Toward using HYMAGYC to explore kinetic effects on MHD modes

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

2021 Annual TSVV 2 Workshop
Thursday December 2, 2021

Toward using HYMAGYC to explore kinetic effects on MHD modes

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)**.

...

Non-ideal effects will be investigated by G. Fogaccia with the hybrid MHD- Gyrokinetic code HYMAGYC, with a particular focus on DTT NT equilibria. This code solves the gyrokinetic equation for fast particles and treats the bulk plasma as a fluid by solving the full linear resistive MHD equations. Also, the kinetic corrections to the bulk ions can be retained by evolving the corresponding gyrokinetic equation. Thus, HYMAGYC is well suited to investigate gyrokinetic corrections to MHD modes as well as Alfvénic modes driven by energetic particles.

...

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

HYMAGYC (HYBRID MAGNETOHYDRODINAMIC GYROKINETIC CODE)

- Suited to study the interaction between EPs and Alfvénic modes
- For high-β axisymmetric equilibria
- Electromagnetic fields are fully retained: electrostatic potential ϕ and vector potential $\mathbf{A}$
- Thermal plasma is described as a single fluid by full resistive linear MHD equations.
- The fields solver originates from the code MARS transformed from an eigenvalue solver to an initial value one.
- Energetic particles are described by nonlinear gyrokinetic Vlasov equations expanded up to order $O(\varepsilon^2)$ and $O(\varepsilon\varepsilon_B)$ and solved by particle-in-cell (PIC) techniques.
- The MHD and the gyrokinetic modules, are coupled together by inserting the divergence of the EP pressure tensor in the MHD momentum equations

ORDERING and DEFINITIONS

- gyrokinetic ordering parameter $\varepsilon \simeq \varrho_H/L_n$; $\varepsilon_B \simeq \varrho_H/L_B$; ϱ_H the EP Larmor radius
- L_n / L_B the characteristic length scales of the equilibrium plasma density/magnetic field.
- Space-time ordering for the fluctuating electromagnetic fields: $k_\perp \varrho_H = O(1)$, $k_{||} \varrho_H = O(\varepsilon)$, $\omega/\Omega_H = O(\varepsilon)$
- $k_\perp$ the perpendicular (to the equilibrium magnetic field) wave vector; $k_{||}$ the parallel one
- ω: characteristic fluctuation frequency and Ω_H the EP gyrofrequency.

Toward using HYMAGYC to explore kinetic effects on MHD modes

Illustrate an example of including kinetic effects in hybrid codes: XHMGC and e-fishbones, see G. Vlad et al., "*Theory and modeling of electron fishbones*" New J. Phys. 18 (2016) 105004

Following [9], where the model implemented in XHMGC has been described in detail, let us consider the perpendicular component of the extended MHD momentum equation:
[9] Wang X, Briguglio S, Chen L, Di Troia C, Fogaccia G, Vlad G and Zonca F , 2011 Phys. Plasmas 18052504

$$\rho_b \left[\frac{\partial}{\partial t} + \left(\underbrace{\frac{\mathbf{b} \times \nabla P_{0i\perp}}{\rho_i \omega_{ci}}}_{\text{diamagnetic, bulk ions}} + \delta \mathbf{v}_b \right) \cdot \nabla \right] \delta \mathbf{v}_b = - \underbrace{(\nabla \cdot \mathbf{P}_e)_\perp}_{\text{bulk electrons}} - \underbrace{(\nabla \cdot \mathbf{P}_i)_\perp}_{\text{bulk ions}} - \underbrace{(\nabla \cdot \mathbf{P}_{Ee})_\perp}_{\text{energetic electrons}} + \left(\frac{\mathbf{J} \times \mathbf{B}}{c} \right)_\perp ,$$

