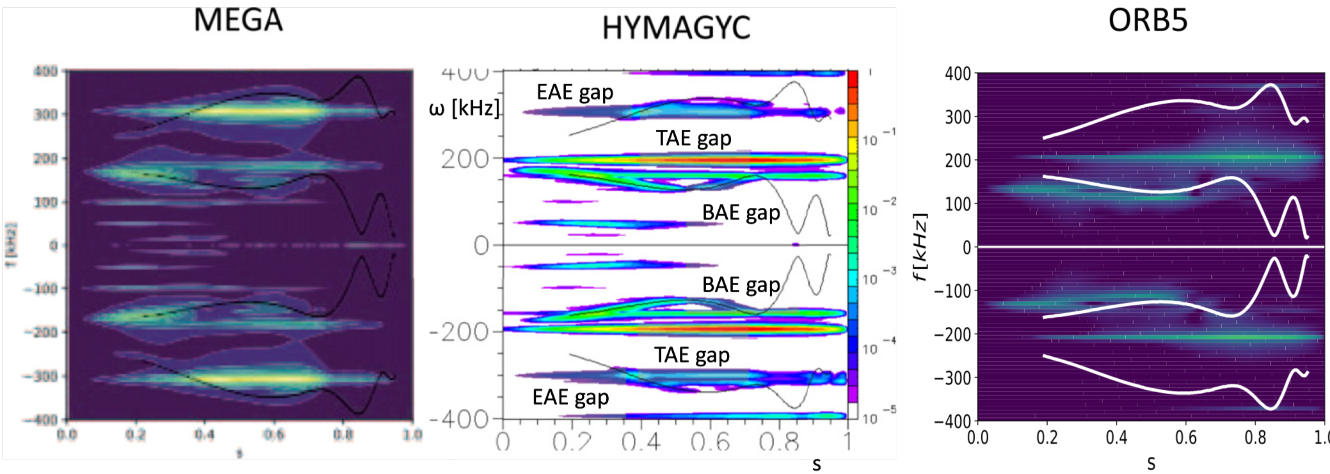


Figure 6. Frequency spectra in the MHD limit for MEGA (left), HYMAGYC (centre), and ORB5 (right). Logarithmic color scale is used for the intensity of the e.s. field $|\varphi(s,\omega)|^2$. Shear Alfvén continuous spectra are also shown using black continuous lines for the MEGA and HYMAGYC spectra, and as white continuous lines for the ORB5 spectra, as obtained by the FALCON code. In the central frame the main gaps are also indicated for reference.

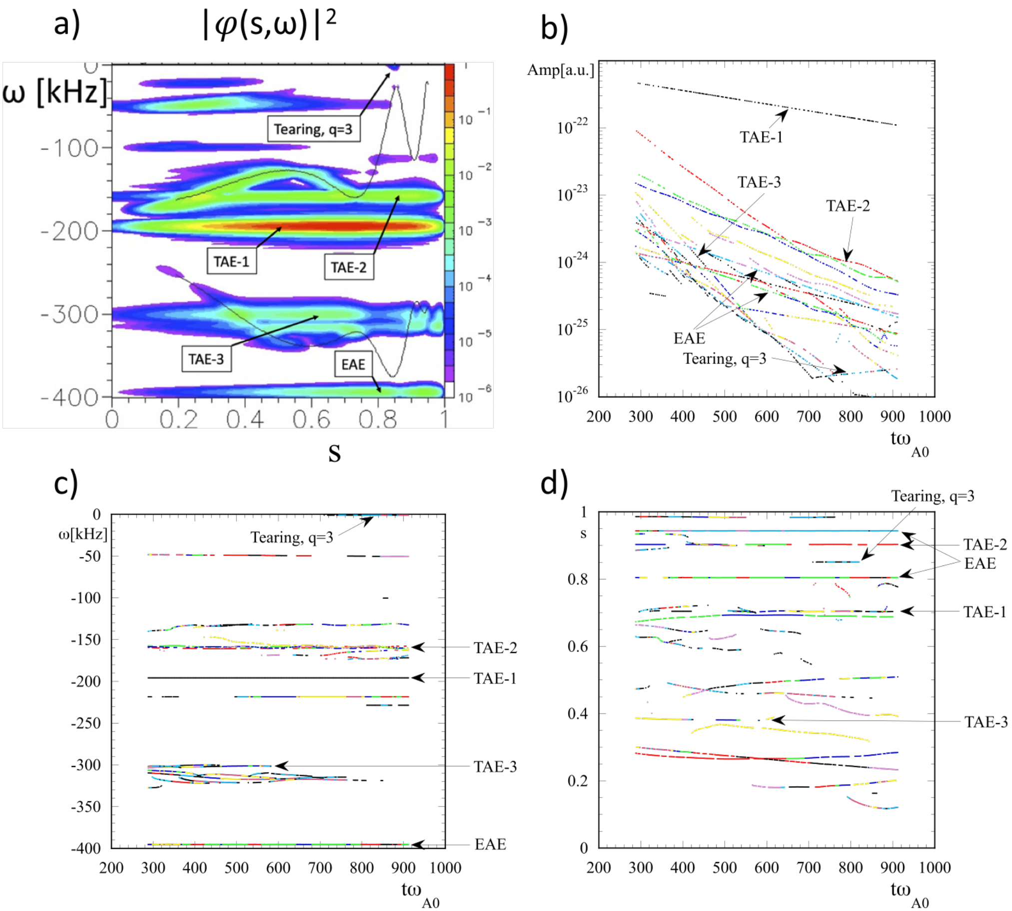
Table 4. Growth rates (s^{-1}) and real frequencies (kHz) of some of the modes observed in figure 6, corresponding to the HYMAGYC, MEGA and ORB5 purely MHD simulations, on-axis AUG reference case.

