Preliminary studies of Energetic Particle driven Alfvénic modes for a model DTT equilibrium using HYMAGYC

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Summary

- Introduction
- HYMAGYC & case study for DTT
- MHD characterization of the equilibrium
- Energetic particle driven Alfvénic modes vs. toroidal mode number
- Conclusions

DTT, the Divertor Tokamak Test facility, is the new plasma physics research device under construction in Italy, which will benefit from a substantial support from EUROfusion to specifically address the problem of heating and power exhaust in ITER and DEMO devices. DTT characteristic parameters considered here are: toroidal field $B_0 \approx 6.0T$, major radius $R_0 \approx 2.08m$, aspect ratio $A \approx 3.2$, plasma current $I_p \approx 5.5$ MA, additional power $P_{Tot} \approx 45$ MW (note that the device parameters have been slightly updated, e.g., $R_0 \approx 2.18m$).

The equilibrium and plasma parameters for the Single Null (SN) original baseline scenario (2018) can be found at https://www.afs.enea.it/vlad/Miscellaneous/Testcase_DTT_HYMAGYC_2019/:

It is a "engineering" equilibrium, with bulk ion density resulting from a METIS simulation: energetic particle density profile as from ITER-SC2 scenario; high resolution model equilibrium recomputed by CHEASE (B_0, I_p>0, COCOS=2 coordinate system)

DTT, v1, Single Null, t=36s

$B_0 \approx 6.0T$

$R_0 \approx 2.08m$

$\beta_{th,0} \approx 4\%$

$T_H = 0.45MeV$

$n_{H0}/n_{i0} \approx 0.05$

$\beta_{H,0}/\beta_{th,0} \gtrsim 1$

$m_H/m_i = 0.5$ (H EPs/D bulk ions)

$\rho_H/a \approx 0.017$

$v_H/v_{A0} \approx 1.$

Γ=5/3 (adiabatic coefficient)

η=0 (ideal plasma)

Isotropic Maxwellian EPs, FOW only

Quantity	Value	Data definition/Origin
B_geo [T]	5.9994	EQDSK, vacuum magnetic field at R=R_geo
R_geo [m]	2.0802	geometric major radius (R_LCMS_max+R_LCMS_min)/2
B0 [T]	B0=B_geo	normalization coefficient for the magnetic field
R0 [m]	R0=R_geo	normalization coefficient for the lengths
a [m]	0.65	minor radius (R_LCMS_max-R_LCMS_min)/2
epsilon_dev [m]	0.31247	inverse Aspect ratio (a/R_geo)
n_i0 [10^20/m^3]	2.0739	from METIS simulation
n_EP0/n_i0	0.05	EP density/bulk ion density
m_i/Z_i	2/1	bulk ion mass/charge (D) (in units of proton mass/electron charge)
m_EP/Z_EP	1/1	EP mass/charge (H) (in units of proton mass/electron charge)
m_EP/m_i	0.5	mass ratio (EP/bulk ion)
T_EP0 [MeV]	0.45	on-axis EP Temperature (constant on radius), Maxwellian distribution
v_A0 [m/s]	6.42242x10^6	on-axis Alfvén velocity => 2.18x10^6 B0[T]/sqrt(m_i n_i0[10^20/m^3])
tau_A0 [s]	3.23865x10^-7	R0/v_A0
omega_A0 [rad/s]	3.08770x10^6	1/tau_A0
v_EPth0 [m/s]	6.92258x10^6	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	1.07788	
omega_ci [rad/s]	5.747425x10^8	EP gyrofrequency => 9.58x10^7 Z_EP B0[T]/m_EP
rho_EP0 [m]	0.01204466	on-axis EP Larmor radius (v_EPth0/omega_ci) => 0.102 sqrt(m_EP T_EP0[MeV])/Z_EP/B_mag[T]
rho_EP0/R0	0.00577926	on-axis EP Larmor radius/R0
rho_EP0/a	0.0184954	on-axis EP Larmor radius/a

HYMAGYC code description

HYMAGYC [1] is a hybrid MHD-Gyrokinetic code.

- It is 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 MARS [2], transformed from an eigenvalue solver to an initial value one.
- Energetic particles are described by nonlinear gyrokinetic Vlasov equations [3] 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 toghether by inserting the divergence of the EP pressure tensor in the MHD momentum equations [4]
- It uses the equilibrium solver CHEASE; it is IMAS compliant

ORDERING and DEFINITIONS

- gyrokinetic ordering parameter $\varepsilon \simeq \rho_H/L_n$
- $\varepsilon_B \simeq \rho_H/L_B$,
- 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: $k_\perp \rho_H = O(1)$, $k_\| \rho_H = O(\varepsilon)$, $\omega/\Omega_H = O(\varepsilon)$
- $k_\perp$ the perpendicular (to the equilibrium magnetic field) wave vector
- $k_\|$ the parallel one
- ω: characteristic fluctuation frequency and Ω_H the EP gyrofrequency.

References

[1] G. Fogaccia, G. Vlad, S. Briguglio, Nucl. Fusion 56 (2016) 112004

[2] Bondeson A., Vlad G. and Lütjens H. 1992 IAEA Technical Committee Meeting on Advances in Simulations and Modelling of Thermonuclear Plasmas (Montreal, 15–17June 1992) p. 306 (Vienna, Austria: International Atomic Energy Agency)

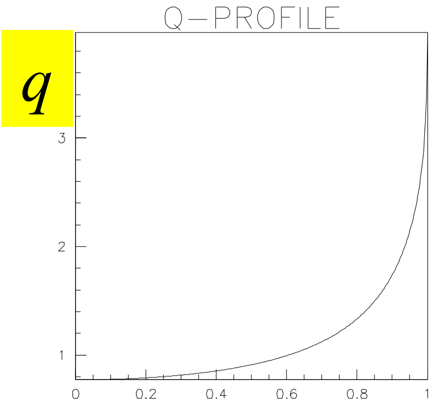
[3] Brizard A.J. and Hahm T.S. 2007 Rev. Mod. Phys. 79 421–68

[4] Park W. et al 1992 Phys. Fluids B 4 2033

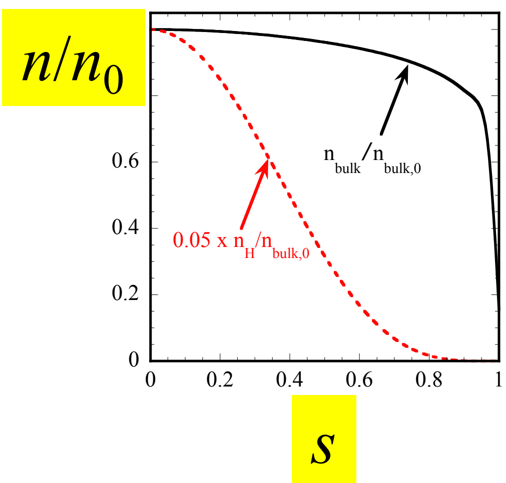
[5] T. Wang, Z. Qiu, F. Zonca, S. Briguglio, G. Fogaccia, G. Vlad, and X. Wang, Phys. Plasmas 25, 062509 (2018)

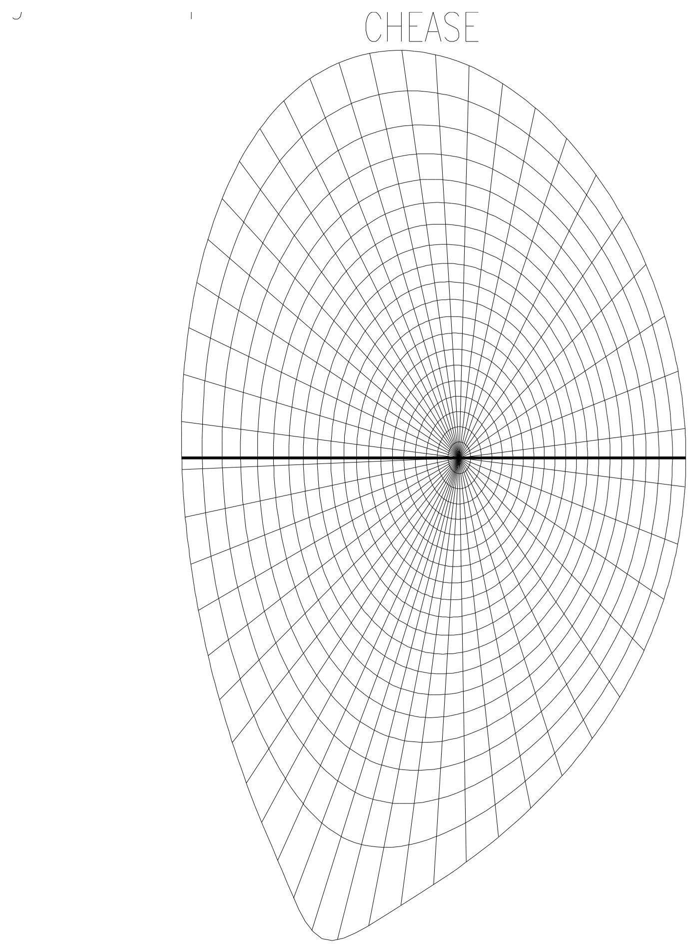
[6]T. Wang, X. Wang, S. Briguglio, Z. Qiu, G. Vlad, and F. Zonca, Physics of Plasmas 26, 012504 (2019)

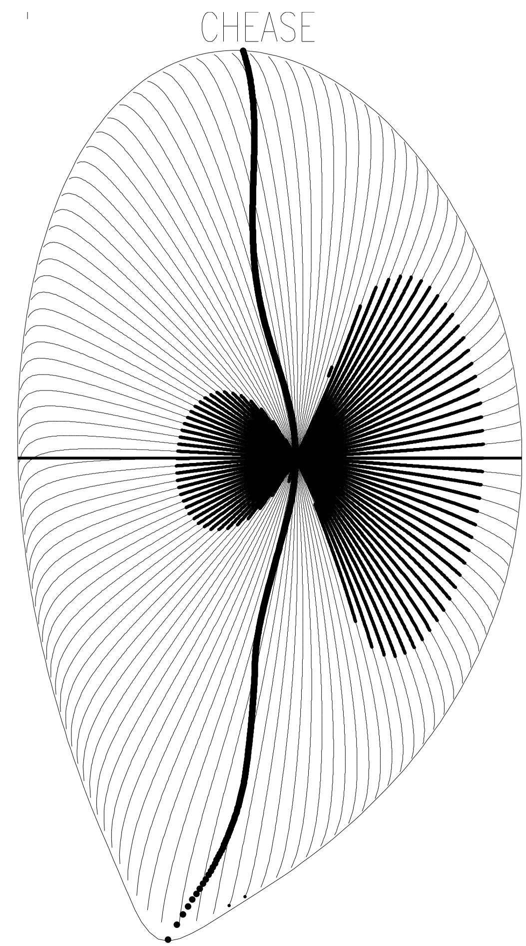
DTT equilibrium (CHEASE), reference case



$s \equiv \mathrm{sqrt}(\psi/\psi_{surf})$



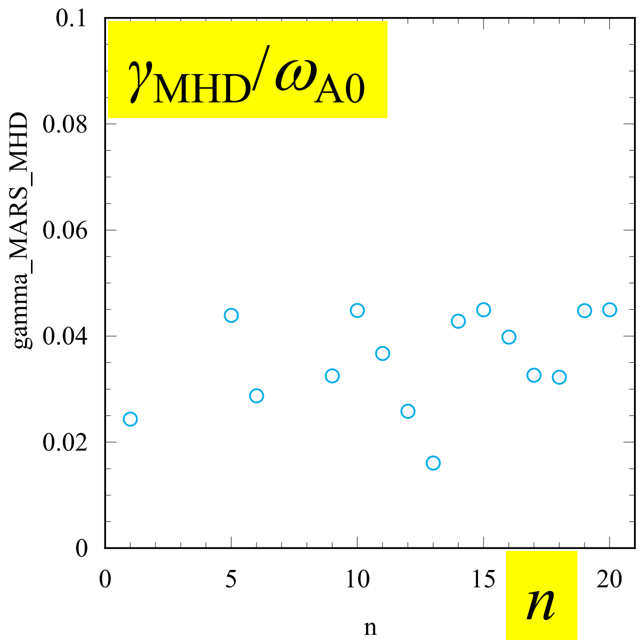


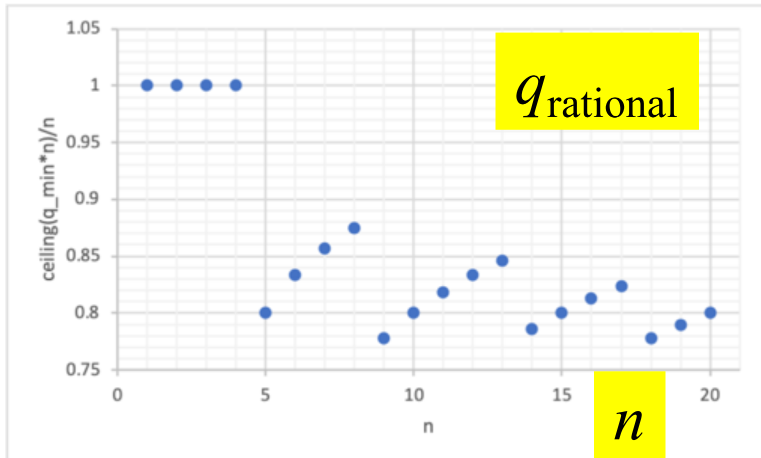


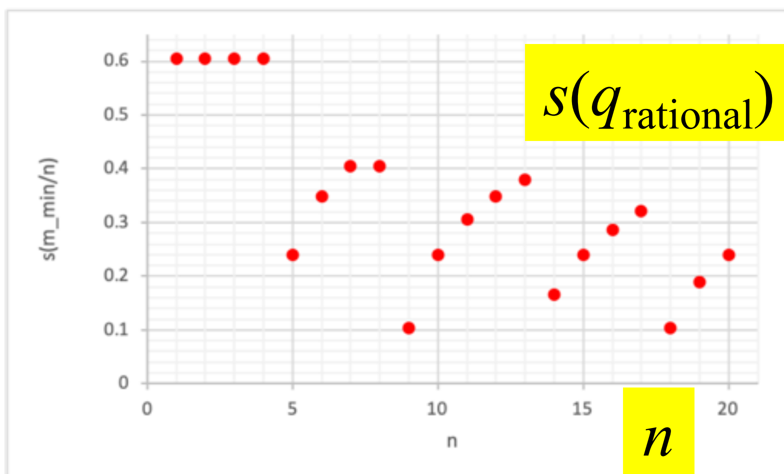
***
*** EquilzDTTzSNzv1zlplz5d5MAzR0z2d08zbetapz0d43zliz0d895ztzatz36szrefzmesh−rwle
*** cocoszin=11, ntmf0=0, ncscal=4 (no scaling), tensbnd=−300.0,
*** cocoszout=13,

