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ITER-like Fusion Devices Plasma Behavior Simulation: Enhancement utilizing Adaptive Mesh Application

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Introduction

The Finite-Element-Grid enhancement software is being developed for adaptive, numerical simulation of the Tokamak plasma edge behavior. The entire poloidal cross section of the reaction torus is represented by an unstructured, adaptive FE grid discretization, that provides for the treatment of extreme gradients of plasma property changes as well as for the complex geometry representation and structure of the ITER like fusion devices. [1]

For a short time now the Finite Element Method is considered for modeling application purposes with the Tokamak-SOL-Plasmas. [2]

Such simulations require a particular treatment of steep, contiguous parameter front behavior changes as a consequence of magneto dynamic, ionization and recombination effects.

These fronts are characterized by short dimensions in the range of millimeters, provided the machine dimensions are in the order of meters. The locations of these fronts are a priori unknown. Location and parameters of these fronts, however, are of paramount importance for the accurate modeling of edge plasmas. This in turn is required for design improvements of future fusion devices, as well as for the assessment of experimental results from Tokamak research devices. Very refined spatial structures require enhanced resolution in both angular and radial directions.

Therefore the applicability of structured grid discretization like the ones commonly used is rather limited. Such a grid cannot be refined locally, since this would have to be extended to adding elements entire row or column wise. High space-resolution of the actual front area as required can be accomplished only by using a huge number of nodes which in turn increases the run time of the solver code. Unstructured adaptive grid algorithms apparently tackle the problem more adequately. [3]

Initial Data

The data used are part of the output of the so-called EFIT code. EFIT (Equilibrium Fitting) is a computer code developed to translate measurements from diagnostics into useful information like plasma geometry, stored energy, and current electron/ion/plasma profiles. For our purposes it is especially suitable to represent magnetic flux behavior (MHD-psi values), separatrix strike points and the limiter outline. The plasma toroidal current is modeled by a number of filamentary toroidal current elements whose (r,z) locations are defined by a set of points on a (cross-sectional) square equidistant grid. [4]

Available grid sizes are too coarse for computing the isomagnetic contour lines and of lines of slope of the magnetic flux. Therefore an interpolation of the initial data is used.

Initial Mesh

Theory studies indicate a strong coherence of the plasma core and the plasma edge behavior, therefore the entire poloidal area is treated. The computer program developed generates the initial grid to a large portion automatically and can be adapted to the intentions of the user with the interactive generators' extensions.

The positioning of the elements adheres to user selected the isomagnetic contour lines and to pre-selected lines of slope. Quadrilateral Elements are generated with each two of their edges

approximately following the data represented by the isomagnetic contour lines and lines of slope. This way the extreme anisotropy of Plasma-Transport Coefficients is taken into consideration along and perpendicular to the magnetic field. The commonly used triangular elements would not provide for comparable results in this very case.
Fig. 1 shows an initial mesh for the Alcator-C-MOD Tokamak:

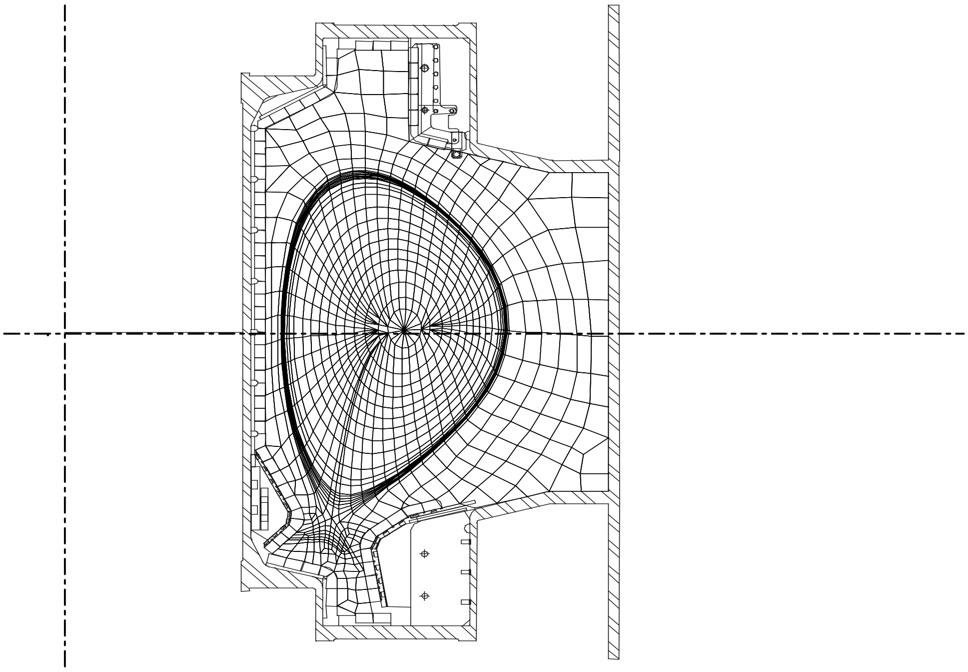

Fig. 1

Adaptation procedures

A mesh refinement and -coarsening procedure is used. It is driven by deviation estimates or explicitly defined element groups properties development. The adaptation can be executed automatically, but at any point also manual refinement/coarsening can be applied for zones of interest. The position of nodes and therefore the shape of elements can also be corrected at any time manually to meet specific requirements regarding quality and shape of selected elements. For these purposes the code offers multiple options e.g. for capturing nodes to the isomagnetic contour lines and lines of slope right after manual adjustment of the grid.
The edges of the new elements produced by the refinement process are readjusted to the isomagnetic contour lines of the magnetic field. The reduction in edge length associated with subdividing individual elements results in an improved adaptation to the curvature of the isomagnetic contour lines and slope lines when compared with the initial grid. Subsequently each refinement step improves data representation. This improves convergence and subsequently the stability of the numerical solution - even if the original grid is not adjusted exactly. The refined elements moving away from the front will be coarsened in order to keep the number of nodes roughly the same during the entire transient sequence. With coarsening the grid this improvement is set back.
The Fig. 2a, 3a, 4a show a model transient for the better understanding three snapshots out of a series of iteration steps are presented and Fig. 2b, 3b, 4b show details of the front.
The Element-Connectivity-Condition of the MIT-Solvers is strictly observed by this code, namely: every element edge can border to a maximum of two adjacent elements edges. [5] This feature in turn creates a propagation effect in both the cases of refinement and coarsening - a propagating refinement and a propagating collapsing effect: Per se such elements would

not be eligible for a change but additional nodes or nodes becoming obsolete which violate the connectivity requirement mentioned have to be adapted in excess of those representing the core of the required changes. Again this can eventually result in nonconforming elements which have to be treated to comply with the prerequisites already mentioned.

Coarsening represents not only a mere "UnDo" of the preceding refinement or the one before; inconveniently in such a case also many additional elements would be merged to a coarse mesh, which could cause convergence problems. A more sophisticated approach has been selected, namely the selection of elements excessively fulfilling the error criteria and coarsening subsequently just those. However, because of the propagation effect the coarsening must not be applied in a too radical manner.

Even though - wherever feasible - the grid is composed by quadrilateral elements, there are cases where degenerated quadrilaterals emerge, visualized as triangles. This can be the case mainly at the central core area as well as close to the limiter. These elements can also be touched by the refinement/coarsening procedure as required, in order to keep tying and connectivity conditions.

Another challenge to the code processing capabilities is, what one would call, a miniaturization problem: The initial data raster of a set of e.g. 64 by 64 or 128 by 128 data points provides for a certain descriptive quality relating to the refinement option in a typical way. Although these initial data were interpolated the elements minor edge length in the refined areas are in the range of 1/10 to 1/100 of the initial data sets grid spacing. Therefore the isomagnetic contour lines are defined in a rather fuzzy manner. For the algorithms the decision as to whether or not a node is positioned on an isomagnetic contour line requires a set of considerations regarding interrelated tolerances in order to provide for stability of the code also in areas of extreme refinement.

Conclusion

The approach presented here emphasizes the application of appropriate FE-techniques to improve performance, convergence and stability of the numerical solutions. Such behavior is essential when solving problems like bifurcation of the solution, prone to react extremely sensitive to the spatial resolution. The code developed enables to create an initial nodalization, which can be adapted to the users needs applying a selection of tools. It then uses refinement and coarsening features to adapt and remap the transient step data sets according to the requirements set by the solver, e.g. convergence criteria, maximum allowable gradient. A reduction to a nodalization code module interacting with the solver program is envisaged as the ultimate code improvement, after all testing an verification will be accomplished.

References

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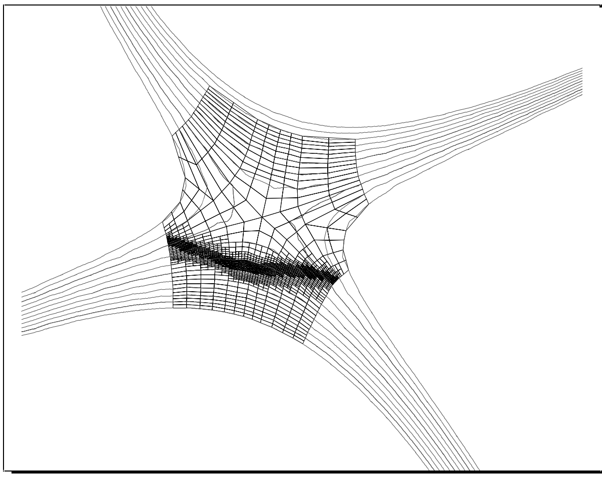


