Collaborazioni EUROfusion: introduzione e TSVV

M.V. Falessi, G. Vlad, F. Zonca

Introduzione su EUROfusion - Teoria
FP9 (next EU Framework Programme for Research and Technological Development)
Horizon Europe 2021-2027

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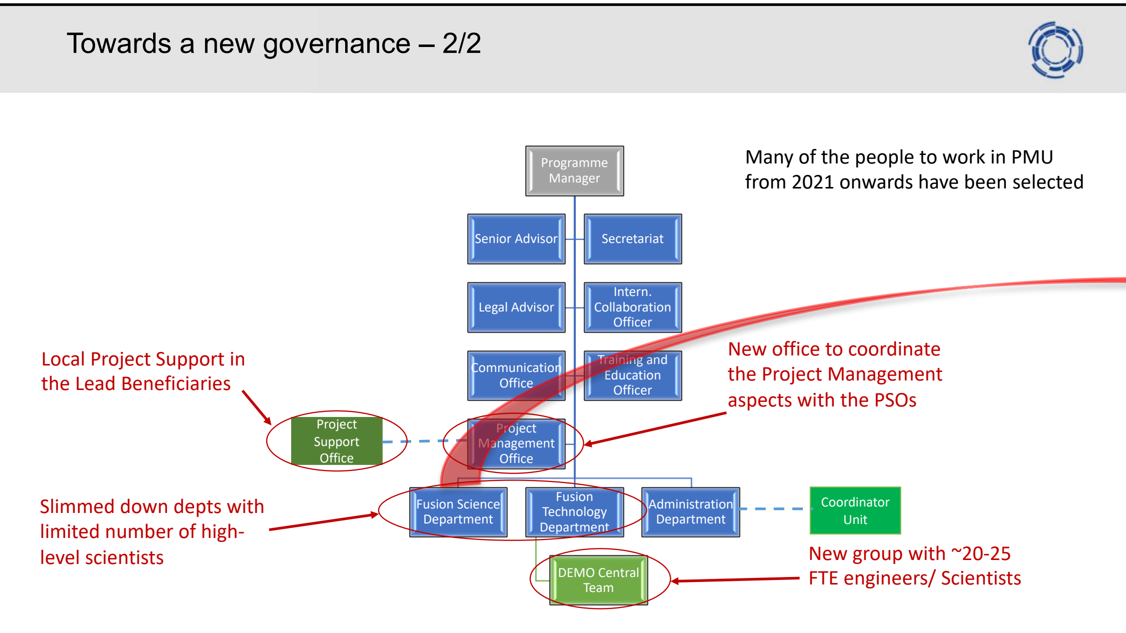
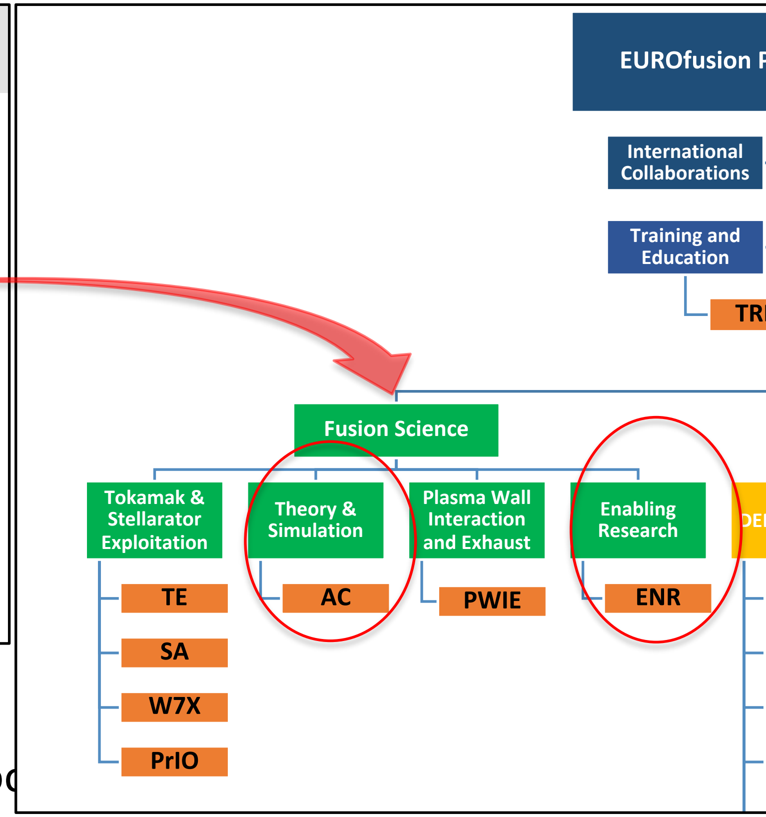




Fusion Science Department (FSD)

E-TASC: EUROfusion-Theory and Advanced Simulation Coo

Theory, Simulation, Verification and Validation (TSVV)

Enabling Research (ENR)

X L LITAUDON et al 2021 Plasma Phys. Control. Fusion in press https://doi.org/10.1088/1361- 6587/ac44e4:

"EUROfusion-THEORY AND ADVANCED SIMULATION COORDINATION (E-TASC): PROGRAMME AND THE ROLE OF HIGH PERFORMANCE COMPUTING"