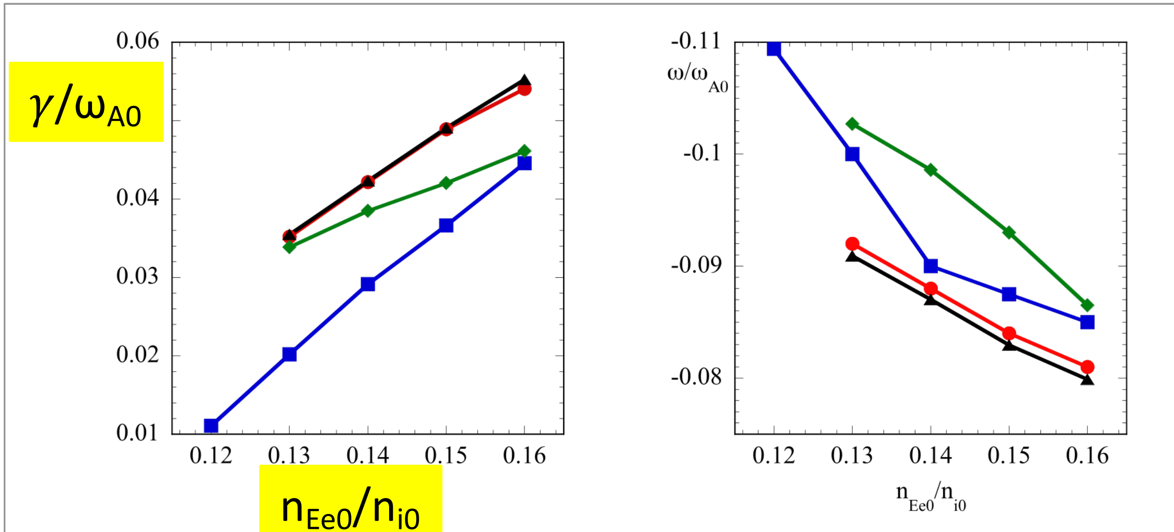
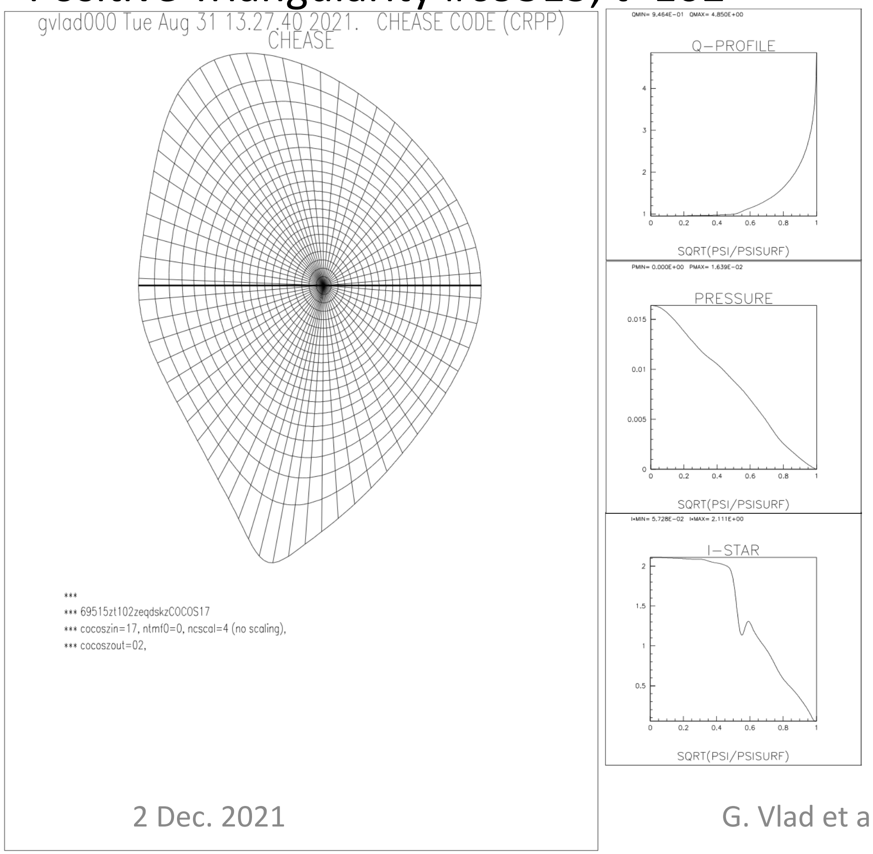


