Kinetic corrections to MHD modes using HYMAGYC

G. Vlad, G. Fogaccia, V. Fusco
ENEA, Dipartimento FSN, C. R. Frascati, via E. Fermi 45, I-00044 Frascati (Roma), Italy

2022 TSVV 2 Annual Meeting
Wednesday November 30, 2022

Deliverable 2: Interpretive and predictive tools regarding NT stability in terms of MHD (e.g., β- and current limits, both global and in the pedestal) and extended MHD (e.g., exploring kinetic and plasma compressibility effects).

Milestone	Description	Participants	Target date
M2.2.1	Use HYMAGYC to investigate kinetic corrections to MHD	G. Fogaccia	12.2021
M2.2.2	Use HYMAGYC to investigate Alfvénic modes driven by energetic particles, with particular reference to DTT NT equilibria	G. Fogaccia	12.2023
M2.2.3	Use HYMAGYC to investigate the kinetic effects of energetic particles and core ions on the renormalized plasma inertia (compressibility) in scenarios of interest to plasmas close to ignition	G. Fogaccia	12.2025

Deliverable	Description	Participants	Target date
D2.2	Report on MHD stability properties of NT equilibria, including non-ideal effects in NT DTT equilibria and pedestal studies	A. Merle, G. Fogaccia	12.2023

Deliverable 5: Predictive capability of the effect of shaping on fast ion confinement.

Deliverable	Description	Participants	Target date
D5.2	Report on fast particle confinement and fast particle driven instabilities in NT	M. Vallar, G. Fogaccia	12.2023

Kinetic corrections to MHD modes using HYMAGYC

Implement in HYMAGYC the possibility to retain, besides energetic particles, the kinetic effects also on thermal ions

Following [Wang et al.], where the model implemented in XHMGC has been described in detail, let us consider the perpendicular component of the extended MHD momentum equation:

$$\left[\rho_b\left(\frac{\partial}{\partial t}+\mathbf{v}_b\cdot\nabla\right)+\frac{\mathbf{b}\times\nabla P_{0E\perp}}{\omega_{cE}}\cdot\nabla\right]\delta\mathbf{v}_b$$
$$=-\nabla_\perp P_e-(\nabla\cdot\mathbf{P}_i)_\perp-(\nabla\cdot\mathbf{P}_E)_\perp+\left(\frac{\mathbf{J}\times\mathbf{B}}{c}\right)_\perp. \quad \text{(A9)}$$

Now consider only thermal species, neglect Energetic particles contribution, neglect non-linear terms fluid terms (HYMAGYC assumption)

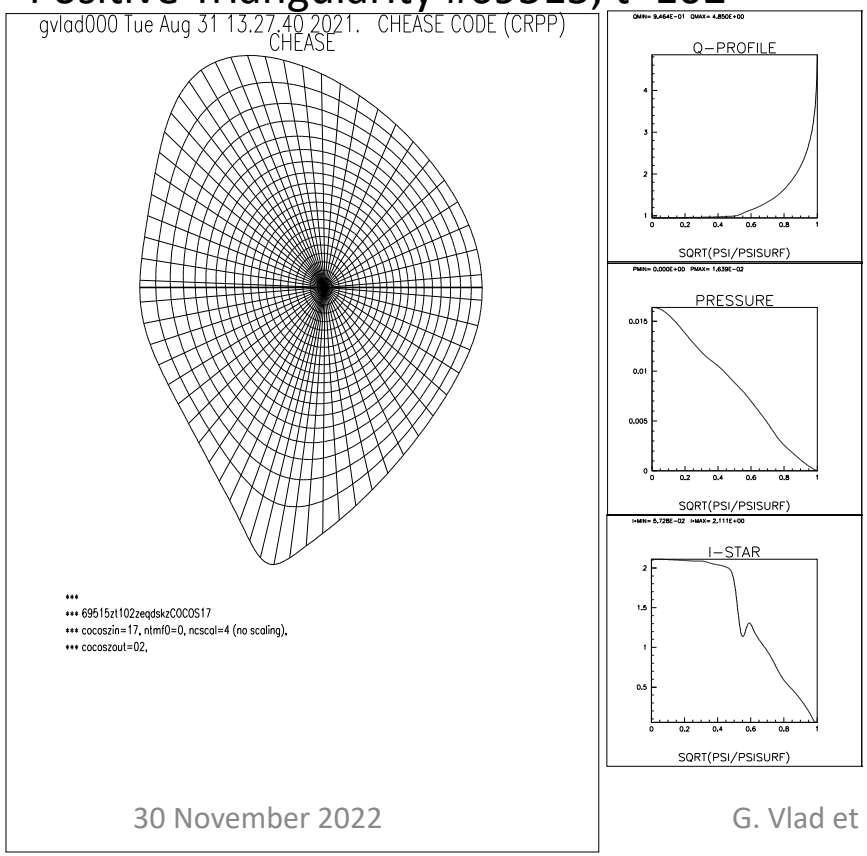
[Wang et al.] Wang X, Briguglio S, Chen L, Di Troia C, Fogaccia G, Vlad G and Zonca F , 2011 Phys. Plasmas 18052504

At first, we use two experimental TCV equilibria as a test cases:
Positive Triangularity #69515, t=102, and Negative Triangularity #69271, t=160

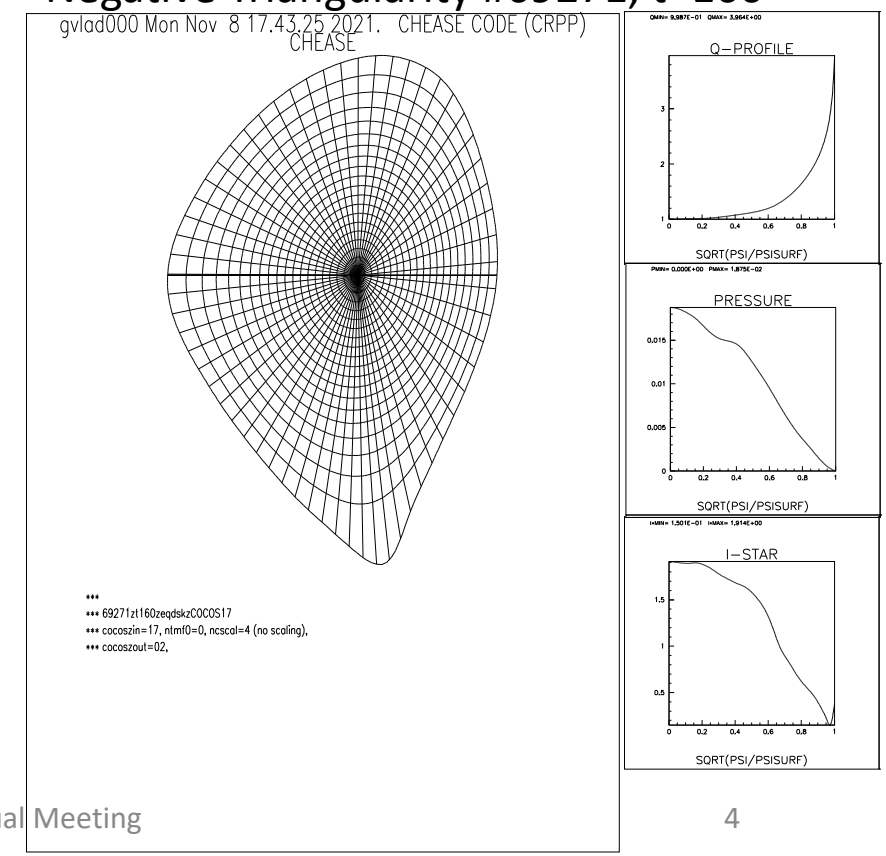
Quite difficult cases: internal kink unstable; when treating thermal ions kinetically, a numerical instability arise close to the magnetic axis: experimental kinetic profiles (pressure) do not behave “nicely” toward magnetic axis...