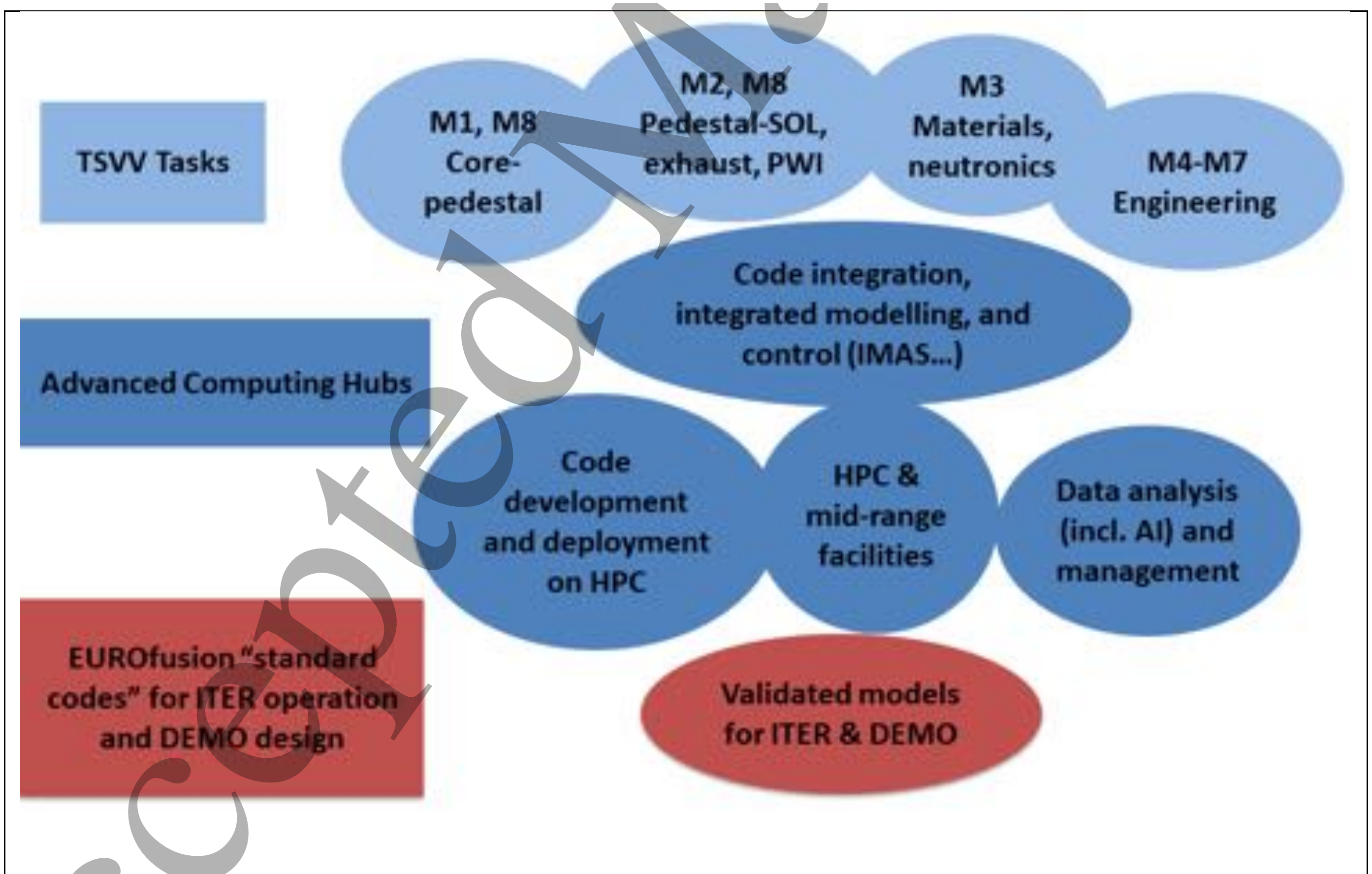


Fig. 1: Sketch of the E-TASC programme in support of the EUROfusion Roadmap missions as a mix of coordinated de-centralized TSVV tasks and more centralized ACH efforts operating in a virtuous cycle to deliver validated models for ITER and DEMO.

Four Research areas for TSVV projects

Three Categories for the 5 ACHs

Fusion Science Eight Missions (M#):

1. Plasma regimes of operation
2. Heat-exhaust systems
3. Neutron resistant materials
4. Tritium self-sufficiency
5. Implementation of the intrinsic safety features of fusion
6. Integrated DEMO design and system development
7. Competitive cost of electricity
8. Stellarator

Overview table of the TSVV tasks and related Work-Packages (WPs)

Dep.	WP	#	Title	
FSD	TE	1	Physics of the L-H Transition and Pedestals	
FSD	TE	2	Physics Properties of Strongly Shaped Configurations	ENEA-Frascati
FSD	TE	3	Plasma Particle/Heat Exhaust: Fluid/Gyrofluid Edge Codes	
FSD	TE	4	Plasma Particle/Heat Exhaust: Gyrokinetic/Kinetic Edge Codes	
FSD	PWIE	5	Neutral Gas Dynamics in the Edge	
FSD	PWIE	6	Impurity Sources, Transport, and Screening	
FSD	PWIE	7	Plasma-Wall Interaction in DEMO	
FSD	TE	8	Integrated Modelling of Transient MHD Events	ENEA-CNR-CREATE
FSD	TE	9	Dynamics of Runaway Electrons in Tokamak Disruptions	
FSD	TE	10	Physics of Burning Plasmas	ENEA-Frascati
FSD	PrIO	11	Validated Frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks	
FSD	W7X	12	Stellarator Optimization	
FSD	W7X	13	Stellarator Turbulence Simulation	
FTD	DES	14	Multi-Fidelity Systems Code for DEMO	

- **FSD**: Fusion Science Department
- **FTD**: Fusion Technology Department
- **WPTE**: EU Tokamaks Exploitation and Theory-Simulation-Verification-Validation
- **WPW7X**: Exploitation of W7-X and Theory-Simulation-Verification-Validation
- **WPPWIE**: Plasma Wall Interaction and Exhaust and Theory-Simulation-Verification-Validation
- **WPPrIO**: Preparation of ITER Operation
- **WPDES**: Design-assist Activities

Budget in FP9 for Theory related tasks-1:

ENR

The General Assembly of EUROfusion selected 16 out of 72 Enabling Research proposals to be granted in its 2021-2023 work programme, based on the recommendations of the scientific boards in four research categories. EUROfusion will invest a total of € 20.1 million in these projects, of which € 9.9 million comes as a contribution from the consortium.

Materials (5 projects granted)

- Additive manufacturing as tool to produce and maintain plasma facing components
  Daniel Dorow-Gerspach, FZJ (DE)
- NanoDust in Metal Tokamak (DUST-FORM)
  Flavian Stokker Cheregi, IAP (RO)
- Detection of defects and hydrogen by ion beam analysis in channelling mode for fusion
  Sabina Markelj, JSI (SI)
- Investigation of defects and disorder in non-irradiated and irradiated Doped Diamond and Related Materials for fusion diagnostic applications (DDRM) – Theoretical and Experimental analysis
  Aleksandr Lushchik, UT (EE)
- Electronic interactions of slow ions and their influence on defect formation & sputter yields for plasma facing components
  Marcos Moro, VR (SE)

Inertial Fusion (1 project granted)

- Advancing shock ignition for direct-drive inertial fusion
  Dimitri Batani, CEA (FR)

Theory & Modelling (4 projects granted)

- Operation limiting plasma instabilities in high performance tokamaks: fundamental understanding and solutions for critical problems
  Jonathan Graves, EPFL (CH)
- Development of machine learning methods and integration of surrogate model predictor schemes for plasma-exhaust and PWI in fusion
  Sven Wiesen, FZJ (DE)
- Energetic particle optimization of stellarator devices using near-axis magnetic fields
  Rogerio Jorge, IST (PT)
- Advanced energetic particle transport models (ATEP)
  Philipp Lauber, MPG (DE)

Technology & Systems (6 projects granted)