Figure 2. Growth rate (left) and frequency (right) of the electron fishbone mode versus n_{Ee0}/n_{i0}. The results of considering only the energetic electron contribution (red filled cirlces) and adding, one ofter the other, the diamagnetic bulk ion contribution (black filled triangles), the complete bulk ion contribution (blue filled squares) and the bulk electron one (green filled diamonds) are shown.

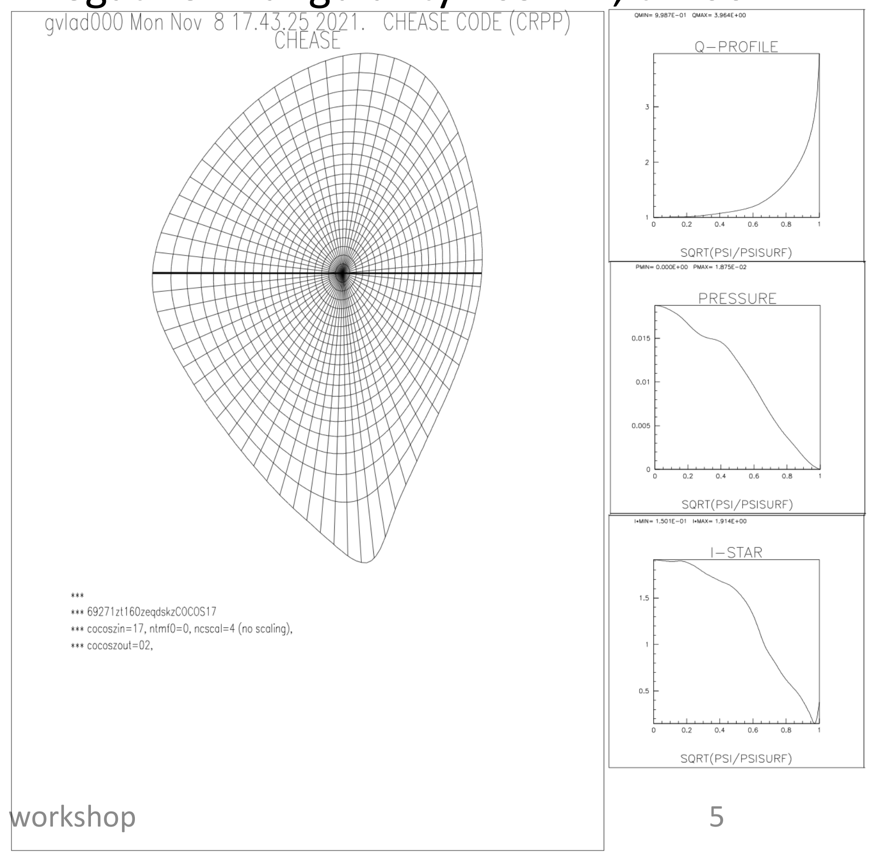
Use as a test cases two experimental TCV equilibria:
Positive Triangularity #69515, t=102, and Negative Triangularity #69271, t=160.

