Benchmarks between HYMAGYC, HMGC, MEGA and ORB5 on Alfvénic modes driven by Energetic Particles

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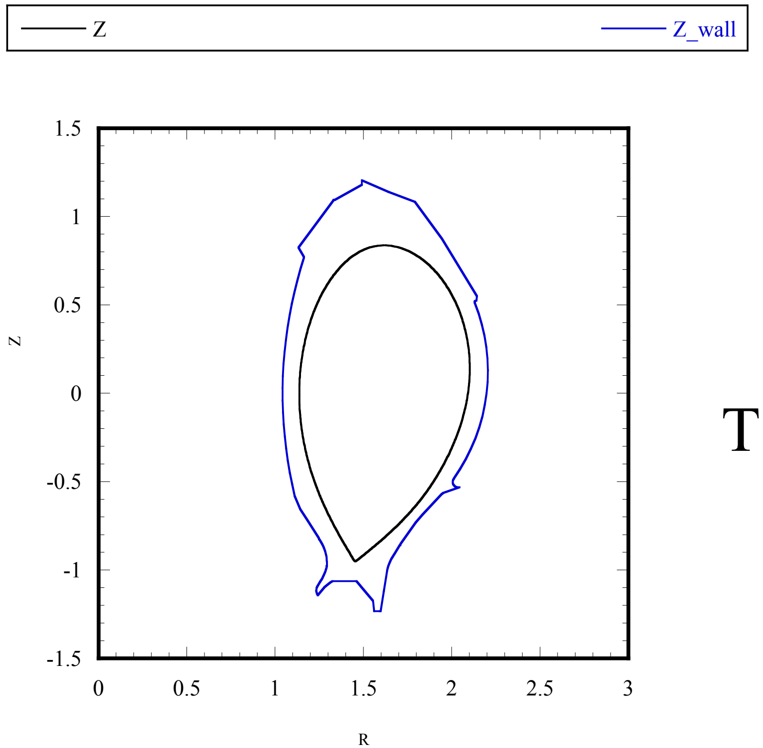
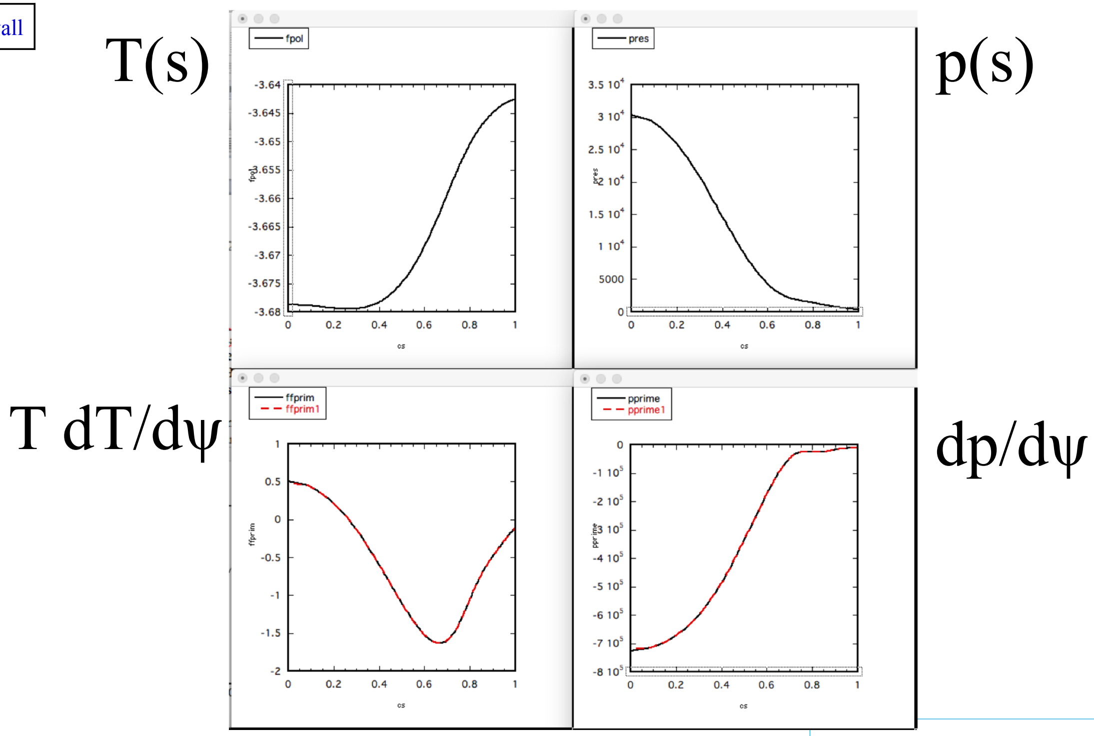
Introduction

- AUG test case proposed by Philipp Lauber
- Shot considered is AUG #31213, at t=0.84s (shortly, #31213@0.84s), see http://www2.ipp.mpg.de/~pwl/NLED_AUG/data.html
- In order to use such test case to benchmark HYMAGYC on a realistic, fully shaped equilibrium, we have considered the experimental EQDSK g031213.00003 (after some iteration with Philipp):





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Introduction

From IAEA FEC2020 synopsis:

One of the major challenges in magnetic confinement thermonuclear fusion research concerns the confinement, inside the reaction chamber, of the energetic particles (EPs) produced by fusion reactions and/or by additional heating systems, as, e.g., electron and ion cyclotron resonant heating, and neutral beam injection. In such experiments, EPs, having their velocities of the order of the Alfvén velocity, can resonantly interact with the shear Alfvén waves. In order to predict and, eventually, minimize the Energetic Particle (EP) transport in the next generation fusion devices, several numerical models, based on different theoretical approaches, have been developed. In this respect, it is crucial to cross verify and validate the different numerical instruments available in the fusion community. For this purpose, in the frame of the Enabling Research project MET [1], 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 in regimes of interest for the forthcoming generation devices (e.g., ITER [2], JT-60SA [3], DTT [4]). The codes considered in this exercise are HYMAGYC [5], MEGA [6], and ORB5 [7, 8], 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).

Setting up of the benchmark equilibrium and parameters

The so-called NLED-AUG [9] reference case has been considered, both for the peaked off-axis and peaked on-axis EP density profile cases, using its shaped cross section version. This case poses an exceptional challenge to the codes due to its high EP pressure, the rich spectrum of experimentally observed instabilities and their non-linear interaction [10].

Particular care has been devoted to consider plasma and numerical parameters as close as possible among the three codes: the same input equilibrium file (EQDSK) has been considered, ion density profile has been obtained by imposing quasi-neutrality ($Z_i n_i + Z_H n_H = n_e$), as required by ORB5 (here n_i, n_e, n_H are the bulk ions, electrons, and EP densities (both bulk ion and EPs are assumed to be Deuterons), respectively, and Z_i, Z_H their electric charge numbers); finite resistivity η and the adiabatic index, $\Gamma = 5/3$, have been assumed for both the hybrid codes (this is the usual choice used in MEGA, where also some viscosity is considered to help numerical convergence; note that HYMAGYC do not include viscosity).

Only finite orbit width (FOW) effects has been retained for now, and an isotropic Maxwellian EP distribution function of Deuterons with T_H =93 keV, constant in radius, has been considered.