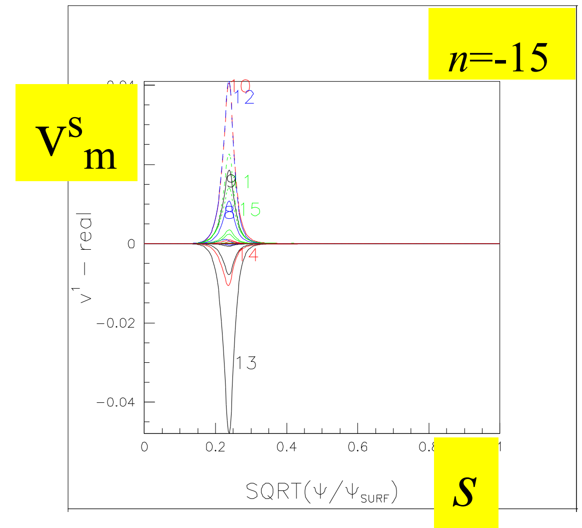
MHD unstable modes, ω/ω_{A0}=0: infernal modes (MARS)

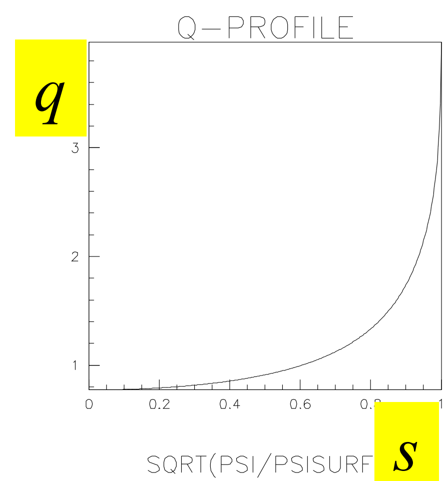
"When the shear is sufficiently weak, the oscillations can result in bands of unstable n-values, which are present even when the standard ballooning theory predicts complete stability. These instabilities are named 'infernal modes'. The occurrence of these instabilities at integer n is shown to be a sensitive function of the q-axis, raising the possibility of a sharp onset as the plasma parameters evolve." (from the original paper by J. Manickam et al 1987 Nucl. Fusion 27 1461)











Adding Energetic Particle contribution

- Linear growth-rate of Alfvén modes and EPMs is proportional to the energetic particle diamagnetic drift frequency ω_{*Es} (Liu Chen et al, PRL 1984);
- from gyrokinetic description of the perturbed EP distribution function, stability given by δW_k

trapped particles: $\delta\widehat{W}_k \propto \mathcal{I} \circ \frac{1}{n\overline{\omega}_d + \ell\omega_b - \omega} QF_0$

circulating particles: $\delta\widehat{W}_k \propto \mathcal{I} \circ \frac{1}{n\overline{\omega}_d + [\ell + nq(r) - m]\omega_t - \omega} QF_0$

$\mathcal{I}\circ$: integro-differential operator

$$QF_0 \;=\; \omega \left(\partial_E + \frac{\widehat{\omega}_{*Es}}{\omega} \right) F_0 \qquad \widehat{\omega}_{*Es} F_0 \;=\; \frac{1}{\omega_c} \frac{\mathbf{k} \times \mathbf{B}}{B} \cdot \nabla F_0$$

$$\omega_{*Es} \;\approx\; \frac{m_{pol}}{n_{\rm H} e_s r B} \frac{dp_{\rm H}}{dr} = \frac{nq(r)}{n_{\rm H} e_s r B} \frac{dp_{\rm H}}{dr}$$

$\omega_{*Es} \propto nq(r)$: short wavelength favored

- Lower bound for wavelength set by characteristic energetic particle orbit width, ρ_E: $k_\perp \rho_E \approx 1$ (finite orbit width averaging; magnetic drifts usually larger than Larmor radius)
- optimal condition: $n_{max} q \lesssim (r/\rho_E)$
- $n_{\text{max-ITER}} \approx O(10)$

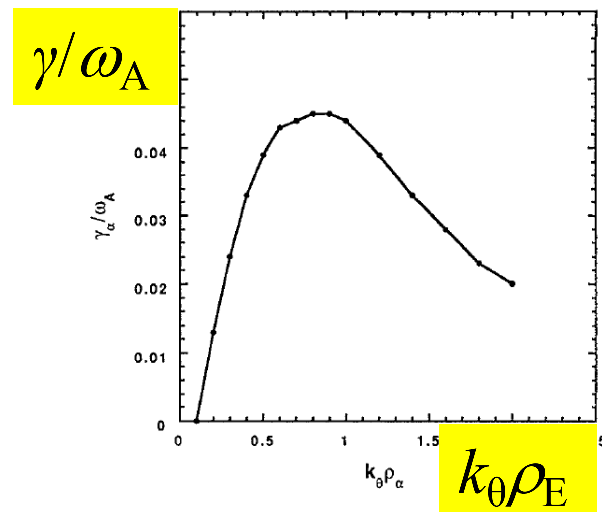


FIG. 3. Growth rate induced by circulating alpha particles as a function of $k_\theta\rho_\alpha$ for s=0.6, Δ_p=0, and v_α/v_A=2.0.

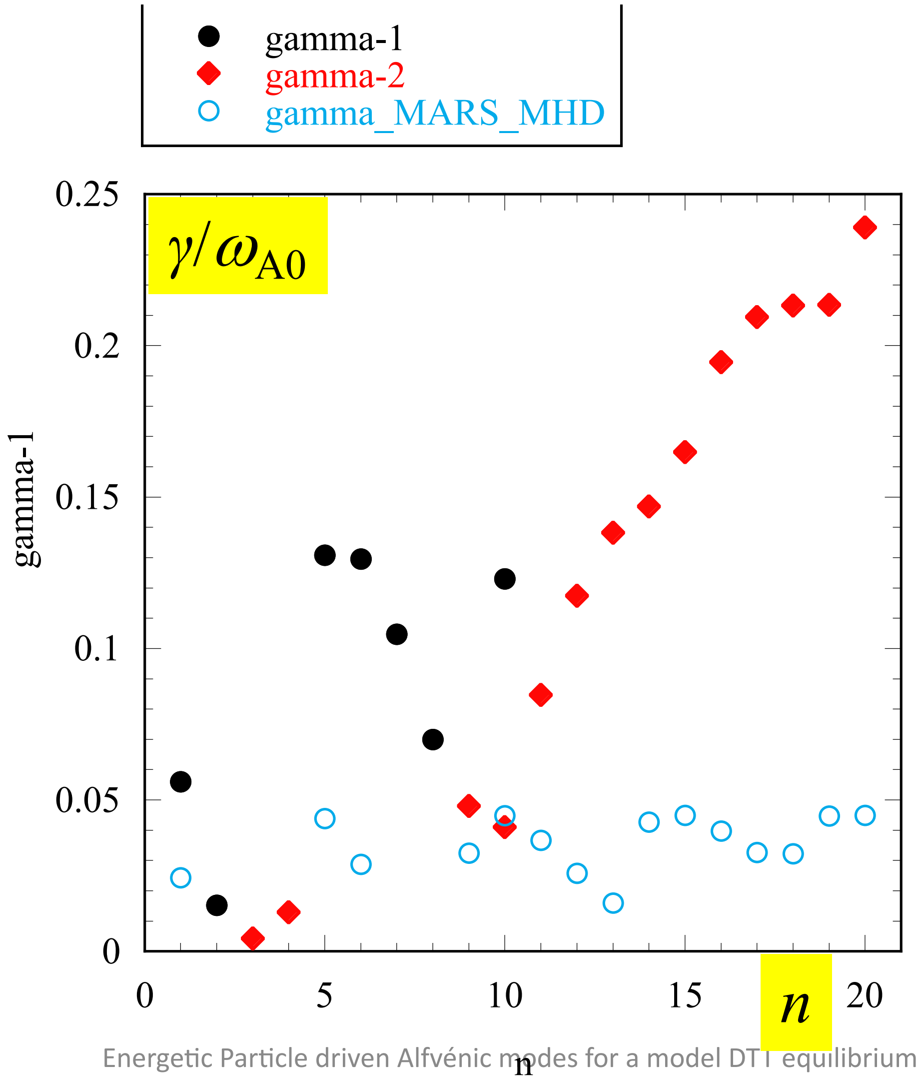
G.Y. Fu et al., Phys. Fluids B4, 3722 (1992)

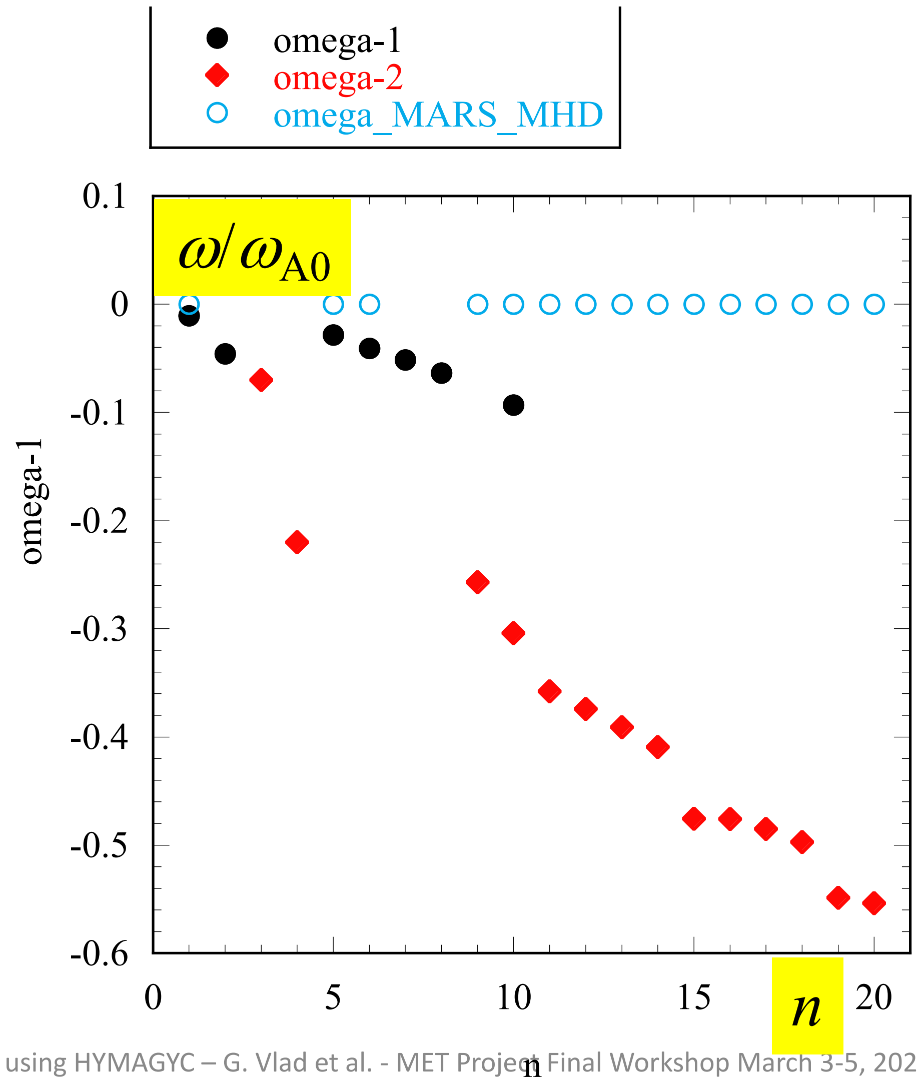
Adding Energetic Particles contribution (contd.)

