FINDIF CODE SIMULATIONS OF OP-1.1 WENDELSTEIN 7-X DISCHARGES

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The current development state of the finite difference, multi-fluid, 3D plasma code Findif is detailed. The code was run on four meshes prepared for the OP-1.1 wall geometry of the Wendelstein 7-X stellarator. The meshes were produced for 4 magnetic configurations; two of them are finite-beta (non vacuum). The simulated volume covers plasma edge; the computations of limiter heat load distributions were the main goal. Plasma radiation was not taken into account.

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INTRODUCTION

The multitude of discharge scenarios available on fusion devices calls for a fast, if simplified, numerical tool to study them and assess prior to the experiments. 3D, finite difference, multi-fluid edge code Findif [1] is designed as a flexible tool that may be applied to edge phenomena in both intrinsically 3D geometries of stellarators (W7-X as in this paper, LHD) and estimation of the effect of 3D field perturbations in axi-symmetric devices (TEXTOR-DED [2]). The code can, in principle, simulate the whole machines, but unless the core temperatures are low (< 1 keV) the plasma collisionality might be to low for the fluid approach to be really accurate.

Very strong anisotropy of the transport coefficients is characteristic to plasmas confined in a magnetic field **B**. Fast, parallel transport can be naturally decoupled from the slow, cross-field one on a field-aligned meshes. Such as the ones Findif uses. This comes at a price of a somewhat complicated and quite labour-intensive mesh generation process. This process, however, has already been automatised to a large extent [3].

This paper presents the results of steady state simulations of hydrogen discharges in distinct magnetic configurations of W7-X with limiters (OP-1.1 phase [4]). Vacuum, standard configuration with big 5/5 magnetic islands external to the core (case 1) and high-mirror field with 5/6 island chain inside the core was the other. Three high-mirror field cases where considered: vacuum, β= 0.84 and 1.7 % (cases 2, 3, 4) [5].

In this paper we are particularly interested in heat flux distributions and ion temperatures at plasma facing components (PFC – limiters in the cases considered in this paper) to estimate the ablation danger for the plates.

1. THE FINDIF CODE

In its current state the code simulates main plasma (no impurities) and energy transport. Namely: plasma density, velocity along the field line, electron and ion temperatures (n, $v_\|$, T_e, T_i).

Neutral atoms behaviour and ionisation / recombination processes are not modelled yet. So, only discharges in which the plasma temperatures in the regions of appreciable density are high enough, should be simulated using Findif. The error introduced by neglecting neutrals may otherwise be unacceptable.

It is assumed that the parallel transport obeys Braginskii equations, while the perpendicular one can be modelled by diffusive approximation (anomalous particle diffusion, viscosity and thermal conductivity).

The quasi-time evolution equations are solved for each (n, $v_\|$, T_e, T_i) field separately and iterated for self-consistence. The scheme is implicit along the lines and explicit in the perpendicular direction. Implicit treatment of fast transport offers better stability / allows longer time steps, while explicit terms help to keep memory demands in check and allows straightforward coarse-grained parallelisation of the code.

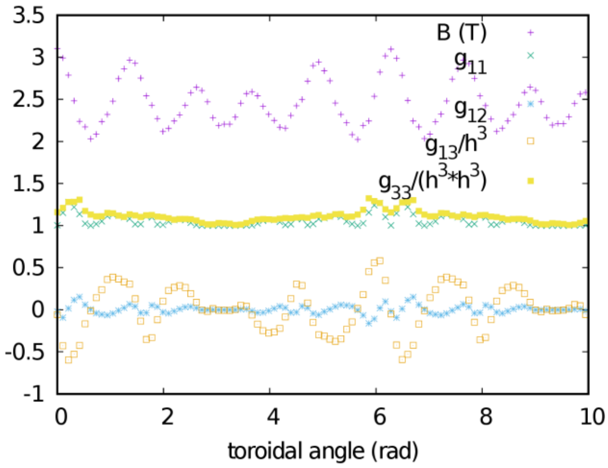


Fig. 1. Variations of magnetic field strength and sample metric tensor coefficients along one line in case 4 magnetic configuration

Mesh points are located where one of the chosen field lines crosses one of the poloidal planes ("cut") or plasma-facing components.

Global, cylindrical coordinates (R, z, φ) do not provide a framework that naturally distinguishes along-a-line transport; therefore, the equations are discretised in non-orthogonal, field-aligned local magnetic coordinates. In these coordinates we normally have non-diagonal metric tensors. Metric coefficients vary as pictured in Fig. 1.

Spacial derivatives are calculated using finite difference approximation. In case of the on-a-cut derivatives "free point method" is applied.

2. SIMULATIONS CONDUCTED

All computations where done on 60-cut meshes, one for each magnetic field configuration. The numbers of field lines where around 4 thousand and the numbers of points – around half a million.