Mode	$\gamma_{\mathrm{HYMAGYC}}$ (s^{-1})	$\omega_{\mathrm{HYMAGYC}}$ (kHz)	γ_{MEGA} (s^{-1})	ω_{MEGA} (kHz)	$\gamma^{a}_{\mathrm{ORB5}}$ (s^{-1})	$\omega^{a}_{\mathrm{ORB5}}$ (kHz)
Tearing-$q=3$	4080.2	0.0				
TAE-2	−14594.6	−159.2	−45060.0	−171.9	≈ −10000	−146
TAE-1	−6455.3	−195.8	−36057.0	−185.2	≈ −6000	−206
TAE-3	−29484.2	−301.4	−30120.0	−304.2		
EAE	−13542.3	−395.8				

[a]Note that for the ORB5 simulation, $n_i = n_e$ has been considered, whereas both HYMAGYC and MEGA assume $n_i = n_e - n_{h,on-axis}$, with $n_{h,on-axis}$ the peaked on-axis EP density, while neglecting the EP contribution in the fluid equations.

Characterization of Alfvénic spectra ($|\varphi(s,\omega)|^2$) in MHD limit-2

Nucl. Fusion **61** (2021) 116026 G. Vlad *et al*



animated gif:
.../casi_AUG_monotonic-BM-2020-scaled_n_H/
caso_AUG-monotonic-BM-2020-T_H0.093_scaled_n_H_MHD/
an_wt_ph_ipow2_DT576_w_-400_0_log6_falcon_kHz.gif

