The European Integrated Tokamak Modelling Effort: Achievements and First Physics Results

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The **Integrated Tokamak Modelling Task Force (ITM-TF)** [1,2] was established in 2004 to coordinate the European tokamak modelling activities under **EFDA**. **AIM:** provide a **standardized simulation framework** supplying transparent, consistent and efficient integration of most of the state-of-the-art EU codes **modelling both the plasma physics and the tokamak subsystems**, for the **simulation of present experiments** and the **prediction of complete discharges in ITER and beyond.**

EU ITM-TF philosophy and approach

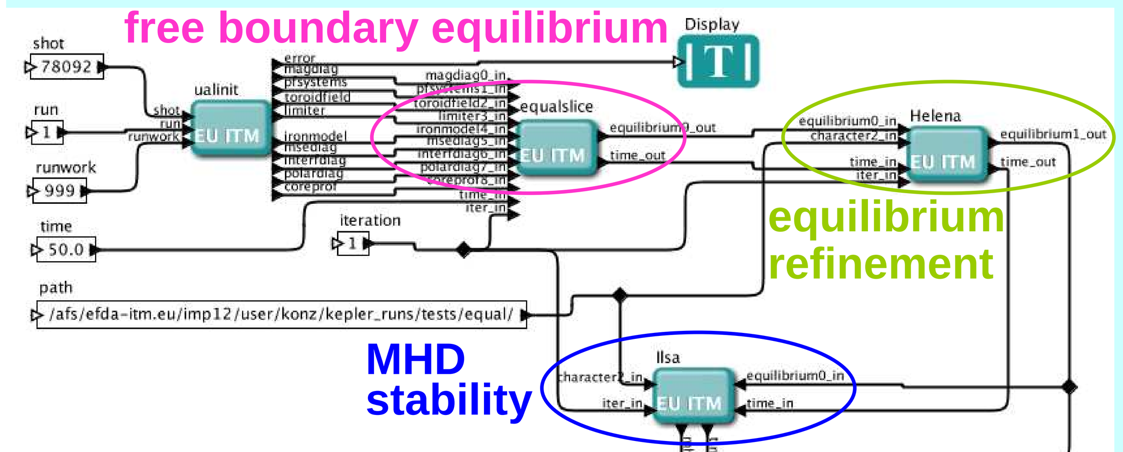
Comprehensive integrated tokamak modelling:

- ✓ infrastructure describing both **the tokamak physics** and **the machine within a unique framework**
- ✓ strategy**:** divide the global problem into Elementary Physics Problems (equilibrium, transport, MHD, sources, diagnostic response, …)
- ✓ **fully modular and flexible simulation platform**
- ✓ **standardized interfaces for physics and technology**
  - ➢ generic data and communication ontology
  - ➢ Consistent Physical Objects (**CPO**) [3]
- ✓ completely generic workflow

Equilibrium reconstruction and MHD stability chain

The ITM-TF integrated workflow coupling a free-boundary equilibrium reconstruction code, EQUAL [8](or CLISTE, CEDRES++…) , a high resolution fixed-boundary Grad-Shafranov solver, HELENA, and a linear MHD stability code, ILSA [7, refs therein] was used to carry out first physical studies:

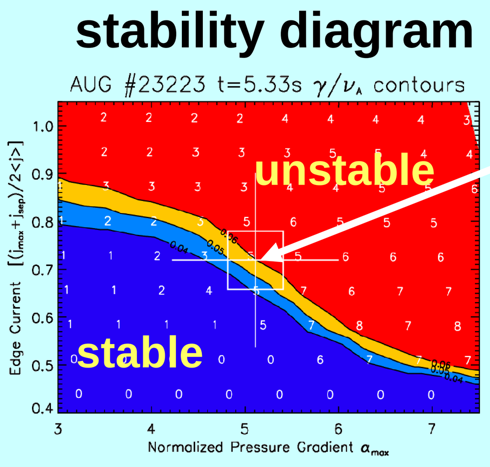
- ✓ **analysis of edge MHD stability of ASDEX Upgrade type-I ELMy H-mode** discharges
- ✓ **core and pedestal scans of β_N for an ITER hybrid scenario**