AUG experimental reference case #31213

From Ph. Lauber notes, NLED_AUG_benchmark_case.pdf:

ASDEX Upgrade

ASDEX Upgrade: early off-axis NBI drive [93keV]: bursting EGAMs, RSAEs and TAE/EPMs

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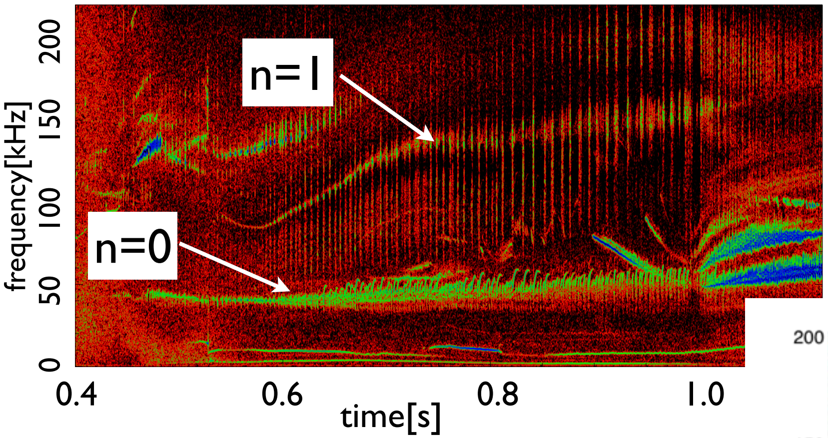
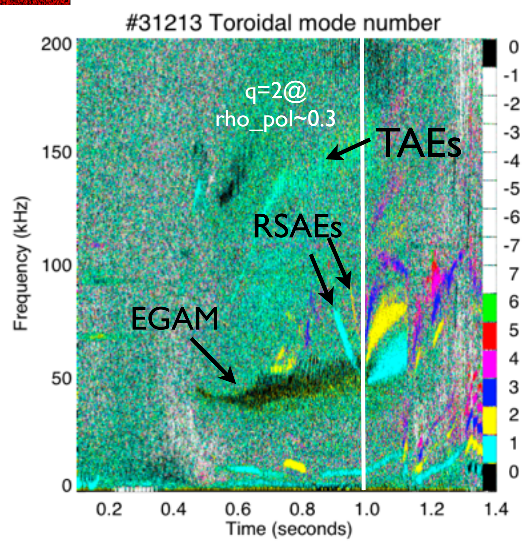


[July 2014]

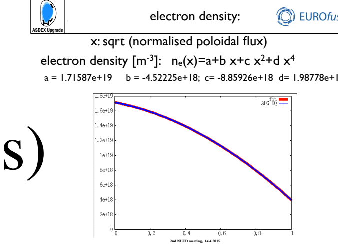
B0=2.2T
I=0.6-1.0MA
P_{beam}=2.5MW



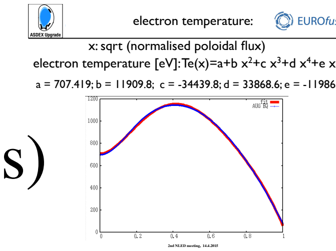
- rather well reproducible scenario
- no 'sea' of Alfvenic modes (TAEs/RSAEs)
- but strongly chirping n=0 modes and n=1 'bursts'

2nd NLED meeting, 14.4.2015

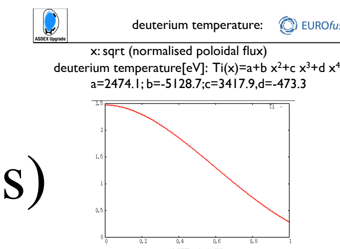
$n_e(s)$



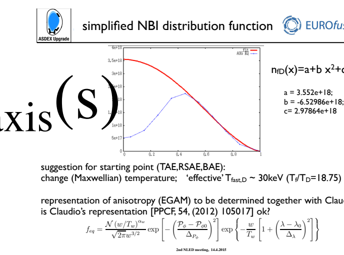
$T_e(s)$



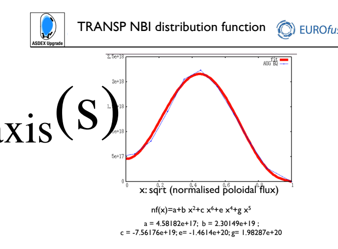
$T_i(s)$



$n_{H,on-axis}(s)$



$n_{H,off-axis}(s)$



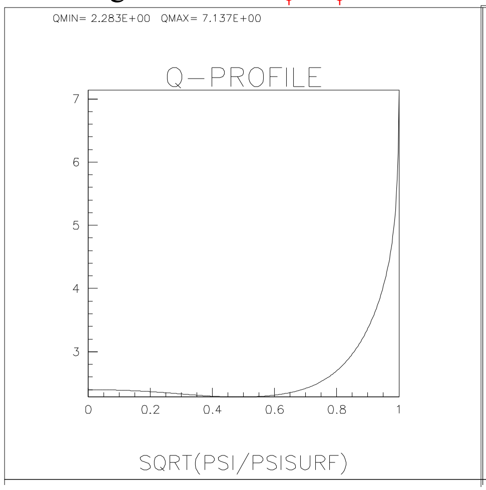
Equilibrium reconstruction

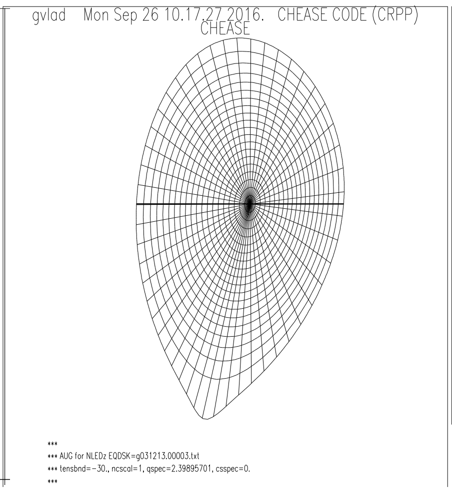
From https://www.afs.enea.it/vlad/Miscellaneous/Benchmark_AUG_testcase_MEGA_ORB5_HYMAGYC_2019/

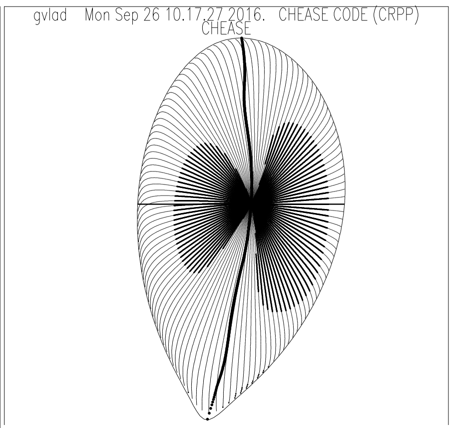
- The file EQDSK g031213.00003 has been used to reconstruct the experimental equilibrium with CHEASE:
  - magnetic field normalization B_0, and length R_0 used in g031213.00003: $B_0=B_{magnetic\text{-}axis}$= -0.220811798E+01, $R_0=R_{magnetic\text{-}axis}$=0.166599977E+0
  - some parameters used in CHEASE:
    - NTMF0=1
    - assign q(s=0) to on-axis q value found in g031213.00003: required to have an "open" toroidal gap: NCSCAL=1, QSPEC=2.39895701, CSSPEC=0.
    - add some smoothing to the boundary to make CHEASE converge more easily: TENSBND=-30.
  - in HYMAGYC (and MARS) use Jacobian: $J \sim R/|\nabla\psi|$
  - Consider an equivalent equilibrium with $B_0 \Rightarrow |B_{magnetic\text{-}axis}|$ and the toroidal current parallel to the toroidal magnetic field: $I_\phi // B_\phi$