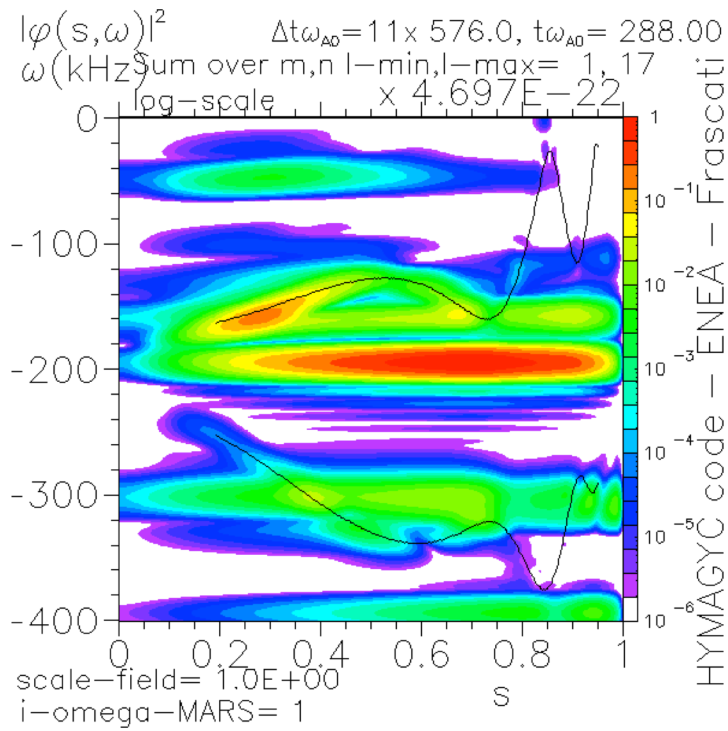


Figure 7. Frequency power spectra of the e.s. field $|\varphi(s,\omega)|^2$ for the HYMAGYC simulation shown in figure 6 (only negative portion of the frequency plane), with the identification of the dominant modes observed (*a*). Amplitude (*b*), frequency (*c*), and radial position (*d*) versus time of the relative maxima of the frequency spectra of the HYMAGYC simulation shown in (*a*). A fixed sequence of colors (related to the values of the $amp_{rel.\ max.}(t)$: black the highest value, red the second highest, and then green, blue, yellow, violet and cyan, and then cycled) is used for each time; the same colors of the dots are used also for the other plots (*c*) and (*d*), to help the identification of the modes.

Nucl. Fusion **61** (2021) 116026 G. Vlad *et al*

Table 4. Growth rates (s^{-1}) and real frequencies (kHz) of some of the modes observed in figure 6, corresponding to the HYMAGYC, MEGA and ORB5 purely MHD simulations, on-axis AUG reference case.

Mode	$\gamma_{HYMAGYC}$ (s^{-1})	$\omega_{HYMAGYC}$ (kHz)	γ_{MEGA} (s^{-1})	ω_{MEGA} (kHz)	γ^a_{ORB5} (s^{-1})	ω^a_{ORB5} (kHz)
Tearing-$q = 3$	4080.2	0.0				
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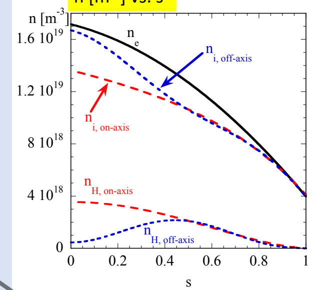
TAE-3	−29484.2	−301.4	−30120.0	−304.2		
EAE	−13542.3	−395.8				

Density profiles

n [m^{-3}] vs. s

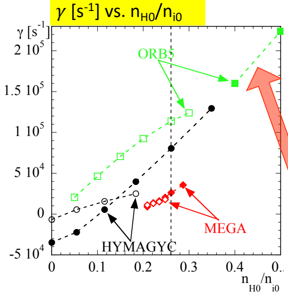


peaked on-axis EP density profile

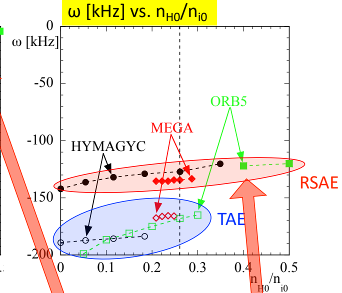
EP density scan

peaked on-axis EP density profile

γ [s^{-1}] vs. n_{H0}/n_{i0}



ω [kHz] vs. n_{H0}/n_{i0}

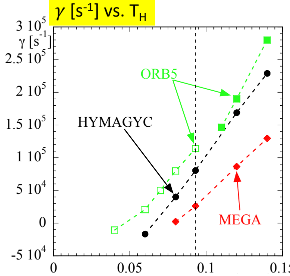


- All codes observe as most unstable mode:
  - a TAE for low values of n_{H0}/n_{i0},
  - a RSAE for high values of n_{H0}/n_{i0}.