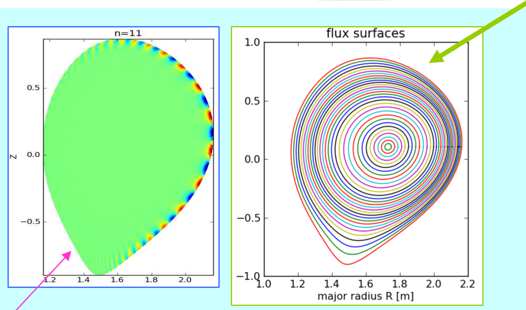
Kepler workflow for equilibrium reconstruction and MHD stability
http://kepler-project.org

Replacing EQUAL with J-α actor: modify pressure & current profiles in a loop
➔ parameter study

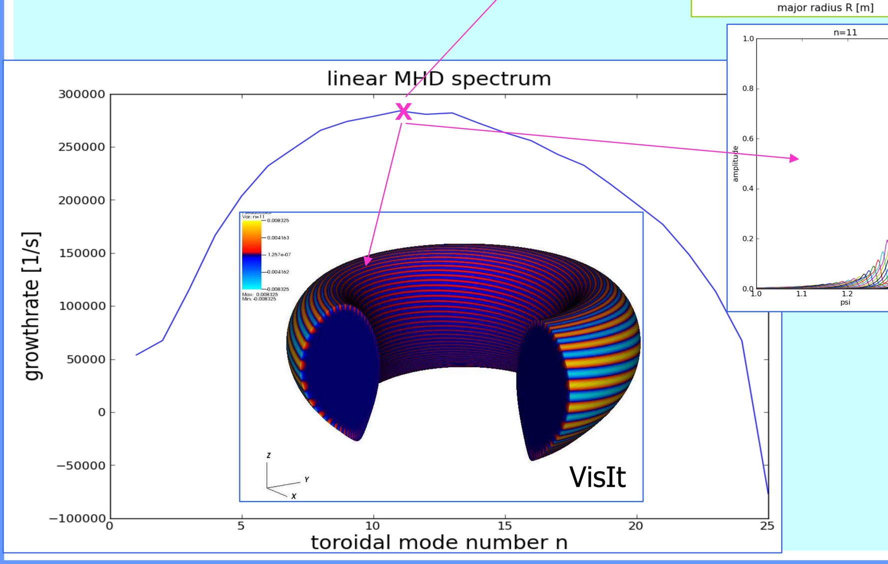
Pedestal height : stability diagram



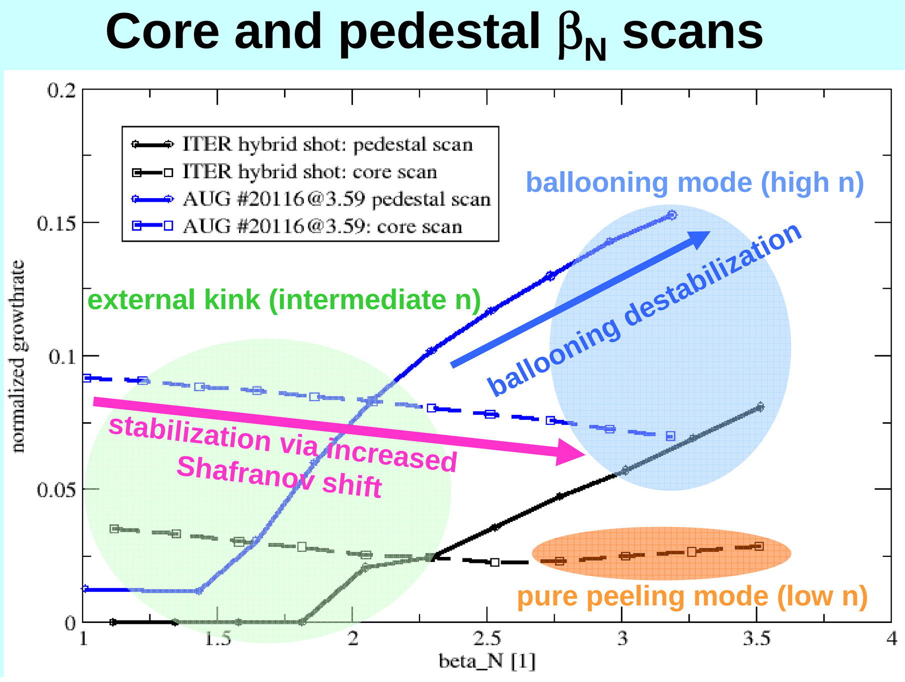
experimental equilibrium marginally unstable n=5 indicates strong peeling component



