

First physics applications of the Integrated Tokamak Modelling (ITM-TF) tools to the MHD stability analysis of experimental data and ITER scenarios

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Introduction: The European Task Force on Integrated Tokamak Modelling (ITM-TF) has the long term goal of providing the European fusion community with a validated suite of simulation tools for ITER exploitation. The ITM-TF has developed a set of generic consistent data structures (Consistent Physical Objects - CPOs) allowing for standardized interfaces of physics modules and for the description of the geometry of present day tokamaks as well as experimental data from these machines [1]. The data exchange along the chain of integrated modules (workflow) is standardized and independent of the programming language. We present the first applications of these modules to a variety of physics problems related to equilibrium reconstruction and linear MHD stability. Communication with the ITM-TF database is done via automatically generated access tools, referred to as the Universal Access Layer (UAL).

Workflows for the linear MHD stability analysis of the plasma edge: The ITM-TF employs the open source workflow system Kepler [2] as an orchestration tool for its scientific workflows. Because of the standardization of all ITM-TF physics modules, scientific workflows can be developed in a generic way, meaning modules in Kepler, so called *actors*, of the same physics class, e.g., fixed boundary equilibrium solvers, become interchangeable due to the standardization of their interfaces. With all machine related data having been extracted into standardized machine descriptions, physics modules like equilibrium reconstruction tools also become independent of the specific tokamak experiment which they had been developed for. Examples for such machine independent equilibrium reconstruction tools which are currently being validated are the EQUAL module [3] and the CLISTE module [4]. Here we present results for the linear ideal MHD stability of the plasma edge in the ASDEX Upgrade tokamak using the CLISTE module to reconstruct experimental equilibria.

The workflow for the linear MHD stability chain consists of the following elements: read-

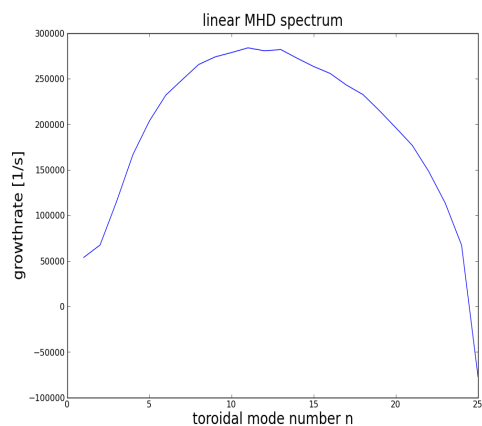


Figure 1: linear ideal MHD spectrum for AUG #20116 at $t = 3.59$ s

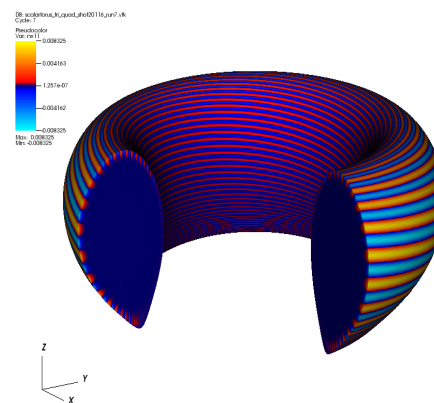


Figure 2: mode structure for the fastest growing mode ($n=11$)

ing of the CPOs containing the machine description and experimental signals from the ITM-TF database using the UAL, a free boundary equilibrium reconstruction code like EQUAL or CLISTE, a high resolution fixed-boundary Grad-Shafranov solver like HELENA [5], and currently the linear MHD stability module ILSA which is used here in MISHKA mode [6]. The details of this workflow have been described in [7]. Finally the resulting CPOs are written to the ITM-TF database via the UAL.

Fig. 1 shows the linear MHD spectrum of the ASDEX Upgrade type-I ELMy discharge #20116 at $t = 3.59$ s. The spectrum exhibits a maximum growth rate for the toroidal mode number $n = 11$ indicating a coupled peeling-ballooning mode [8]. The ballooning character of the mode can nicely be seen in a three dimensional representation of the mode structure as in Fig. 2. Bluish and reddish hues indicate alternating phases of the mode. The plots were done using generic visualization methods in Python and VisIt employing UAL access routines.

j - α Stability: The j - α stability workflow reads a previously calculated fixed boundary equilibrium from the database, modifies the pressure profile $p(\rho_{\text{vol}})$ and/or the flux surface averaged current density $\langle j_{\text{tor}} \rangle(\rho_{\text{vol}})$, and computes the new high resolution equilibrium. Here ρ_{vol} denotes the normalized radius derived from the volume enclosed by each flux surface. The module `jalpha` allows for profile modifications in a variety of different ways. To separate the effects of the current density drive and pressure gradient drive for edge modes, the pressure and current density profiles can be modified independently from each other.