Comparison Num.	Description	Constants of comparison	Machine	Discharge	Time (sec)	elong	delta	betaN	P_nbi (kW)	q95	Ip (kA)	<ne> (x10^19 m^-3)	Comments
2	Diverted, PT	q95, ne, Pheat	TCV	69515	1.02	1.43	+0.29	0.97	636	3.17	242	4.0	not great q95 match
2	Diverted, NT	q95, ne, Pheat	TCV	69271	1.60	1.42	-0.27	1.59	612	2.90	217	4.4	-

Positive Triangularity #69515, t=102

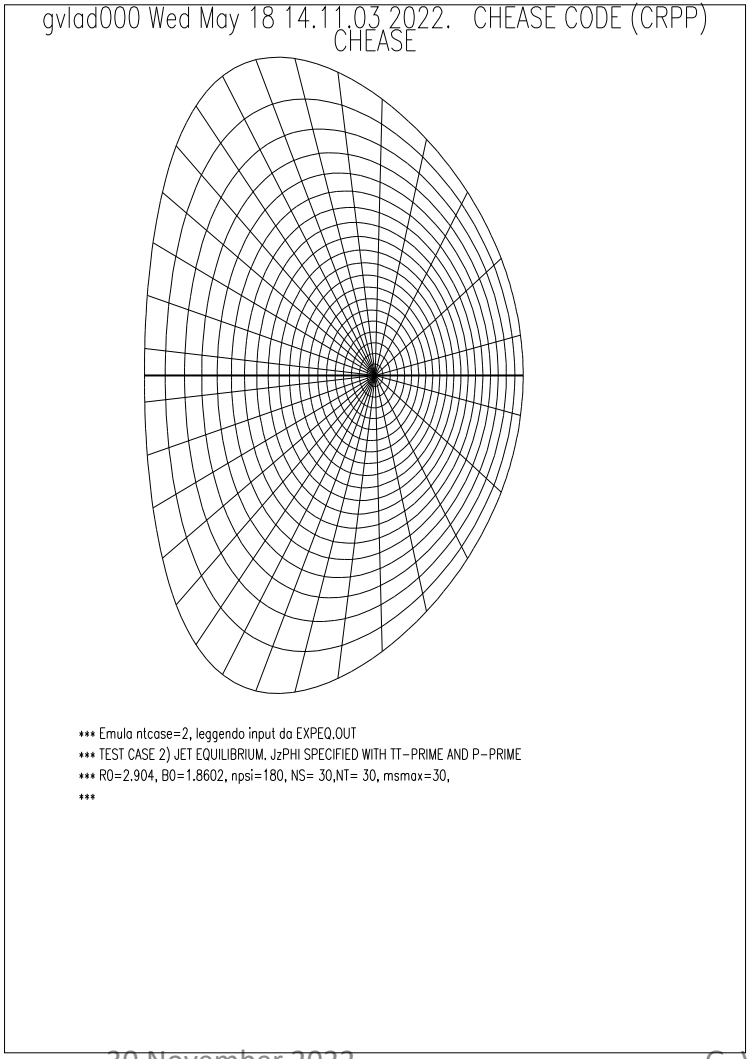


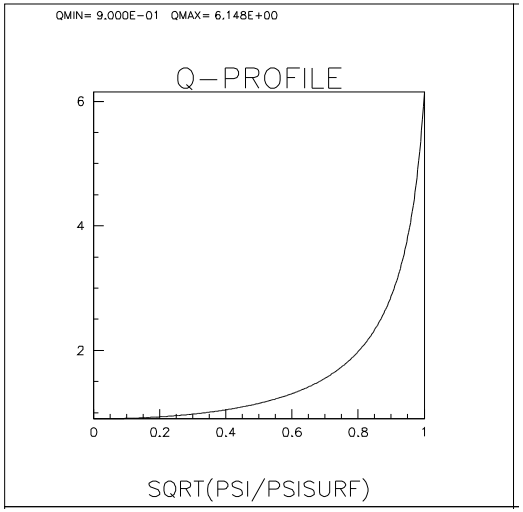
Negative Triangularity #69271, t=160

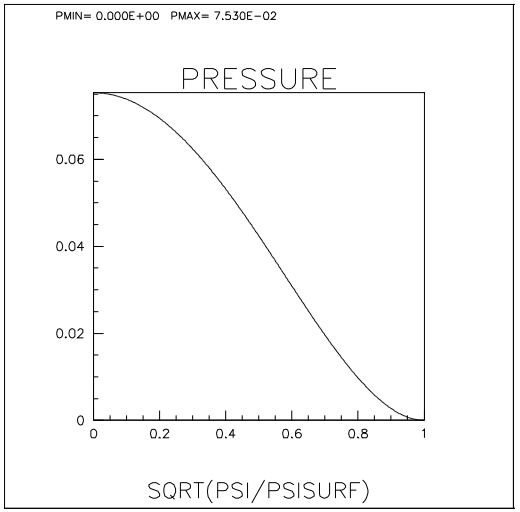


Kinetic corrections to MHD modes using HYMAGYC

Thus, we consider a simpler equilibrium: use the JET shaped test case casted in CHEASE (ntcase=2): it is a n=1 Internal Kink unstable case, but pressure profile behaves “nicely” on the magnetic axis...



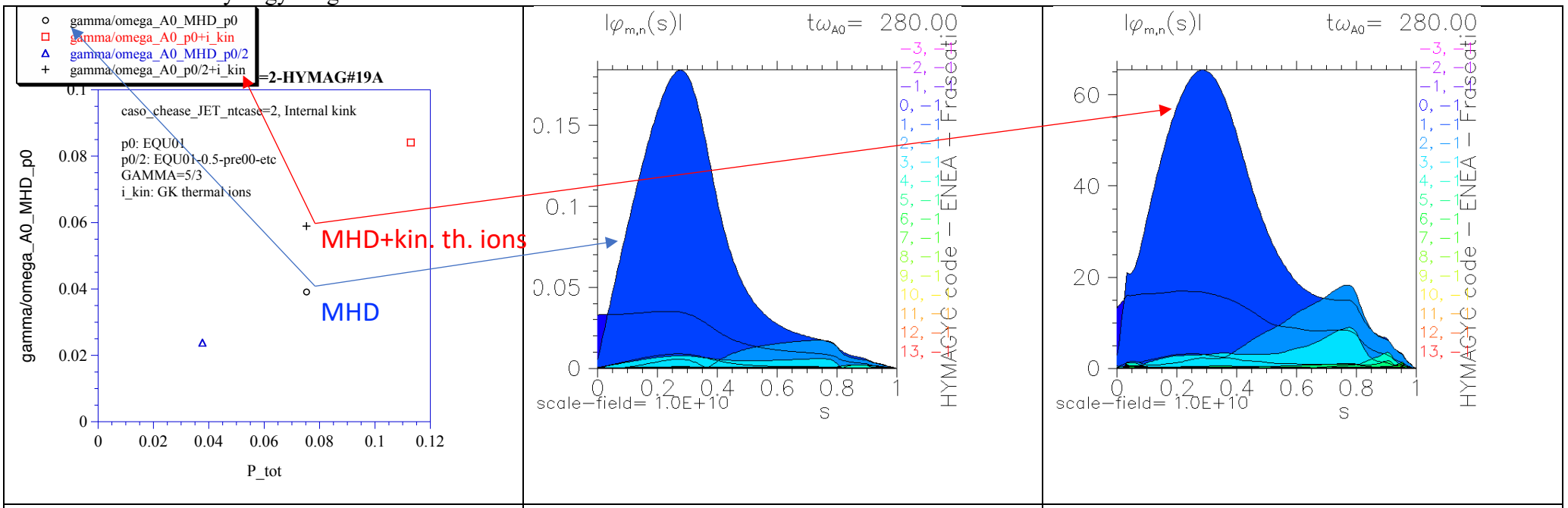




Kinetic corrections to MHD modes using HYMAGYC

Thermal ions: described by isotropic Maxwellian distribution function: $n_{i0}=3\times10^{19}$ m^{-3}, $T_{i0} \approx 21.6$ keV