ASDEX Upgrade #20116 at 3.59s type-I ELMs



Core and pedestal β_N scans



The **EU ITM-TF framework is a valuable environment** for both **code benchmarking** and **coupling into complex integrated simulations**: different physics codes are integrated as modules sharing the same standardized interface for data input/output and can be easily interchanged in the same ITM workflow

- ➢ minimize the possible sources of discrepancy in benchmarks
- ➢ easily refine the physics description

Benchmarking of electron cyclotron heating and current drive codes on an ITER scenario

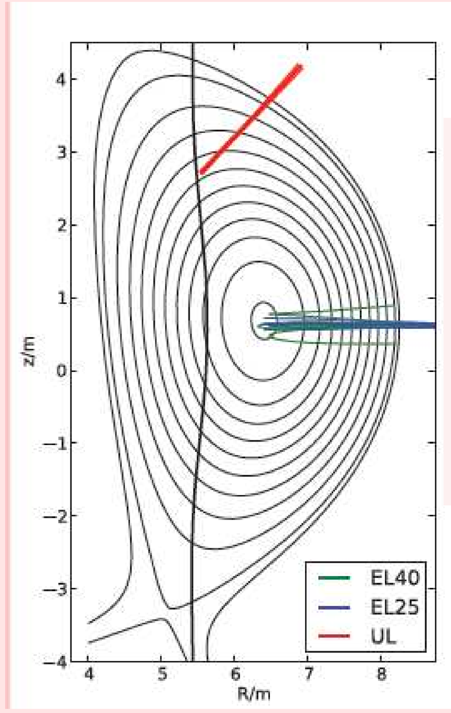
A benchmark among five European EC beam/ray-tracing codes (C3PO, GRAY, TORAY-FOM, TORBEAM, TRAVIS)[9,refs therein] was successfully performed for the standard inductive H-mode ITER "Scenario 2" for three different launching conditions from the Equatorial Launcher (EL) and Upper Launcher (UL).

1) **Divergent** beam from EL at small toroidal launching angle → Heating and CD in the **core**
2) Same as 1), with larger toroidal launching angle → **off-axis** H&CD
3) **Focused** beam from the UL, aimed at the **q=3/2** flux surface → (Antennas CPO)

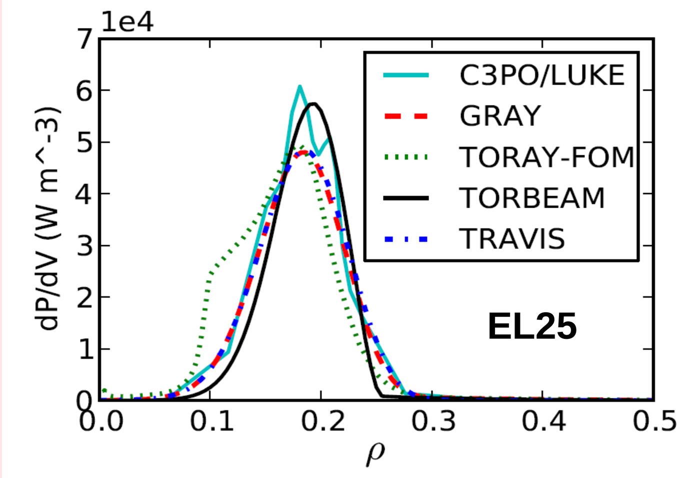
Case	R_0 (m)	z_0 (m)	α (º)	β (º)	w_0 (m)	d (m)
1 (EL25)	9.27	0.62	0	25	0.030	0.00
2 (EL40)	9.27	0.62	0	40	0.030	0.00
3 (UL)	6.90	4.18	48	18	0.021	1.62