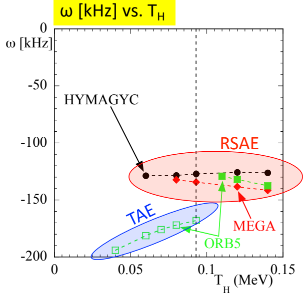
EP T_H scan

peaked on-axis EP density profile

γ [s^{-1}] vs. T_H

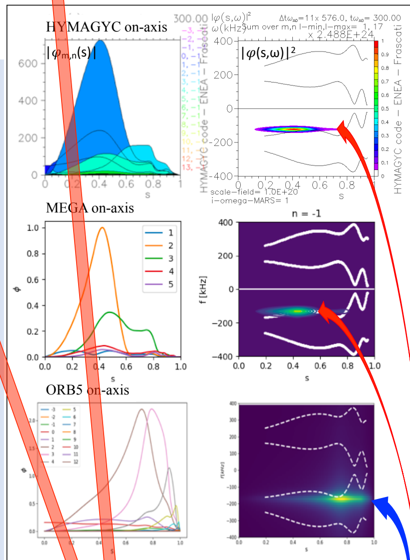


ω [kHz] vs. T_H



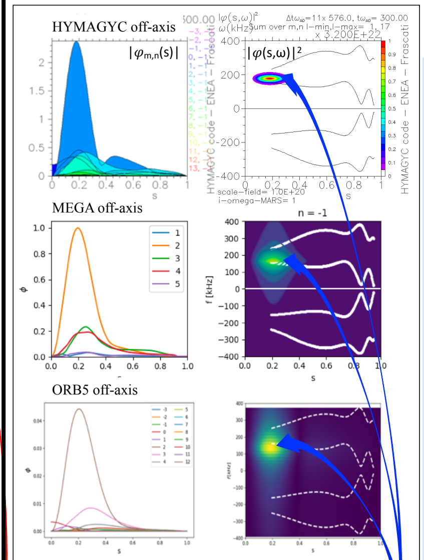
Nominal cases comparison, n=1

- Toroidal mode number n=1



- Peaked on-axis EP density profile
- HYMAGYC and MEGA observe a Reversed Shear Alfvén mode (RSAE)
- ORB5 observes an external TAE

(note that RSAE appears at higher EP densities!)



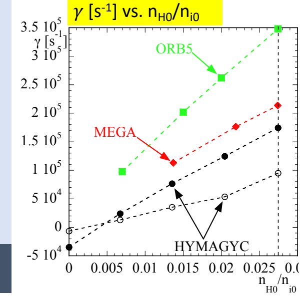
- Peaked off-axis EP density profile
- All the codes observe a core TAE

peaked off-axis EP density profile

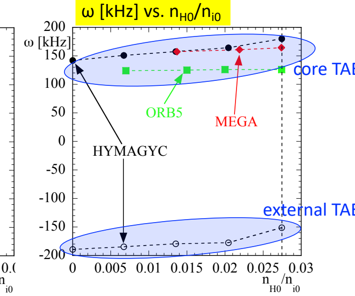
EP density scan

peaked off-axis EP density profile

γ [s^{-1}] vs. n_{H0}/n_{i0}



ω [kHz] vs. n_{H0}/n_{i0}

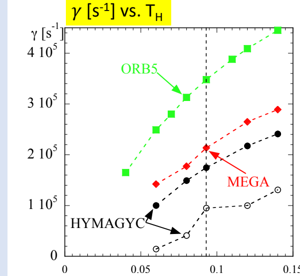


- All codes observe a core TAE;
- HYMAGYC observes also a (weaker) external TAE

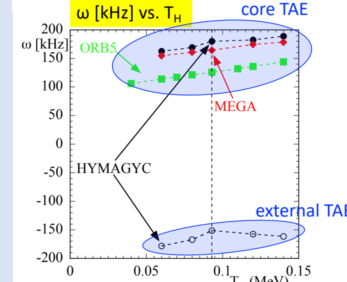
EP T_H scan

peaked off-axis EP density profile

γ [s^{-1}] vs. T_H



ω [kHz] vs. T_H



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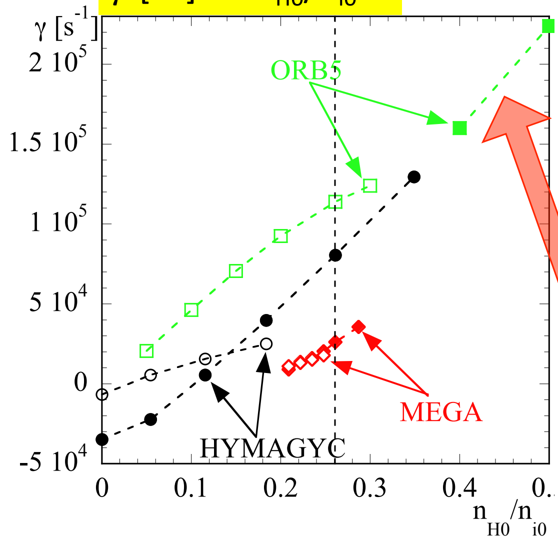
peaked on-axis EP density profile