Results-chease-mars-hymagyc-logbook-TSVV#2.docx

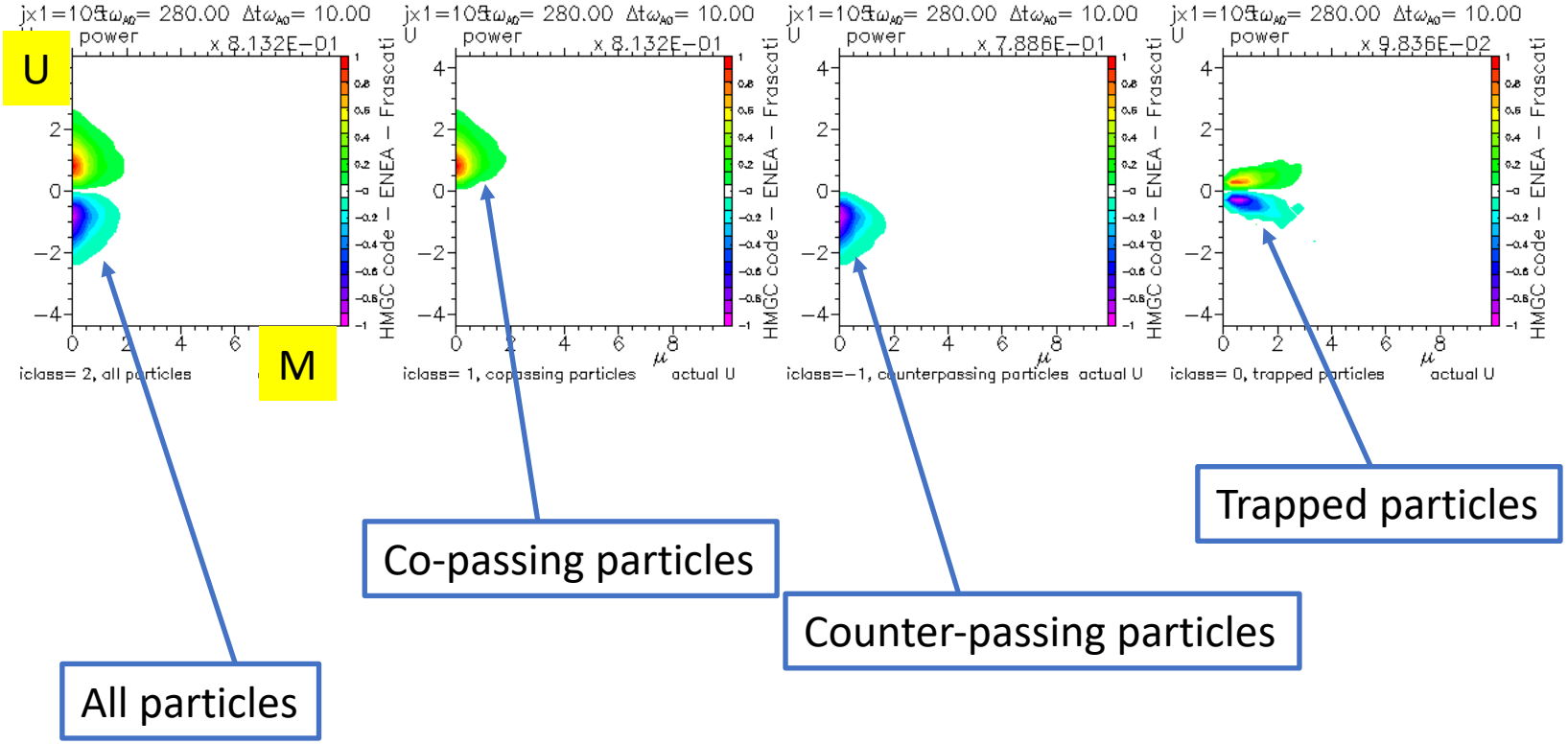


Growth-rate vs. on-axis pressure (p0: reference equilibrium, p0/2 mimics only electrons described by MHD pressure, "i_kin" are the thermal ions (half of the reference pressure p0) described by GK eqs. using n_i(0)=n_e(0)=3x10+19 m^(-3) it follows T_i(0)=21.5706 keV	caso_hymagyc_JET_01_ntcase=2_R0=2.904_B0=1.8602_360x360_Gamma53_ETA0_n=-1_MHD	caso_hymagyc_JET_01_ntcase=2_R0=2.904_B0=1.8602_360x360_Gamma53_ETA0_EQU01-0p5-pre00-etc_n=-1_+kin-bulk-i_00

Kinetic corrections to MHD modes using HYMAGYC

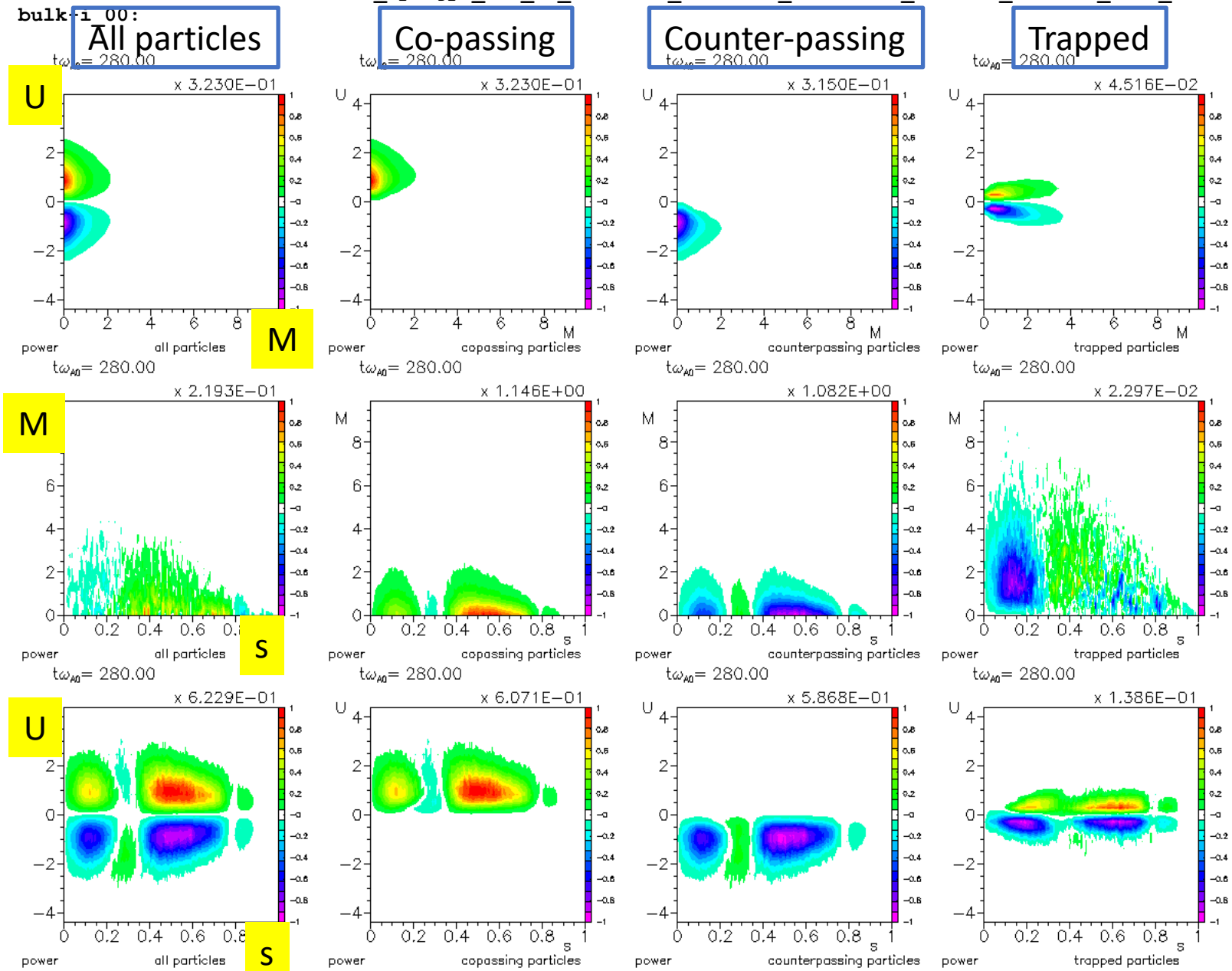
Wave-particle power exchange as function of [M, U], at the radial location s≈0.56

