ENEA contribution to TSVV Task 10: Physics of Burning Plasmas - Part II

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Background

- **Center for Nonlinear Plasma Science**
  - Established in February 2020 at ENEA C.R. Frascati
  - “Virtual Center” based on two hubs (ENEA, Frascati; USTC, Hefei) to promote joint research collaboration
  - Topics of interest cover nonlinear plasma science in a broad sense
  - Magnetic fusion activities are collocated under the umbrella of the CFETR-DTT collaboration agreement
  - Strong interconnection with ENEA - TSM and EUROfusion (earlier ENR project(s) MET: https://www.afs.enea.it/zonca/METproject/)
  - Framework for extending research activities beyond MF
  - Information at https://www.afs.enea.it/zonca/CNPS/
    - Mission, Activities, Projects, Publications

SMART/Deliverable 2

- **SMART (Specific Measurable Assignable Realistic Time-related) deliverables**
  - **Deliverable 2. Simulations of global modes and fast-particle interaction**
    - (S) Study the role of phase-space structures in ITER plasmas.
    - (M) Perform HMGC and HYMAGYC simulations of ITER plasmas employing Hamiltonian diagnostics and using theoretical information on the phase-space structure evolution.
    - (A) This work will be done by G. Vlad, S. Briguglio, F. Zonca, and T. Hayward-Schneider.
    - (R) This deliverable is not very risky but it requires careful and tedious work.
    - (T) The results of this work involving theory, simulations, and experiment will be reported in December 2025.

SMART/Deliverable 5

- **SMART (Specific Measurable Assignable Realistic Time-related) deliverables**
  - **Deliverable 5. Burn control and energy deposition optimization strategies**
    - (S) ITER burning-plasma ETS simulations using reduced fast-ion models.
    - (M) Perform extensive burning-plasma scenario studies using ETS and the most efficient fast-ion transport models coupled through an IMAS interface.
    - (A) This work will be done by F. Zonca, P. Lauber, R. Dumont, and J. Ferreira.
    - (R) This deliverable relies on success of the previous stage (model coupling to ETS).
    - (T) This deliverable will be reported in December 2025.