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



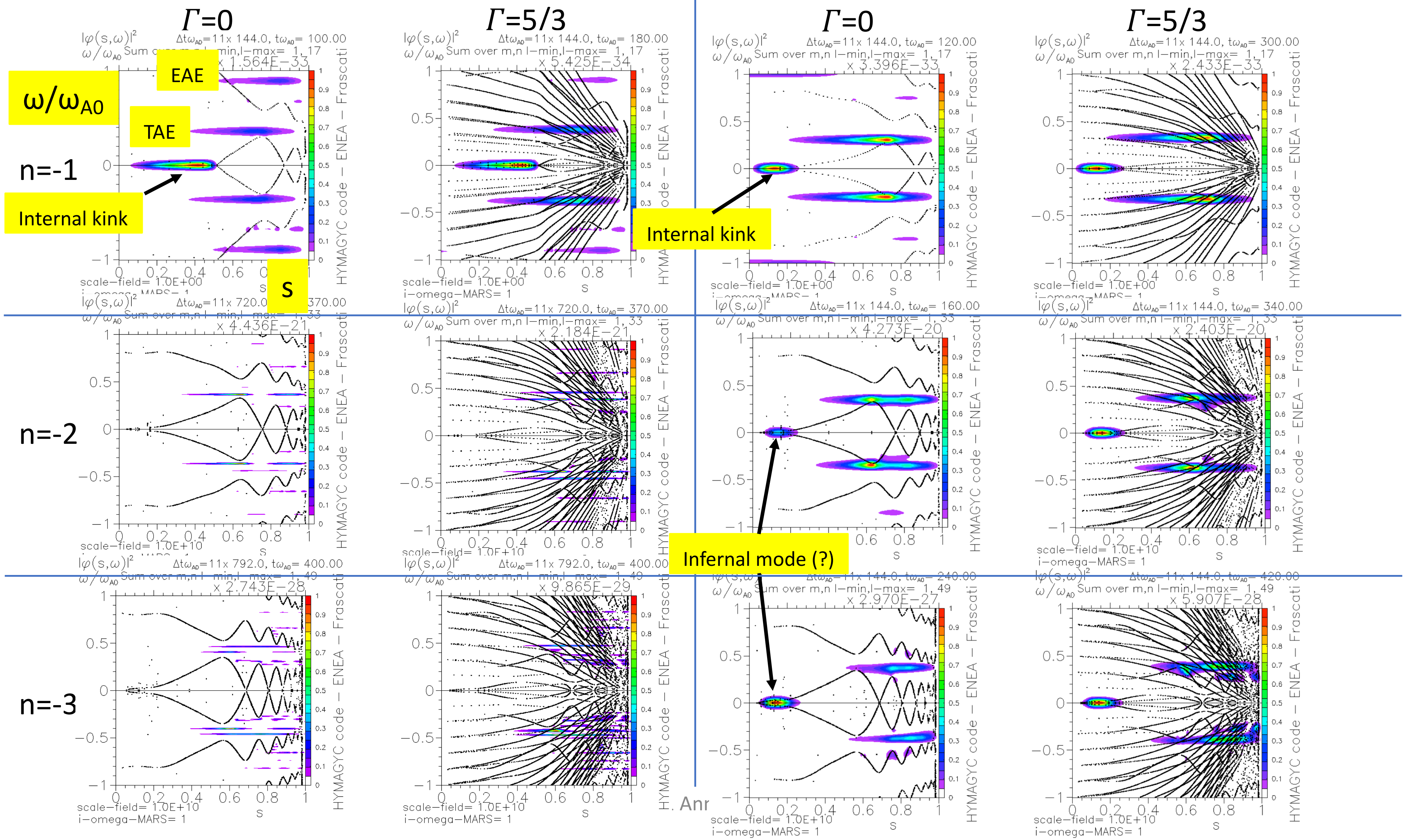
Negative Triangularity #69271, t=160