Wave-particles (thermal ions) power exchange at s=105/181 \approx 0.58 (location of max power exchange…) in the plane magnetic moment MU and parallel velocity U at t=280 for the simulation caso_hymagyc_JET_01_ntcase=2_R0=2.904_B0=1.8602_360x360_Gamma53_ETA0_EQU01-0p5-pre00-etc_n=-1_+kin-bulk-i_00:



Kinetic corrections to MHD modes using HYMAGYC

Wave-particles (thermal ions) power exchange projections on parallel thermal velocity U, magnetic moment MU, and radius s, at t=280 for the simulation caso_hymagyc_JET_01_ntcase=2_R0=2.904_B0=1.8602_360x360_Gamma53_ETA0_EQU01-0p5-pre00-etc_n=-1_+kin-bulk-1_00:



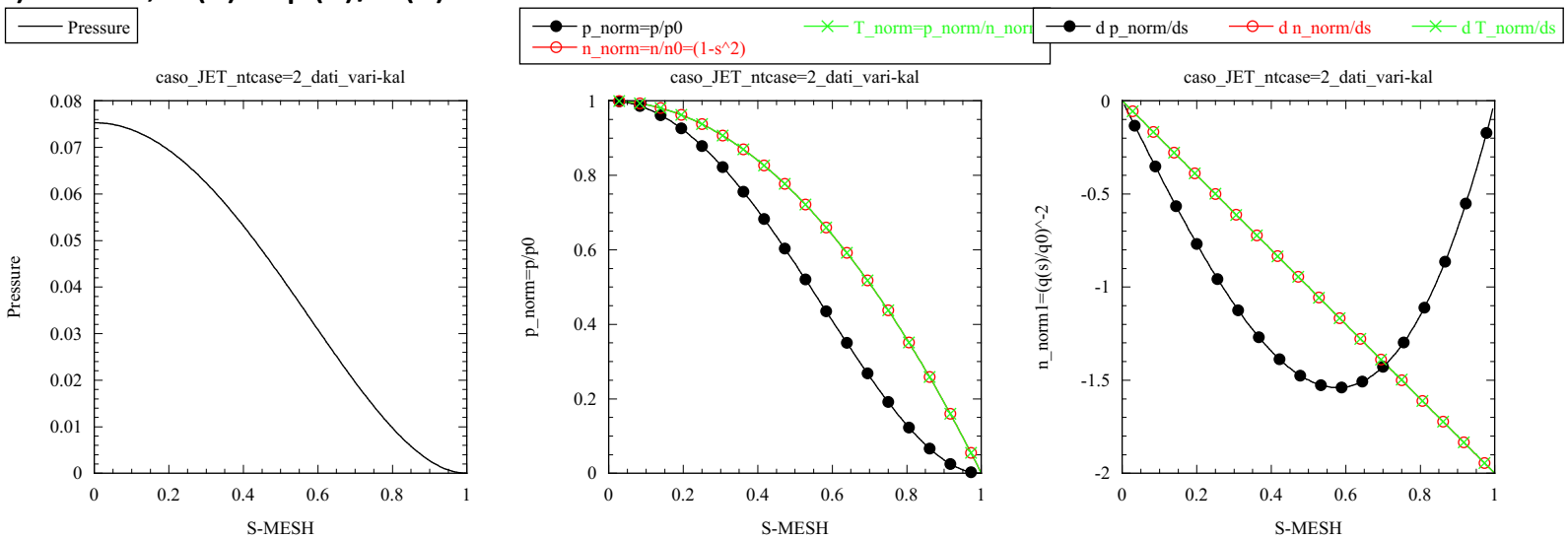
Wave-particle power exchange as function of [M,U], [s,M], [s,U] (summed over the third coordinate)

Kinetic corrections to MHD modes using HYMAGYC

Smoothly switch on the kinetic contribution of thermal ions, while reducing simultaneously the corresponding fluid contribution:

- maintaining the magnetic equilibrium unchanged (but reducing the terms proportional to the pressure ($\nabla p_{th,i}$) in the momentum equation to avoid to "double count" for the thermal ion contribution);
- add the term computed by the gyrokinetic formalism ($\nabla \cdot p_{th,i}$) to the momentum equation

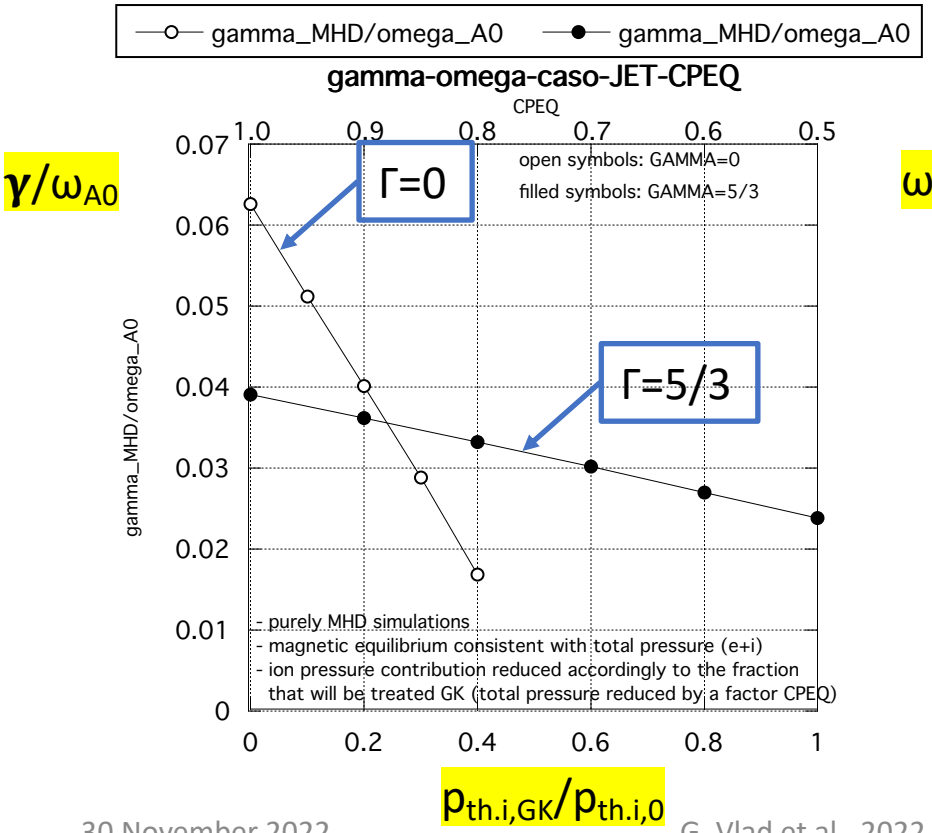
- JET CHEASE test case (ntcase=2):
  - $\beta_{axis} \approx 15\%$
  - Assuming $n_{i,0}=n_{e,0} = 3\times10^{19}\ m^{-3}$, $T_i=T_e \Rightarrow T_{i,0} \approx 21.57$keV, $v_{th}/v_{A0} \approx 0.212$, $\varrho_{i,0}/R_0 \approx 0.0039$
  - $n(s) \approx 1-s^2$, $T(s) \approx p(s)/n(s)$