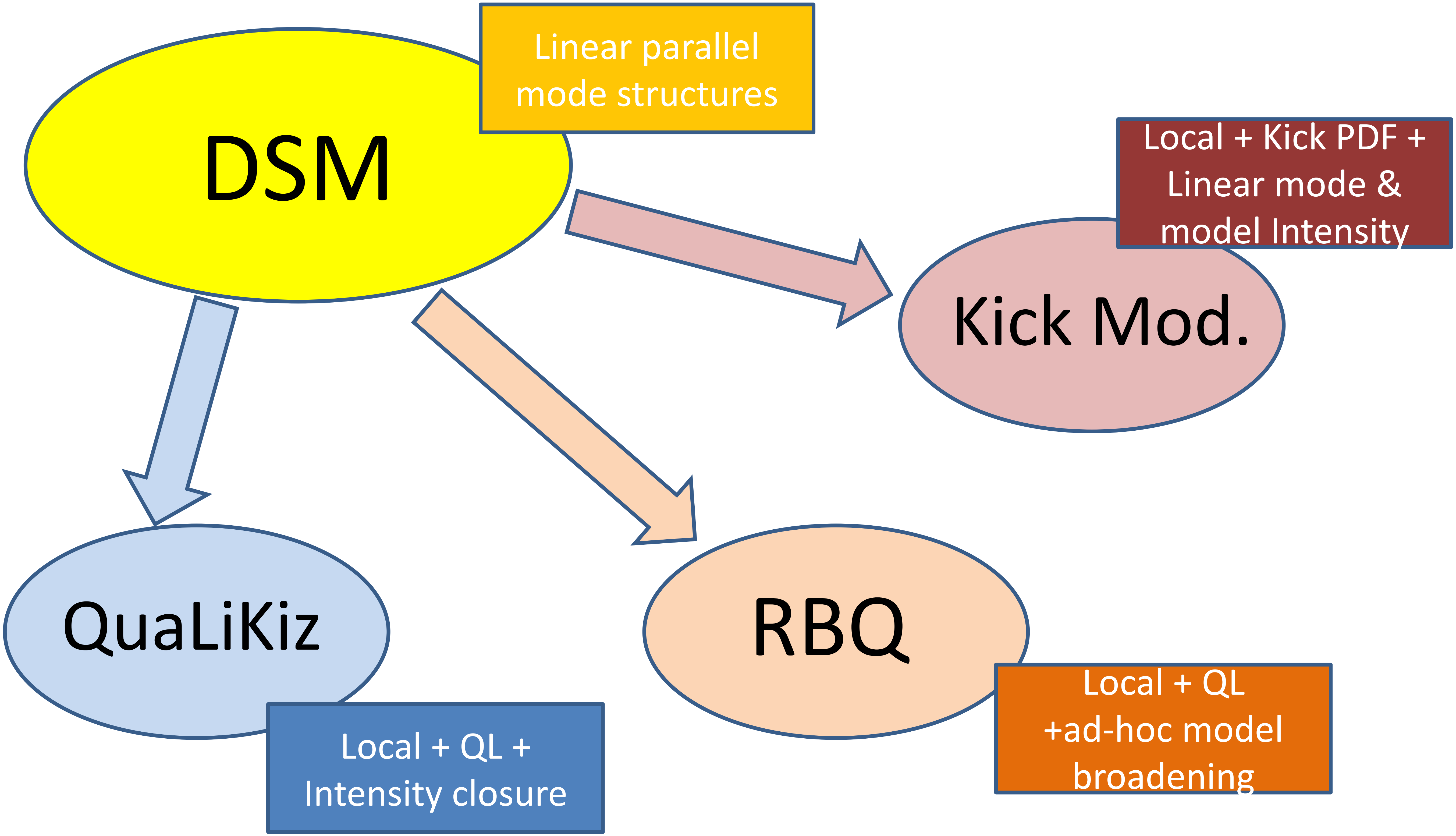
SMART/Deliverable 6

- **SMART (Specific Measurable Assignable Realistic Time-related) deliverables**
  - **Deliverable 6. Reduced models for AE/EPM stability and nonlinear dynamics**
    - (S) Implementation of phase-space resolved fluxes into the transport solver (ETS), as given by the kick model or more advanced nonlinear computations or models.
    - (M) Compare the performance (accuracy vs. speed) of time dependent transport simulations with phase-space resolved EP transport models to the CG model.
    - (A) This work will be done by Ph. Lauber, F. Zonca, R. Dumont, and J. Ferreira.
    - (R) Optimal strategies for time dependence of the couplings between the EP transport model and the transport code have to be developed.
    - (T) This deliverable will be reported in December 2025.

The Dyson Schrödinger Model

- **The Dyson Schrödinger Model (DSM) (FZ etal, JPCS 2021)**
  - **Significant advance with respect to existing reduced gyrokinetic transport models**
    - Among fundamental contribution of earlier ENR project(s) MET: https://www.afs.enea.it/zonca/METproject/
    - Based on NL GK description (full-F and delta-F)
      - Phase space (GK) response divided into
        - NL equilibrium (full-F → Phase Space Zonal Struct.)
        - Fluctuations (delta-F → Symmetry breaking)
      - Intensity evolution equation (NLSE) assuming linear parallel mode structure
    - Can recover all known reduced models in the proper limit
    - Extension ready for Stellarators (ENR ATEP) → no overlap!
      - TSVV 10: focus on numerical implementation/IMAS
      - ENR ATEP: focus on fundamental and theoretical aspects

From DSM to…



Linear parallel mode structures
DSM
Local + Kick PDF + Linear mode & model Intensity
Kick Mod.
QuaLiKiz
Local + QL + Intensity closure
RBQ
Local + QL +ad-hoc model broadening

The Dyson Schrödinger Model

- **SMART foresee relaxed time scale for DSM application**
  - **December 2025** for Deliverables 2,5,6
    - Focus on numerical implementation/IMAS framework
  - Consistent with the timeline of ENR ATEP (2021-23)
    - Focus on fundamental and theoretical aspects
  - **TSVV 10 activities have started on April 1st, as agreed**