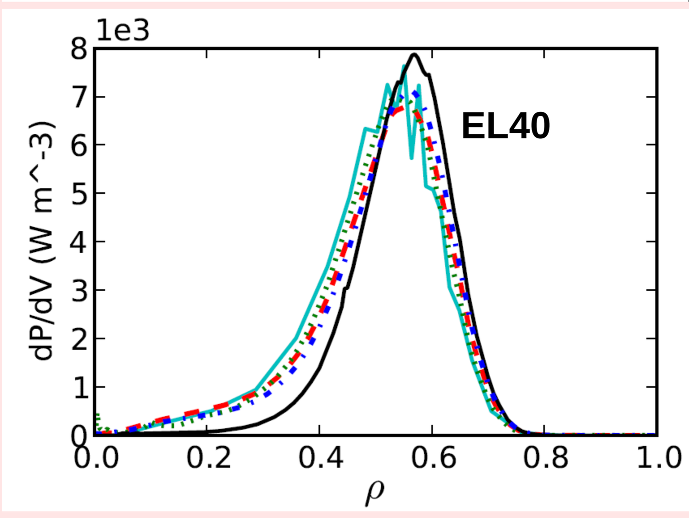
For all the cases:
P0 = 1 MW
f = 170 GHz
Ordinary Mode

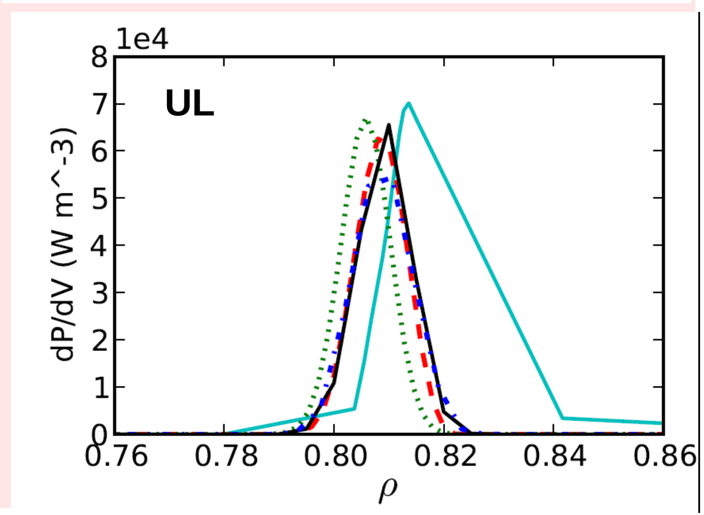
(R_0,z_0): launching point
α: poloidal angle
β: toroidal angle
w_0: beam waist
d: focus distance



ITER "scenario 2"
$B_T(0) = -5.3$ T @ $R_0 = 6.2$ m
$I_p = -15$ MA
$q = 3/2$ @ $\rho_p = 0.8$
$n_e(0) = 10^{20}$ m^{-3}
$T_e(0) = 25$ keV
$Z_{eff} = 1.7$







Heating and current drive

Good agreement of all five codes is found in all the 3 cases:

- ➢ $|\delta I_{CD}/ I_{CD}| < 15\%$,
- ➢ $\delta(dP/dV)/ dP/dV \sim |\delta J_{CD}/ J_{CD}| \sim 10\%$,
- ➢ peaking positions match within $\delta\rho \sim 0.02$

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** See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US.