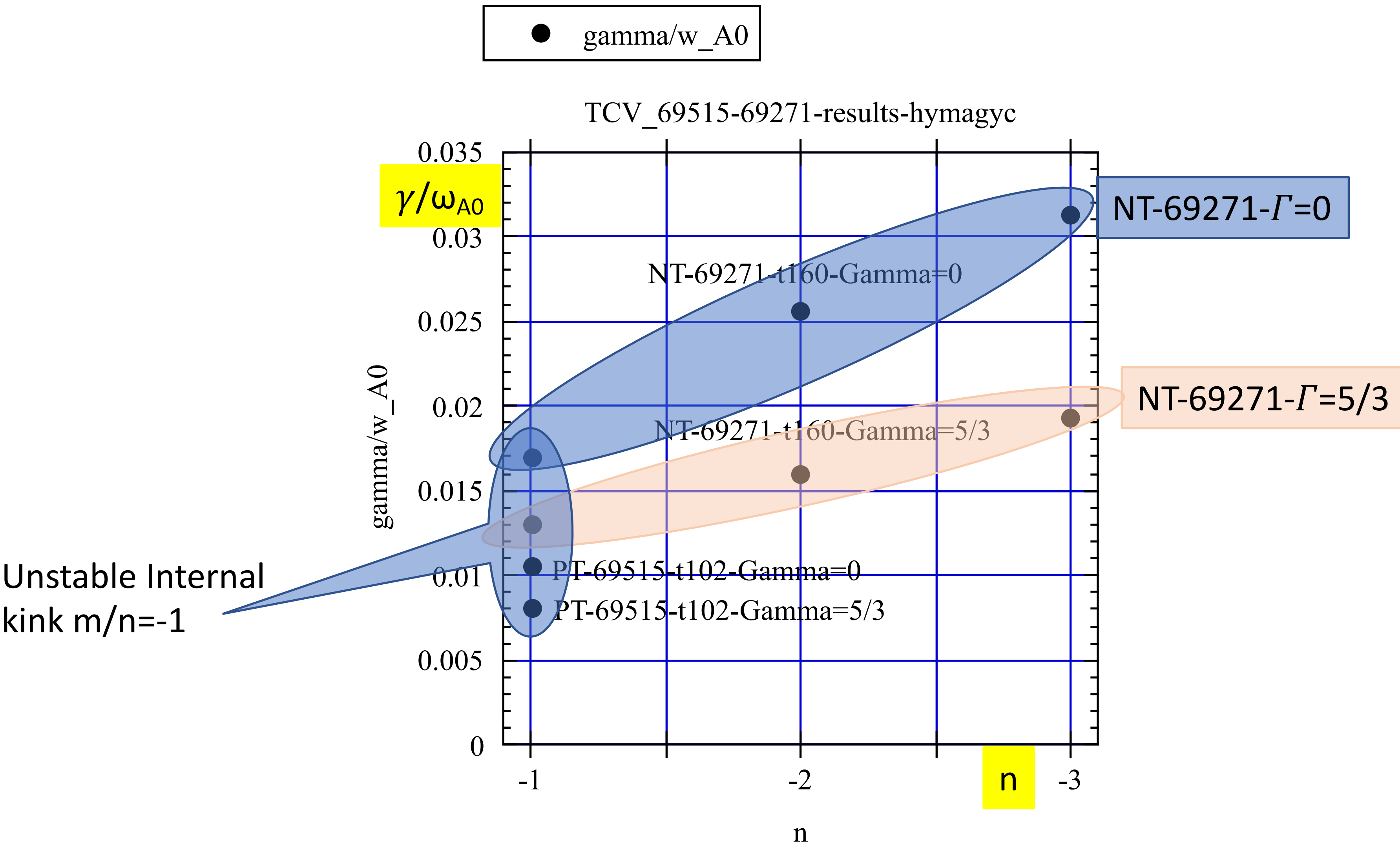
Alfvén continua (using MARS); characterization of low-n MHD modes using HYMAGYC (purely MHD)