Quantity	Value (peaked on-axis case)	Value (peaked off-axis case)	Data definition/Origin
B_mag [T]	2.20811798	2.20811798	EQDSK, magnetic field on the magnetic axis (R=R_mag)
R_mag [m]	1.66599977	1.66599977	EQDSK, magnetic axis major radius
B0 [T]	B0=B_mag	B0=B_mag	normalization coefficient for the magnetic field
R0 [m]	R0=R_mag	R0=R_mag	normalization coefficient for the lengths
R_geo [m]	1.62	1.62	geometric major radius (R_LCMS_max+R_LCMS_min)/2
a [m]	0.48262	0.48262	minor radius (R_LCMS_max-R_LCMS_min)/2
epsilon_dev [m]	0.297898	0.297898	inverse Aspect ratio (a/R_geo)
n_e0 (n_e(s=0)) [10^20/m^3]	0.171587	0.171587	p.17 NLED_AUG_benchmark_case.pdf
n_EP0 (n_EP(s=0)) [10^20/m^3]	0.03552	0.00458182	p.21/p.20 NLED_AUG_benchmark_case.pdf
n_i0 (n_i(s=0)) [10^20/m^3]	0.136067	0.16700518	from n_i(s=0)=n_e(s=0)-n_H(s=0)
n_EP0/n_i0	0.261048	0.0274352	EP density/bulk ion density
m_i/Z_i	2/1	2/1	bulk ion mass/charge (D) (in units of proton mass/electron charge)
m_EP/Z_EP	2/1	2/1	EP mass/charge (D) (in units of proton mass/electron charge)
m_EP/m_i	1	1	mass ratio (EP/bulk ion)
T_EP0 [MeV]	0.093	0.093	on-axis EP Temperature (constant on radius), Maxwellian distribution
v_A0 [m/s]	9.22757x10^6	8.32911x10^6	on-axis Alfvén velocity => 2.18x10^6 B_axis[T]/sqrt(m_i n_i0[10^20/m^3])
tau_A0 [s]	1.80546x10^-7	2.00021x10^-7	R0/v_A0
omega_A0 [rad/s]	5.53876x10^6	4.99947x10^6	1/tau_A0
v_EPth0 [m/s]	2.1111x10^6	2.1111x10^6	sqrt(T_EP0/m_EP) => 9.79x10^6 sqrt(T_EP0[MeV]/m_EP) note the definition w/o sqrt(2)!
v_EPth0/v_A0	0.228782	0.253461	
omega_ci [rad/s]	1.057688x10^8	1.057688x10^8	EP gyrofrequency => 9.58x10^7 Z_EP B0[T]/m_EP
rho_EP0 [m]	0.0199221	0.0199221	on-axis EP Larmor radius (v_EPth0/omega_ci) => 0.102 sqrt(m_EP T_EP0[MeV])/Z_EP/B0[T]
rho_EP0/R0	0.011958	0.011958	on-axis EP Larmor radius/R0
rho_EP0/a	0.041279	0.041279	on-axis EP Larmor radius/a

Table 1.







Codes and constrains

- MEGA: Hybrid MHD-Gyrokinetic (bulk: nonlinear MHD, Energetic Particles: GK, coupling term through EP current density j'_H)

[Todo, Y. & Sato, T. Linear and nonlinear particle-magnetohydrodynamic simulations of the toroidal Alfvén eigenmode. Phys. Plasmas 5, 1321–1327 (1998); Todo, Y., Shinohara, K., Takechi, M. & Ishikawa, M. Computer simulation of frequency sweeping of energetic particle mode in a JT-60U experiment. J. Plasma Fusion Res. 79, 1107–1108 (2003)]

Main features: (R, Z) coordinates (flux coordinates for analysis), includes resistivity η, viscosity ν, adiabatic index Γ in the MHD solver

- ORB5: Fully Gyrokinetic, electromagnetic (bulk (e, i) & Energetic Particles: GK) [E. Lanti et al., Computer Physics Communications (2019)]
- HYMAGYC: Hybrid MHD-Gyrokinetic (bulk: linear, resistive, full MHD, Energetic Particles: GK, coupling term through divergence of EP pressure tensor)) [G. Fogaccia, G. Vlad, S. Briguglio, Nucl. Fusion 56 (2016) 112004]

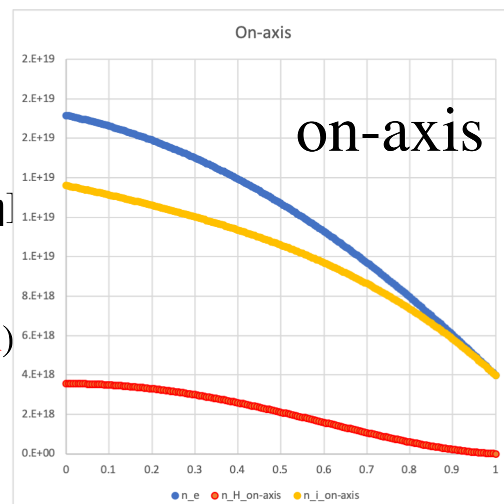
Main features: (s, χ, ϕ) flux coordinates, generalized curvilinear coordinates, can include, in the MHD solver: resistivity η , adiabatic index Γ, (but no viscosity)

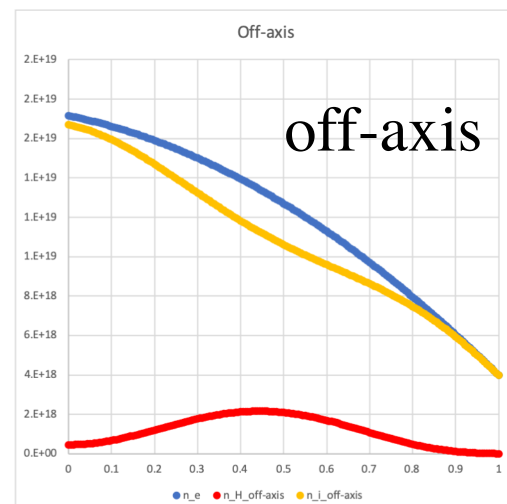
We consider, for the purpose of this benchmark, only Finite Orbit Width (FOW) effects, neglecting Finite Larmor radius (FLR) ones.

Parameters required by each code:

- MEGA: norm. resistivity $S^{-1}_{MEGA}=5\times10^{-7}$ [MEGA units: $S_{MEGA}=\mu_0 R_0 v_{A0}/\eta$, $S_{HYMAGYC}=\mu_0 (a^2/R_0) v_{A0}/\eta$] (HYMAGYC-MEGA)
- MEGA: norm. viscosity $\nu_{norm}=\nu/(R_0 v_{A0})=5\times10^{-7}$
- MEGA: adiabatic index Γ=5/3 (HYMAGYC-MEGA)
- ORB5: quasi-neutrality $Z_i n_i(s)=n_e(s)-Z_H n_H(s)$ (ORB5-HYMAGYC-MEGA)
- Maxwellian EPs, TH=0.093MeV (ORB5-HYMAGYC-MEGA)

