

Equilibrium Calculations of HDH- and High- β Discharges in W7-AS Using the HINT2-Code

*J.Geiger**, *Y.Suzuki*⁺

** Max-Planck-Institut für Plasmaphysik, EURATOM Assoc., Greifswald, Germany*

+ National Institute for Fusion Science, Toki, Gifu, Japan

Introduction

The interpretation of experimental results in fusion devices requires an accurate knowledge of the 3-D MHD-equilibrium. For stellarators, this problem is usually solved using the VMEC-code¹ whose numerics require the existence of nested flux surfaces. The applicability is problematic if islands or ergodic regions play a major role in the equilibrium description as in high- κ configurations of W7-AS. These need to be investigated by more advanced codes like PIES² or HINT³, where no assumption of nested flux surfaces is made. Here, we present first results using HINT2⁴, the new version of HINT, for configurations used in the divertor campaign of W7-AS, for experiments showing the HDH-mode⁵ and in high- β discharges.

The HINT2 code

HINT2 is the new version of the HINT-code capable of calculating 3D-MHD equilibria without making the assumption of nested flux surfaces. The numerical scheme applied is different from that used in PIES. HINT2 solves the MHD-equations using a time-dependent relaxation method. Each iteration step in the calculation is split into two steps, A and B. In step A, the pressure distribution is relaxed by mapping it using field line tracing onto the magnetic field structure. The magnetic field is kept constant in this step. The length of the field line tracing is an important input parameter. For large lengths the pressure distribution is tightly aligned to flux surfaces, whereas for small lengths deviations are possible. The latter can be interpreted as simulating the restriction in parallel transport at high collisionality. There is, however, no transport model included in the code. In the presented calculations we use a length of 50m for the averaging process. This compares with a central electron mean free path $\lambda \approx 5\text{m}$ for $T_e=300\text{eV}$, $n_e=2 \cdot 10^{20} \text{ m}^{-3}$ in the case of high- β , or $\lambda \approx 8\text{m}$ for $T_e=450\text{eV}$, $n_e=3 \cdot 10^{20} \text{ m}^{-3}$ in the case of HDH-discharges. In step B, the magnetic field is relaxed by solving Faraday's law in combination with Ohm's and Ampere's law by the time-dependent relaxation method while the pressure distribution is kept constant. The inclusion of net toroidal current densities such as bootstrap current is not yet reimplemented in the new version. The iterations are repeated until convergence is seen. HINT2 has cpu-time advantages over the more rigorous solution of the time-independent differential equations implemented in PIES. It is also highly parallelized giving it acceptable turnaround times even if the computing requirements are still demanding (22.5hrs turn-around time on 22 3GHz Intel-Xeon processors for 45 iterations on a 201x121x59 grid).

HDH-mode configuration

The standard divertor configuration (SDC) for HDH-discharges has a boundary κ -value of the vacuum field of 5/9, where 9 natural islands form a clear separatrix. Additionally, correction coils located inside the vacuum vessel are used to increase the island size and maintain a larger distance to the divertor plates. The corrugated separatrix boundary of such configurations can not be treated by free-boundary VMEC and thus equilibrium calculations were not available to date. We compare the influence of different pressure profile forms on the configuration. The initial profiles used in this study are shown in Fig.1. They were chosen for variability and to have a zero pressure gradient at the boundary. Fig.2 shows how the initially flat κ -profile builds up shear by a central increase due to the Shafranov-shift. Thus, the 5/9-reso-

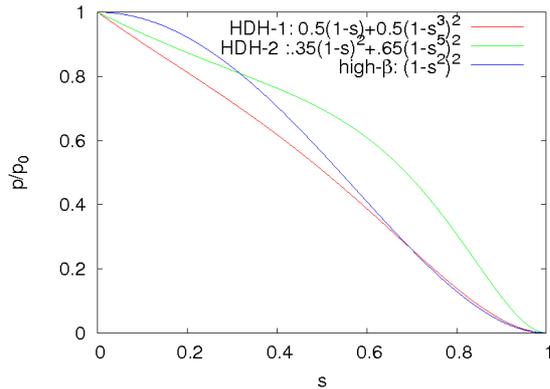


Fig. 1: Pressure profiles used in the paper given as polynomials in the normalized toroidal flux s .