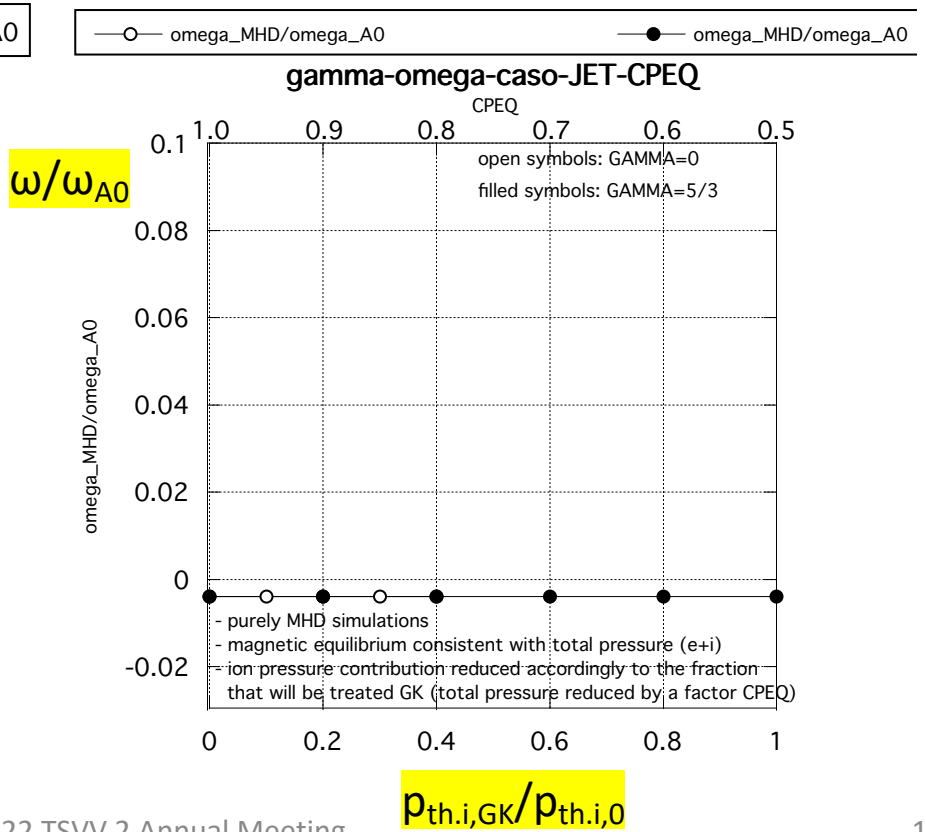


Kinetic corrections to MHD modes using HYMAGYC

- Consider two cases: Γ=0 (open symbols in plots), Γ=5/3 (filled symbols in plots)
- Smoothly switching on the kinetic contribution of thermal ions:
  - varying thermal ion density (keeping the thermal ion temperature unchanged)
  - varying thermal ion temperature (keeping the thermal ion density unchanged, thermal ion resonances changes in this latter case…)

Purely MHD simulations (reduce fluid pressure contribution)

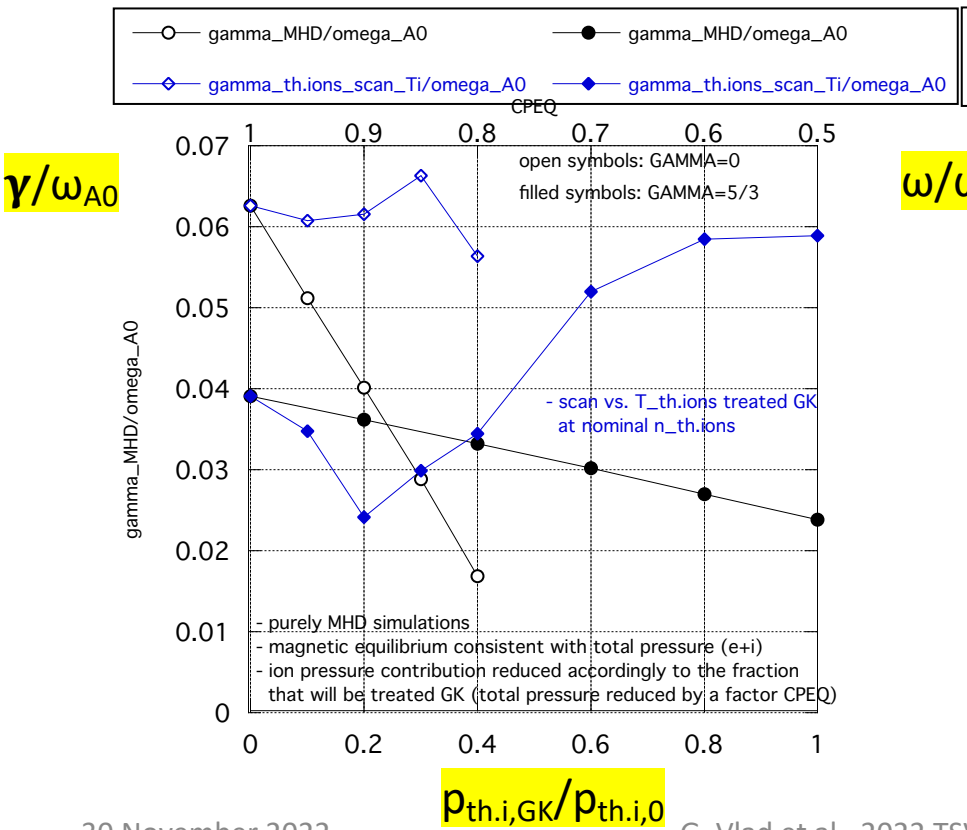


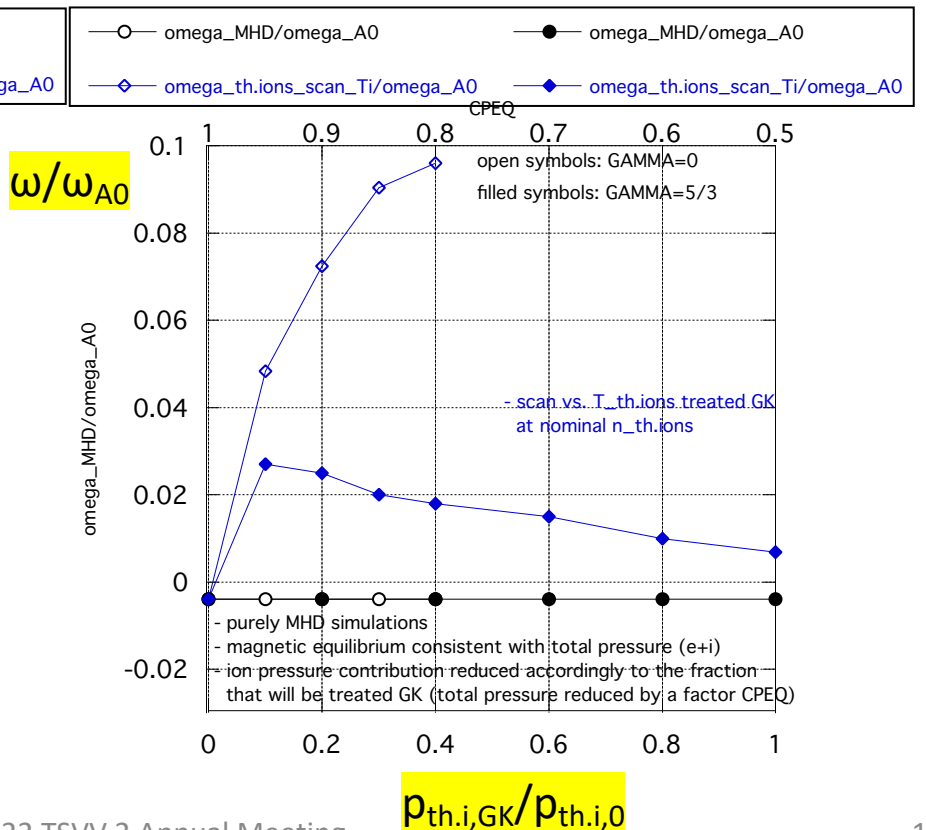


Kinetic corrections to MHD modes using HYMAGYC

- Consider two cases: Γ=0 (open symbols in plots), Γ=5/3 (filled symbols in plots)
- Smoothly switching on the kinetic contribution of thermal ions:
  - varying thermal ion temperature (keeping the thermal ion density unchanged, thermal ion resonances changes in this latter case…)
  - varying thermal ion density (keeping the thermal ion temperature unchanged)