$n_e(s)$, $n_H(s)$ => $n_i(s)$





Alfvén continua, stability

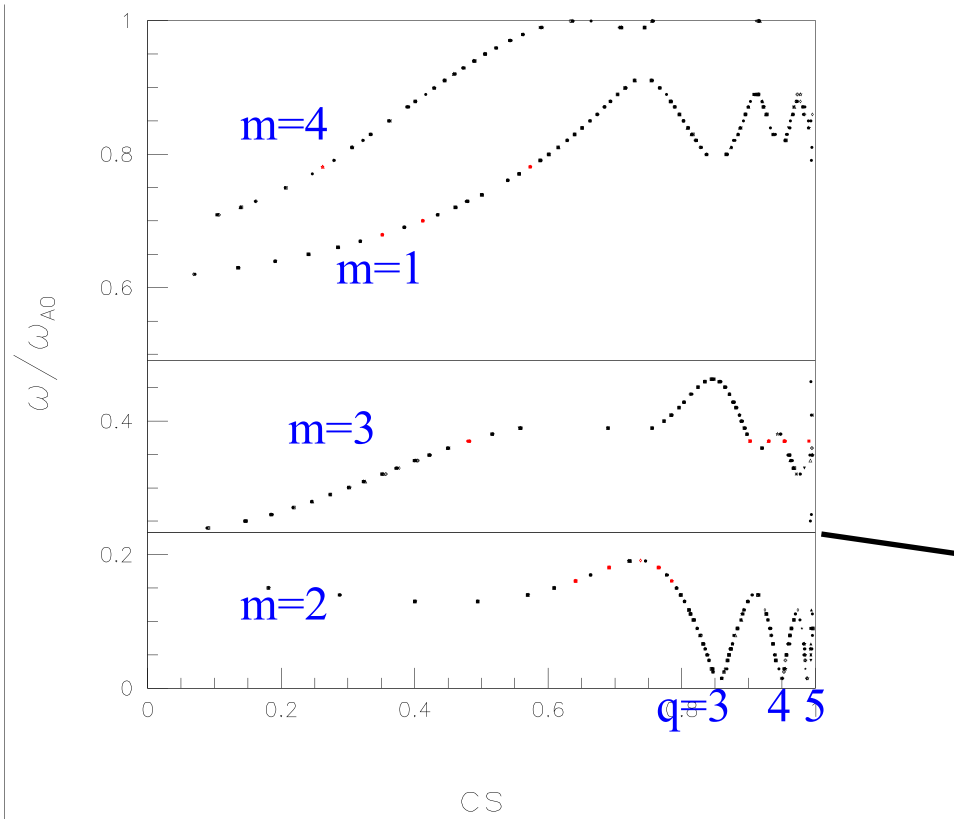
Following Philipp notes, we look for ideal (η=0) MHD Alfvén continua, in the limit n_H=0:

- step 2: shaped bulk density profile (independent on bulk temperature profile):

  $n_i(x)=n_e(x)=a + b\,x + c\,x^2 + d\,x^4$ (MARS and HYMAGYC modifies accordingly…)

  shaped bulk density profile "opens" the toroidal gap for n=-1;

  normalized coefficients: a=1, b=-2.63554E-01, c=-5.16313E-01, d=1.15847E-02



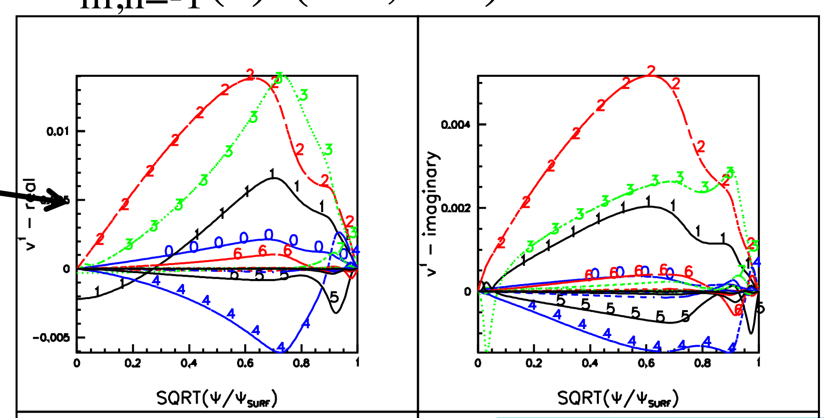
MARS result (Γ=0, η=0):

almost marginally stable mode is a TAE:

dominant components m=2, 3;

$\omega/\omega_{A0}=\pm 0.23280$

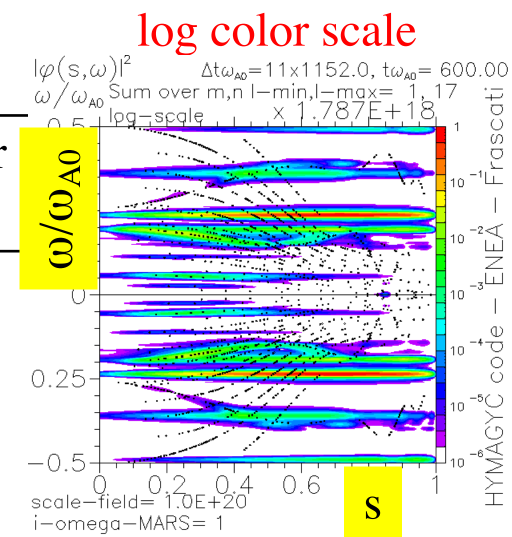
$v^s_{m,n=-1}(s)$ (Re, Im)

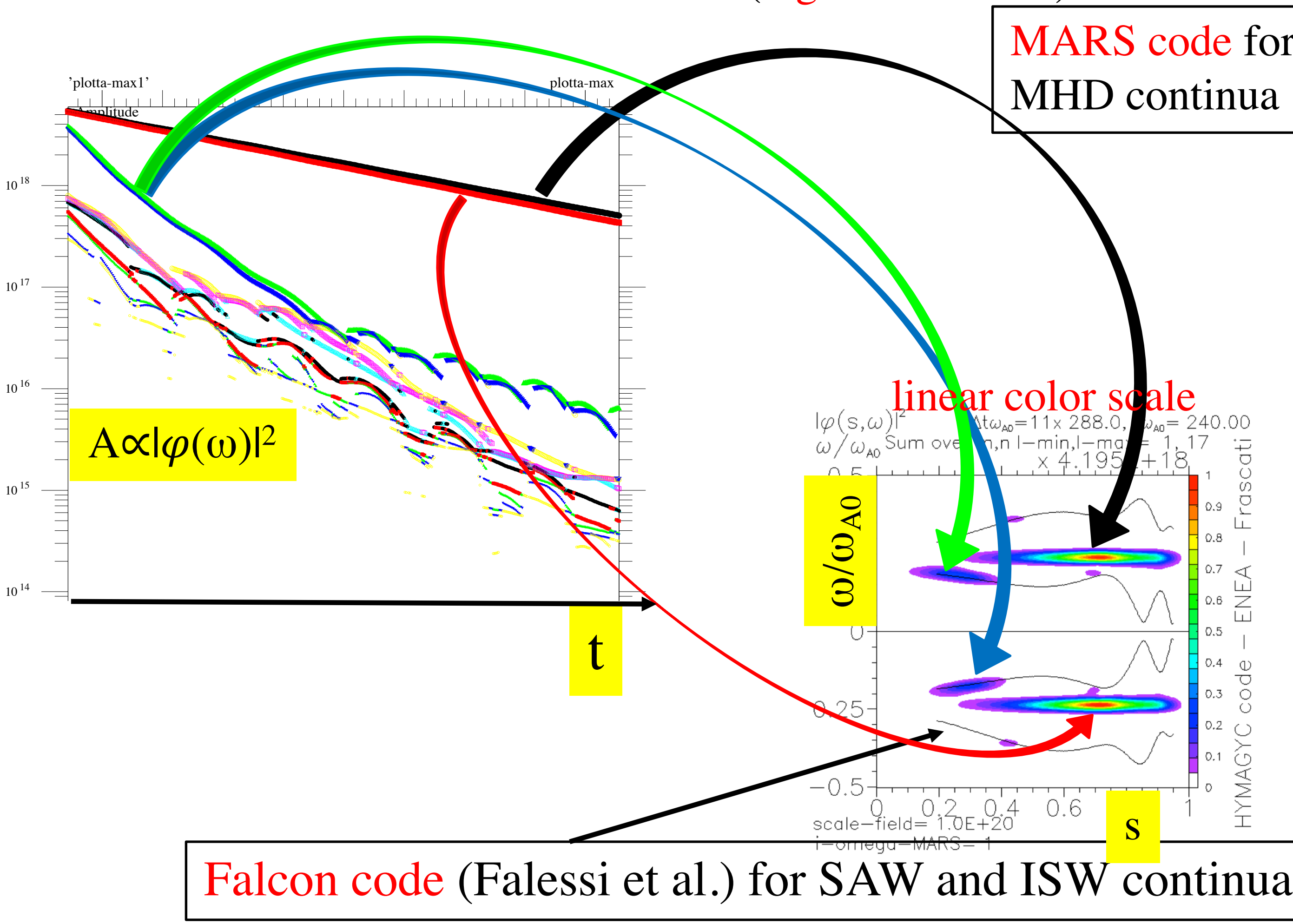


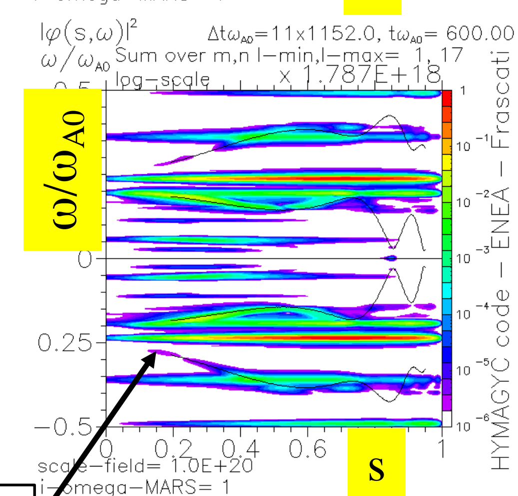
HYMAGYC: Alfvén continua, "decay simulation"