- Multivariable feedback control of radiative loss-processes using multi-spectral imaging
  Matthijs van Berkel, DIFFER (NL)
- Development of GEM detector as a compact neutron spectrometer for fusion plasmas
  Marek Scholz, IPPLM (PL)
- Advances in real-time reflectometry plasma tracking for next generation machines: Application to DEMO
  Filipe Da Silva, IST (PT)
- New generation of megawatt-class fusion gyrotron systems based on highly efficient operation at the second harmonic of the cyclotron frequency
  Ioannis Pagonakis, KIT (DE)
- Reconstruction of 4D and 5D fast-ion phase space distribution functions in tokamaks and stellarators
  Dmitry Moseev, MPG (DE)
- Silicon photonics steady-state magnetic field sensor
  Antti Salmi, VTT (FI)

ENR: ≈ 49% from Beneficiaries, ≈ 51% from EUROfusion
total per year: ≈ € 6.7 million

only 4 ENRs for Theory & Modelling (ATEP Project has Matteo Falessi as co-PI)

Budget in FP9 for Theory related tasks-2:

ACH & TSVV

The General Assembly of EUROfusion awarded funding for five ACH proposals and fourteen TSVV tasks in the Work Plan 2021-2025. These decisions were made on the basis of the advice from the E-TASC Scientific Board and from five independent experts from outside EUROfusion. EUROfusion will invest a total of € 59.8 million in these projects, of which € 32 million comes as a national contribution from the consortium members.

Theory, Simulation, Validation and Verification tasks

(14 projects granted for a total value of € 44.4 million, of which € 22.2 million in contribution from the consortium)

- Dynamics of Runaway Electrons in Tokamak Disruptions
  Eric Nardon, CEA (FR)
- European boundary plasma modelling towards reactor relevant simulations
  Patrick Tamain, CEA (FR)
- Impurity Sources, Transport, and Screening
  Guido Ciraolo, CEA (FR)
- Integrated Modelling of Transient MHD Events
  Matthias Hölzl, IPP (DE)
- Multi-Fidelity Systems Code for DEMO
  James Morris, CCFE (UK)
- Neutral Gas Dynamics in the Edge
  Dmitriy Borodin, FZJ (DE)
- Physics of Burning Plasmas
  Oleksiy Mishchenko, IPP (DE)
- Physics of the L-H Transition and Pedestals
  Tobias Görler, IPP (DE)
- Physics Properties of Strongly Shaped Configurations
  Justin Ball, EPFL (CH)
- Plasma Particle/Heat Exhaust: Gyrokinetic/Kinetic Edge Codes
  Daniel Told, IPP (DE)
- Plasma-Wall Interaction in DEMO
  Dmitry Matveev, FZJ (DE)
- Stellarator Optimization
  Per Helander IPP (DE)
- Stellarator Turbulence Simulation
  Jose Manuel Garcia Regana, CIEMAT (ES)
- Validated frameworks for the Reliable Prediction of Plasma Performance
  Clarisse Bourdelle, CEA (FR)

Advanced Computing Hubs

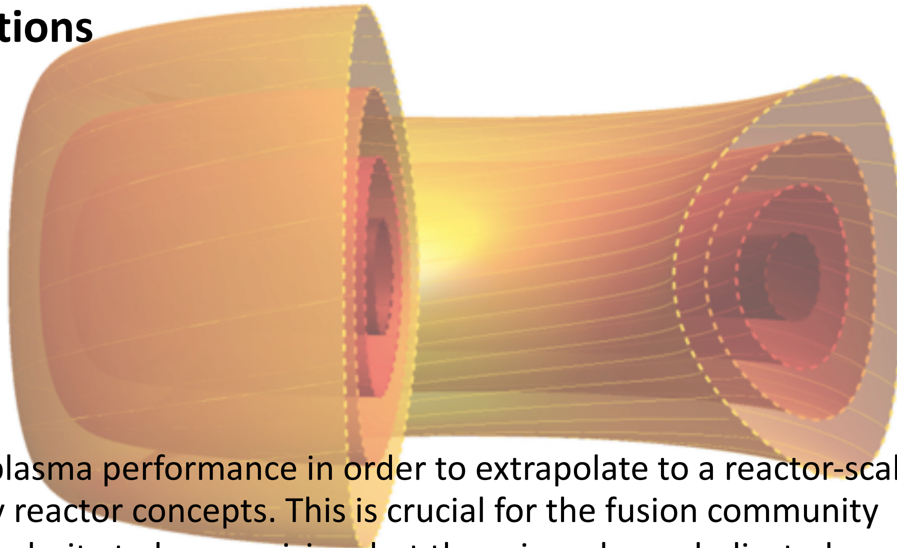
(5 projects granted for a total value of € 15.4 million, of which € 9.8 million in contribution from the consortium)

- CIEMAT (ES) - principal investigator Mervi Mantsinen
- EPFL (CH) - principal investigator Paolo Ricci
- IPPLM (PL) - principal investigator Marcin Plociennik
- IPP (DE) - principal investigator Roman Hatzky
- VTT (FI) - principal investigator Fredric Granberg

TSVV: ≈ 50% from Beneficiaries, ≈ 50% from EUROfusion
total per year: ≈ € 8.8 million

ACH: ≈ 63.6% from Beneficiaries, ≈ 36.4% from EUROfusion
total per year: ≈ € 3.08 million

Collaboration within TSVV#2 - 1



Physics Properties of Strongly Shaped Configurations

https://wiki.euro-fusion.org/wiki/TSVV-02

Principal Investigator: Justin Ball (EPFL)

Team: J. Ball, P. Donnel, G. Fogaccia, G. Vlad, M. Giacomin, P. Innocente, H. Luetjens, P. Mantica, A. Mariani, A. Merle, M.J. Pueschel, O. Sauter, M. Vallar

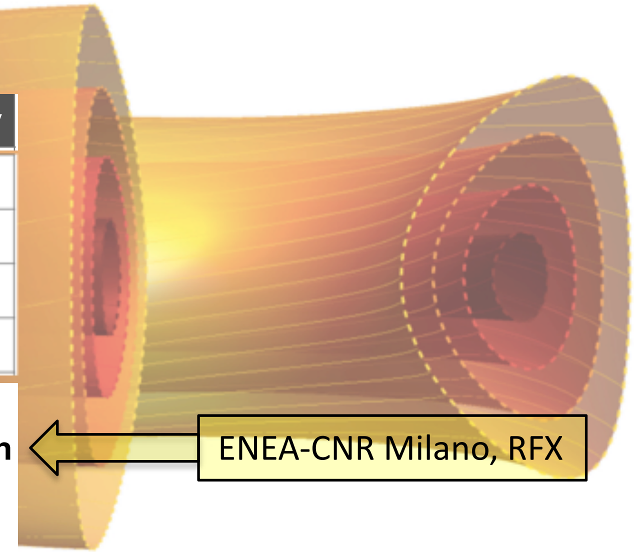
Project objectives:

TSVV 2 aims to explain the effects of negative triangularity on plasma performance in order to extrapolate to a reactor-scale device and compare with more traditional positive triangularity reactor concepts. This is crucial for the fusion community because experimental observations have shown negative triangularity to be promising, but there is no large dedicated negative triangularity experiment and, at this point, minimal supporting theoretical work. In order to accomplish the aims of TSVV 2, we will achieve the following six deliverables:

- Interpretive and predictive tools regarding the properties of NT L-mode confinement of heat, particles (including impurities), and momentum in the core, pedestal, and SOL, based on first-principles-based theory and simulations. Extensions to other types of strong plasma shaping.
- 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).
- Validation of these tools with respect to existing tokamak experiments whenever possible.
- Applications of these tools to predict the behavior of NT plasmas at reactor scales in terms of confinement, stability, and compatibility with highly radiative/dissipative scenarios.
- Predictive capability of the effect of shaping on fast ion confinement.
- Reduced models – extracted from the first-principles-based models – to be used in predictive and systems codes

Collaboration within TSVV#2 - 2

- Relevant for DTT Negative Triangularity scenarios
- ENEA Commitment (GV 0.0ppy):



Family name	First name	Beneficiary	2021 ppy	2022 ppy	2023+ ppy
Mantica	Paola	ENEA CNR Milano	0	0.5	0
Mariani	Alberto	ENEA CNR Milano	0.5	0	0
Fogaccia	Giuliana	ENEA Frascati	0.5	0	0.5
Innocente	Paolo	ENEA rfx	0	0.5	0.5

Deliverable 1: Interpretive and predictive tools regarding the properties of NT L-mode confinement of heat, particles (including impurities), and momentum in the core, pedestal, and SOL, based on first-principles-based theory and simulations. Extensions to other types of strong plasma shaping. ← ENEA-CNR Milano, RFX

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). ← ENEA-Frascati

Deliverable 3: Validation of these tools with respect to existing tokamak experiments whenever possible. ← ENEA-CNR Milano, RFX

Deliverable 4: Applications of these tools to predict the behavior of NT plasmas at reactor scales in terms of confinement, stability, and compatibility with highly radiative/dissipative scenarios. ← ENEA-CNR Milano, RFX

Deliverable 5: Predictive capability of the effect of shaping on fast ion confinement. ← ENEA-Frascati

Deliverable 6: Reduced models – extracted from the first-principles-based models – to be used in predictive and systems codes. ← ENEA-CNR Milano

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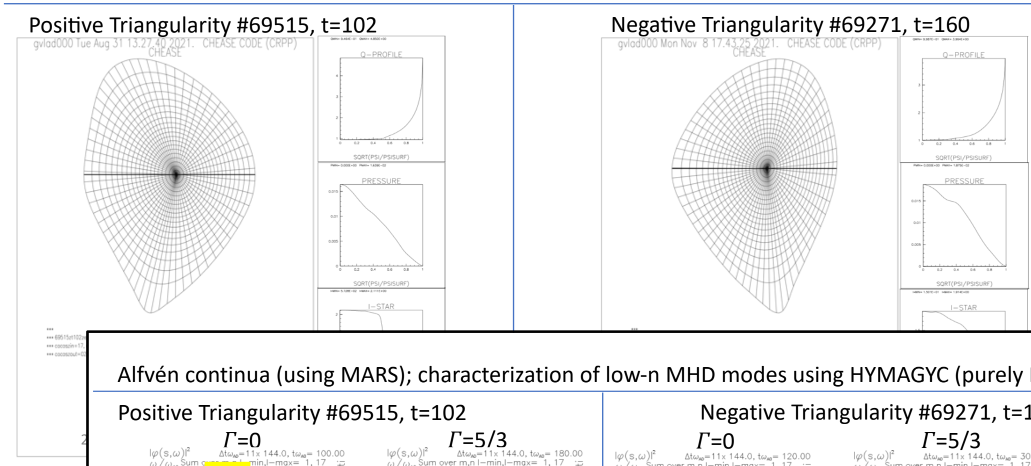
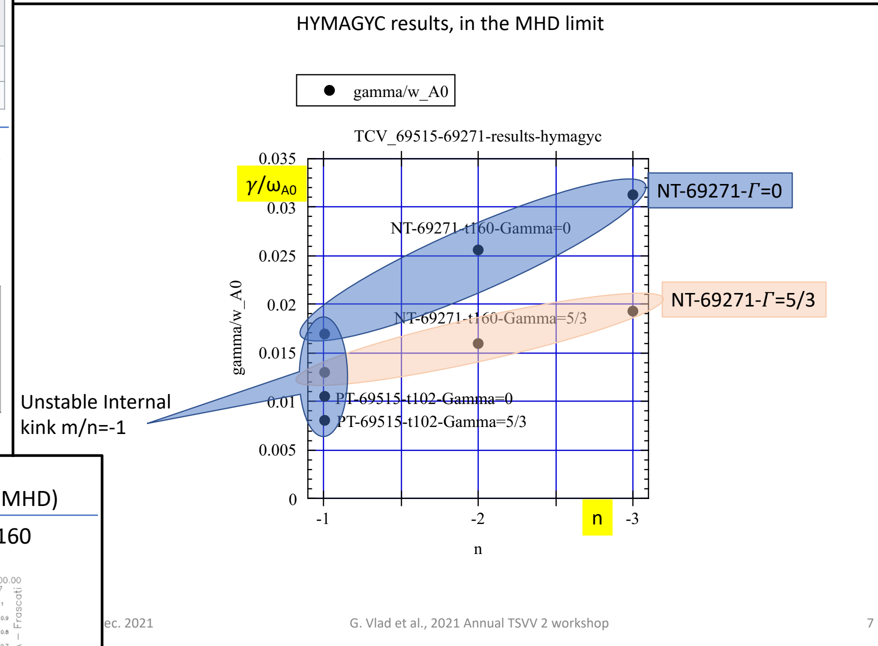
ENEA-Frascati: 0.33 ppy (4PM/y) (media annua), durata 5 anni (dopo tre anni “major” revision)