Now add thermal ions pressure varying the thermal ion temperature (keeping nominal $n_{th,i}$)

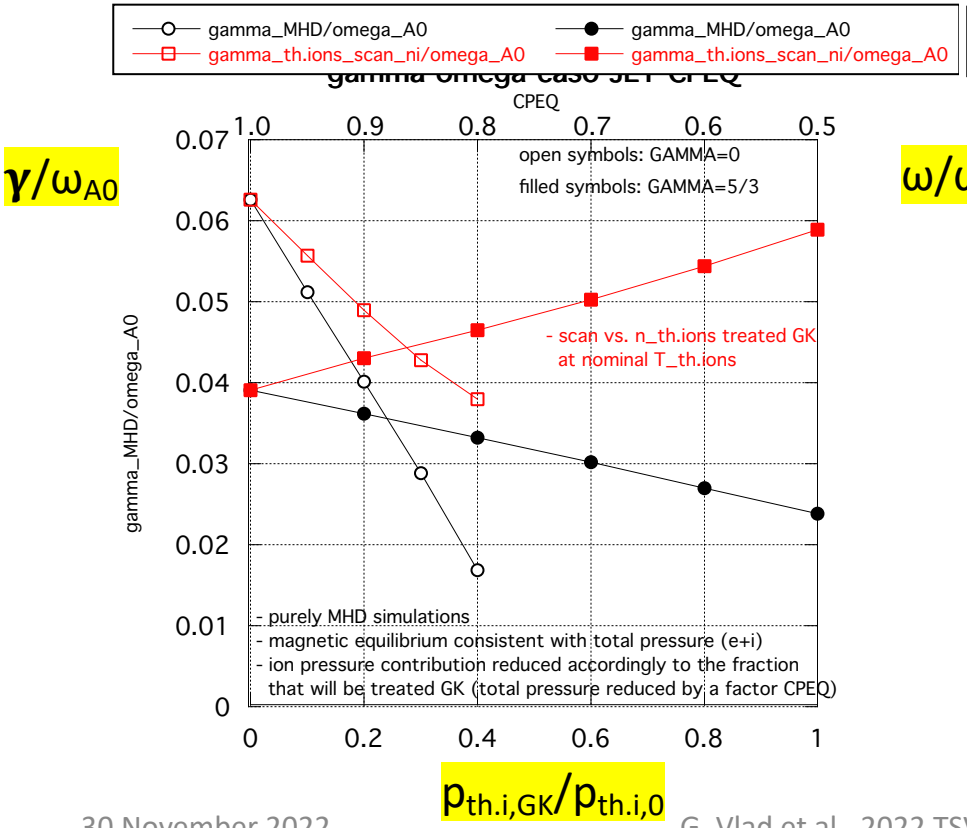


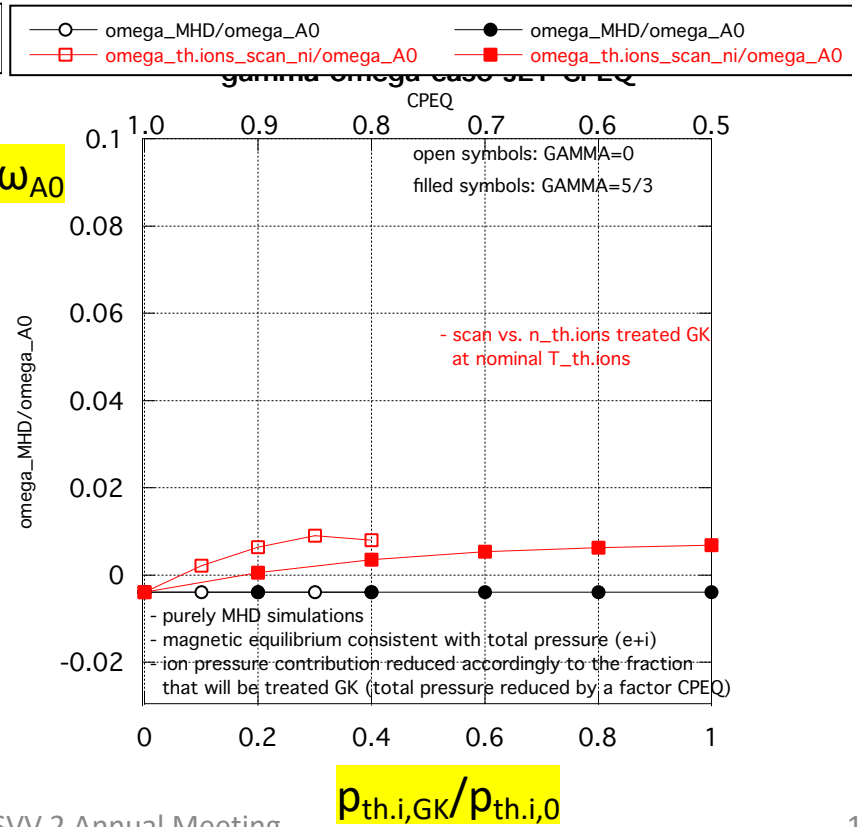


Kinetic corrections to MHD modes using HYMAGYC

- Consider two cases: Γ=0 (open symbols in plots), Γ=5/3 (filled symbols in plots)
- Smoothly switching on the kinetic contribution of thermal ions:
  - varying thermal ion temperature (keeping the thermal ion density unchanged, thermal ion resonances changes in this latter case…)
  - varying thermal ion density (keeping the thermal ion temperature unchanged)

Now add thermal ions pressure varying the thermal ion density (keeping nominal $T_{th,i}$)