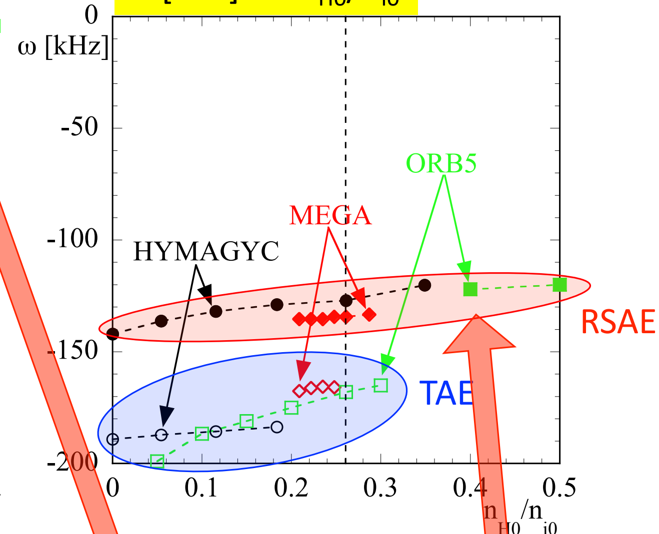
EP density scan

peaked on-axis EP density profile

γ [s^{-1}] vs. n_{H0}/n_{i0}



ω [kHz] vs. n_{H0}/n_{i0}

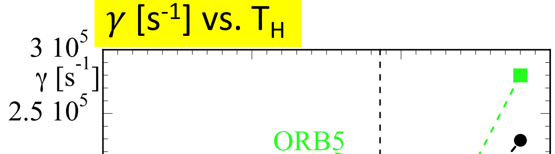


- All codes observe as most unstable mode:
  - a TAE for low values of n_{H0}/n_{i0},
  - a RSAE for high values of n_{H0}/n_{i0}.

