An adaptive code for scrape-off layer plasma fluid simulations

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Introduction

Recent progress in the modeling of particle and energy transport in the scrape-off-layer (SOL) of magnetic confinement fusion experiments requires consideration of problems with high numbers of impurity species and effects like detachment fronts that require localized high spatial resolution [2, 4]. This pushes the limits of existing simulation codes up to the point where simulation wall-clock times become prohibitively long. To address this problem the B2.5 edge plasma fluid code [1] is extended to support solution-adapted grids. Emphasis is put on maintaining the comprehensive physics model of the B2.5 code. In this paper the B2.6-structured code is presented, an intermediate step in this project which introduces the bulk of the required structural changes to the code base and enables structured grid adaptation at runtime.

Development of the B2.6 generation of codes

B2.5 (part of the SOLPS package) is a 2d fluid code that solves a set of fluid transport equations for realistic edge plasma geometries and is most commonly used in combination with the Monte-Carlo neutrals code Eirene. The core solver is formed by an implicit iterative relaxation scheme with a classical finite volume (FV) scheme as spatial discretization. Separation of the highly anisotropic radial and parallel transport is achieved with field-aligned grids that have to be supplied by a grid generator. In [3] a base grid/working grid approach was developed that combines individual cells of a high-resolution grid into composite cells to form a coarser field-aligned working grid for the actual computation. This method is now combined with a data structure optimized for finite-volume type schemes focusing on the computation of face fluxes that supports logically rectangular unstructured grids. Adaptation of the grid is controlled by user-defined criteria which are interpreted by the adaptation algorithms as error measures. Sets of admissible grid modifications are derived from the criteria values with recursive algorithms that enable both isotropic and anisotropic global coarsening and refinement. The anisotropic mode (allowing the aspect ratio of cells to change) is essential to reflect the anisotropy in the physics.

Replacement of the central grid data structure amounts to a major structural change of the code. Furthermore, moving from structured to unstructured grids requires improvement of the FV spatial discretization to account for the more complicated grid geometry, which requires extensive changes to the numerical algorithm. To keep the transition manageable, it is split in two parts: first, the code version B2.6-structured introduces the new data structure and the required mechanics for solution-driven grid adaptation, but retains the spatial discretization of B2.5 (and is therefore limited to grids with structured connectivity). Second, the version B2.6-unstructured will include the improved FV scheme and will allow to fully exploit unstructured grids.

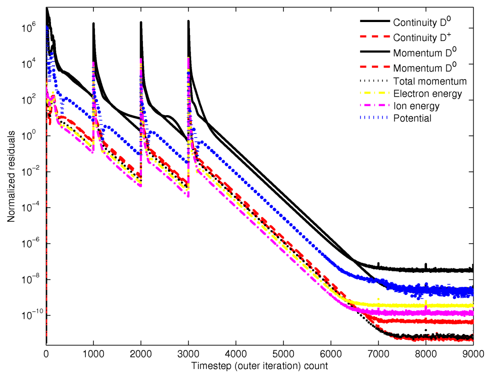
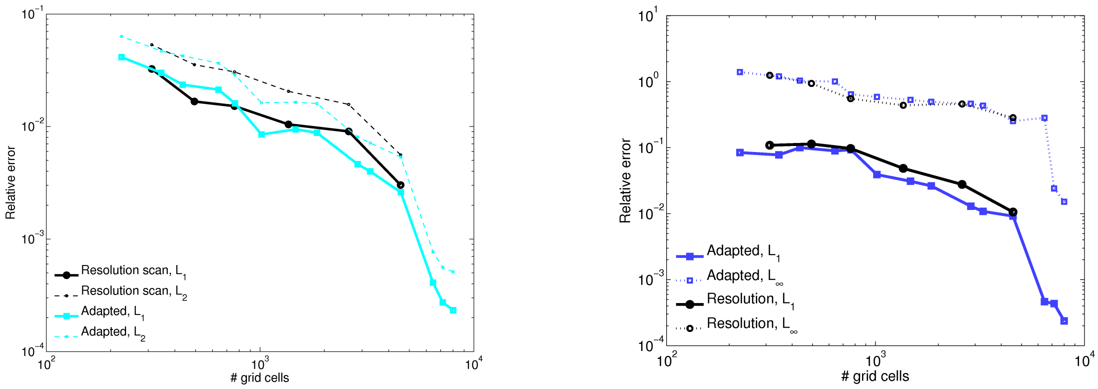