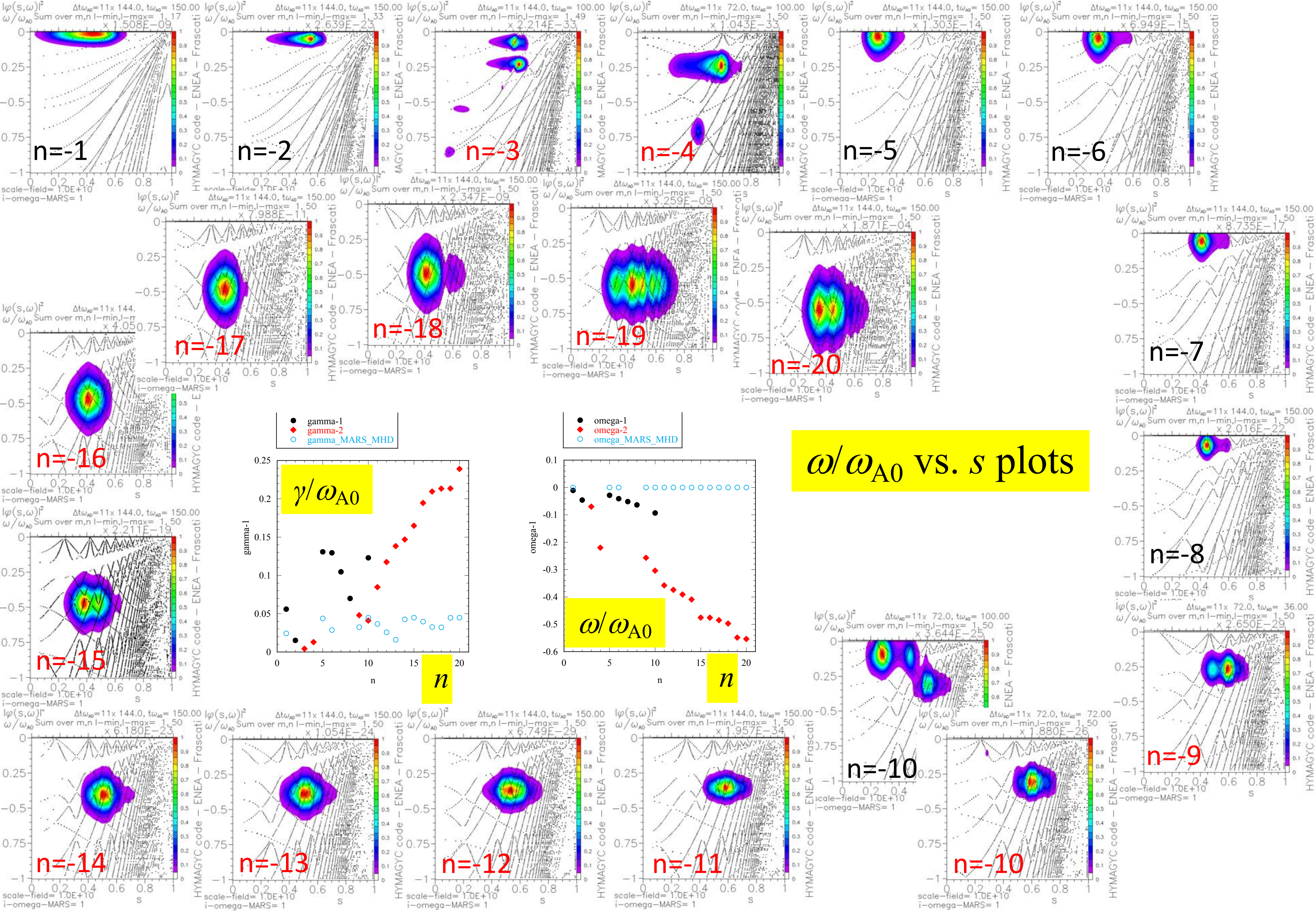
- γ_{MHD},ω_{MHD}:"infernal" modes

Adding Energetic Particle contribution:

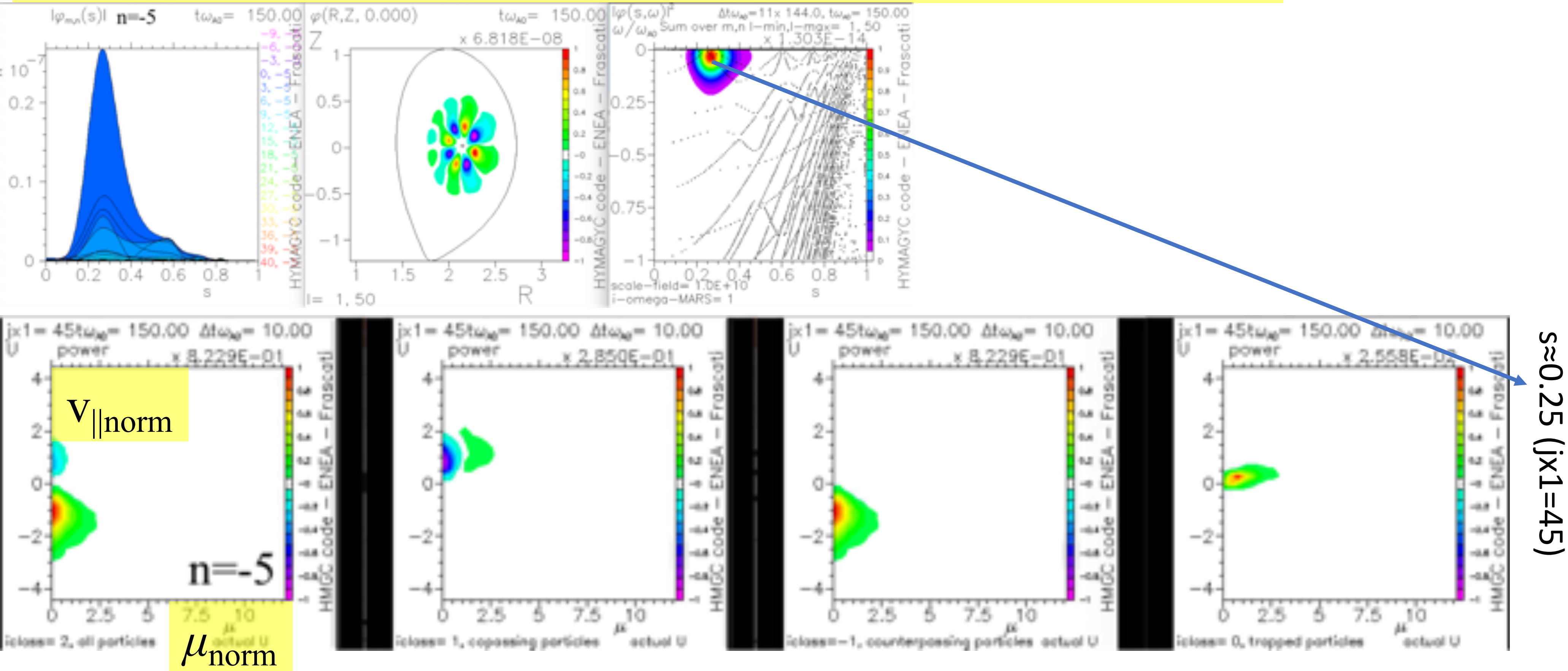
- γ_1,ω_1: EP driven "infernal" modes
- γ_2,ω_2: EP driven Alfvénic modes



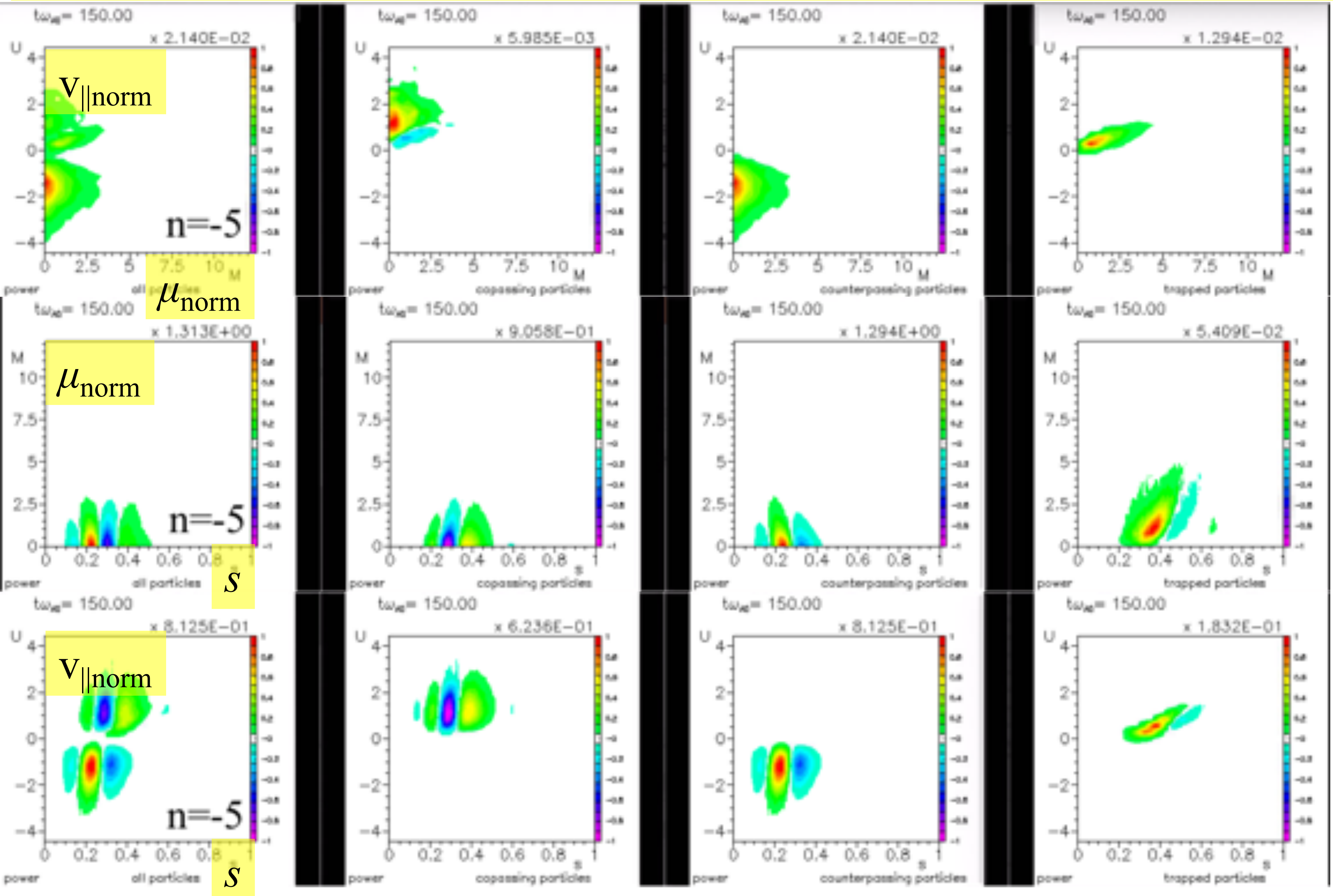



ω/ωA0 vs. s plots
n=-1
n=-2
n=-3
n=-4
n=-5
n=-6
n=-7
n=-8
n=-9
n=-10
n=-10
n=-11
n=-12
n=-13
n=-14
n=-15
n=-16
n=-17
n=-18
n=-19
n=-20
γ/ωA0
gamma-1
gamma-2
gamma_MARS_MHD
ω/ωA0
omega-1
omega-2
omega_MARS_MHD
n
HYMAGYC code – ENEA – Frascati
scale-field= 1.0E+10
i-omega-MARS= 1

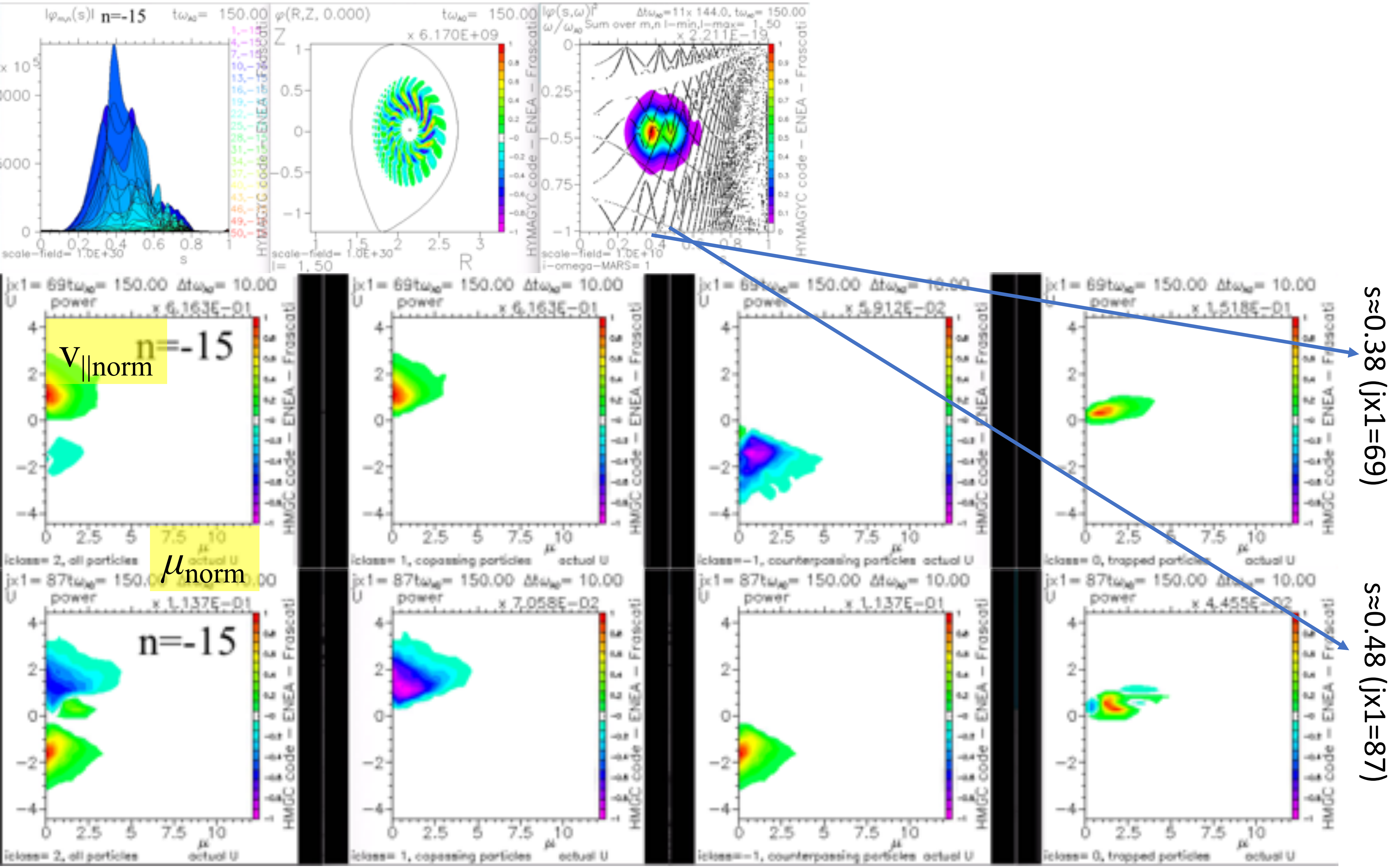
Power transfer between EPs and wave P(s,M,U); n=-5 – 3d plots => counter-passing