The Dyson Schrödinger Model

- Nonlinear envelope equation can be written in NLSE-like form

$$
\begin{aligned}
&\frac{\partial}{\partial t}\left(\frac{\partial D^0_{Rn}}{\partial \omega_n}A_n^2\right)-\frac{\partial}{\partial r}\left(\frac{\partial D^0_{Rn}}{\partial k_{nr}}A_n^2\right)+2D^1_{An}A_n^2-2iD^1_{Rn}A_n^2\\
&\qquad +iA_n\left(\frac{\partial^2 D^0_{Rn}}{\partial k_{nr}^2}+2\frac{\partial \hat{\boldsymbol{e}}_n^+}{\partial k_{nr}}\cdot \boldsymbol{D}^0_{Rn}\cdot\frac{\partial \hat{\boldsymbol{e}}_n}{\partial k_{nr}}\right)\frac{\partial^2 A_n}{\partial r^2}=-2ie^{-iS_n}A_n\hat{\boldsymbol{e}}_n^+\cdot\boldsymbol{F}\\
&-\left(\hat{\boldsymbol{e}}_n^+\cdot\frac{d}{dt}\hat{\boldsymbol{e}}_n-\frac{d}{dt}\hat{\boldsymbol{e}}_n^+\cdot\hat{\boldsymbol{e}}_n\right)\frac{\partial D^0_{Rn}}{\partial \omega_n}A_n^2+\left(\frac{\partial \hat{\boldsymbol{e}}_n^+}{\partial \omega_n}\cdot\boldsymbol{D}^0_{Rn}\cdot\frac{\partial \hat{\boldsymbol{e}}_n}{\partial t}-\frac{\partial \hat{\boldsymbol{e}}_n^+}{\partial t}\cdot\boldsymbol{D}^0_{Rn}\cdot\frac{\partial \hat{\boldsymbol{e}}_n}{\partial \omega_n}\right)A_n^2\\
&-\left(\frac{\partial \hat{\boldsymbol{e}}_n^+}{\partial k_{nr}}\cdot\boldsymbol{D}^0_{Rn}\cdot\frac{\partial \hat{\boldsymbol{e}}_n}{\partial r}-\frac{\partial \hat{\boldsymbol{e}}_n^+}{\partial r}\cdot\boldsymbol{D}^0_{Rn}\cdot\frac{\partial \hat{\boldsymbol{e}}_n}{\partial k_{nr}}\right)A_n^2\,.
\end{aligned}
$$

- The NLSE-like structure is of crucial importance for proper analysis of structure formation in strongly magnetized toroidal plasmas, where wave packets can be focused/defocused and back scattered by both nonlinearities as well as by radial nonuniformities [C&Z RMP16].

Structure of turbulent fluxes

- Since PSZS are undamped by (fast) collisionless dissipation mechanisms, they are naturally expressed as functions of invariants of motion (nearly integrable Hamiltonian system). Separating fast ($[\ldots]_F$) from slow variations,

$$F_z \equiv \bar{F}_0 + e^{-iQ_z}\left(\overline{e^{iQ_z}\delta F_z}\Big|_F + \delta\tilde{F}_{Bz}\right),$$

macro- $\oplus$ meso-scale (CGL) micro-scale collisionless damped

where $\overline{[\ldots]} = \oint d\ell/v_\parallel[\ldots]/\oint d\ell/v_\parallel$, $\overline{[\tilde{\ldots}]} = 0$, F_z is the $n = 0$ gyrocenter particle distribution function. $e^{-iQ_z} \Rightarrow$ nonlocal (integral) particle response

$$\partial_t\overline{e^{iQ_z}\bar{F}_0} = -\overline{e^{iQ_z}\frac{F(\psi)}{B_0}\partial_t\left\langle\delta A_{\parallel g}\right\rangle_z\frac{\partial}{\partial\bar{\psi}}\bar{F}_0}\Big|_S - \frac{1}{\tau_b}\frac{\partial}{\partial\psi}\left[\tau_b\overline{e^{iQ_z}\delta\dot{\psi}_z\delta F_z}\right]_S$$

$$-\frac{1}{\tau_b}\frac{\partial}{\partial\mathcal{E}}\left[\tau_b\overline{e^{iQ_z}\delta\dot{\mathcal{E}}_z\delta F_z}\right]_S - \frac{1}{\tau_b}\frac{\partial}{\partial\psi}\left[\tau_b\overline{e^{iQ_z}\delta\dot{\psi}\delta F}\right]_{zS} - \frac{1}{\tau_b}\frac{\partial}{\partial\mathcal{E}}\left[\tau_b\overline{e^{iQ_z}\delta\dot{\mathcal{E}}\delta F}\right]_{zS}$$

$$+\overline{e^{iQ_z}\left[C_g + \mathcal{S}\right]}\Big|_{zS}.$$

[M.V. Falessi I-14 Varenna 2020]

Your questions are welcome

- **Concluding remarks:**
  - CNPS as virtual center
    - articulated naturally in an international framework of selected collaborations, can be an added value to TSVV 10
  - Theoretical activities within TSVV 10
    - focus on numerical implementation/IMAS
    - no overlaps/conflicts with ENR ATEP, which addresses fundamental and more theoretical aspects
  - Activities started on April 1st as expected
    - work in progress to be soon submitted to journal