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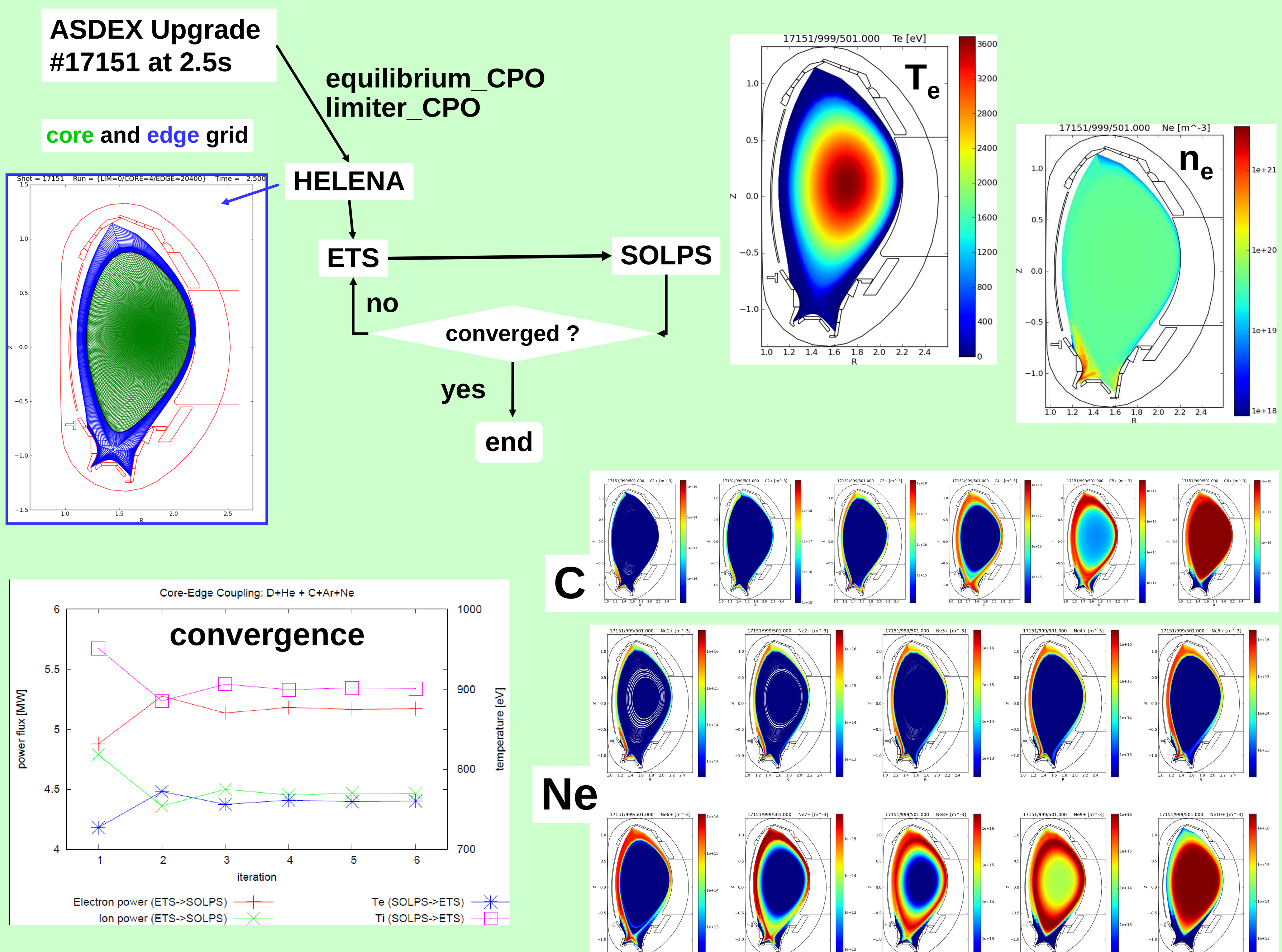
www.efda-itm.eu