A "decay simulation", HYMAGYC result, for n_H=0 (but now Γ=5/3, S^{-1}_{MEGA}=5 × 10^{-7}):

- two weakly stable modes, TAE: dominant components m=2, 3; $\omega/\omega_{A0}\approx\pm0.23$
- a rich spectrum of global modes
- SAW Alfvén continua also observed (log color scale...)







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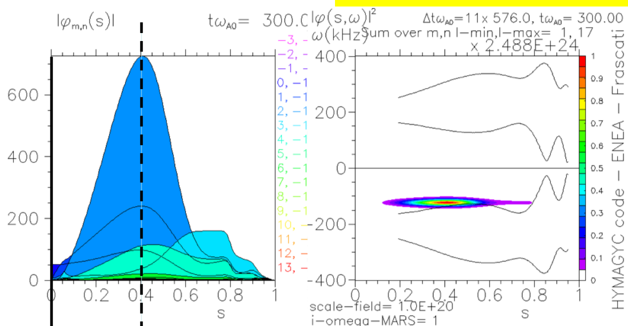
Nominal case comparison

on-axis EPs density profile

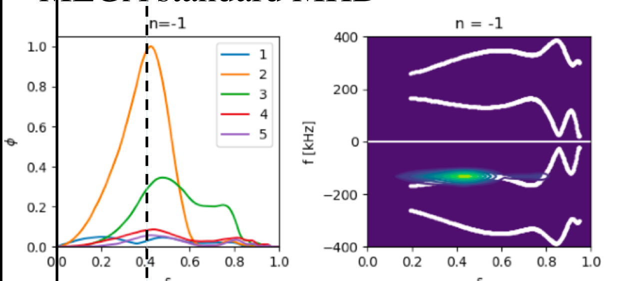
$n_{H0}/n_{i0} \simeq 0.261$, $T_H = 0.093$ keV

HYMAGYC

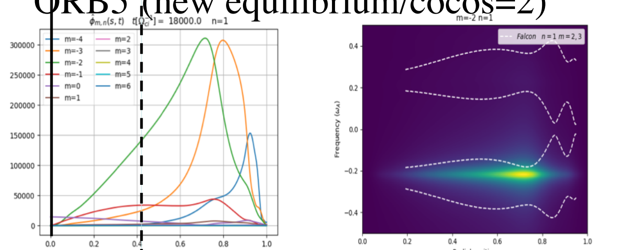
ω vs. s [kHz]



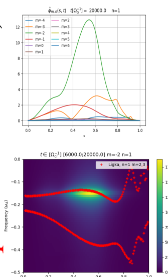
MEGA standard MHD



ORB5 (new equilibrium/cocos=2)



ORB5 (wrong equilibrium/cocos?)



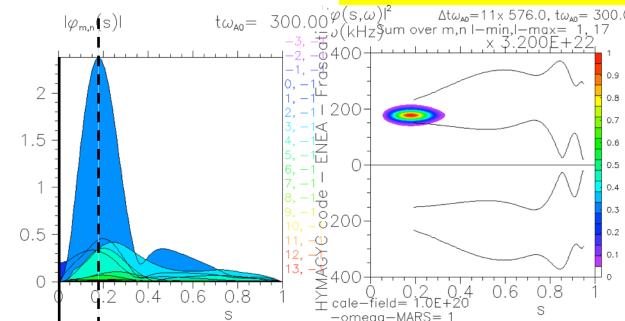
similar to TAE in HYMAGYC $n_H=0$ "decay experiment"

off-axis EPs density profile

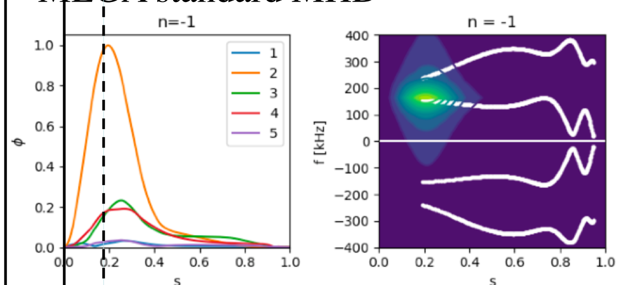
$n_{H0}/n_{i0} \simeq 0.0274$, $T_H = 0.093$ keV

HYMAGYC

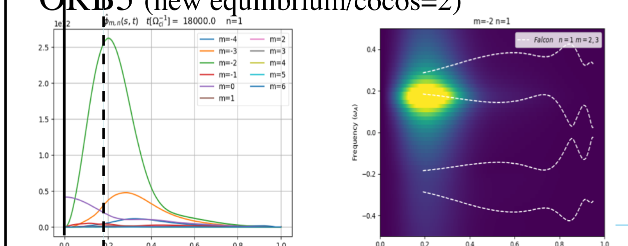
ω vs. s [kHz]