EP T_H scan

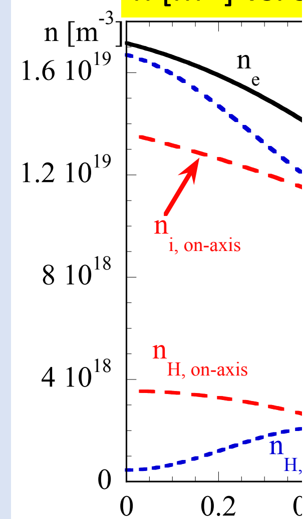
peaked on-axis EP density profile

γ [s^{-1}] vs. T_H



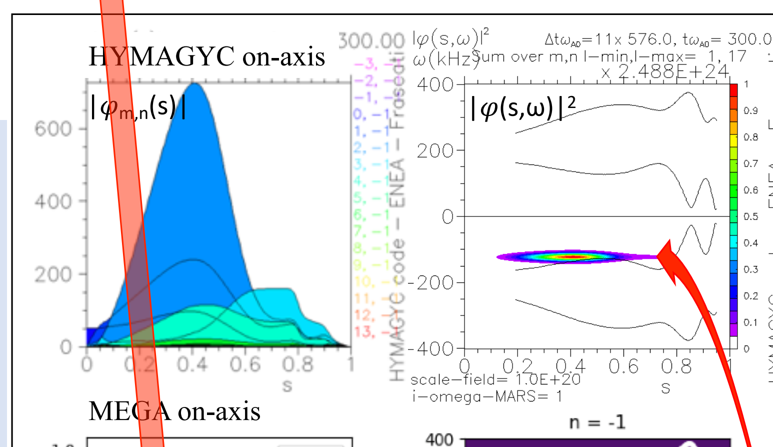
Densit

n [m^{-3}] vs. s



Nominal cases

- Toroidal mo



Peaked on-axis EP density profile case: energetic particle density scan

Nucl. Fusion **61** (2021) 116026 G. Vlad *et al*

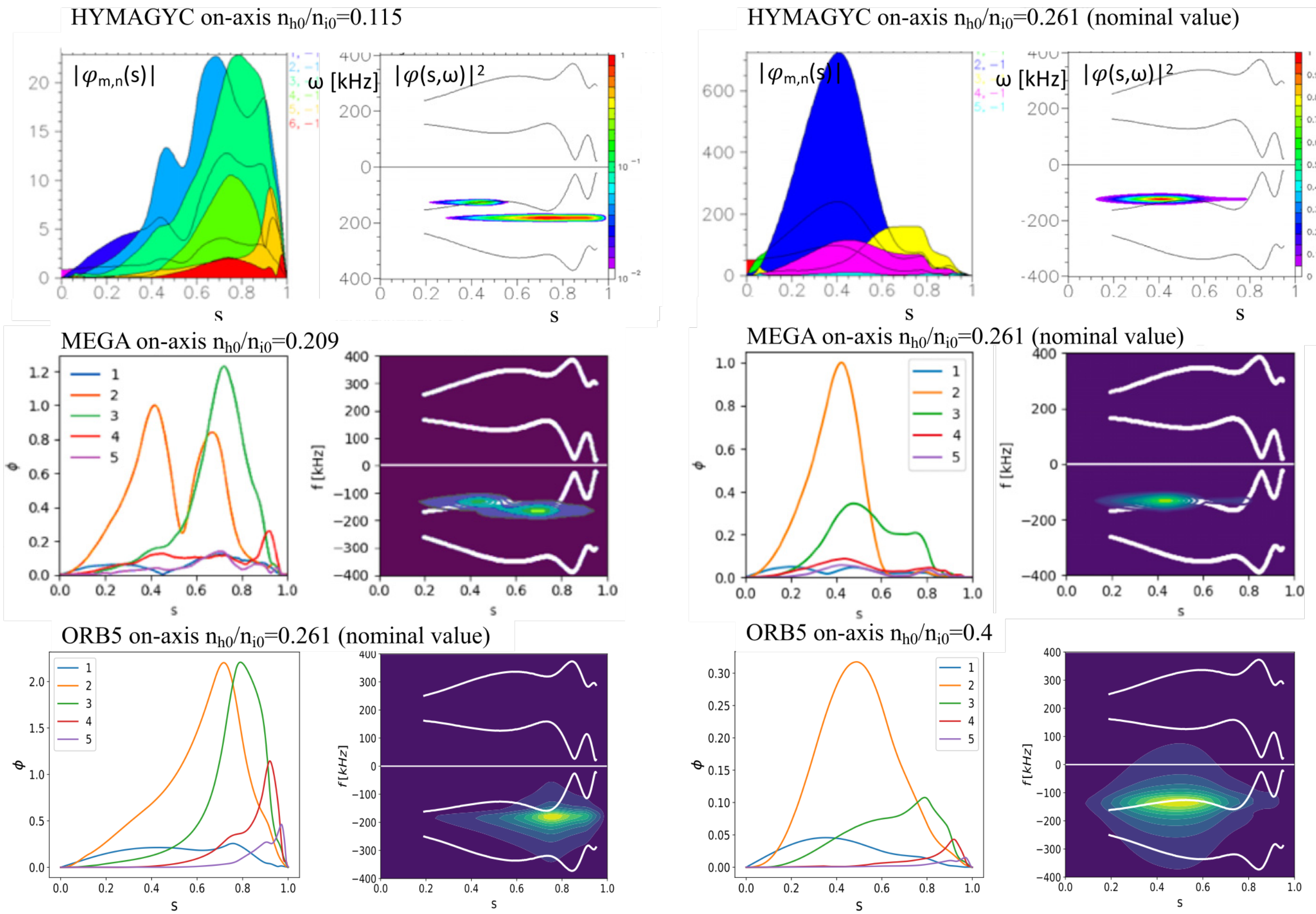
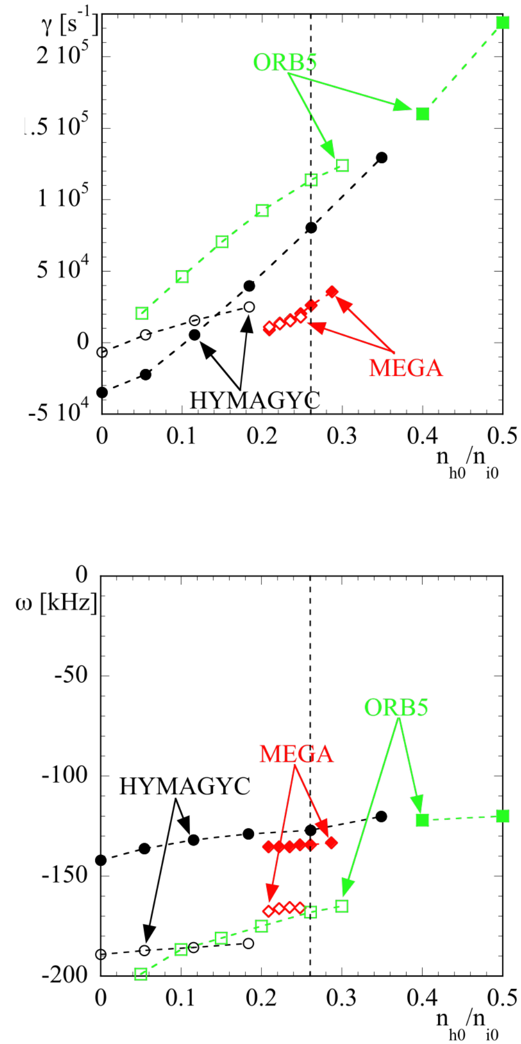