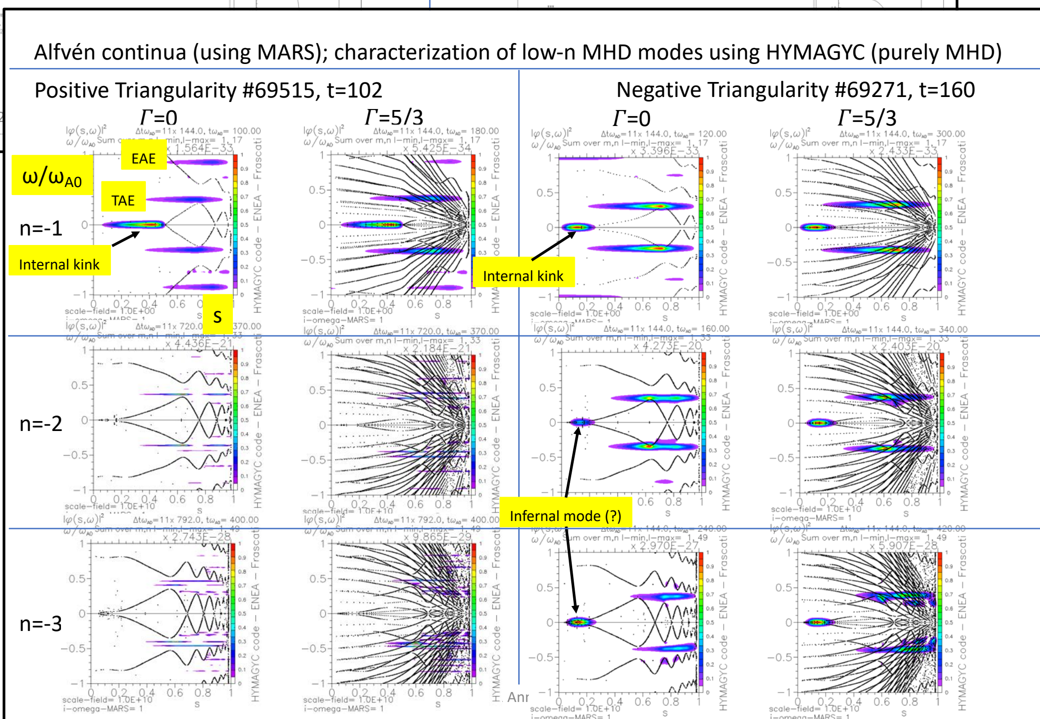
Collaboration within TSVV#2 - 3

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	-







Collaboration within TSVV#10 - 1

https://wiki.euro-fusion.org/wiki/TSVV-10 **Physics of Burning Plasmas**

Principal Investigator: Alexey Mishchenko (MPG); Team:

MPG: Ph. Lauber, A. Bottino, A. Biancalani, Th. Hayward-Schneider, M. Campos Pinto, E. Poli, A. Koenies, R. Kleiber, Ch. Slaby

CEA: R. Dumont, X. Garbet, H. Luetjens

ENEA: F. Zonca, G. Vlad, S. Briguglio

EPFL: L. Villard, J. Graves, M. Sadr

IST: J. Ferreira

Project objectives:

- Develop a self-consistent description of, and corresponding simulation tools for, the mutual interaction of energetic particles with MHD modes and turbulence, as well as their interplay with the kinetic plasma profiles in both tokamak and stellarator geometries.
- Develop a theoretical understanding and a validated interpretative/predictive capability of the physics of burning plasmas in both tokamak and stellarator geometries.
- Develop strategies to optimize the deposition of the fusion α energy to the bulk plasma in view of improving the reactor performance.

Key deliverables:

- Nonlinear gyrokinetic (GK) simulations addressing the mutual influence of heating-induced fast ions and α particles with turbulence.
- Linear and nonlinear simulations (e.g., GK, extended-MHD, and/or hybrid-MHD-GK) addressing the mutual influence of MHD/EPM and fusion α's as well as suprathermal particles dynamics (also including energetic particles originating from heating sources).
- Coupling of an extended-MHD/hybrid-MHD-GK code with a transport code to address self-consistently the mutualinfluence of MHD/EPM driven by fusion α's as well as suprathermal particles and corresponding repercussions on respective deposition profiles and, finally, on bulk density and temperature profiles evolution.
- Investigation of the role of a large population of fusion alphas, as well as of other suprathermal particles, on the global MHD stability limits of the plasma (e.g., impact on the global beta-limit of the kinetic stabilization of the low-n kink modes, or determination of the sawtooth period by inclusion of kinetic effects).
- Exploration of active strategies to optimize the deposition of α particle energy, aiming at a maximization of the fusion power yield (e.g., α channeling for a direct ion heating); modelling of burn control through auxiliary heating and fuelling strategies; prediction of current profile, particularly in predominantly ohmically driven scenarios, consistent with bootstrap contributions from pressure profile and fast particles.
- Reduced AE/EPM stability and nonlinear dynamics models for use inpredictive and systems codes, aiming, e.g., at predicting tritium burn-up rates and core plasma helium content.

ENEA-Frascati: 1.5 ppy (18PM/y), durata 5 anni (dopo tre anni "major" revision)

Collaboration within TSVV#10 - 2

Deliverable 2. Simulations of global modes and fast-particle interaction

"Linear and nonlinear simulations (e.g., GK, extended-MHD, and/or hybrid-MHD-GK) addressing the mutual influence of MHD/EPM and fusion α's as well as suprathermal particles dynamics (also including energetic particles originating from heating sources)."

Within the unified ORB5&EUTERPE gyrokinetic framework ... This activity will be supported and extended by the hybrid MHD-gyrokinetic codes HMGC and HYMAGYC. These codes solve the gyrokinetic equation for fast particles whereas the bulk plasma is treated as a fluid. For this fluid part, HMGC solves reduced nonlinear visco-resistive MHD equations while the MHD module of HYMAGYC (an initial-value version of MARS) solves linear resistive full MHD equations. Moreover, HYMAGYC, being developed within WPCD, is almost fully IMAS- compliant. In particular, it is fully IMAS-compliant for the MHD part; the IMAS compliance of the HYMAGYC gyrokinetic module will be completed within our TSVV project. This experience will then be used to make ORB5&EUTERPE IMAS-compliant**.** Besides these points, comparing results obtained by the hybrid- and fully-gyrokinetic codes will be of pivotal value for the Verification part of our TSVV project. Currently, the benchmark activities on the NLED AUG testcase are carried out in the frame of the ENR MET project, involving MEGA, ORB5, and HYMAGYC codes. This quite fruitful and interesting benchmark will be continued and expanded to ITER geometry in the proposed TSVV project. On the theoretical side, evolution of the zonal structures in the fast-particle phase space will be analytically described and compared with simulation results.

SMART (Specific Measurable Assignable Realistic Time-related) deliverables:

- (S) Verify and validate the hybrid-gyrokinetic set of the codes.
- (M) Finish the NLED-AUG benchmark (code verification) and compare the results to the ASDEX-Upgrade experiments (code validation).
- (A) This work will be performed by G. Vlad, Ph. Lauber, A. Koenies, R. Kleiber, L. Villard, M. Sadr, A. Biancalani, and J. Graves.

- (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.