MEGA standard MHD

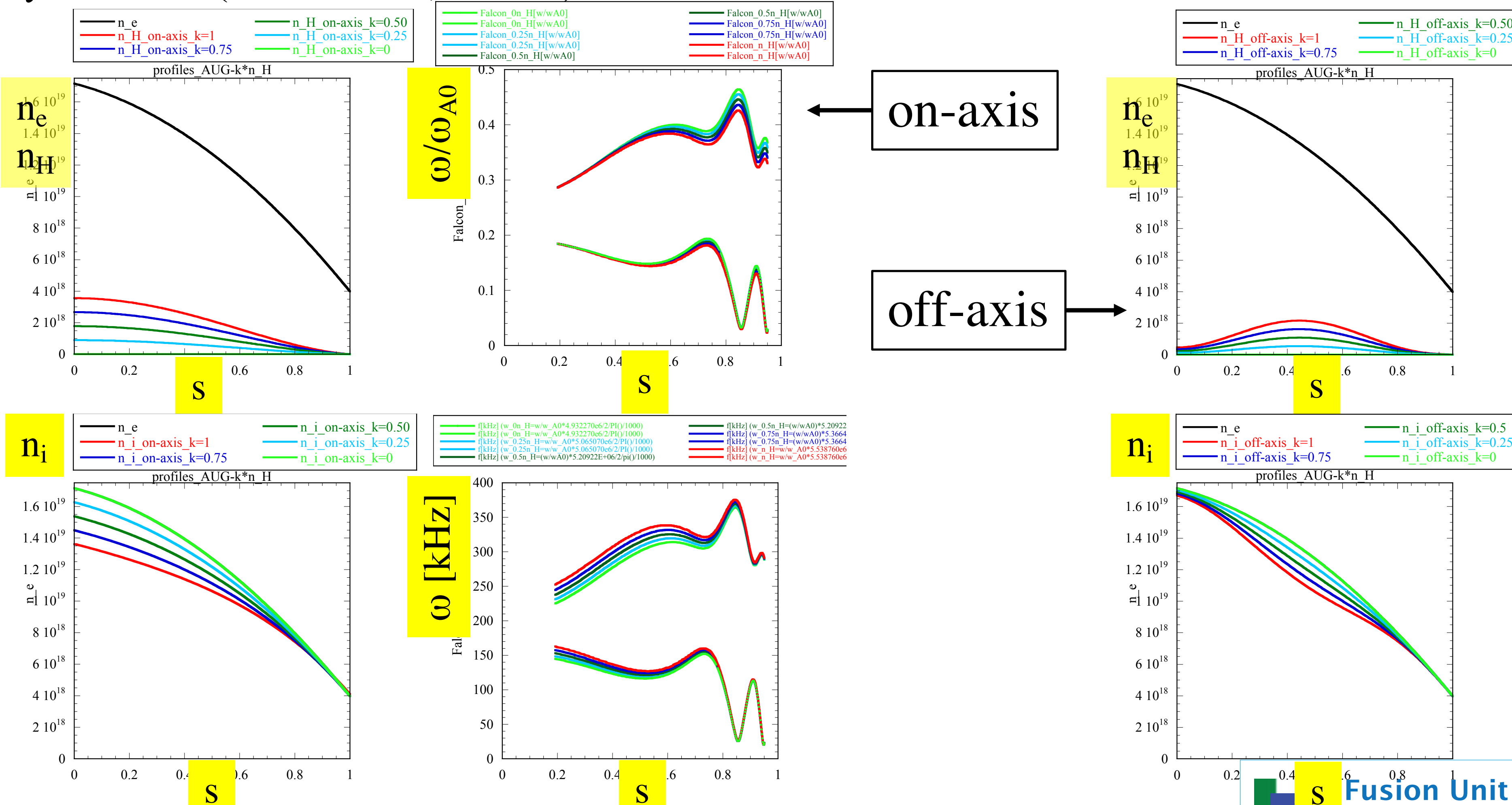


ORB5 (new equilibrium/cocos=2)



EP density scan

Note: because of the imposed quasi-neutrality condition $[Z_i n_i(s)=n_e(s)-Z_H n_H(s)]$, varying n_H results in varying the bulk ion density profile, i.e., the mass density profile entering in the MHD momentum equation and the Alfvén velocity and frequency used in the normalization of the hybrid codes (HYMAGYC, MEGA). SAW continua from FALCON code.



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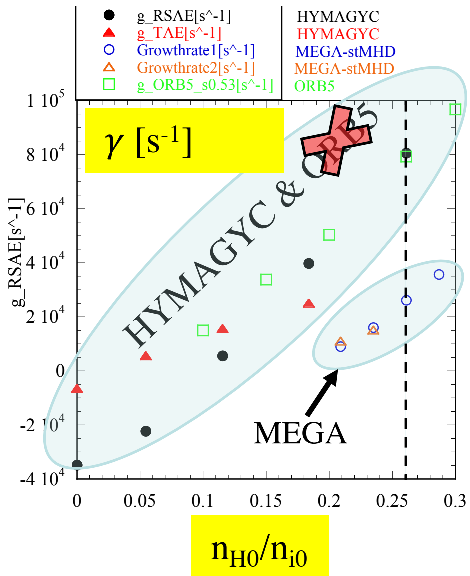
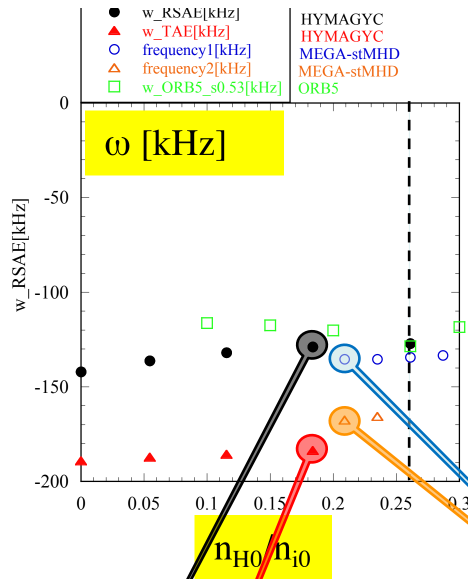
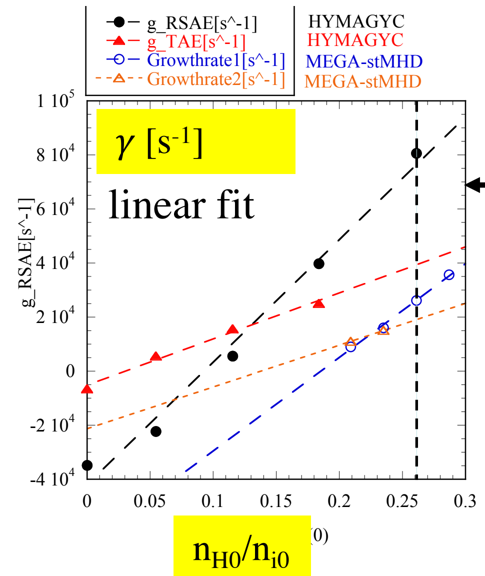
EP density scan

on-axis EPs density profile - HYMAGYC vs. ORB5 vs. MEGA: HYMAGYC & ORB5 have similar γ for the most unstable mode (ORB5 only observes one single mode); MEGA observes two modes but exhibits lower γ (viscosity ν?)