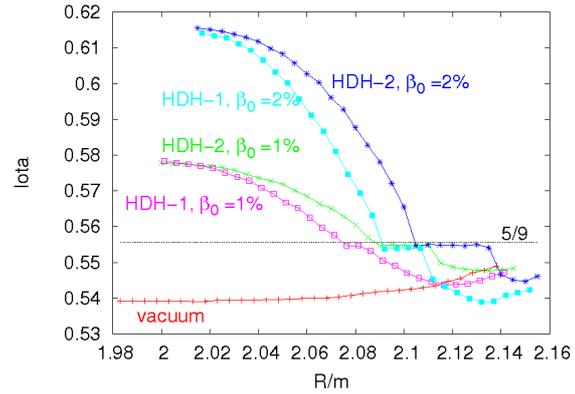


Fig. 2: τ -profiles of vacuum and finite- β calculations with different pressure profiles.

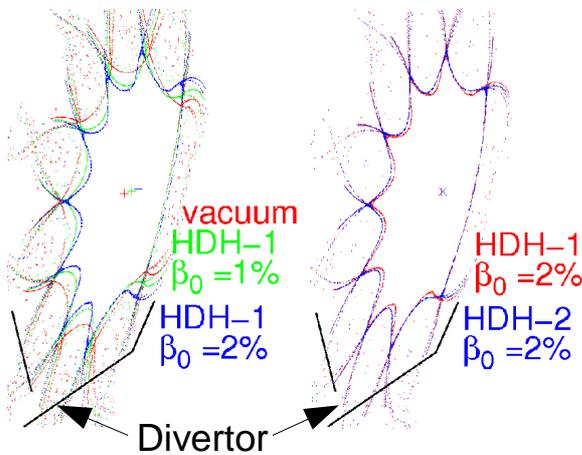


Fig. 3: Axis position and separatrix depending on β (left) and on pressure profile form (right).

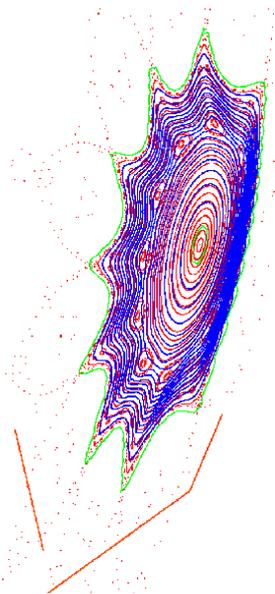


Fig. 4: Comparison of Poincaré plot (red) and pressure contours (blue, $p/p_0=1\%$ and 99% in green).

nance appears in the τ -profile and islands develop whose position depends on the β and the underlying profile form. The broader profile (HDH-2) leads to larger islands closer to the boundary.

The indentations of the separatrix formed by the 5/9 boundary islands increase with β as seen in Fig. 3. We also note that the x-points move poloidally which was already observed in the study performed with the old HINT-code⁶. Both effects are due to the poloidal expansion of the flux tubes due to the Shafranov-shift. Additionally, the island fans are moving radially on the target plates of the divertor which is also seen in the experiment. We note, that the separatrix structure seems not to depend strongly on the profile changes if the energy content is kept constant which is approximately fulfilled for the two profiles compared here.

Fig. 4 shows the alignment of the pressure contours with the magnetic surfaces. As the length for pressure equilibration in these calculations was chosen to be 50m, the field line performs about 4 toroidal turns and a strict alignment to the flux surface structure is only seen for the good flux surfaces. The 5/9-island chain is not resolved, and the pressure extends into the open field line region, the 1% line of the pressure contours being outside the separatrix.

The present calculations still have some deficiencies. First, the pressure profiles must more closely match the experimental ones. Moreover, the inclusion of toroidal net-current densities is important since we expect that the corresponding changes in the τ -profile, especially the avoidance of internal rational values and the shear at the boundary, could influence the quality of the boundary flux surfaces. Furthermore, magnetic field line mapping done at W7-AS after shut-down showed that the τ -value provided by the vacuum field has a B depen-

dence due to the coil deformations caused by the electromagnetic forces of the vacuum field on the current carrying main field coils. Since the HDH-discharges were performed at high field (2.5T) this effect is strongest. To compare with experimental data, this effect must be included since x-point and strike line locations will heavily depend on it. First estimations show that the plasma volume might be increased by 20%. Further, convergence studies with respect to the space grid must be performed since the structures in pressure and current density are comparable to the present grid size ($\Delta R = \Delta z = 0.5\text{cm}$). However, the cpu and memory demands grow rapidly; increasing the size by a factor of n , cpu-time increases by roughly $O(n^3)$.