Positive Triangularity #69515, t=102

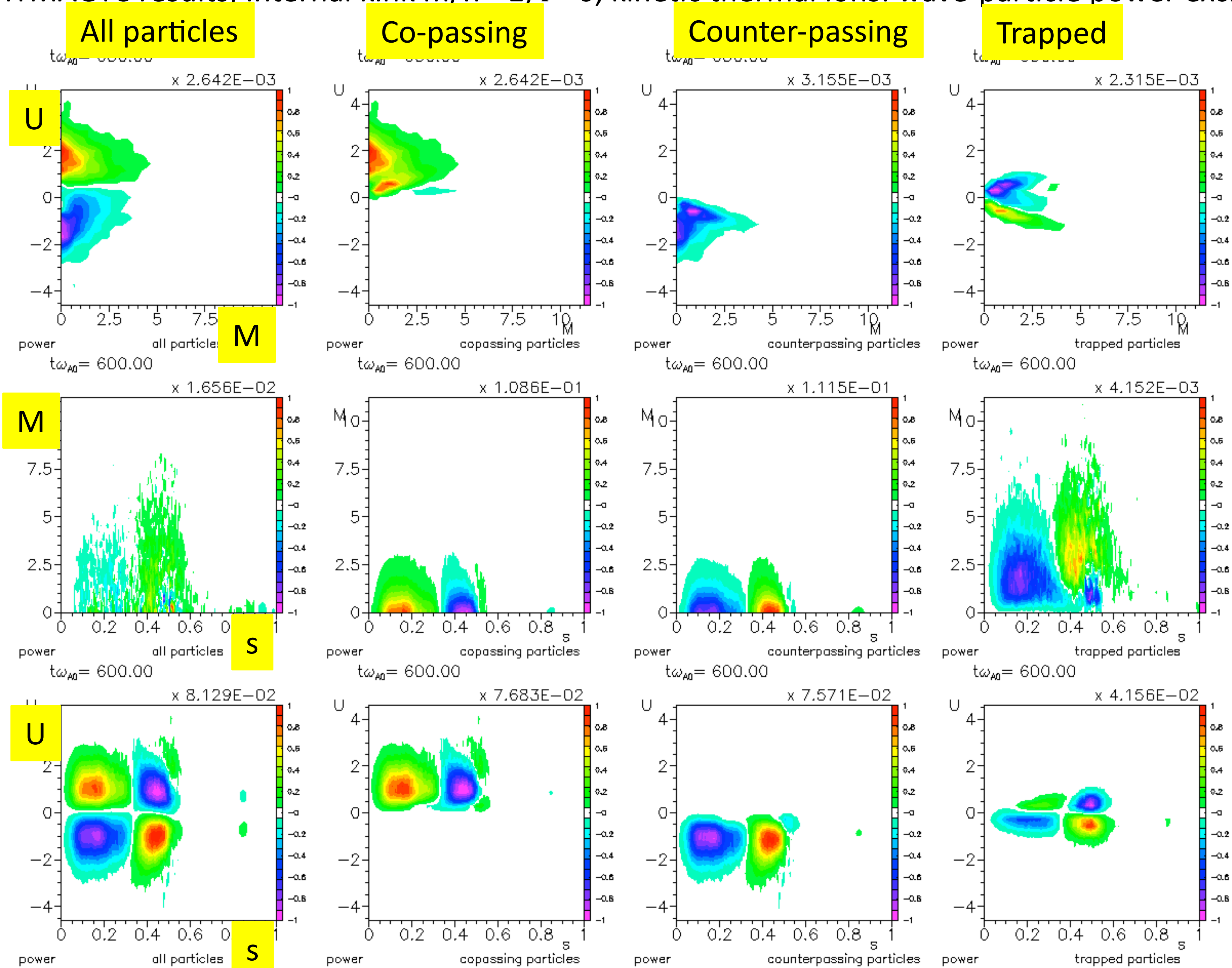
Negative Triangularity #69271, t=160



HYMAGYC results, in the MHD limit



HYMAGYC results, Internal kink m/n=-1, Γ=0, kinetic thermal ions: wave-particle power exchange



caso_hymagyc_TCV_PT_69515_t102-MHD-nrp1-181-Gamma0-ETA0-n=1_kin_bulk_FLR_01

To be done:

- Complete the implementation of the kinetic bulk species contributions in HYMAGYC (following what has been already done in XHMGC)
- Apply to TCV experimental cases
- Use also the DTT reference Negative triangularity cases
- Include also Energetic Particles driven modes to auxiliary heated cases