Figure 1: Residual plot for adaptive run

Considering the massive size of the B2.5 code base and the scope and nature of the proposed changes, comprehensive testing of the resulting codes is mandatory. The approach to this is twofold. The new grid management and FV solver components are developed as standalone libraries and are tested and verified individually. Testing of the full B2.6 codes is then done with a framework that allows detailed automated regression tests against B2.5 and enables test-driven development even for code sections requiring complex context, significantly simplifying the code conversion process and speeding up development of the B2.6 code line. Using this approach, exact agreement between B2.5 and B2.6-structured is established when using the same grid, and a time-consuming re-verification of the new code is avoided. For B2.6-unstructured the same process is used, but with more relaxed error tolerances due to the differing spatial discretization.



(a) Electron density

(b) Total energy flux error (inner target)

Figure 2: Relative error vs. cell count for key quantities. Color = adaptive, black = resolution scan

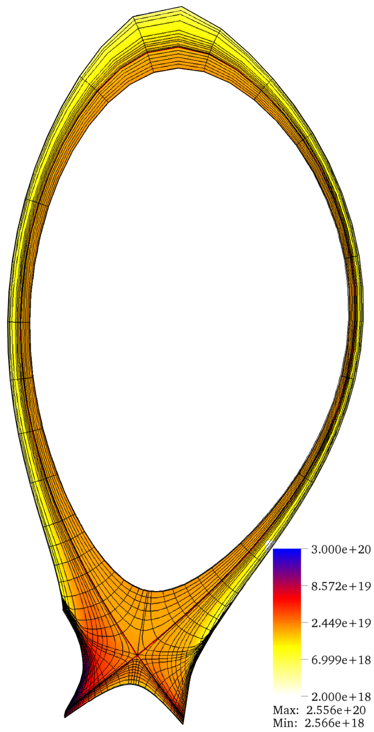
B2.6-structured code benchmark

The intermediate stage B2.6-structured retains the numerics and a large part of the comprehensive physics model of B2.5. The most notable omission are drifts and currents, where the adoption of the treatment recently developed in [5] is planned. Missing parts of the B2.5 model can be converted quickly on an on-demand basis using the conversion process described previously, which also allows to easily follow changes in the B2.5 development line.

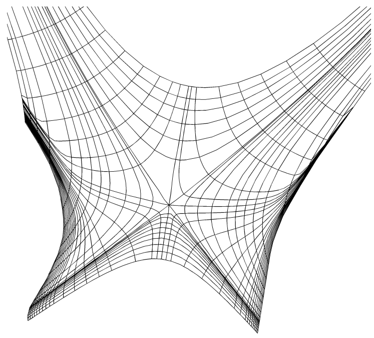
To evaluate the capabilities of B2.6-structured it is applied to a benchmark case of a hydrogen plasma L-mode discharge in single-null geometry with a fluid neutrals model. A base grid with a resolution of 128 cells in the poloidal and 64 cells in the radial direction is used. The solution on this grid serves as reference against which the adaptive runs are compared.

In the current implementation grid adaptation is performed at preset time-points in the outermost (time-step) iteration loop. As adaptation criteria a set of feature detectors measuring data variation of the primary plasma quantities is used, which are combined into a single normalized criterion using a weighted average. To comply with the limitations of the numerical scheme, the adaptation algorithms are forced to create structured grids by averaging the adaptation criteria along field lines. A resulting example grid is shown in figure 3. Robust convergence behavior (as in B2.5) is observed, but modifications to the grid and subsequent interpolation of the plasma state cause kicks in the residuals and slow down convergence (c.f. figure 1). Depending on the sensitivity of the criteria, grid adaptation has to be suspended after a preset time to allow the code to fully converge. By linearly rescaling the adaptation thresholds a series of solution-adapted grids is obtained, ranging from very coarse (< 200 cells) to very fine (up to the maximum of 8192 cells) resolution.