The meshes consisted of closed field lines (outer region of the core + islands) and open lines, that crossed PFC (almost exclusively limiters). The volume of lesser importance: away from the core and "behind" the limiters was removed from calculations by the introduction of "artificial wall".

On the inner boundary of computational domain (located shallow in the core) we imposed Dirichlet boundary conditions fixing density ($n = 5{\cdot}10^{19}/\mathrm{m}^3$), velocity (0 m/s) and temperatures (both 150 eV). We used another Dirichlet conditions at the artificial wall ($v_\parallel = 0$ m/s, $T_e = T_i = 10$ eV) and Bohm conditions on the PFC. The anomalous diffusion coefficient $D_{ie} = 0.5\ \mathrm{m}^2/\mathrm{s}$ and anomalous thermal conductivity $\chi_{ie} = 1\ \mathrm{m}^2/\mathrm{s}$ was set.

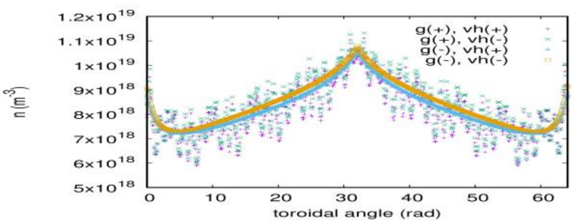


Fig. 2. 1D density distribution (artificial particle and energy source in the middle, sinks (plates) at the boundaries) in case 4 magnetic field. Profiles marked "vh(-)" have viscous heating turned off, "vh(+)" – on; "g(+)" have original metric coefficients, "g(-)" – flattened

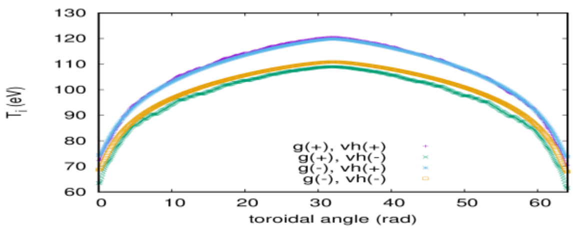
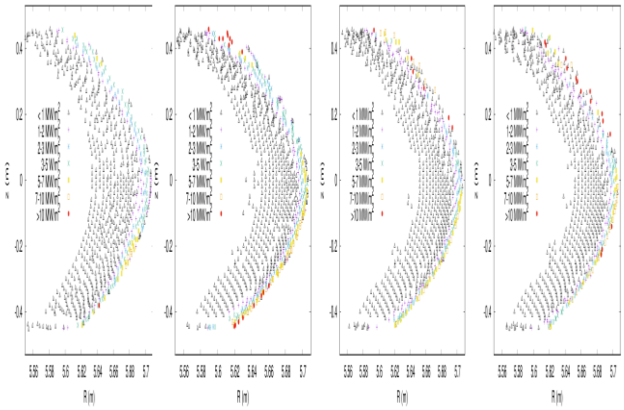


Fig. 3. 1D ion temperature (artificial particle and energy source in the middle, sinks (plates) at the boundaries) in case 4 magnetic field. Meaning of vh(±) and g(±) – as above

Due to convergence issues, we had to turn off viscous heating in 3D calculations, but, based on 1D solutions, we expect that this omission should not cause an error which might qualitatively change the solutions. For density and ion temperature profiles see Figs. 2, 3; the changes in velocity are barely noticeable. Appreciable difference is seen when metric coefficients are artificially flattened.

RESULTS

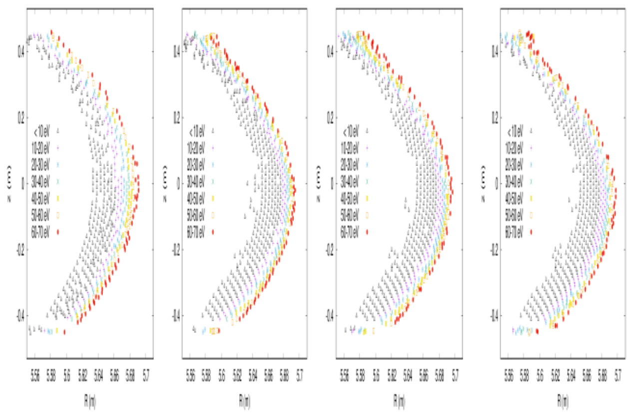
Our simulations imply (Figs. 4,a-d) that, from the point of view of incident energy flux density, the standard magnetic configuration (case 1) is best suited for the geometry of the limiters installed for the OP-1.1 campaign. High load (> 10 MW/m^2) regions are almost non-existent and the power is spread across wider surface.



a ***b*** ***c*** ***d***

Fig. 4. Heat flux densities on the surfaces of limiters (front sides) for the case 1–4 magnetic fields. The position coordinates are global cylindrical coordinates of the machine. Front side of the limiter is projected on the $\varphi = 0°$ poloidal plane