Core-edge coupling within EU-ITM infrastructure

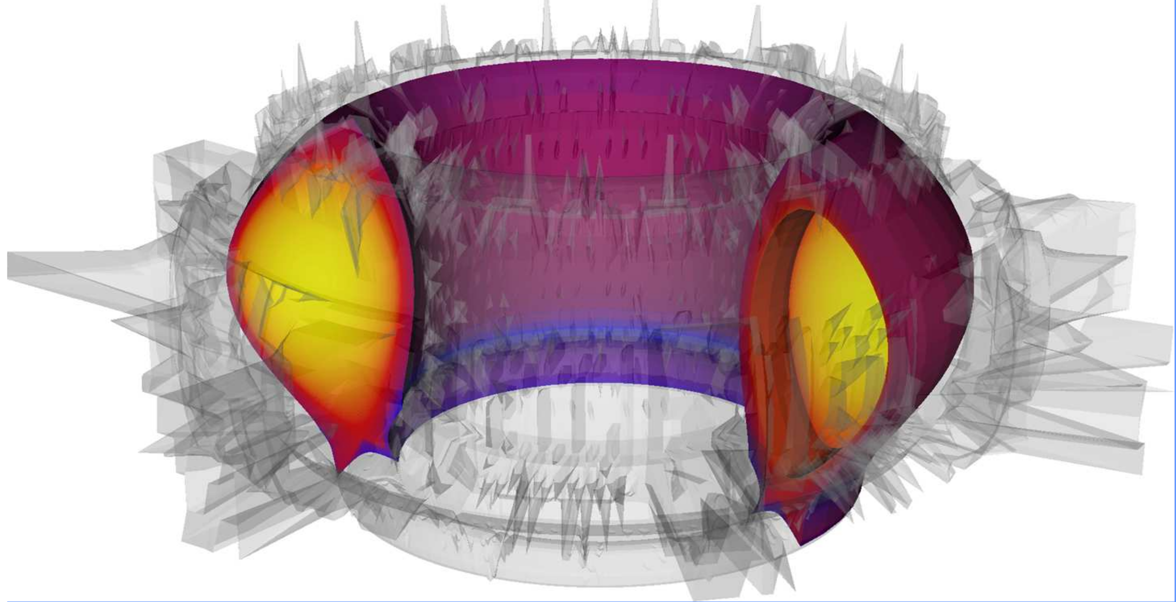
Automated **direct coupling** of an edge 2D transport code (SOLPS [11]) and a 1D core transport code (ETS, the European Transport Solver [12], including an impurity module [4]) was demonstrated for the particular case of **steady state** and **multiple impurities** (D+He+C+Ar+Ne 42 states) [5].
Neutrals here not treated by the core codes.



Case converged after 5 iterations

Visualization of core-edge coupled simulation results using EU ITM-TF tools: electron temperature, calculated in the
- core from ETS
- edge from SOLPS

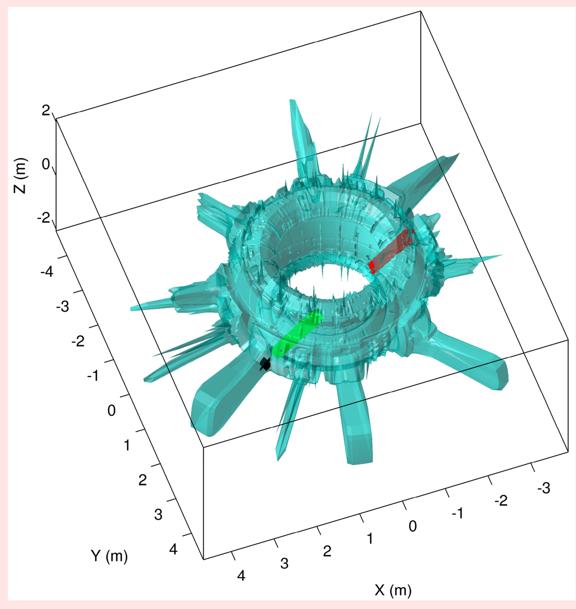
within defeatured 3D first wall of ASDEX Upgrade obtained by ray-tracing rasterization and smoothing [13]