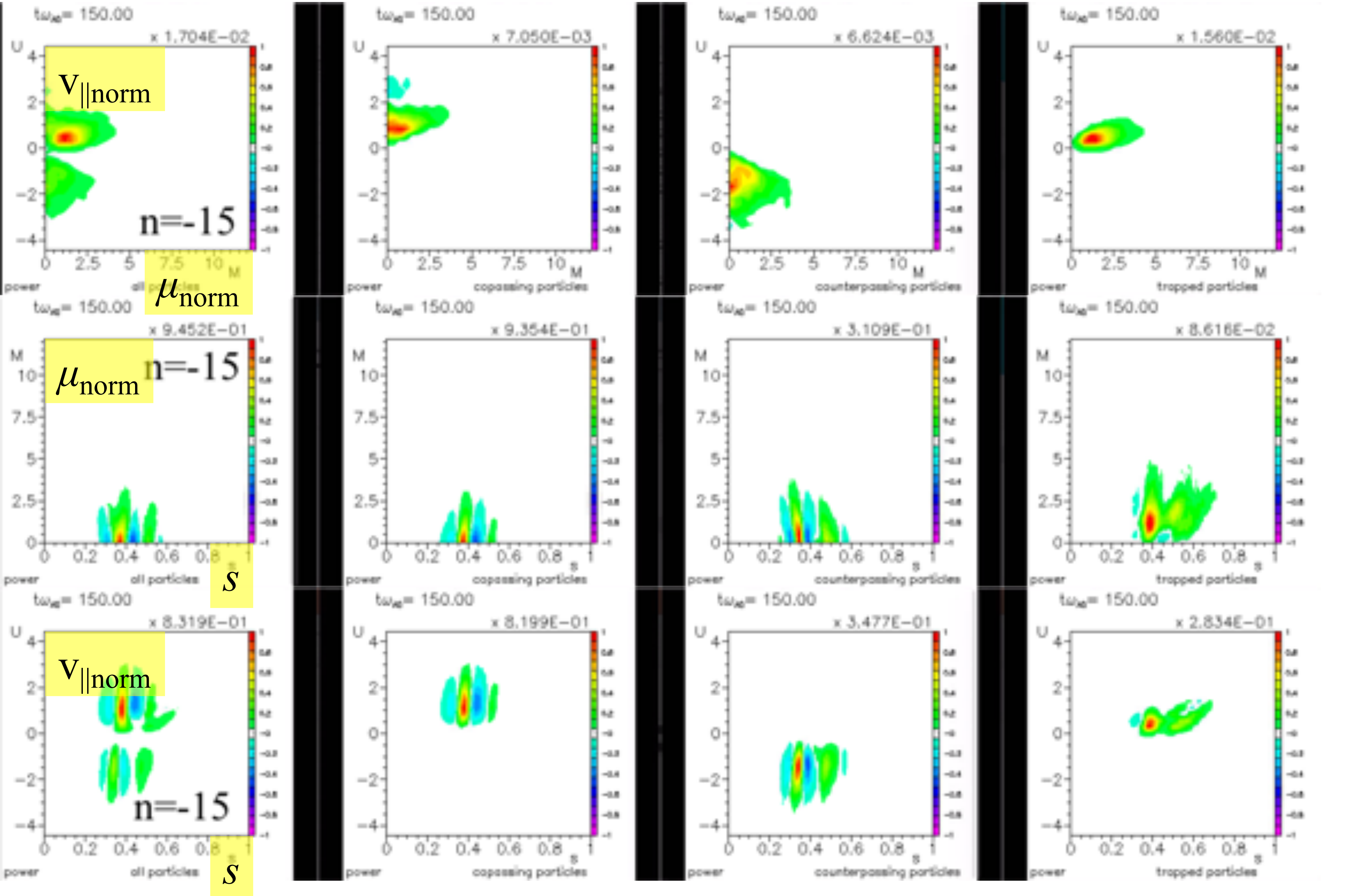
Power transfer between EPs and wave P(s,M,U); n=-5 – 2d plots (reduced over third coord.) => counter-passing



Power transfer between EPs and wave P(s,M,U); n=-15 – 3d plots => trapped particles



Power transfer between EPs and wave P(s,M,U); n=-15 – 2d plots (reduced over third coord.) => trapped particles

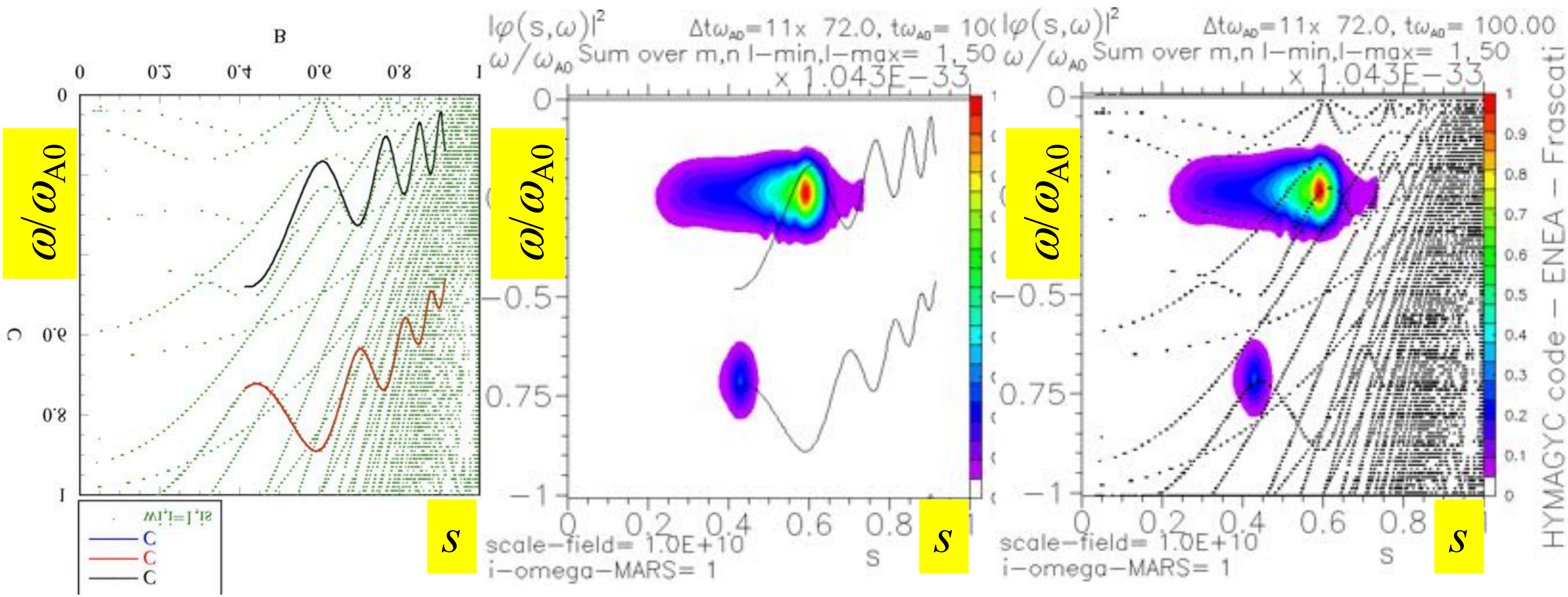


n=-4 Alfvén continuous spectrum, detailed structure

comparison between MARS continua and approximated (Falcon) Shear Alfvén Wave continua using slow-sound approximation: comparison is satisfactory for the upper continuum of the toroidal gap, not satisfactory for the lower continuum and below (BAAE gap, etc.).

GREEN: complete MARS continua;

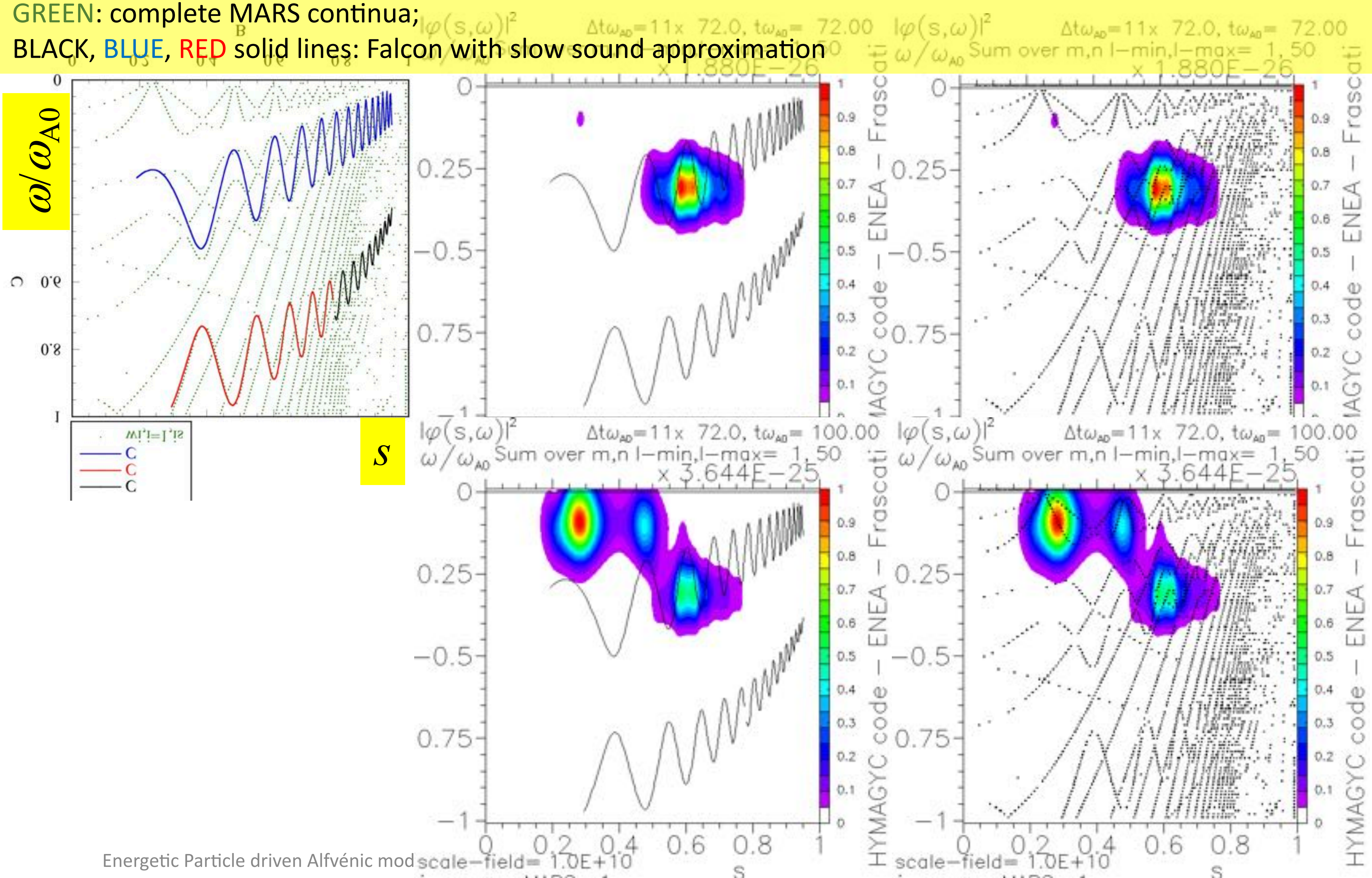
BLACK, RED solid lines: Falcon with slow sound approximation