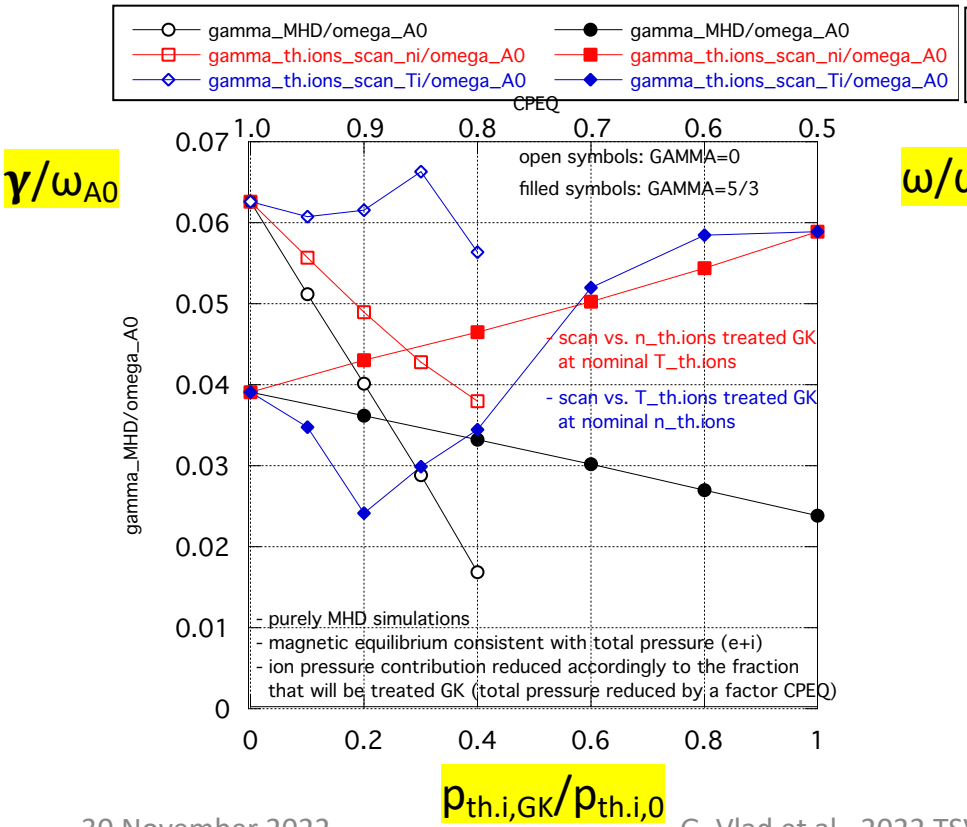


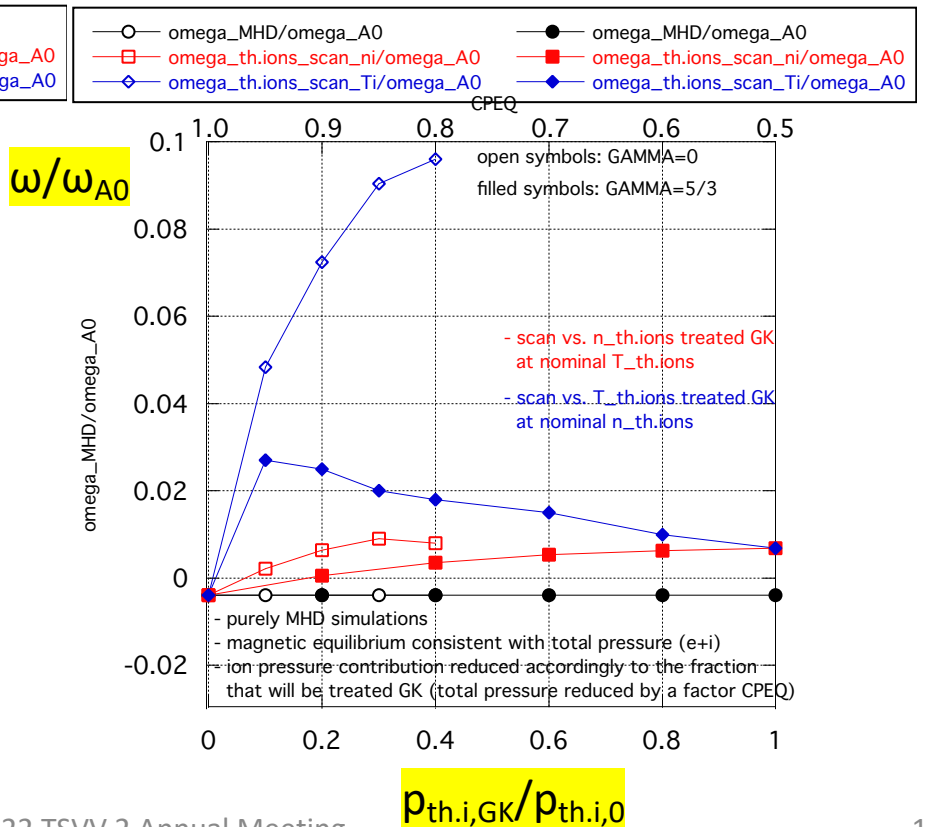
Thank you for your attention

Kinetic corrections to MHD modes using HYMAGYC

- Consider two cases: Γ=0 (open symbols in plots), Γ=5/3 (filled symbols in plots)
- Smoothly switching on the kinetic contribution of thermal ions:
  - varying thermal ion temperature (keeping the thermal ion density unchanged, thermal ion resonances changes in this latter case…)
  - varying thermal ion density (keeping the thermal ion temperature unchanged)

Summary plots





Kinetic corrections to MHD modes using HYMAGYC

- It would be worthwhile to compare the results of HYMAGYC (kinetic effects on MHD modes) with other code results (see, e.g., Brochard et al, Nucl. Fusion 62 (2022) 036021)

IOP Publishing | International Atomic Energy Agency Nuclear Fusion

Nucl. Fusion 62 (2022) 036021 (17pp) https://doi.org/10.1088/1741-4326/ac48a6

Verification and validation of linear gyrokinetic and kinetic-MHD simulations for internal kink instability in DIII-D tokamak

G. Brochard[1,8,*], J. Bao[2,8], C. Liu[3,8], N. Gorelenkov[3], G. Choi[1], G. Dong[3], P. Liu[1], J. Mc.Clenaghan[4], J.H. Nicolau[1], F. Wang[5], W.H. Wang[1], X. Wei[1], W.L. Zhang[2], W. Heidbrink[1], J.P. Graves[6], Z. Lin[1] and H. Lütiens[7]