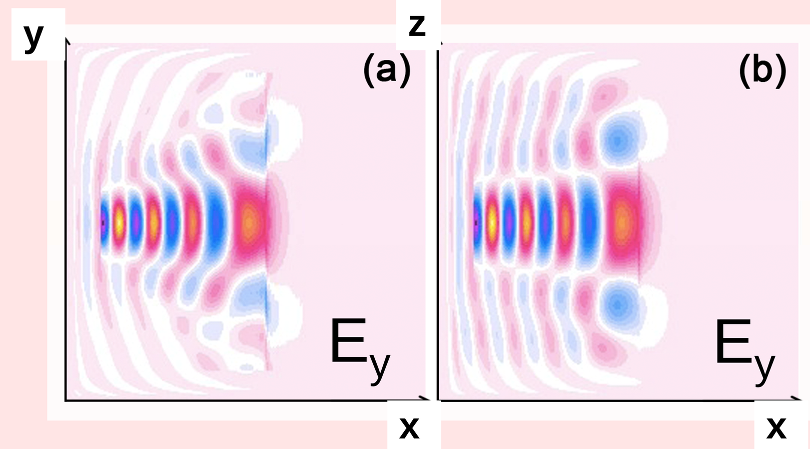
Integration & validation of Synthetic Diagnostics

[6]

Neutral Particle Analyser (born neutrals from ASCOT + pitch velocity in collimator domain)

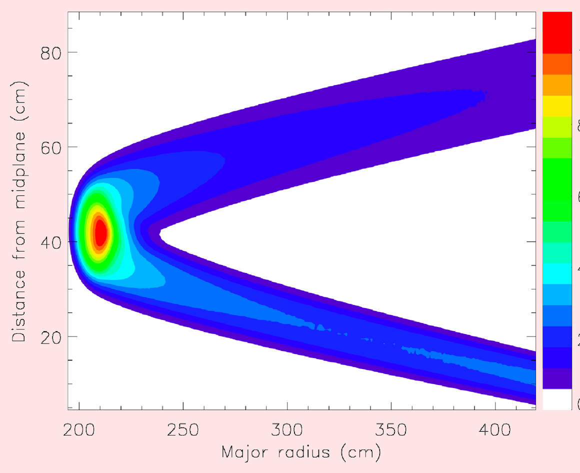


ASDEX Upgrade 3D wall and collimator domain



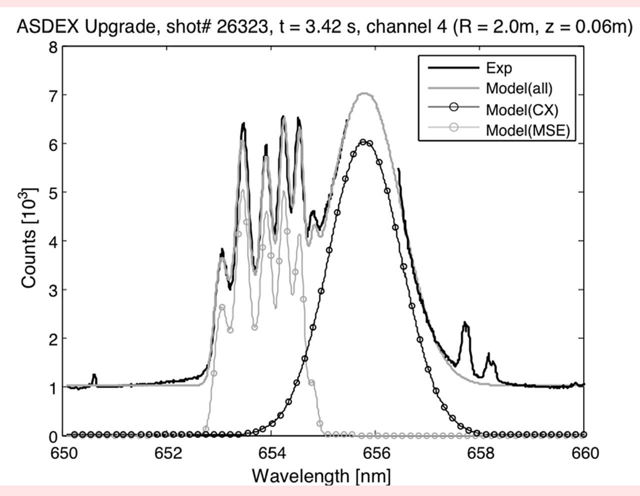
Synthetic reflectometry: full-wave 3D code (ERC3d) valid for both O and X-mode polarizations is being tested

A generic framework for neutron synthetic diagnostics has been integrated (domain voxelization + neutron source rate/spectra + diagnostic response)



JET neutron MPR "solid angle" contribution

Validation of a spectral MSE forward model [14] for MSE spectra and charge exchange of the plasma + beam (full, ½ and 1/3 beam components included) started on ASDEX Upgrade.