The ion temperatures (Figs. 5,a-d) of the plasma hitting the areas of the limiter located in the immediate vicinity of the core were high enough for the bombarding plasma to cause significant physical sputtering on the carbon targets.



a ***b*** ***c*** ***d***

Fig. 5. Ion temperatures on the surfaces of limiters (front sides) for the case 1–4 magnetic fields. The position coordinates are global cylindrical coordinates of the machine. Front side of the limiter is projected on the $\varphi = 0°$ plane

The ion temperature distributions show less top-to-bottom asymmetry than heat flux ones. While generally similar, the standard magnetic configuration (see Fig. 5,a) seams to provide slightly wider and less peaked temperature distribution than all high mirrors (see Figs. 5,b-d).

An inspection of computed on-a-cut density distribution (Figs. 6, 7) shows that both core islands (vacuum field case 1, see Fig. 6) and islands in the scrape-off layer (finite beta, case 4, Fig. 7) are regions of elevated density – at least as compared to the surrounding volumes. It is the bases of island divertor concept mounted on W7-X before later experimental sessions.

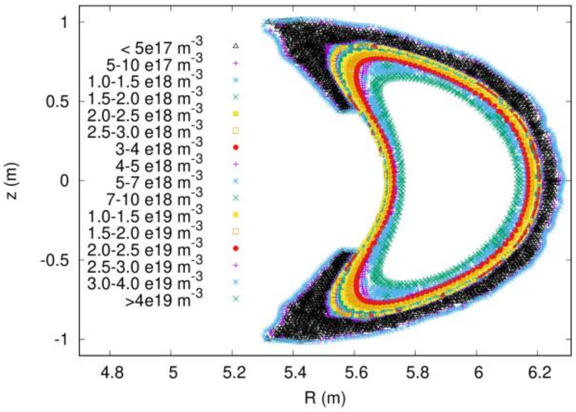


Fig. 6. Plasma density on the φ = 0° cut for the case 1 magnetic field

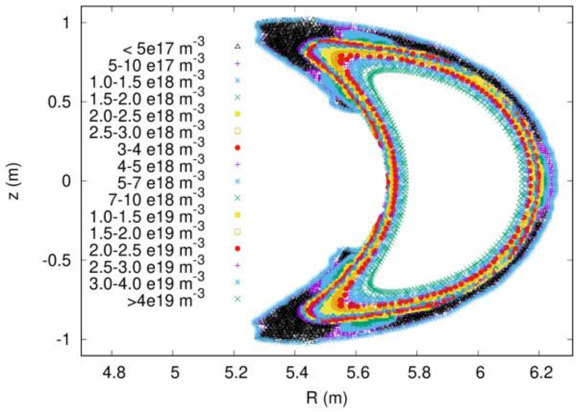


Fig. 7. Plasma density on the φ = 0° cut for the case 4 magnetic field

Applied Dirichlet boundary conditions clearly assumed to high wall density (outermost density higher than deeper in the plasma), but the error introduced seems well localised in low density (= low interest) region.

CONCLUSIONS

The program Findif can be used to simulate plasma transport in the edge region of thermonuclear devices to predict density, velocity, ion and electron temperatures. The code uses and accuracy are quite limited currently, because it includes only a handful of physical effects. Thus further development is necessary.

ACKNOWLEDGEMENTS

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МОДЕЛИРОВАНИЕ РАЗРЯДОВ OP-1.1 WENDELSTEIN 7-X С ПОМОЩЬЮ КОДА FINDIF

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Подробно изложена текущая стадия разработки конечно-разностного трехмерного кода Findif для многожидкостной модели плазмы. Код был запущен на четырех сетках, подготовленных для геометрии стенки OP-1.1 стелларатора Wendelstein 7-X. Сетки сгенерированы для 4-х магнитных конфигураций, две из которых – с конечным бета (не вакуум). Смоделированный объем охватывает край плазмы; основная цель заключается в расчетах распределений тепловых нагрузок на лимитер. Излучение плазмы не учитывалось.

МОДЕЛЮВАННЯ РОЗРЯДІВ OP-1.1 WENDELSTEIN 7-X ЗА ДОПОМОГОЮ КОДУ FINDIF

G. Pełka, W. Stępniewski, R. Zagórski and W7-X Team

Докладно наведено поточну стадію розробки кінцево-різницевого тривимірного коду Findif для багаторідинної моделі плазми. Код було запущено на чотирьох сітках, підготовлених для геометрії стінки OP-1.1 стеларатора Wendelstein 7-X. Сітки згенеровано для 4-х магнітних конфігурацій, дві з яких – зі скінченним бета (не вакуум). Змодельований об’єм охоплює край плазми; основна мета полягає в розрахунках розподілів теплових навантажень на лімітер. Випромінювання плазми не враховувалося.