Collaboration within TSVV#10 – 2a

Deliverable 2. Simulations of global modes and fast-particle interaction

A benchmark between HYMAGYC, MEGA and ORB5 codes using the NLED-AUG test case to study Alfvénic modes driven by energetic particles

G. Vlad[1] (gregorio.vlad@enea.it), X. Wang[3], F. Vannini[2], S. Briguglio[1], N. Carlevaro[1], M. Falessi[1], G. Fogaccia[1], V. Fusco[1], F. Zonca[1,3], A. Biancalani[2], A. Bottino[2], T. Hayward-Schneider[2], P. Lauber[2]

[1]ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy
[2]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
[3]IFTS and Department of Physics, Zhejiang University, Hangzhou 310027, People's Republic of China

I will briefly present few excerpts from the Poster…

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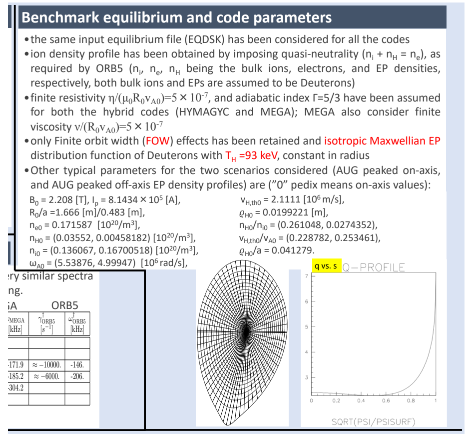
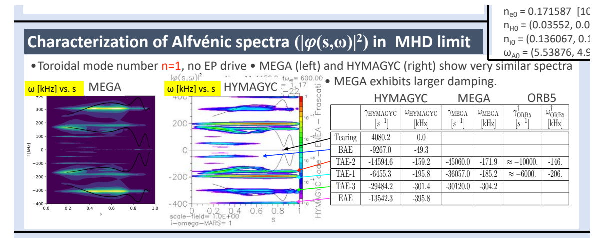
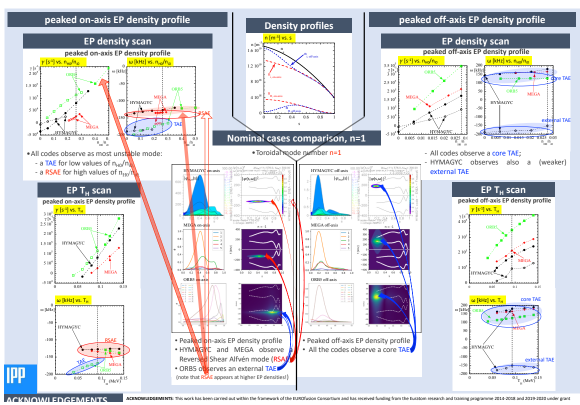
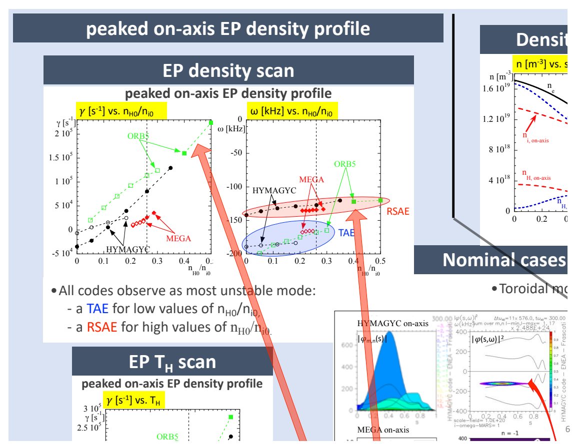






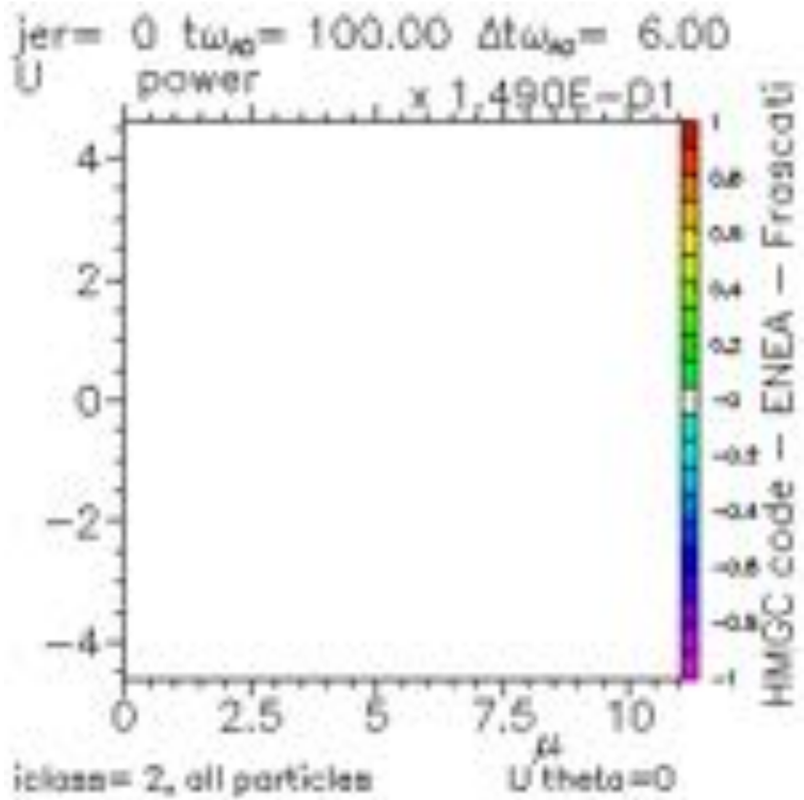


G. Vlad, X. Wang, F. Vannini, S. Briguglio, N. Carlevaro, M. Falessi, G. Fogaccia, V. Fusco, F. Zonca, A. Biancalani, A. Bottino, T. Hayward-Schneider, and Ph. Lauber. A linear benchmark between HYMAGYC, MEGA and ORB5 codes using the NLED-AUG test case to study Alfvénic modes driven by energetic particles. Nuclear Fusion, 61:116026, 2021. doi: https://doi.org/10.1088/1741-4326/ac2522. Online version at http://www.afs.enea.it/vlad/Papers/vlad21nf.pdf