Nucl. Fusion 62 (2022) 036021 G. Brochard *et al*

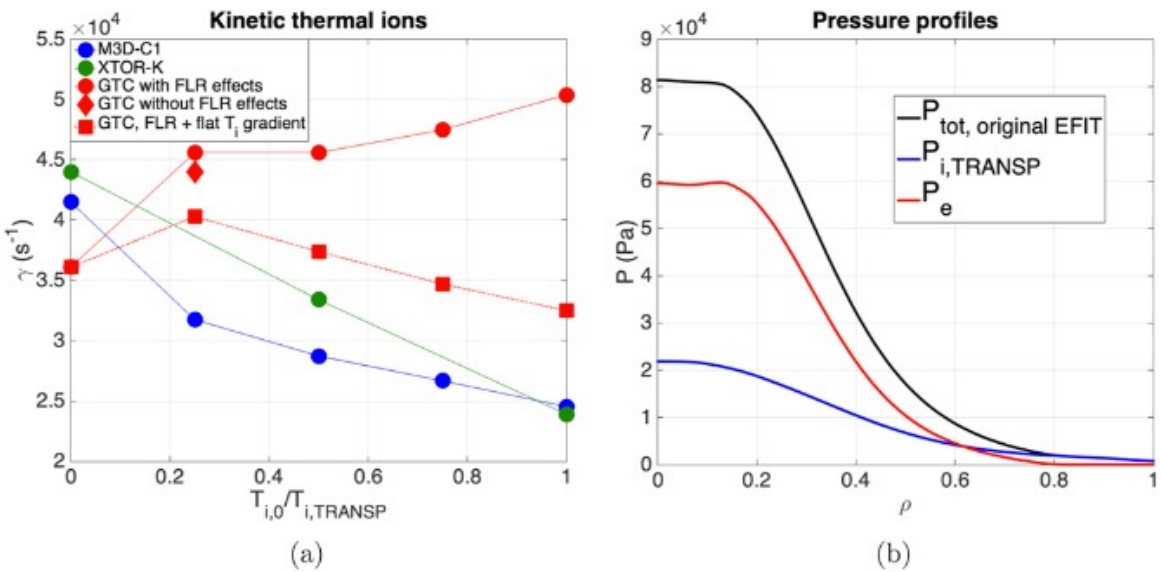
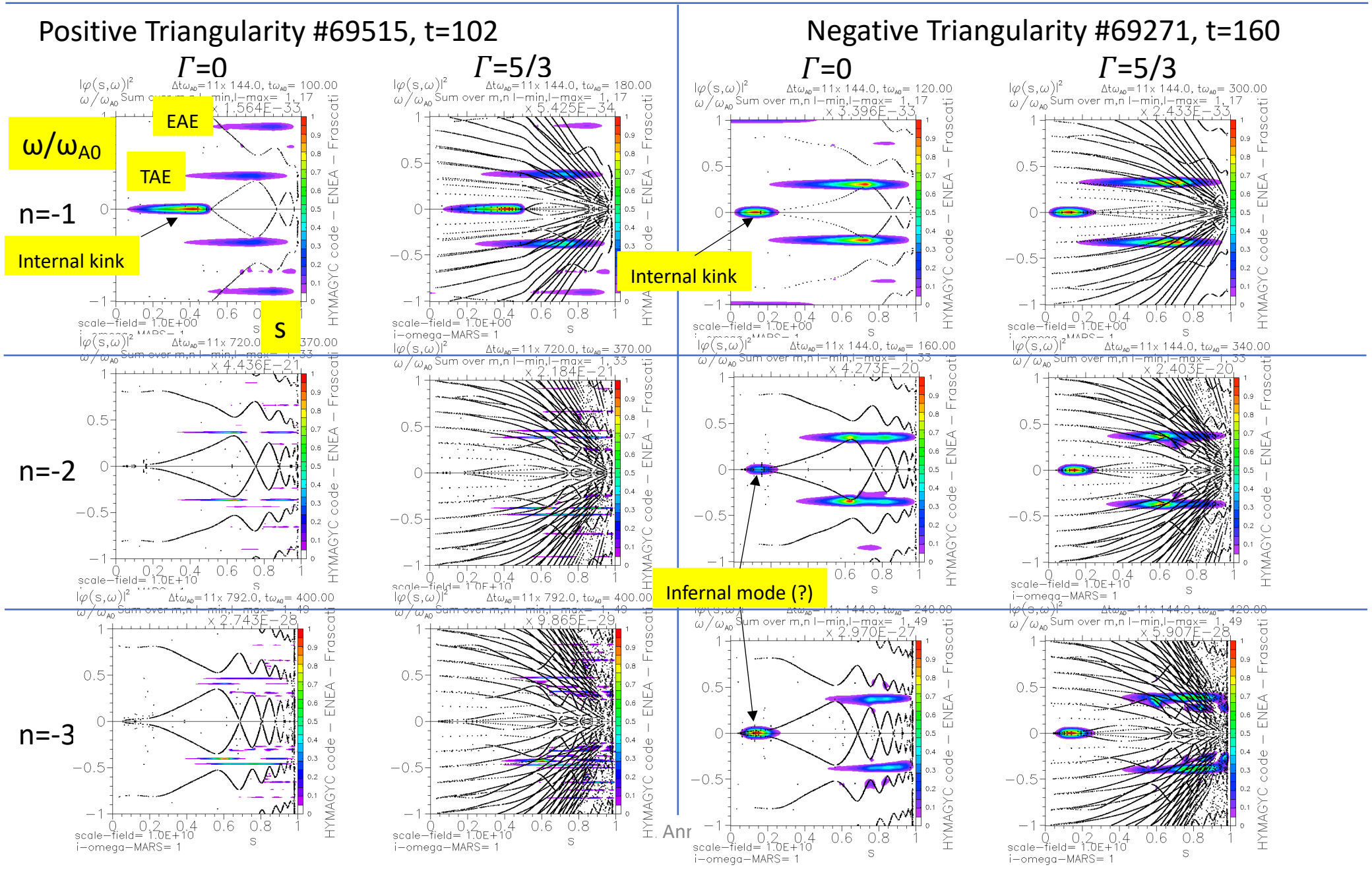
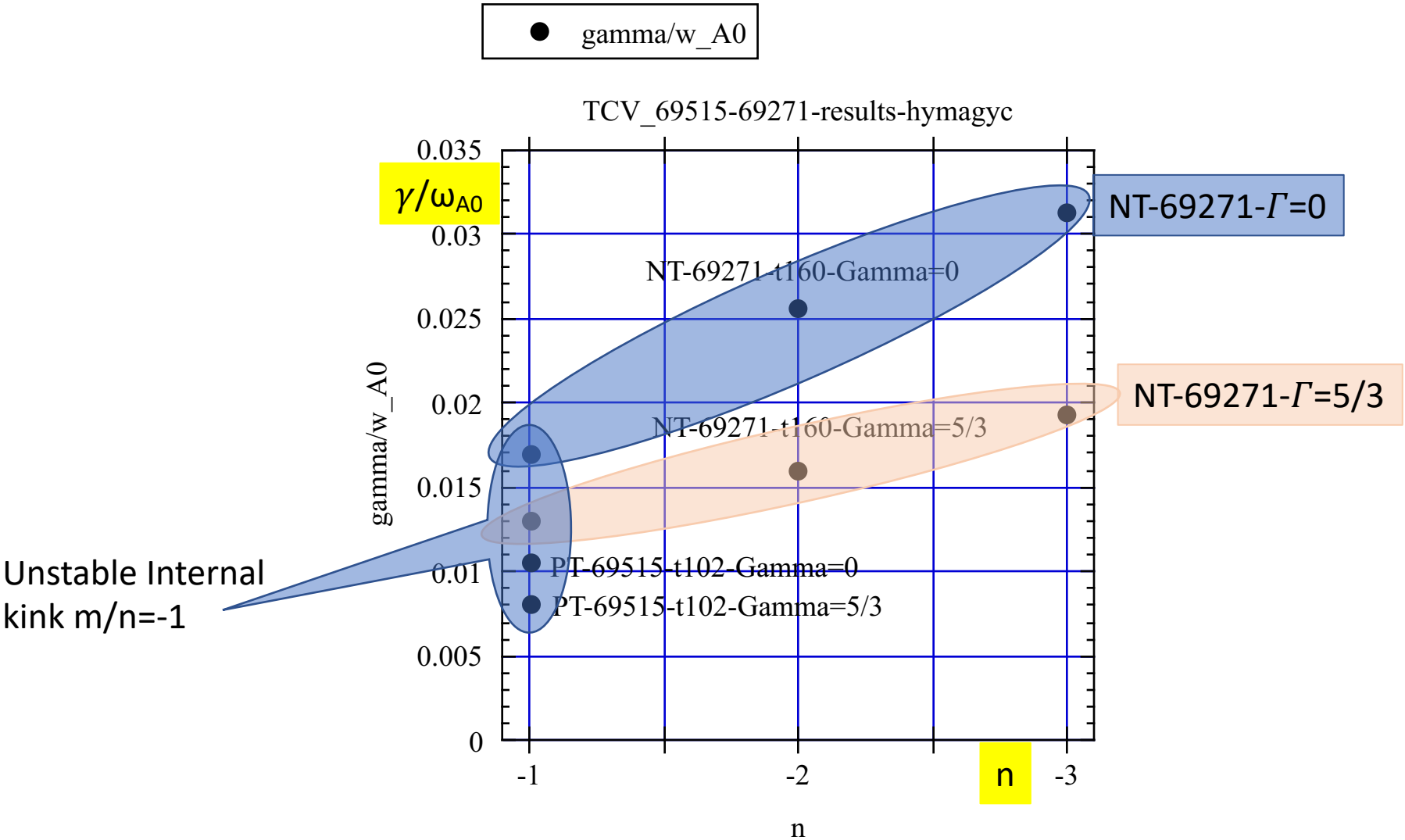


Figure 9. (*a*) Thermal ion temperature scan for the internal kink growth rate obtained from M3D-C1, XTOR-K and GTC. (*b*) Pressure profiles for thermal electrons and ions. The thermal ion pressure is taken from TRANSP simulations, the electron pressure profile is defined such that the sum of electron and ion pressures adds up to the total pressure obtained from original EFIT pressure.

Alfvén continua (using MARS); characterization of low-n MHD modes using HYMAGYC (purely MHD)



HYMAGYC results, in the MHD limit