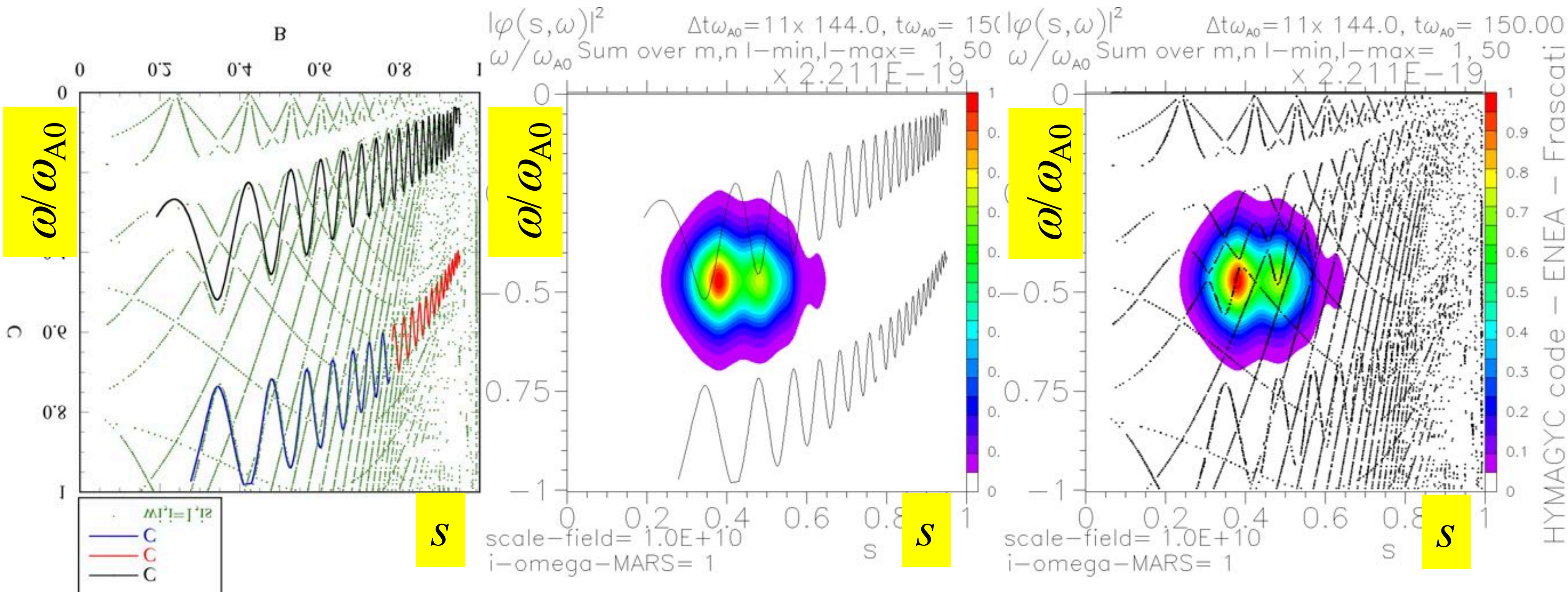
n=-10 Alfvén continuous spectrum, detailed structure: comparison between MARS continua and approximated (Falcon) Shear Alfvén Wave continua using slow-sound approximation: comparison is satisfactory for the upper continuum of the toroidal gap, not satisfactory for the lower continuum and below (BAAE gap, etc.).

GREEN: complete MARS continua;

BLACK, BLUE, RED solid lines: Falcon with slow sound approximation

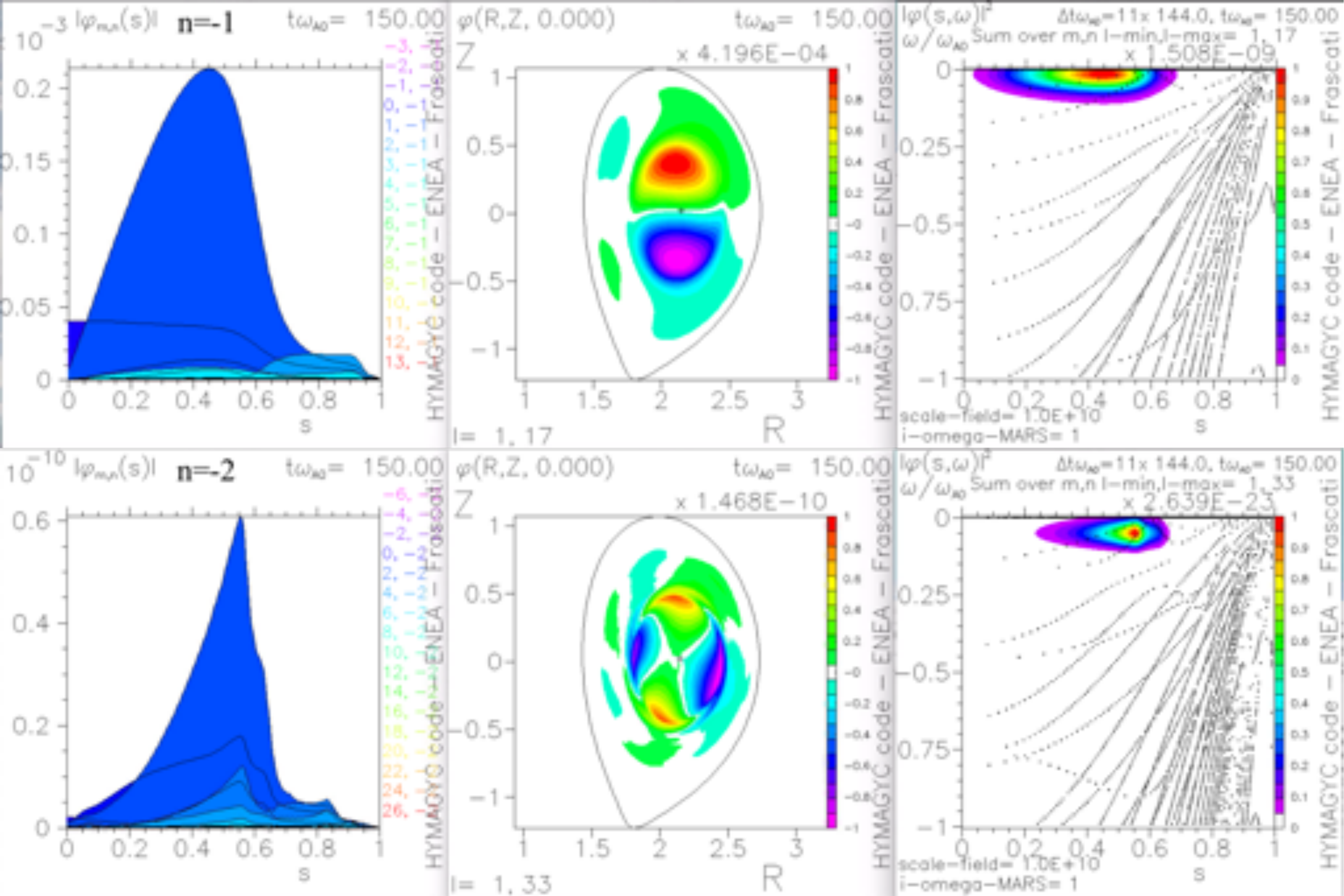


n=-15 Alfvén continuous spectrum, detailed structure
comparison between MARS continua and approximated (Falcon) Shear Alfvén Wave continua using slow-sound approximation: comparison is satisfactory for the upper continuum of the toroidal gap, not satisfactory for the lower continuum and below (BAAE gap, etc.).
GREEN: complete MARS continua;
BLACK, BLUE, RED solid lines: Falcon with slow sound approximation

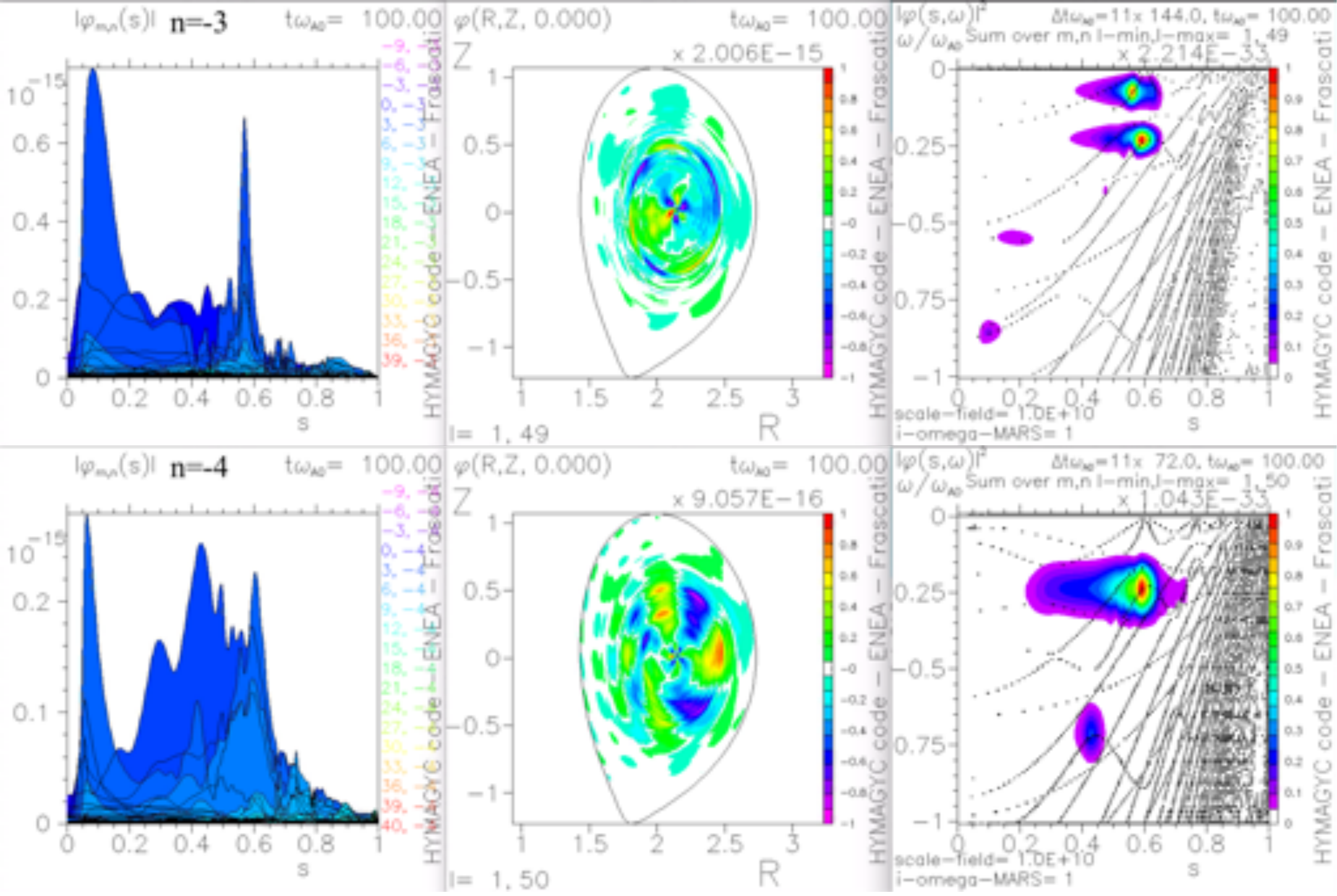


Conclusions

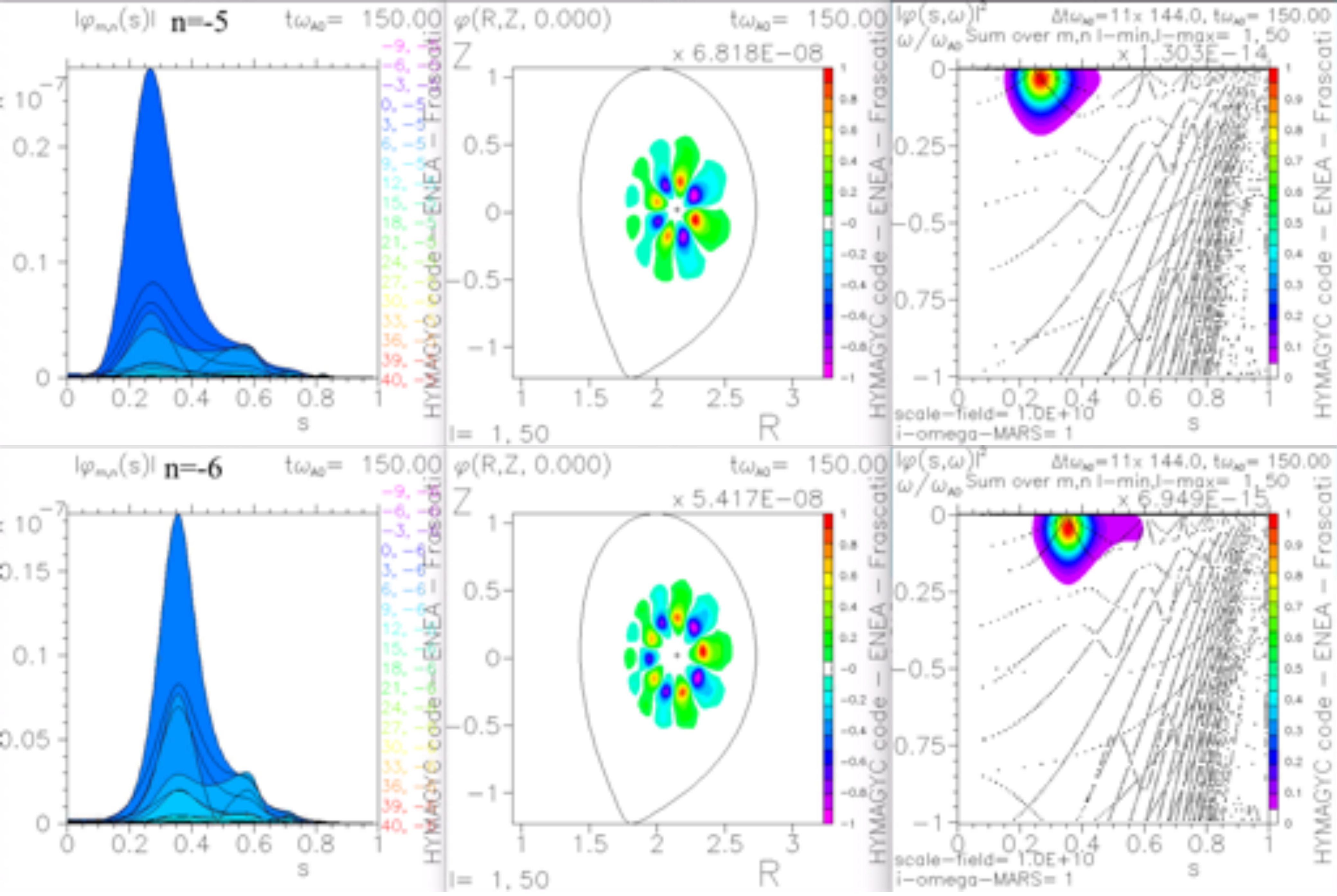
- First systematic investigation on Energetic Particle driven Alfvénic Modes on DTT model equilibrium using HYMAGYC:
  - useful exercise to test HYMAGYC potentialities in realistic scenarios environment;
  - moderately high toroidal mode numbers have been tested ($n \leqq 20$);
  - useful testbed for checking numerics, convergence, etc.
- Model equilibrium should be updated to latest DTT scenarios (slightly larger device dimensions, different heating mix, use proper B_0, I_p signs, etc.), possibly using more realistic scenarios as obtained by. e.g., transport code simulations (consistent scenario...)
- More appropriate Energetic Particles distribution function to be used (e.g., anisotropic slowing down, instead of isotropic Maxwellian, Constant of Motion parametrized distribution function, etc.)
- Hamiltonian mapping "machinery", largely used with HMGC, is available also for HYMAGYC
- ...