Collaboration within TSVV#10 – 2b

Diagnostics for nolinear dynamics

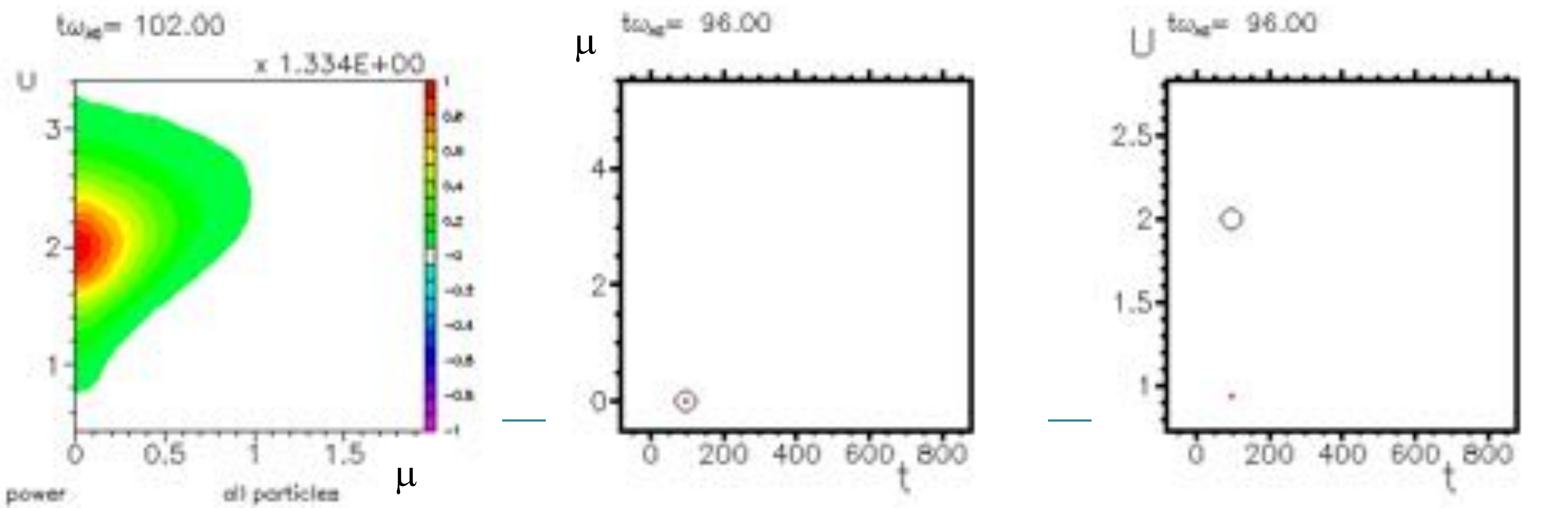
- Power transfer in reduced 3D phase space, after averaging over poloidal and toroidal angles:
  - the calculation can be done in any coordinate system, provided the coordinates of each macroparticle can be computed
  - it is worth computing the time derivative of the macroparticle energy by explicitly using the equations of motion and enforcing exact cancellations



Collaboration within TSVV#10 – 2c

Diagnostics for nolinear dynamics

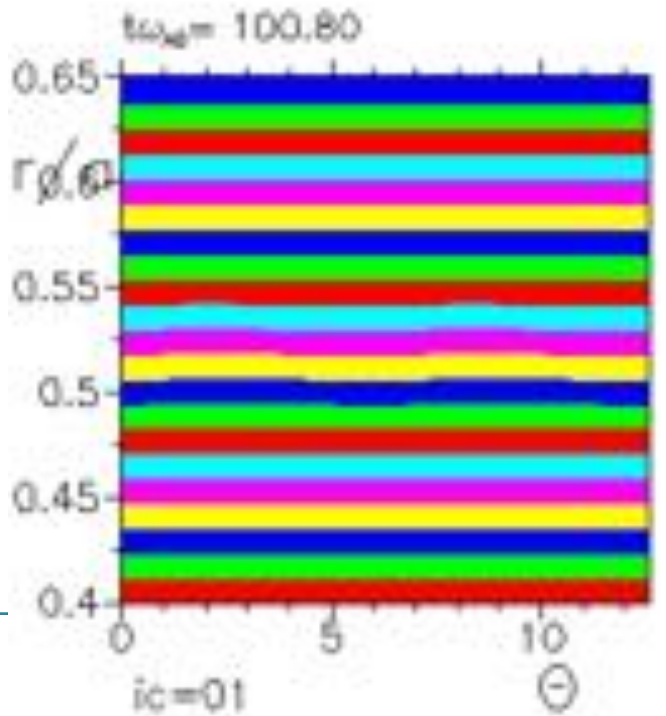
- Identification of the relevant resonances:
  - it is worth adopting a coordinate system including one more constant besides the magnetic moment μ (for example, the initial value of the parallel velocity U_0)
  - this allows to identify isolated resonances: given (μ, U_0), there is no flow along μ or U_0
  - it also allows to distinguish whether the mode is driven by a succession of different resonances or by a single evolving resonance

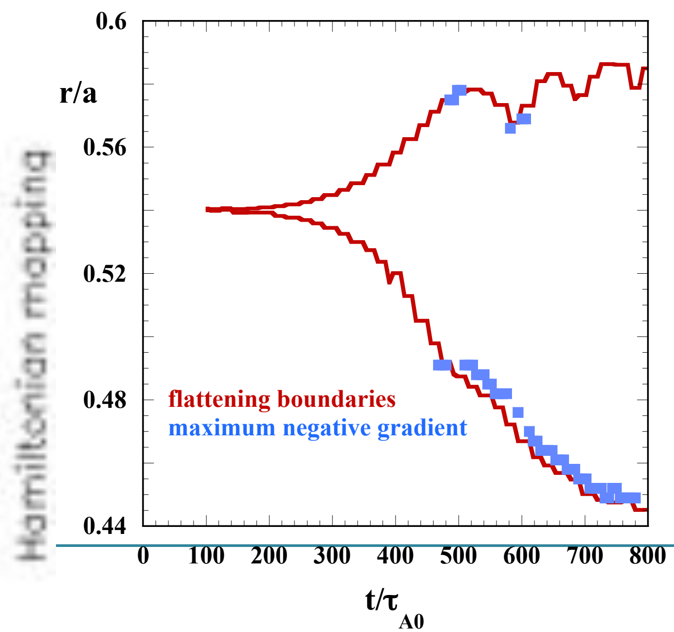


Collaboration within TSVV#10 – 2d

Diagnostics for nolinear dynamics

- Hamiltonian-mapping techniques for investigation of the nonlinear evolution of the relevant resonances:
  - once we have identified an isolated resonance, we can investigate its dynamics by test particle techniques
  - here, the formation of an island in the space (phase,r), yielding density flattening and the formation of large negative density gradients at its boundaries





Collaboration within TSVV#10 - 3

Deliverable 3. Coupling of MHD and gyrokinetic codes with a transport code

"Coupling of an extended- MHD/hybrid-MHD-GK code with a transport code to address self-consistently the mutual influence of MHD/EPM driven by fusion α's as well as suprathermal particles and corresponding repercussions on respective deposition profiles and, finally, on bulk density and temperature profiles evolution." As mentioned in the previous section, we plan to extend the IMAS compliance to the gyrokinetic module of HYMAGYC and then use this experience to make also ORB5&EUTERPE IMAS-compliant. In addition to this, we will add reduced models of the energetic-particle dynamics, such as the critical-gradient model (CG) [R. Waltz et al, NF **55**, 12 (2015)], and quasi-linear (QL) or kick-like models [M. Podesta et al, NF **56**, 11 (2016)], to a transport code via IMAS.