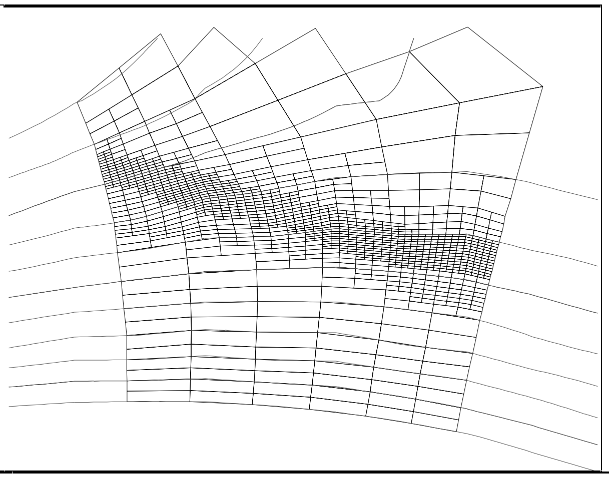
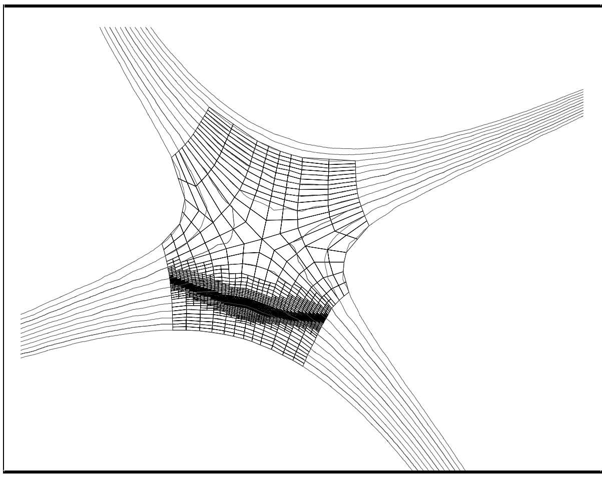


Fig. 2a

Fig. 2b



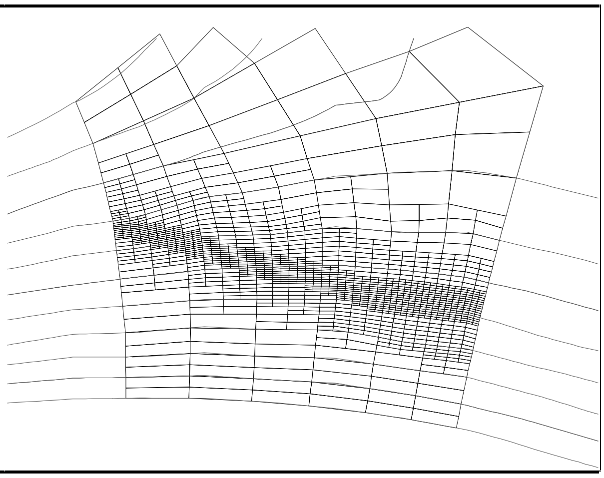
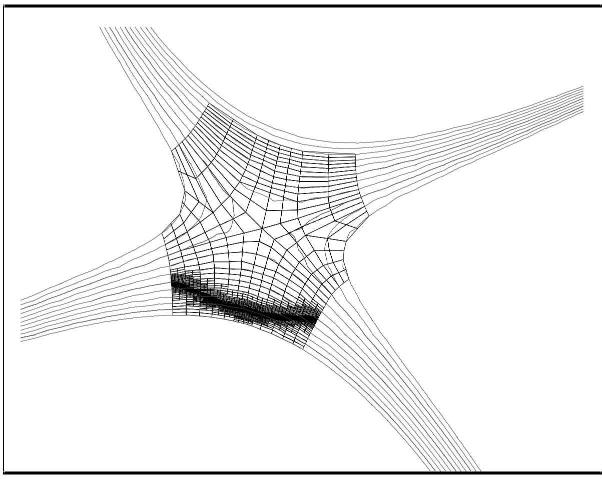


Fig. 3a

Fig. 3b



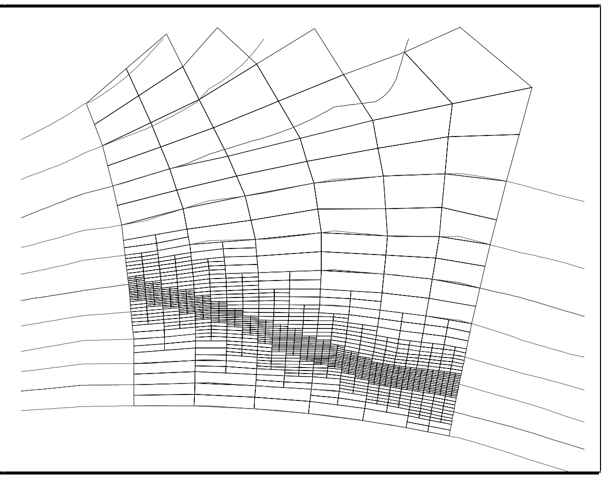


Fig. 4a

Fig. 4b

Exemplary snap shots out of a simulated transient exhibiting the mesh refinement/coarsening behavior in the closer X-point region and the corresponding the isomagnetic contour lines.
For the black and white version of this paper: The in some areas more erratic lines are equipotential data representations for locating the mesh nodes, whereas the generally straight lines are edges of quadrilatral elements.

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