For pedestal height studies, the pressure and current density profiles in the edge can be scaled by a constant factor, while the core profiles are adapted to keep the plasma energy W_{MHD} and the total plasma current I_p unchanged. For pedestal width studies, the widths of the pressure and current density pedestals can be scaled independently, again adjusting the core profiles such that

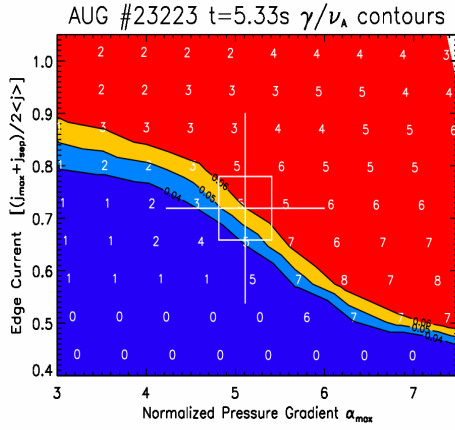


Figure 3: pedestal height study for AUG #23223 at $t = 5.33$ s

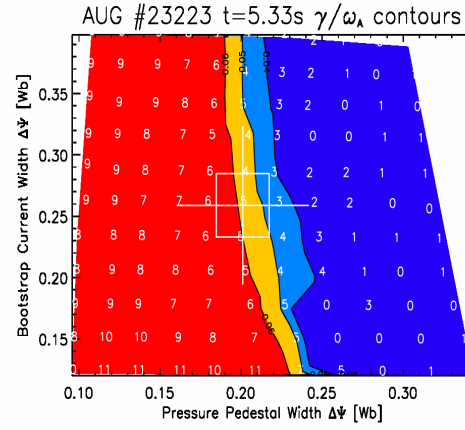


Figure 4: pedestal width study for AUG #23223 at $t = 5.33$ s

W_{MHD} and I_p remain the same. In this case, the pressure at the pedestal top and the amplitude of the bootstrap current remain constant, only the gradients change through variation of the width. Therefore, the total current flowing in the edge is smaller if the width is reduced.

Feeding the resulting *equilibrium CPOs* for the modified profiles to a linear MHD stability module like ILSA and wrapping the linear j - α workflow in a double loop over the pressure and current scaling parameters, so-called stability diagrams can be automatically computed using the Kepler orchestration tool.

Since computation times for the calculation of stability diagrams may be substantial, the ITM-TF in cooperation with the FP7 project EUFORIA [9] has developed Kepler workflows for automatic job submission to Grid and Cloud compute infrastructures.

Fig. 3 shows the stability diagram for the variation of the pedestal height for ASDEX Upgrade shot #23223 at $t = 5.33$ s. The profiles were taken just before the crash of type-I ELMs in the shot and modified using the `jalpha` module. The plot shows the contours of the linear ideal MHD growth rates γ (normalized to the Alfvén frequency ν_A) of the fastest growing edge modes in the plane defined by the maximum normalized edge pressure gradient α_{max} and the normalized edge current density $(j_{\text{max}} + j_{\text{sep}})/2 <j>$. Higher values on the y -axis indicate a stronger peaking of the edge current profile. Three contours for the normalized growthrate indicate the level of the diamagnetic drift frequency separating the stable (blue) from the unstable (red) region. The crosshair indicates the experimental equilibrium including error bars. As expected, the experimental equilibrium is marginally unstable with a toroidal mode number ($n=5$) indicating a strong peeling component.

Fig. 4 shows the stability diagram of the same shot for the variation of the pedestal widths (calculated in the poloidal flux Ψ). Reducing the pedestal width, and thereby increasing the

gradients, clearly drives the equilibrium unstable. It may also be noted that the drive from the current density gradient (small bootstrap current width) dominates the drive from larger edge current (large bootstrap current width).

β_N Scans: Core and pedestal scans of the normalized plasma beta β_N have been performed using the linear MHD stability chain for the ASDEX Upgrade type-I ELMy shot #20116 at $t = 3.59$ s as well as an ITER hybrid scenario (Fig. 5).

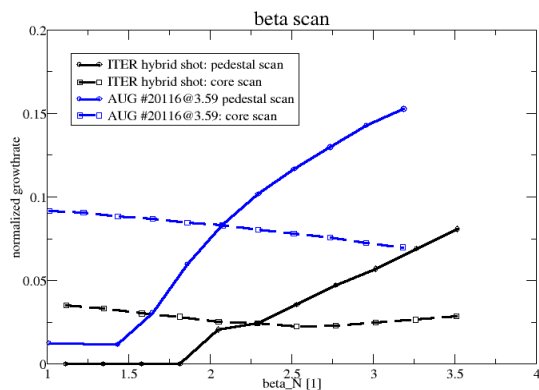


Figure 5: β_N scan: blue - AUG, black - ITER

The dashed lines show modification of the plasma β_N via modification of the core pressure profile while keeping the pedestal pressure unchanged. The solid lines, on the other hand, show modification of the plasma β_N via scaling of the entire pressure profile.

It is apparent from the normalized growth rates of the dashed lines that the increased Shafranov shift acts stabilizing on edge modes. The ITER case shows a slight destabilization of the pure peeling mode for large Shafranov shifts. For scaling of the entire pressure profile, the destabilizing effect of the larger edge pressure gradient strongly dominates over the stabilizing effect by the Shafranov shift.

Conclusions: We demonstrated that the integrated simulation workflows which have been developed by the ITM-TF for the linear MHD stability analysis can be applied to physics studies on experimental data from any generic tokamak.

References

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