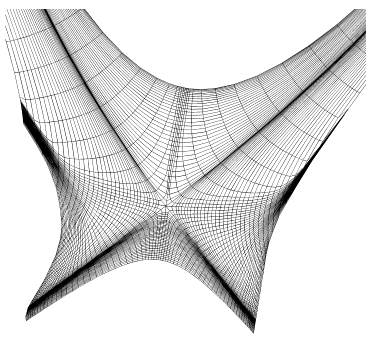
To assess the performance of the feature-detection criteria, in addition to the adaptive runs a straightforward resolution scan



(a) Adapted grid (1476 cells) and electron density ($1/m^3$)



(b) Divertor (adapted)



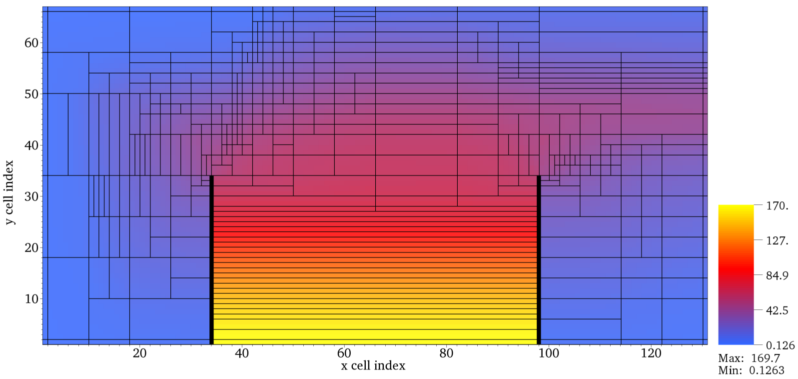
(c) Divertor (base grid)

Figure 3: Grid plots

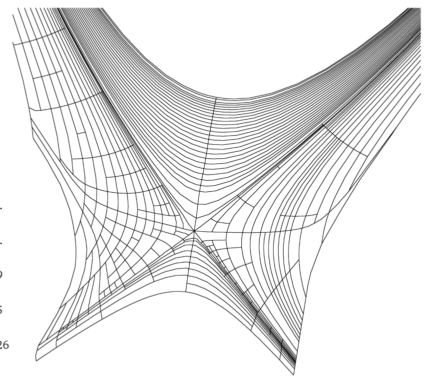
was performed from which a series of best-case grids was hand-picked. For all grids the primary plasma quantities and some key quantities at the target plates are compared to the reference solution on the base grid. Example plots for the development of the relative error of some key quantities are shown in figure 2. The adaptive runs consistently decrease the error with increasing grid resolution and match or outperform the optimal grids from the resolution scan over the entire resolution range. It has not yet been possible to make reliable comparisons of run-times between B2.5 and B2.6-structured as the latter is not yet optimized, however experience from the benchmark runs does indicate a linear dependence between cell count and code runtime.

Conclusions and outlook

In this paper a new development line for the B2.5 code was presented which introduces a solution-adaptive spatial discretization and marks the beginning of a major overhaul of the numerics of the code. The first intermediate product B2.6-structured demonstrates the suitability of the adaptation approach and is currently prepared for production use. It also contains the technologies necessary to support unstructured field-aligned grids (c.f. figure 4), which will be combined with a high-resolution FV scheme in the upcoming code version B2.6-unstructured.



(a) Full grid (computational space) with T_e (eV) solution



(b) Divertor grid (physical space)

Figure 4: Unstructured grid field-aligned grid, solution-adapted in full anisotropic mode.

References

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