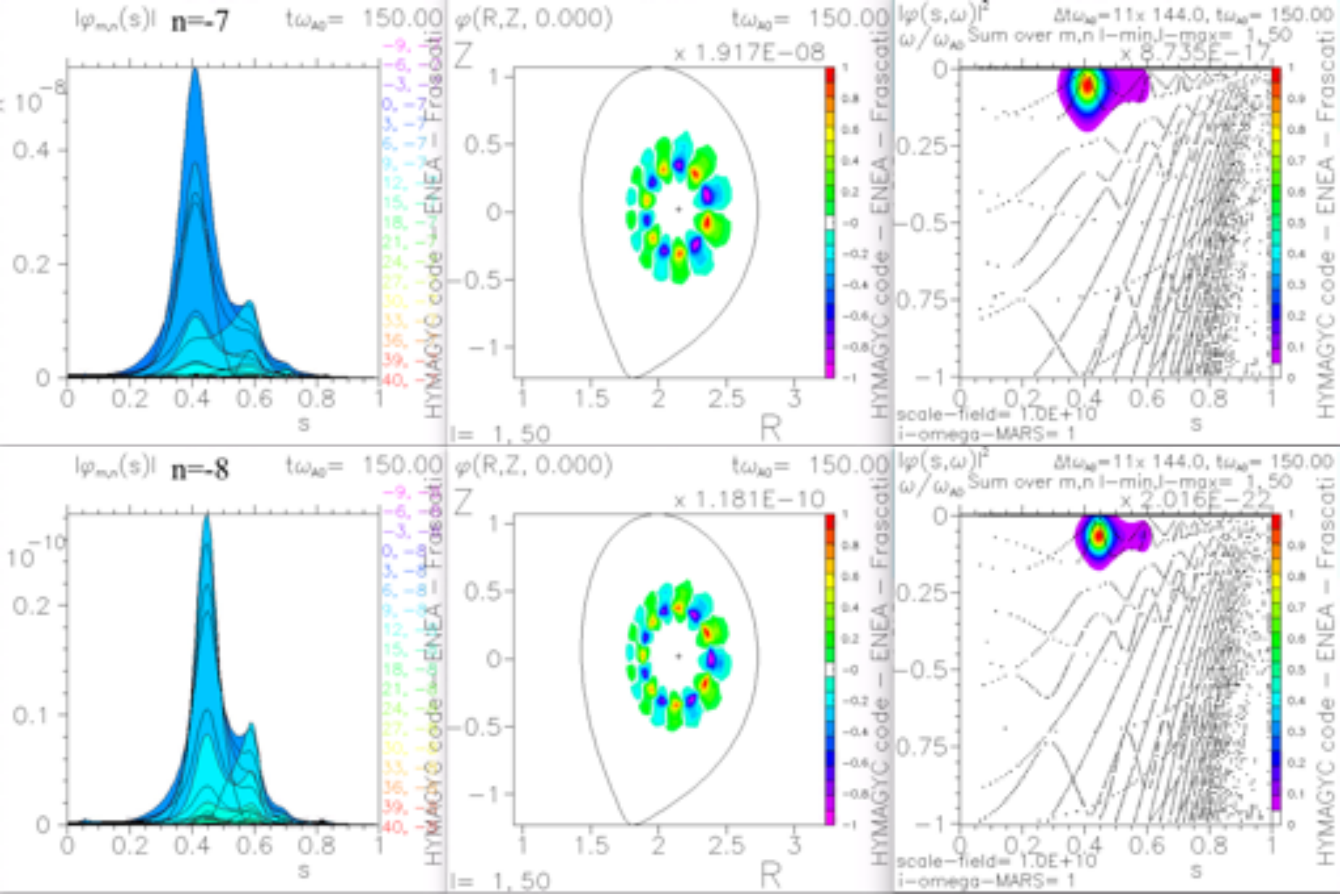
10^{-3} $|\varphi_{m,n}(s)|$ n=-1 $t\omega_{A0}$= 150.00
0.2
0.15
0.1
0.05
0
0 0.2 0.4 0.6 0.8 1
s
-3, -1
-2, -1
-1, -1
0, -1
1, -1
2, -1
3, -1
4, -1
5, -1
6, -1
7, -1
8, -1
9, -1
10, -1
11, -1
12, -1
13, -1
HYMAGYC code – ENEA – Frascati
φ(R,Z, 0.000) $t\omega_{A0}$= 150.00
x 4.196E-04
Z
R
1.5 2 2.5 3
l= 1, 17
|φ(s,ω)|² Δ$t\omega_{A0}$=11x 144.0, $t\omega_{A0}$= 150.00
ω/ω_{A0} Sum over m,n l-min,l-max= 1, 17
x 1.508E-09
0 0.25 0.5 0.75 1
0 0.2 0.4 0.6 0.8 1
s
scale-field= 1.0E+10
i-omega-MARS= 1
10^{-10} $|\varphi_{m,n}(s)|$ n=-2 $t\omega_{A0}$= 150.00
0.6
0.4
0.2
0
-6, -2
-4, -2
-2, -2
0, -2
2, -2
4, -2
6, -2
8, -2
10, -2
12, -2
14, -2
16, -2
18, -2
20, -2
22, -2
24, -2
26, -2
φ(R,Z, 0.000) $t\omega_{A0}$= 150.00
x 1.468E-10
l= 1, 33
|φ(s,ω)|² Δ$t\omega_{A0}$=11x 144.0, $t\omega_{A0}$= 150.00
ω/ω_{A0} Sum over m,n l-min,l-max= 1, 33
x 2.639E-23
scale-field= 1.0E+10
i-omega-MARS= 1



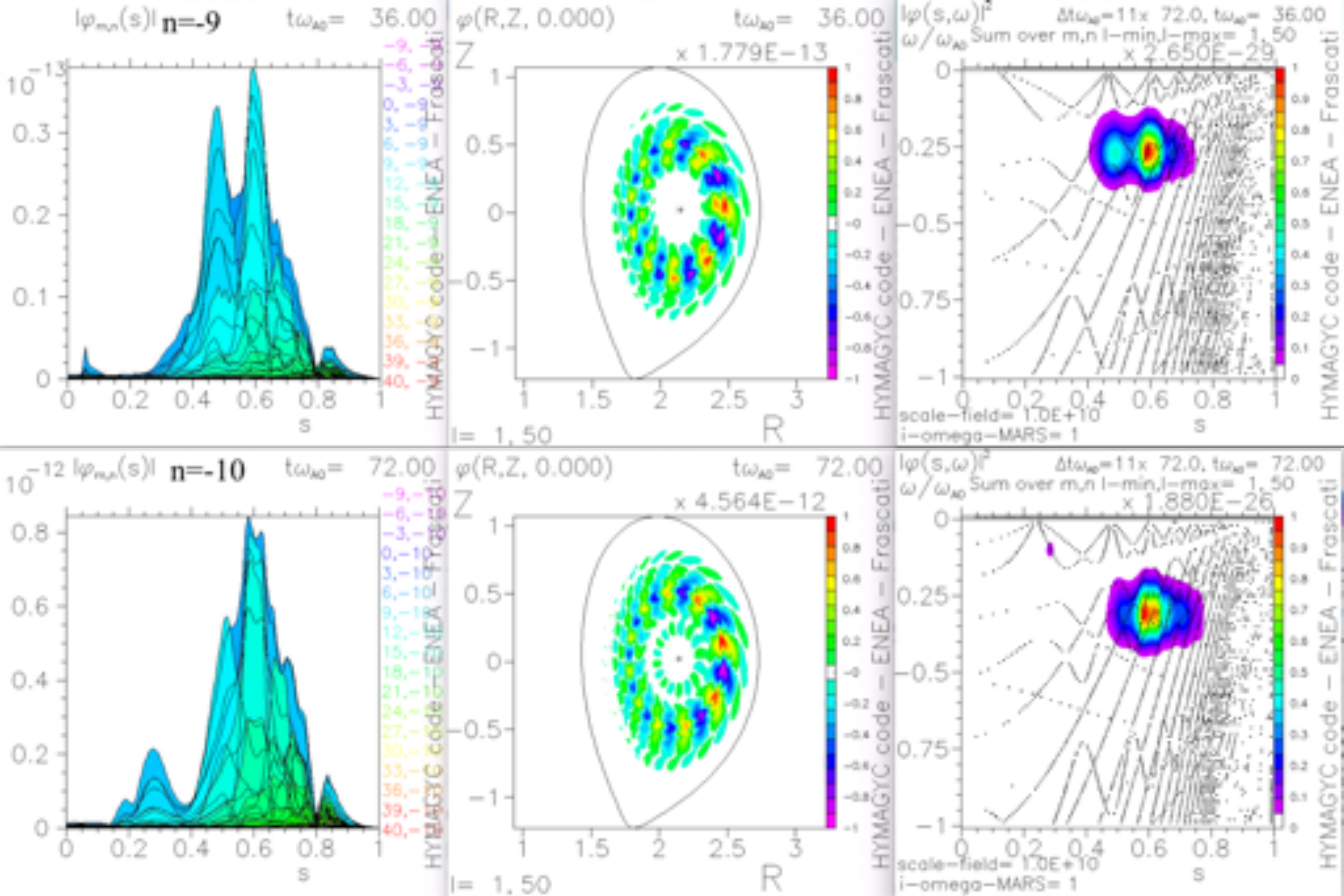
n=-3
n=-4
HYMAGYC code - ENEA - Frascati



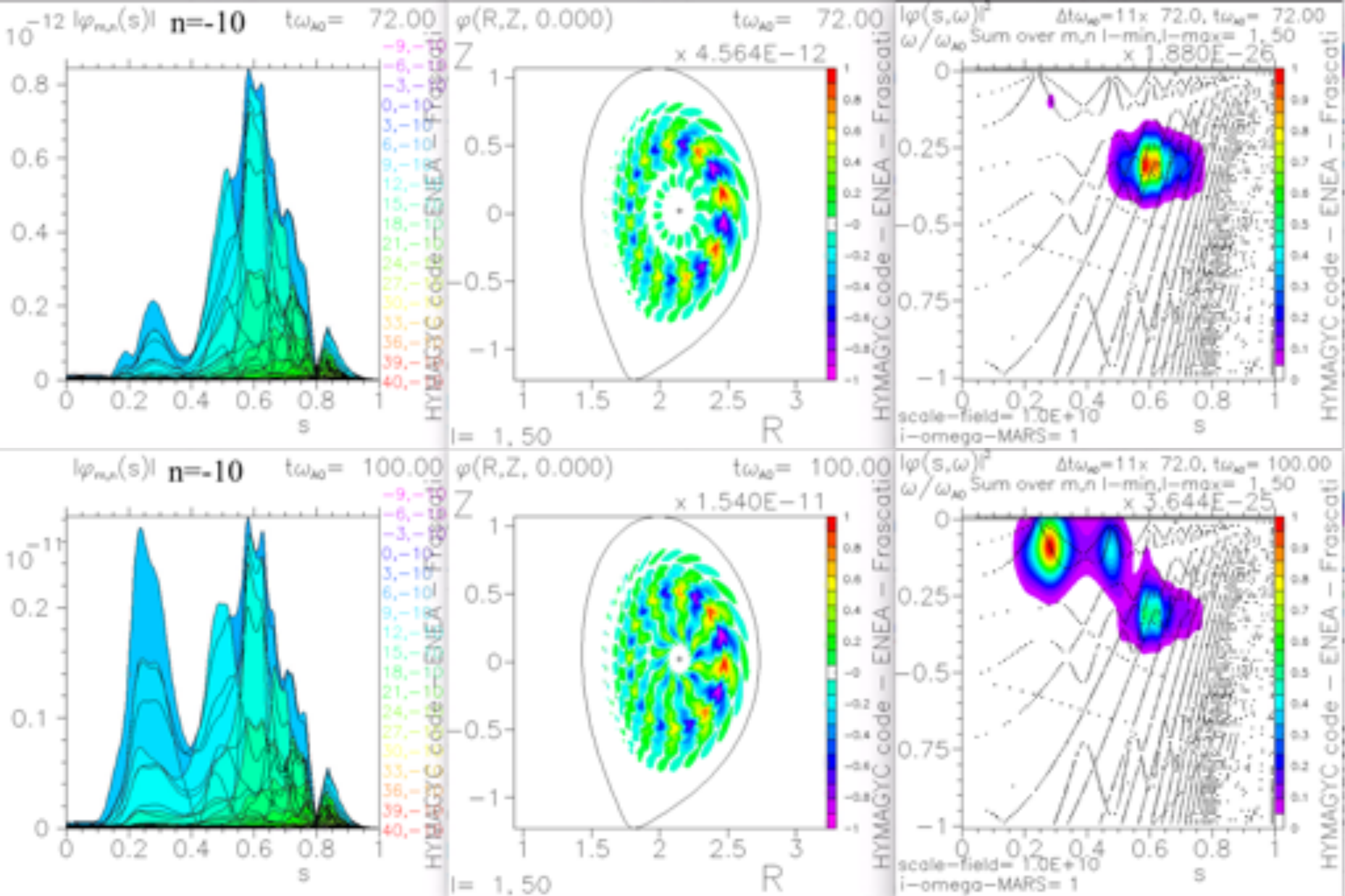
n=-5
|φ_{m,n}(s)|
tω_{A0}= 150.00
φ(R,Z, 0.000)
x 6.818E-08
|φ(s,ω)|²
ω/ω_{A0}
Δtω_{A0}=11x 144.0, tω_{A0}= 150.00
Sum over m,n l-min,l-max= 1, 50
x 1.303E-14
scale-field= 1.0E+10
i-omega-MARS= 1
l= 1, 50
HYMAGYC code - ENEA - Frascati
n=-6
|φ_{m,n}(s)|
tω_{A0}= 150.00
φ(R,Z, 0.000)
x 5.417E-08
|φ(s,ω)|²
ω/ω_{A0}
Δtω_{A0}=11x 144.0, tω_{A0}= 150.00
Sum over m,n l-min,l-max= 1, 50
x 6.949E-15
scale-field= 1.0E+10
i-omega-MARS= 1
l= 1, 50
HYMAGYC code - ENEA - Frascati
s
R
Z