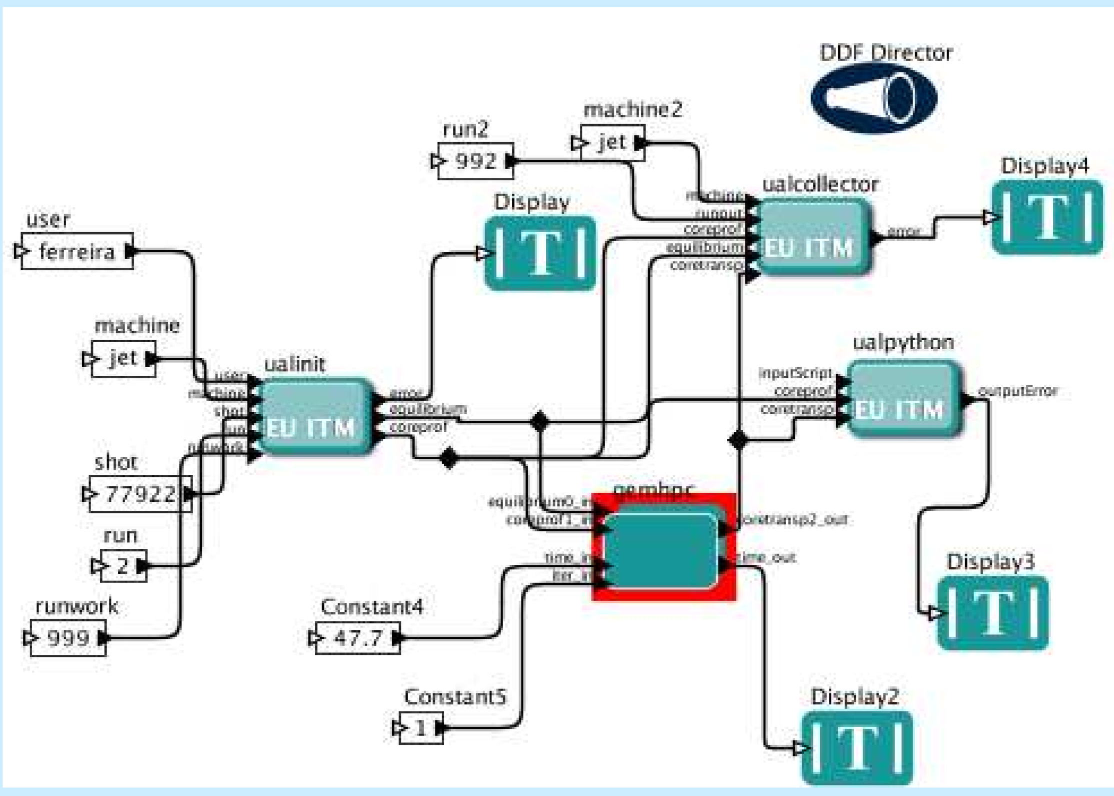


MSE emissivity wavelength spectra for ASDEX Upgrade shot #26323

Turbulence-transport simulations

Turbulence simulations for **JET hybrid discharge #77922** were performed with the electromagnetic non-linear gyrofluid GEM code [10] executed in batch on the HPC-FF within an ITM workflow.
Experimental profiles at 47.7s ($T_{e,i}$,$n_{e,i}$,toroidal current) and basic MHD equilibrium geometry were given and s-α model assumed.
GEM actor runs in parallel 8 independent fluxtube cases, at given reference points on the profile producing particle and heat fluxes profiles for both species. **The experimental case was found to be ITG stable** for most of the profile except for the edge point at r/a=0.96.

Simple Kepler workflow, accessing JET shot data from the ITM database. GEM code actor (produced via HPC2K ITM tool) is executed in batch on the HPC-FF



! Conventional direct comparison of turbulence simulations to experimental measurements and transport is often discrepant, unless some form of artificial convergence is used.

A **transport workflow** was then setup: a **fluxtube chain** consisting of an independent run of the local delta-f model at each of 8 reference points on the profile, as above, but with the fluxes equalised using a profile modification algorithm designed to adjust the profiles into transport equilibrium (prescribed power profile with the correct total power at the outermost surface).
Each workflow step takes the plasma profiles as input, calculates an equilibrium_CPO using, at present, a shifted circular model, both CPOs are then input to GEM for a run segment of 10 τ_{GB} producing flux profiles, finally the simple equilibration model is used to adjust the temperature profiles.
A relaxation time constant is used, which needs to be calibrated.
The workflow is being tested 2000 loop steps are used, corresponding to 2 10^4 τ_{GB} but a fully relaxed case is not yet available.

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