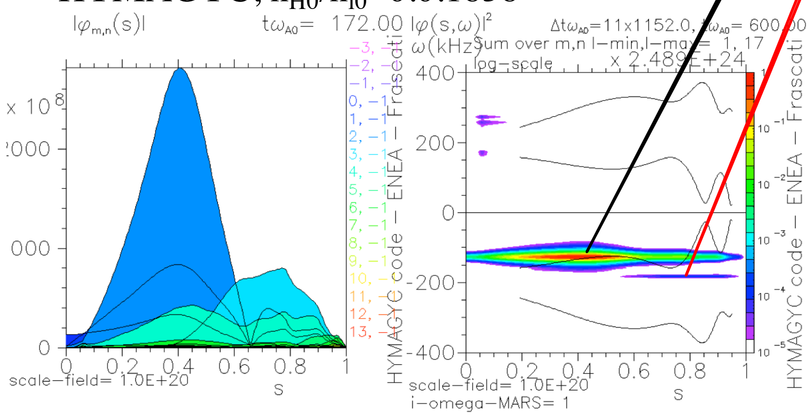




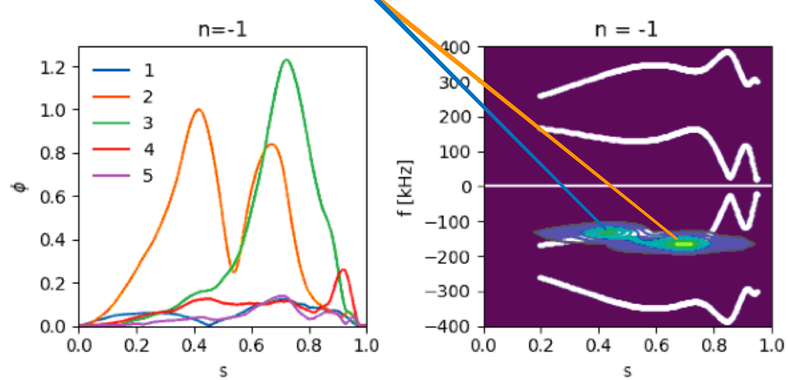


scaling of both branches almost paralle between HYMAGY and MEGA

HYMAGYC, n_{H0}/n_{i0}=0.0.1838

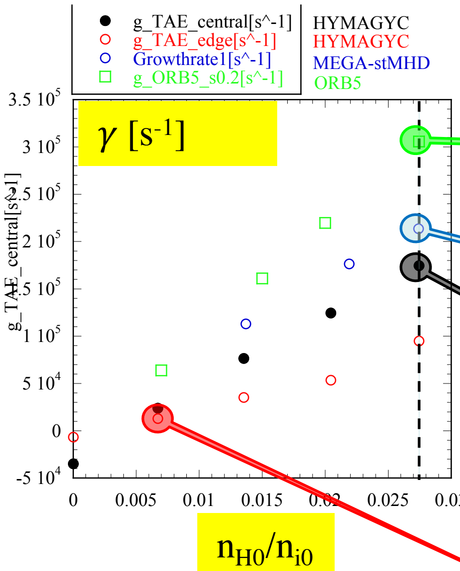


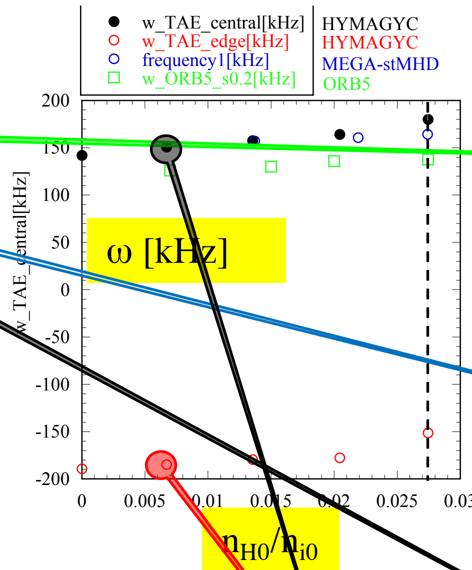
MEGA standard MHD, n_{H0}/n_{i0}=0.208

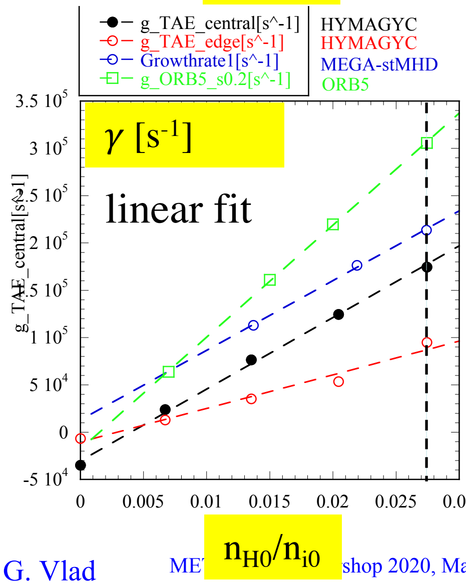


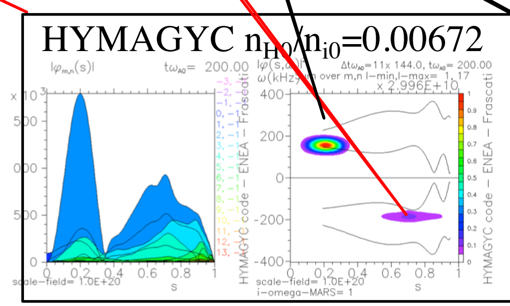
EP density scan

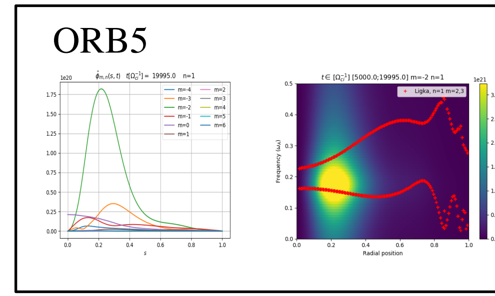
off-axis EPs density profile - HYMAGYC vs. ORB5 vs. MEGA: HYMAGYC & ORB5: reasonable agreement for mode localization in radius and in frequency. HYMAGYC also observe an external TAE, rotating in opposite direction.