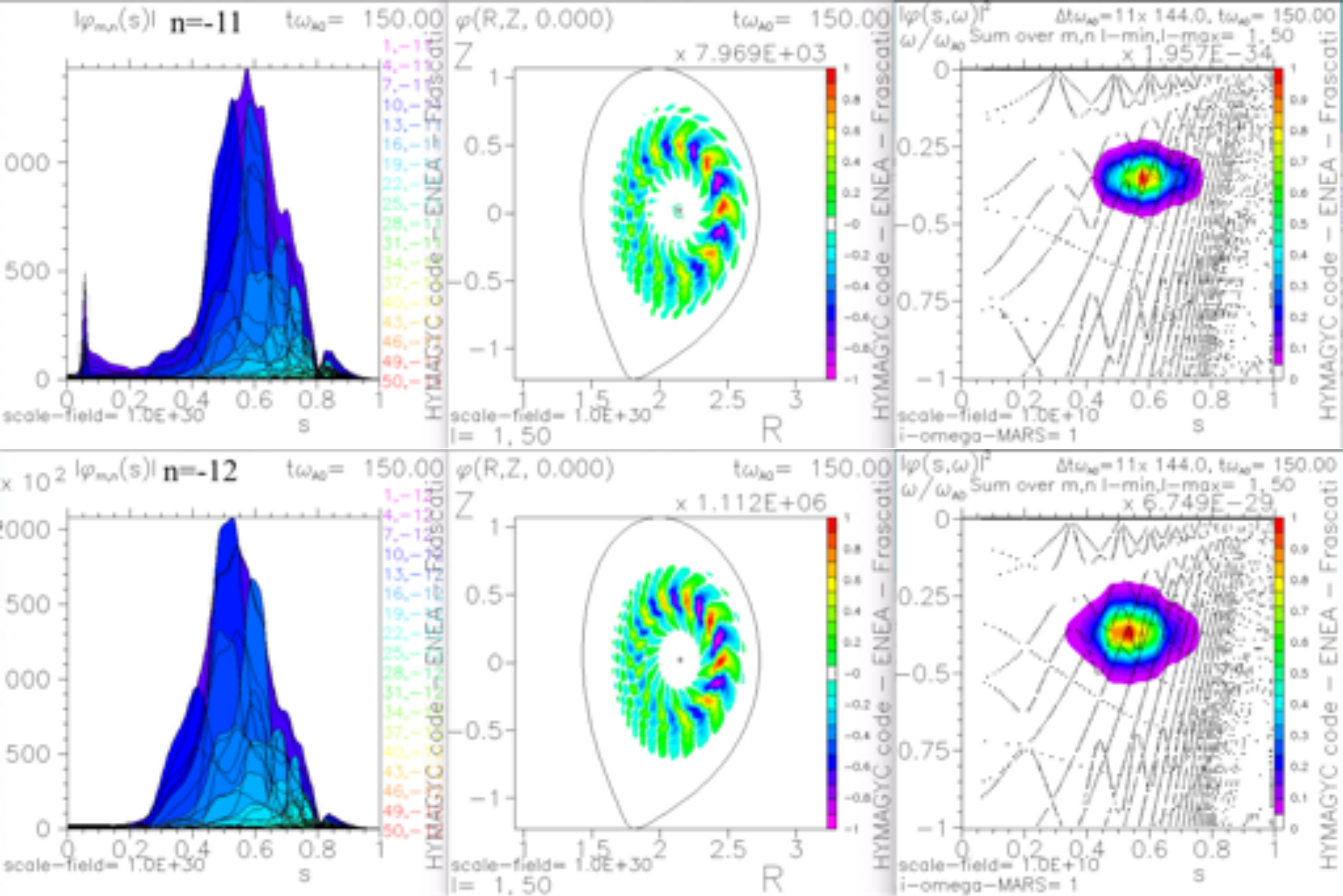
|φ_{m,n}(s)| n=-7 tω_{A0}= 150.00
φ(R,Z, 0.000) tω_{A0}= 150.00
x 1.917E−08
|φ(s,ω)|² Δtω_{A0}=11x 144.0, tω_{A0}= 150.00
ω/ω_{A0} Sum over m,n l−min,l−max= 1, 50
x 8.735E−17
scale−field= 1.0E+10
i−omega−MARS= 1
l= 1, 50
HYMAGYC code − ENEA − Frascati
|φ_{m,n}(s)| n=-8 tω_{A0}= 150.00
φ(R,Z, 0.000) tω_{A0}= 150.00
x 1.181E−10
|φ(s,ω)|² Δtω_{A0}=11x 144.0, tω_{A0}= 150.00
ω/ω_{A0} Sum over m,n l−min,l−max= 1, 50
x 2.016E−22
scale−field= 1.0E+10
i−omega−MARS= 1
l= 1, 50
s
R
Z



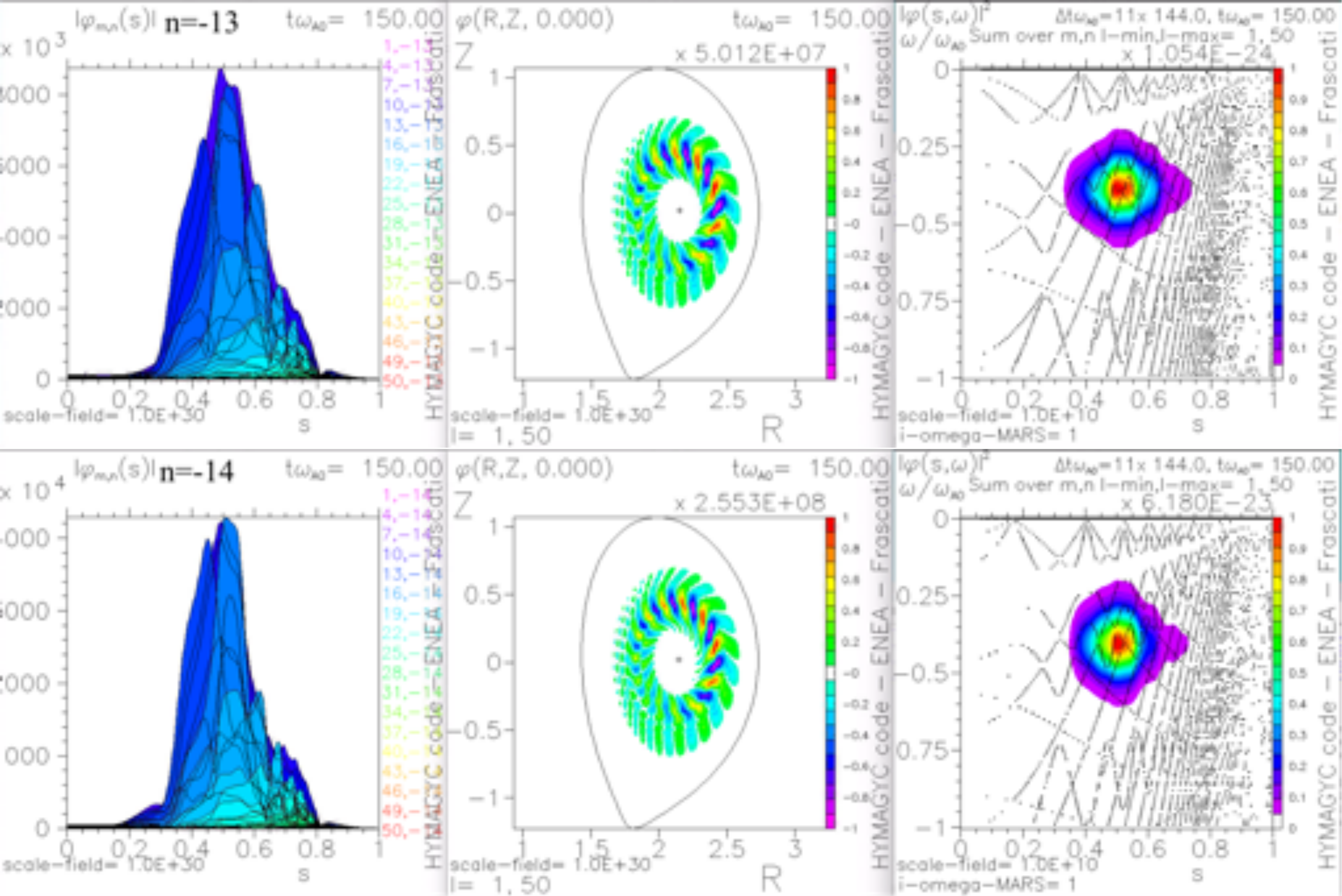
n=-9
n=-10
φ(R,Z, 0.000)
x 1.779E-13
x 4.564E-12
x 2.650E-29
x 1.880E-26
Sum over m,n l-min,l-max= 1, 50
scale-field= 1.0E+10
i-omega-MARS= 1
HYMAGYC code - ENEA - Frascati



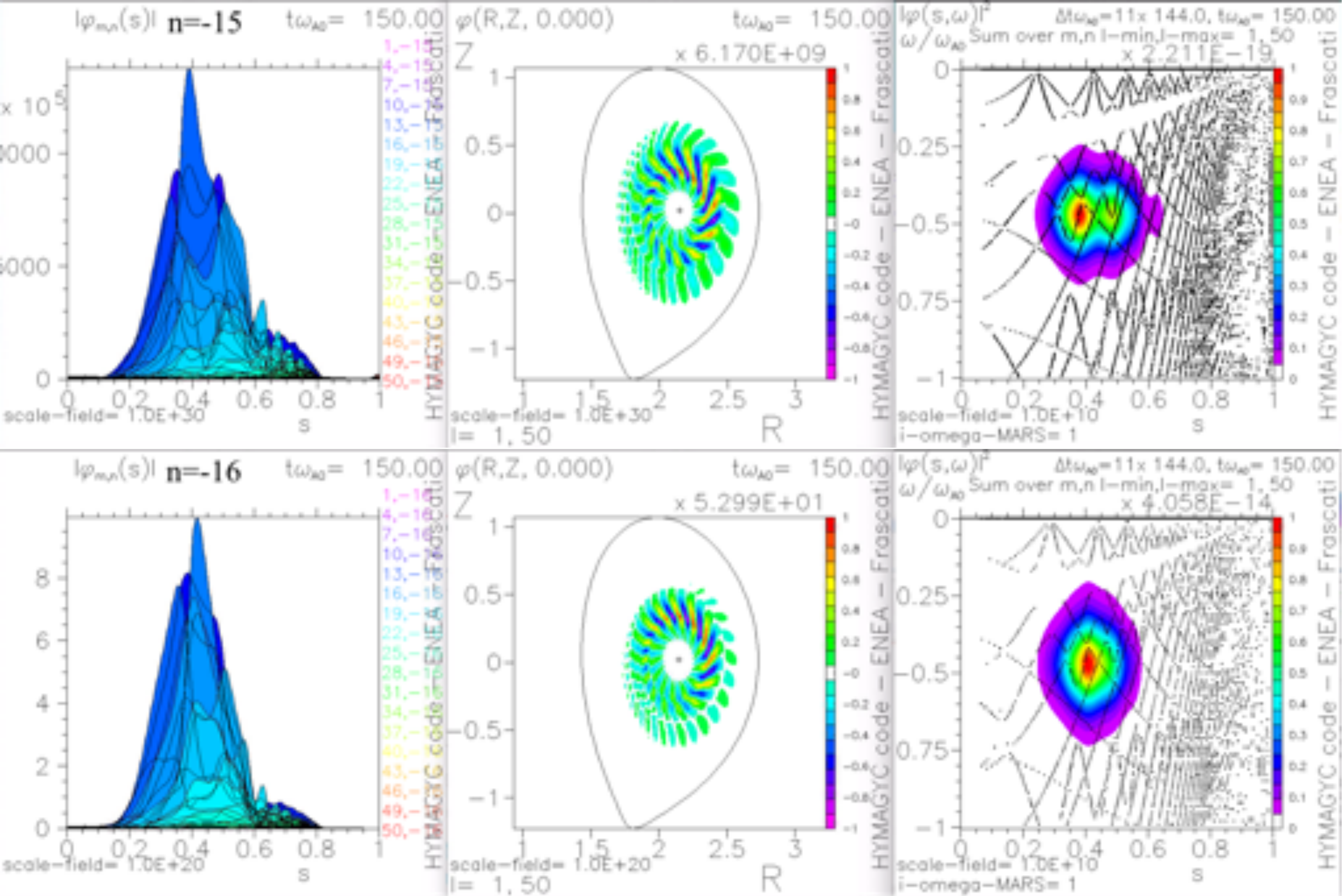
$|\varphi_{m,n}(s)|$ n=-10 $t\omega_{A0}$= 72.00
φ(R,Z, 0.000) $t\omega_{A0}$= 72.00
x 4.564E-12
$|\varphi(s,\omega)|^2$ $\Delta t\omega_{A0}$=11x 72.0, $t\omega_{A0}$= 72.00
ω/ω_{A0} Sum over m,n l-min,l-max= 1, 50
x 1.880E-26
scale-field= 1.0E+10
i-omega-MARS= 1
l= 1, 50
$|\varphi_{m,n}(s)|$ n=-10 $t\omega_{A0}$= 100.00
φ(R,Z, 0.000) $t\omega_{A0}$= 100.00
x 1.540E-11
$|\varphi(s,\omega)|^2$ $\Delta t\omega_{A0}$=11x 72.0, $t\omega_{A0}$= 100.00
ω/ω_{A0} Sum over m,n l-min,l-max= 1, 50
x 3.644E-25
scale-field= 1.0E+10
i-omega-MARS= 1
l= 1, 50
HYMAGYC code – ENEA – Frascati
s
R
Z