SMART (Specific Measurable Assignable Realistic Time-related) deliverables:

- (S) IMAS compliance of the gyrokinetic hybrid codes.
- (M) Make the gyrokinetic module of HYMAGYC IMAS-compliant.
- (A) This work will be performed by G. Vlad and J. Ferreira.

Collaboration within TSVV#10 - 4

Deliverable 5. Burn control and energy deposition optimization strategies

"Exploration of active strategies to optimize the deposition of α particle energy, aiming at a maximization of the fusion power yield (e.g., α channeling for a direct ion heating); modelling of burn control through auxiliary heating and fuelling strategies; prediction of current profile, particularly in predominantly ohmically driven scenarios, consistent with bootstrap contributions from pressure profile and fast particles."

SMART (Specific Measurable Assignable Realistic Time-related) deliverables:

- (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

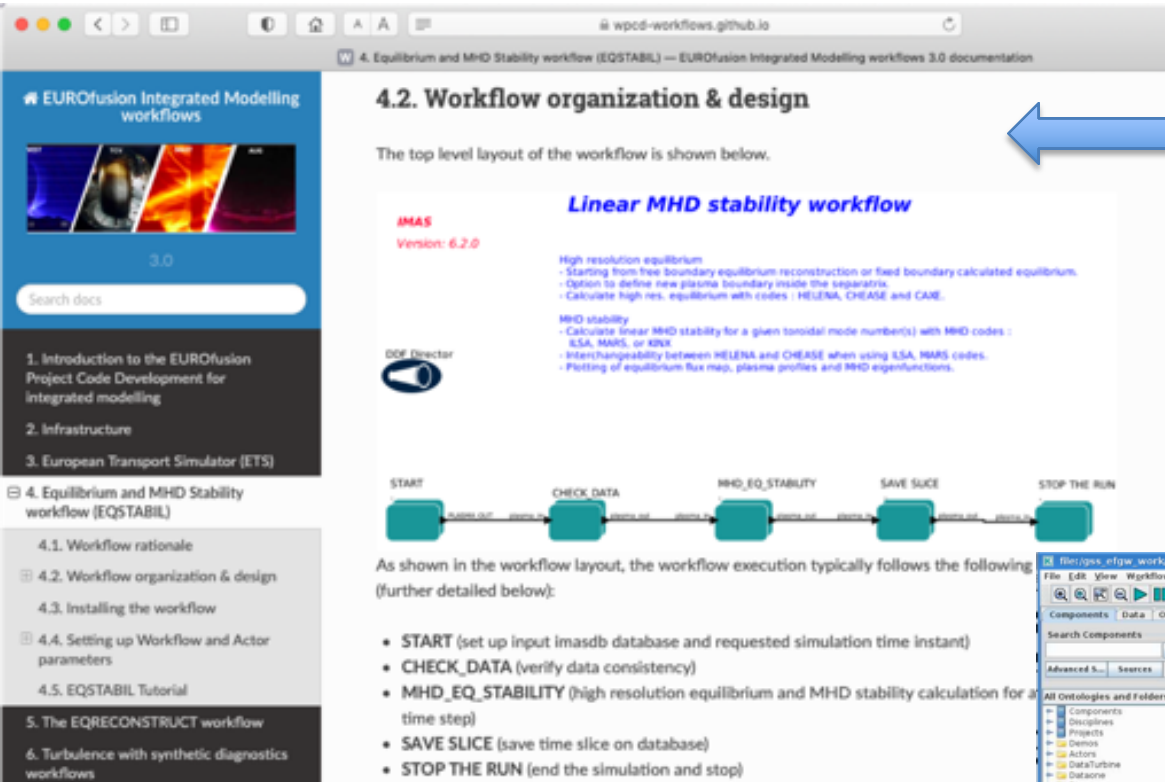
Deliverable 6. Reduced models for AE/EPM stability and nonlinear dynamics

"Reduced AE/EPM stability and nonlinear dynamics models for use in predictive and systems codes, aiming, e.g., at predicting tritium burn-up rates and core plasma helium content"

SMART (Specific Measurable Assignable Realistic Time-related) deliverables:

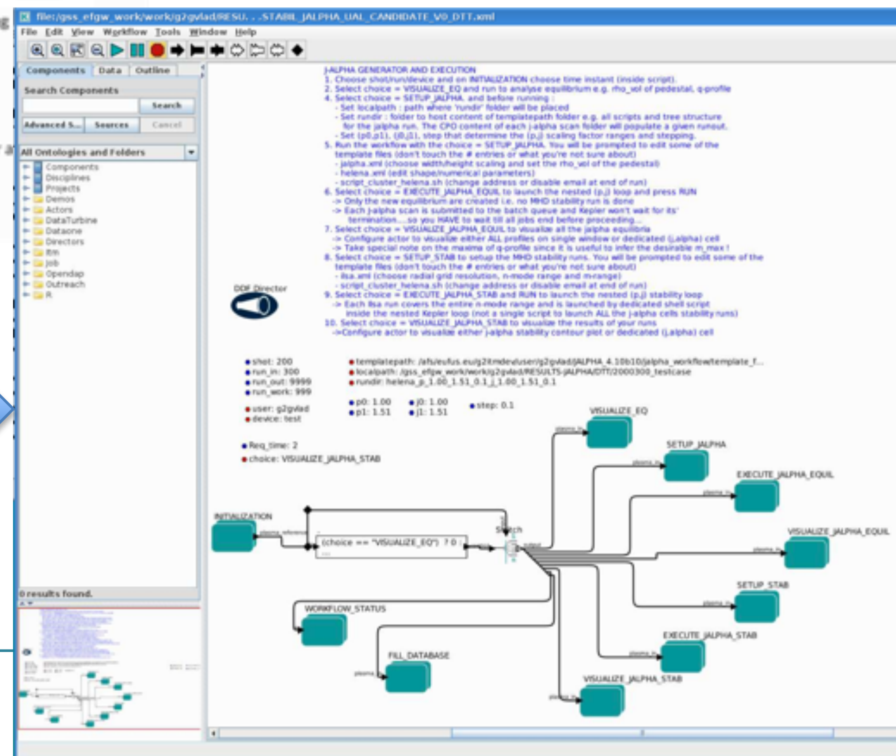
- (S) Implementation of phase-space resolved fluxes into the transport solver (ETS), as given by the kick model or more advanced nonlinear computations or models.
- (M) Compare the performance (accuracy vs. speed) of time dependent transport simulations with phase-space resolved EP transport models to the CG model.
- (A) This work will be done by Ph. Lauber, F. Zonca, R. Dumont, and J. Ferreira.

Collaboration within ITM/WPCD for EQSTABIL and JALPHA Workflows (mainly related to DTT MHD Tasks, in collaboration with V. Fusco and G. Fogaccia)



EQSTABIL Workflow

JALPHA Workflow



Thanks for your attention!