Figure 11. TAE solution (left) and RSAE solution (right) as obtained by HYMAGYC (top), MEGA (middle), and ORB5 (bottom) at 'low' values of EP density (left column), and 'high' density (right column). Note that the values of n_{h0}/n_{i0} varies for each plot; note also that some of the plots shown in this Figure are the same of figure 8 and are reported here for the ease of the reader.



Peaked on-axis EP density profile case: energetic particle drive

Nucl. Fusion **61** (2021) 116026 G. Vlad *et a*

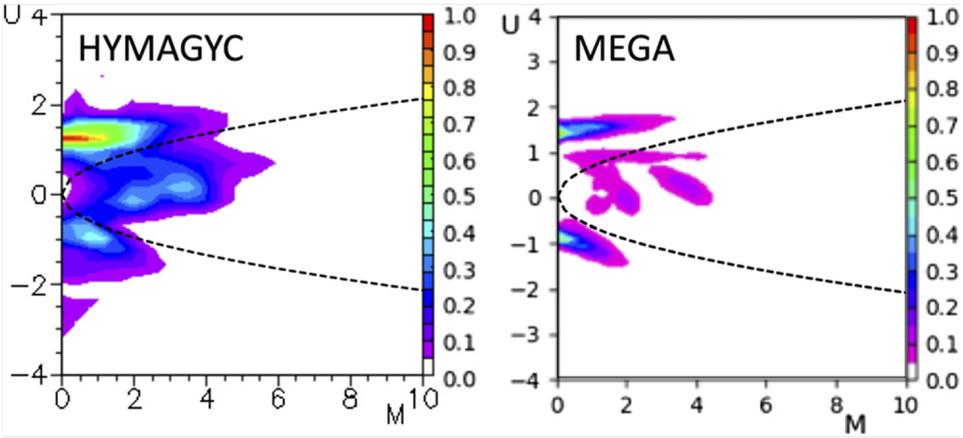


Figure 9. Wave-particle power exchange in the plane $[U, M]$ for the nominal case parameter, peaked on-axis EP density profile. Here U is the normalized (to the EP thermal velocity) EP parallel velocity, and M is the normalized (to T_h/Ω_{h0}, with Ω_{h0} the on-axis EP cyclotron frequency) EP magnetic moment. HYMAGYC result is shown on the left, and MEGA result on the right; red pattern indicates maximum power exchange from EPs to the wave. Also the approximate boundary between trapped and circulating particles (co-passing for positive U values, counter-passing for negative U ones) is drawn, corresponding to the radial region where the mode is maximum ($s \approx 0.4$).