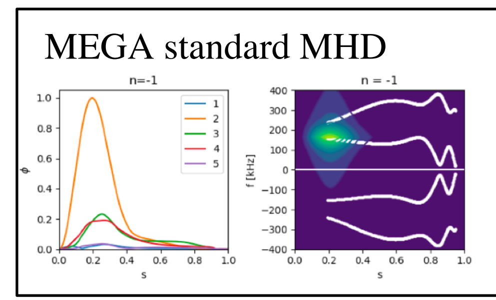


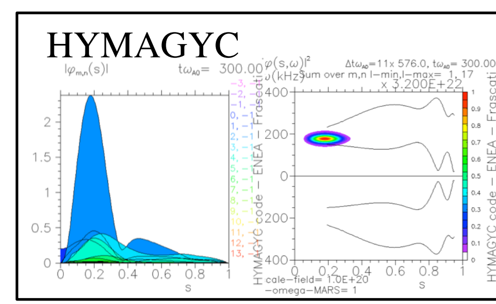


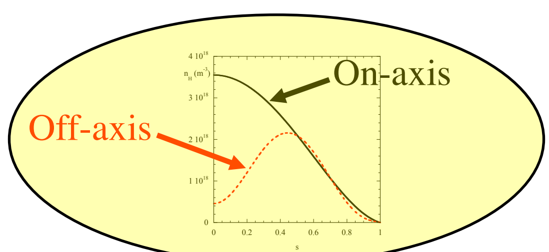








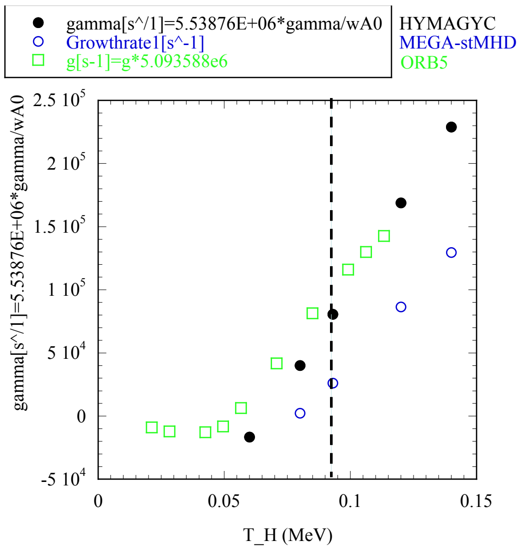


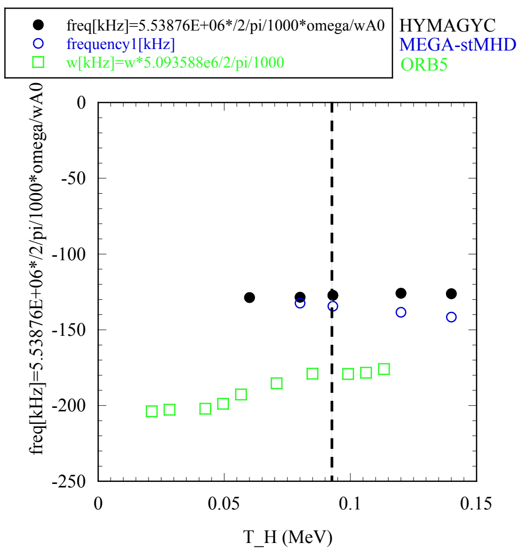


Fusion Unit EUROfusion

EP temperature scan

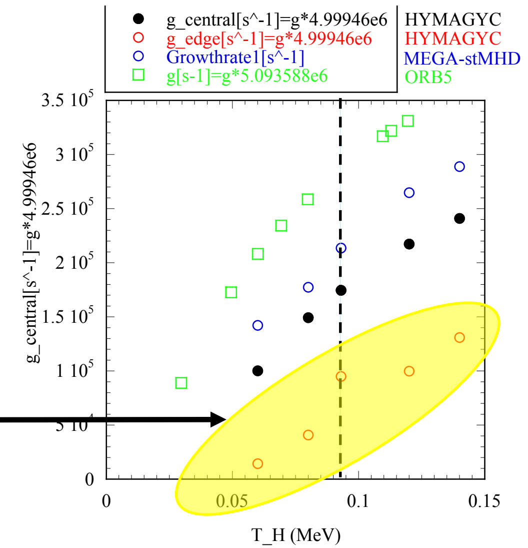
on-axis EPs density profile -

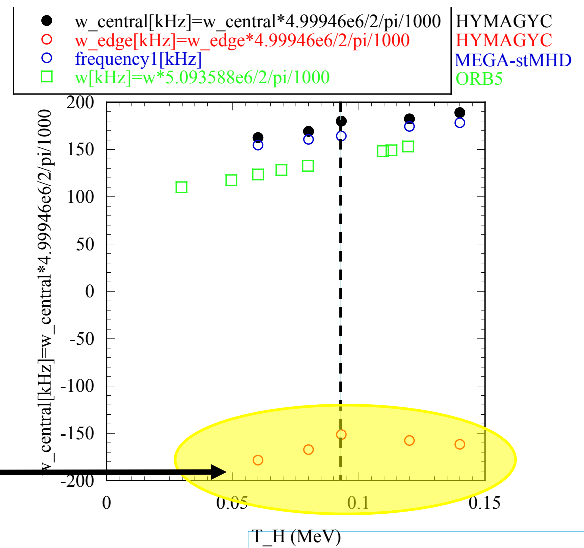




Reasonable agreement among different codes for similar modes

off-axis EPs density profile -





Miscellanea

Careful survey of conventions used in the three codes, e.g.:

- conventions for equilibrium:
  - Grad-Shafranov signs, definition of the flux function ψ => COCOS number!
- conventions for Fourier transforms (space, time):
  - HYMAGYC, e.g., uses:
    - for space variables: $$v^s(s,\chi,\phi) = e^{in\phi} \sum_{m=m_1}^{m_2} v_m^s(s)\, e^{im\chi}$$
    - for Fourier transoform in time (following the usual linear MHD convention, such that $\gamma>0$ corresponds to growing modes, with $\omega=\omega_0+i\gamma$): f(t) = int[f(ω) exp(-i ω t) dω]
  - different definitions of various quantities and normalizations (e.g., ω_{A0}, B_0 (B_{geo}, $B_{mag.\ axis}$, $B_{vacuum/plasma}$, resistivity, etc.)

- To avoid this kind of questions, it would be very useful to work in a same environment (as, e.g., ITMENV, IMAS, ...)

  => HYMAGYC is itmenv/"almost imasenv" compliant

Conclusions

- The benchmark exercise is "precious": each participant can gain a lot of experience, and synergies among different teams is largely beneficial
- A common, shared environment (e.g., itmenv, imasenv) can speed-up a lot the exercise, avoiding differences in the input data, normalizations, definitions of constants, ...
- Main affinity & differences observed (up to now):
  - HYMAGYC vs. MEGA (standard-MHD model):
    - mode observed looks to be the same (for both on-axis and off-axis cases)
    - MEGA growth-rate for the on-axis case: RSAE mode is smaller, but has similar dependence (slope) vs. n_H and T_H=> more damping? (viscosity?)
  - ORB5 (new "correct" equilibrium):
    - the (single) mode observed, for the on-axis case, is similar to the subdominant mode observed by HYMAGYC and MEGA (external TAE) => new scaling with n_H to be done
    - the mode observed for the off-axis case is similar to HYMAGYC and MEGA standard-MHD
  - MEGA using Hazeltine-Meiss MHD model gives quite different results
  - scaling vs. T_H: reasonable agreement among all codes (although the different ORB5 mode observed in on-axis case...)

Conclusions

- Forthcoming work:
  - –Investigate observed differences in linear analysis
  - –Possibly analyze Energetic Particles resonances and phase-space characteristics (e.g., using Hamiltonian Mapping diagnostics)
  - –Extend the benchmark to non-linear regimes to study the mode saturation
  - –...

Thank you!

References

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[10] Ph. Lauber et al, EX1/1 Proc. 27th IAEA FEC (2018)

[11] R. D. Hazeltine and J. D. Meiss, "Plasma Confinement" (Addison-Wesley, Redwood City) p.222 (1992).

MEGA description

Standard MHD equations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}) + \nu_n \Delta(\rho - \rho_{eq}), \quad (1)$$

$$\rho \frac{\partial}{\partial t}\boldsymbol{v} = -\rho \vec{\omega} \times \boldsymbol{v} - \rho \nabla \left(\frac{v^2}{2}\right) - \nabla p + (\boldsymbol{j} - \boldsymbol{j}_h') \times \boldsymbol{B} + \frac{4}{3}\nabla(\nu \rho \nabla \cdot \boldsymbol{v}) - \nabla \times (\nu \rho \vec{\omega}), \quad (2)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}, \quad (3)$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot (p\boldsymbol{v}) - (\gamma - 1)p\nabla \cdot \boldsymbol{v} + (\gamma - 1)[\nu \rho \omega^2 + \frac{4}{3}\nu \rho (\nabla \cdot \boldsymbol{v})^2 + \eta \boldsymbol{j} \cdot (\boldsymbol{j} - \boldsymbol{j}_{eq})] + \chi \Delta(p - p_{eq}), \quad (4)$$

$$\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta(\boldsymbol{j} - \boldsymbol{j}_{eq}), \quad (5)$$

$$\boldsymbol{j} = \frac{1}{\mu_0}\nabla \times \boldsymbol{B}, \quad (6)$$

$$\vec{\omega} = \nabla \times \boldsymbol{v}, \quad (7)$$

- In the MEGA code, the bulk plasma is described using nonlinear MHD equations, and the energetic ions are simulated with both the full-f and δf particle method.
- The energetic ion contribution is included in the MHD momentum equation [Eq. (2)] as the energetic ion current density $\boldsymbol{j}_h'$ that includes the contributions from parallel velocity, magnetic curvature and gradient drifts, and magnetization current. The $\boldsymbol{E} \times \boldsymbol{B}$ drift disappears in $\boldsymbol{j}_h'$ owing to quasi-neutrality. The electromagnetic field is given by the **standard MHD** description. The MHD equations are solved using a fourth-order in the space and time finite-difference scheme.
- The **drift-kinetic** description is employed for the alpha particles in current simulations.
- Current MEGA MHD solver is also extended using **an extended MHD model given by Hazeltine and Meiss.**

ORB5 description

- ORB5[1] is a global, nonlinear, gyrokinetic, electromagnetic, PIC code which can take into account collisions and sources.
- The Vlasov-Maxwell gyrokinetic equations are derived through variational principles from a gyrokinetic Lagrangian. Field equations are derived via functional derivatives.
- The distribution function is discretized through numerical particles (markers). The fields are discretized through cubic B-splines.
- The gyrokinetic model of ORB5 contains the reduced MHD as subset[2].

[1]E. Lanti et al., "ORB5: A global electromagnetic gyrokinetic code using the PIC approach in toroidal geometry". In: Computer Physics Communications (2019).
[2]Naoaki Miyato et al. "A Modification of the Guiding-Centre Fundamental 1-Form with Strong ExB Flow". In: Journal of the Physical Society of Japan (2009).

Continuous frequency spectrum with the MARS and the FALCON code

- In order to gain insight the mode structures excited by energetic particles, we verify carefully the continuous frequency spectrum of the Shear Alfven wave (SAW) and ion sound wave (ISW) which are coupled.
- To this aim we have used the MARS and the FALCON code. We show two plot for the AUG-NLED case (energetic particles peaked on axis and off axis) and one plot for ne DTT scenario.