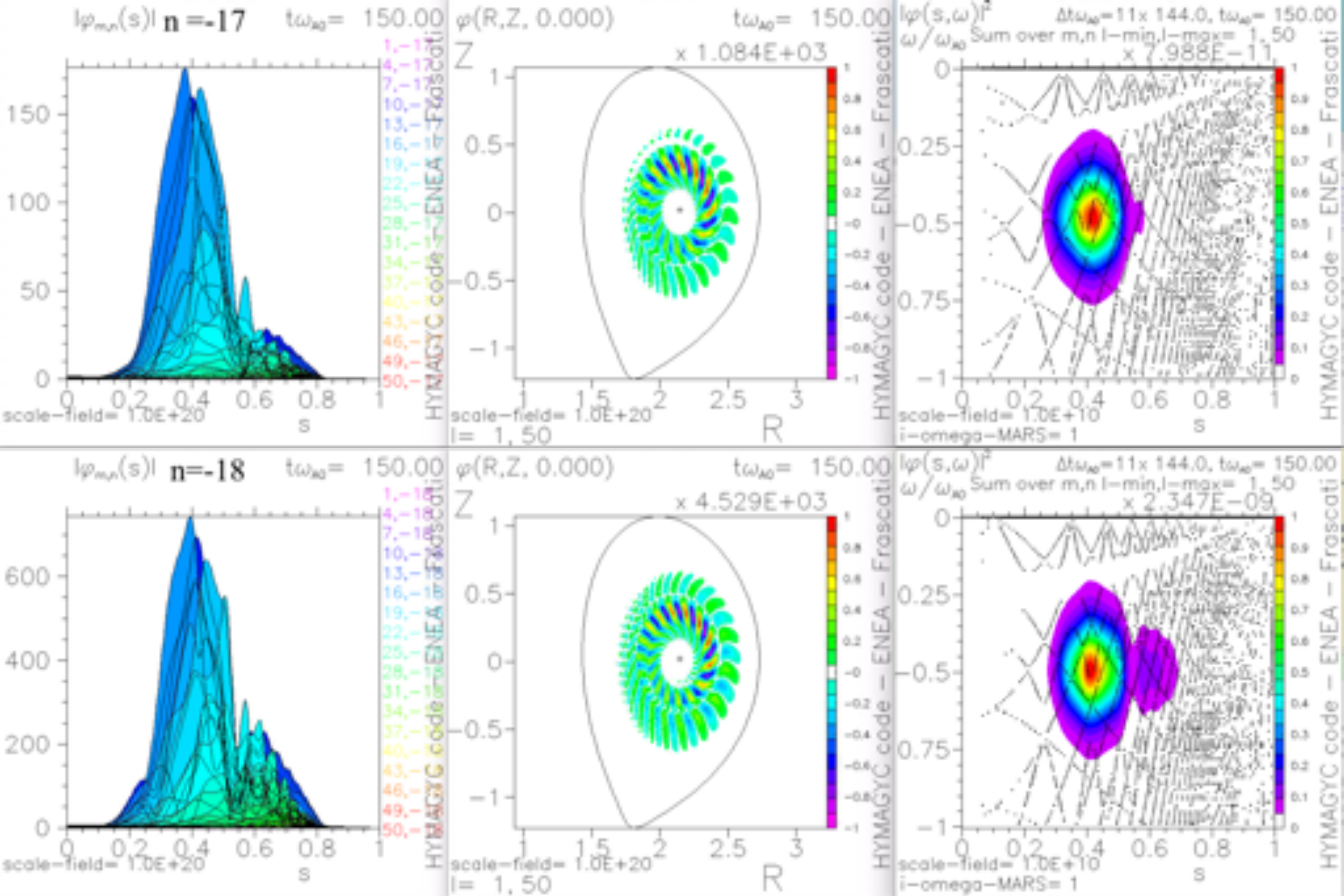
|φm,n(s)| n=-11
tωA0= 150.00
scale-field= 1.0E+30
s
φ(R,Z, 0.000)
tωA0= 150.00
x 7.969E+03
Z
R
scale-field= 1.0E+30
l= 1, 50
|φ(s,ω)|²
ω/ωA0
ΔtωA0=11x 144.0, tωA0= 150.00
Sum over m,n l-min,l-max= 1, 50
x 1.957E-34
scale-field= 1.0E+10
i-omega-MARS= 1
s
HYMAGYC code - ENEA - Frascati
|φm,n(s)| n=-12
x 10²
tωA0= 150.00
scale-field= 1.0E+30
s
φ(R,Z, 0.000)
tωA0= 150.00
x 1.112E+06
Z
R
scale-field= 1.0E+30
l= 1, 50
|φ(s,ω)|²
ω/ωA0
ΔtωA0=11x 144.0, tωA0= 150.00
Sum over m,n l-min,l-max= 1, 50
x 6.749E-29
scale-field= 1.0E+10
i-omega-MARS= 1
s
HYMAGYC code - ENEA - Frascati



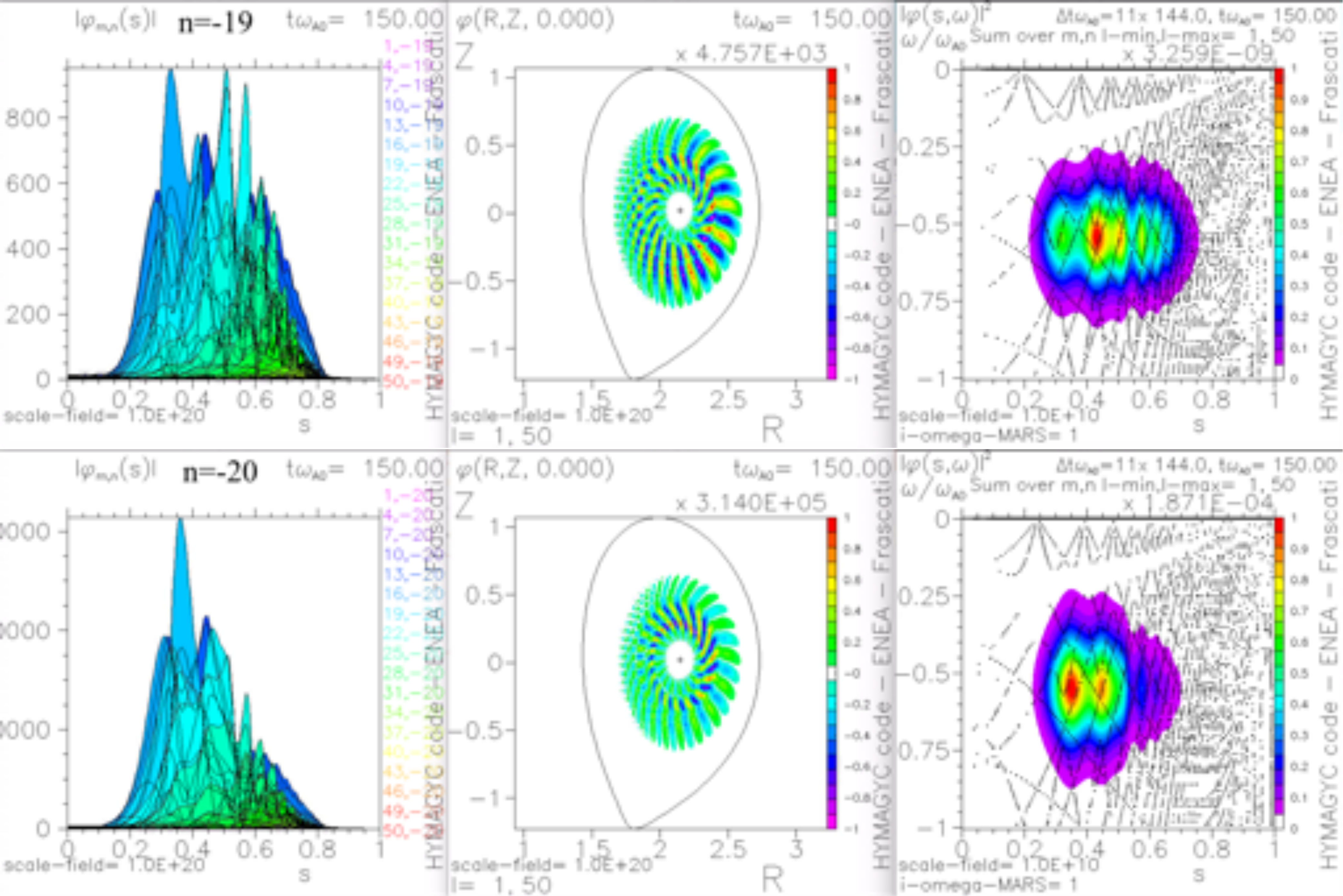
|φm,n(s)| n=-13
tωA0= 150.00
x 10^3
s
scale-field= 1.0E+30
HYMAGYC code – ENEA – Frascati
φ(R,Z, 0.000)
x 5.012E+07
Z
R
l= 1, 50
|φ(s,ω)|²
ω/ωA0
Δtω A0=11x 144.0, tωA0= 150.00
Sum over m,n l-min,l-max= 1, 50
x 1.054E-24
scale-field= 1.0E+10
i-omega-MARS= 1
|φm,n(s)| n=-14
x 10^4
x 2.553E+08
x 6.180E-23



|φm,n(s)| n=-15
tωA0= 150.00
x 10^5
s
scale-field= 1.0E+30
HYMAGYC code - ENEA - Frascati
φ(R,Z, 0.000)
tωA0= 150.00
x 6.170E+09
Z
R
scale-field= 1.0E+30
l= 1, 50
|φ(s,ω)|²
ω/ωA0
ΔtωA0=11x 144.0, tωA0= 150.00
Sum over m,n l-min,l-max= 1, 50
x 2.211E-19
scale-field= 1.0E+10
i-omega-MARS= 1
|φm,n(s)| n=-16
tωA0= 150.00
s
scale-field= 1.0E+20
φ(R,Z, 0.000)
tωA0= 150.00
x 5.299E+01
Z
R
scale-field= 1.0E+20
l= 1, 50
|φ(s,ω)|²
ω/ωA0
ΔtωA0=11x 144.0, tωA0= 150.00
Sum over m,n l-min,l-max= 1, 50
x 4.058E-14
scale-field= 1.0E+10
i-omega-MARS= 1



|φ_{m,n}(s)| n =-17
tω_{A0}= 150.00
scale−field= 1.0E+20
s
φ(R,Z, 0.000)
tω_{A0}= 150.00
x 1.084E+03
Z
R
l= 1, 50
|φ(s,ω)|²
Δtω_{A0}=11x 144.0, tω_{A0}= 150.00
ω/ω_{A0}
Sum over m,n l−min,l−max= 1, 50
x 7.988E−11
scale−field= 1.0E+10
i−omega−MARS= 1
HYMAGYC code − ENEA − Frascati
|φ_{m,n}(s)| n=-18
tω_{A0}= 150.00
scale−field= 1.0E+20
s
φ(R,Z, 0.000)
tω_{A0}= 150.00
x 4.529E+03
Z
R
l= 1, 50
|φ(s,ω)|²
Δtω_{A0}=11x 144.0, tω_{A0}= 150.00
ω/ω_{A0}
Sum over m,n l−min,l−max= 1, 50
x 2.347E−09
scale−field= 1.0E+10
i−omega−MARS= 1
HYMAGYC code − ENEA − Frascati



n=-19
tω_A0= 150.00
φ(R,Z, 0.000)
x 4.757E+03
|φ(s,ω)|²
ω/ω_A0
Δtω_A0=11x 144.0, tω_A0= 150.00
Sum over m,n l-min,l-max= 1, 50
x 3.259E-09
scale-field= 1.0E+20
scale-field= 1.0E+10
i-omega-MARS= 1
l= 1, 50
HYMAGYC code - ENEA - Frascati
s
R
Z
n=-20
x 3.140E+05
x 1.871E-04