High- β configuration

The configuration investigated has a vacuum ι -value of 0.45. The vacuum flux surfaces are highly inward shifted by a strong vertical field to compensate the Shafranov-shift in the high- β phase and thus to center the plasma in the divertor structure. Additionally, the previously mentioned correction coils are used to decrease the size of the natural islands and even overcompensate them. Therefore, in the finite- β range, good flux surfaces are expected instead of a separatrix. This motivated the use of VMEC in previous studies⁷, especially to determine volume-averaged β -values which ranged up to 3.4%. Since the assumption of good flux surfaces can only be supported indirectly, PIES calculations were performed to investigate this proposition numerically and are being continued⁸. We add to these investigation with an independent exploration of the high- β configurations using HINT2. For the HINT2 calculations

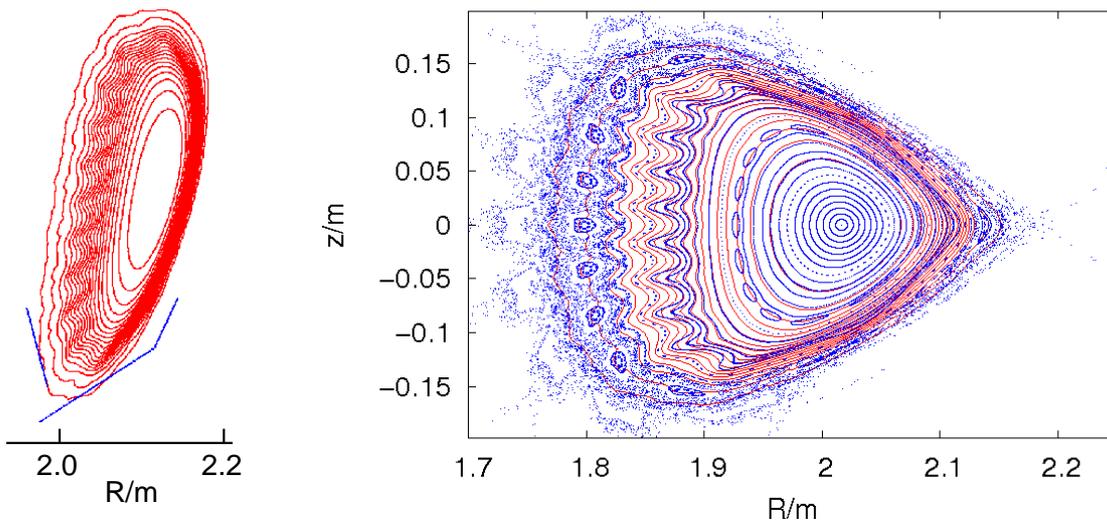


Fig. 5: Left: pressure contours with divertor structure ($\varphi=27^\circ$, $\Delta p/p_0=0.05$) with outer contour at $p/p_0=0.05$. Right: Comparison of pressure contours (red, same spacing as left) and field line tracing (blue) in $\varphi=0^\circ$ plane.

presented, we used an initial pressure profile of the form $p(s) \sim (1-s^2)^2$, to have a vanishing gradient at the boundary, where s is the normalized toroidal flux. This is a slightly broader profile than the $(1-s)$ -profile which is generally used in high- β VMEC-calculations for W7-AS. Fig.5 shows the pressure contours of a calculation reaching an energy content of ca 25kJ compared with ~ 23 kJ achieved in experiments at main field strengths of 1.25T, which means we are at experimentally achieved levels. So far, no adjustment was made in the experimental pressure profiles nor was the limiting effect of the divertor structure included in the calculation. Therefore, the pressure contour for $p/p_0=5\%$ shown in Fig. 5 (left) extends across the divertor plate. The central β -value of the calculation is 6% , the volume-averaged value depends on which volume is taken as the boundary volume. We cite the values defined by the

p/p_0 -cutoff of 10% and 5% which are 3.16% and 2.77%, respectively. Fig.5 (right) shows a comparison of the pressure contours and the result of the field line tracing in the finite- β field. Since we used for pressure equilibration a field line length of only 50m, deviations of flux surfaces and pressure surfaces are allowed, e.g. pressure contours in the „ergodic“ outer part of the field and slight deviations of pressure contours from the flux surfaces in the “meander” structure. The observed ergodization is similar to that seen in PIES calculations⁸ for this configuration. However, the pressure profiles used so far are different and need to be adjusted for a more detailed comparison. A benchmarking of the two codes with this case has not been done but on more well-defined cases (see P2.119, this conference⁹).

The convergence of the present calculation is still under investigation. At present, the convergence properties are inferred from Fig. 6 where the ι -profiles at different iteration steps in the convergence process are shown and identified by the artificial time t connected with the iteration steps. The calculation shown in Fig.5 is at $t=90$, t given in Alfvén times. Even at $t=90$, there is still some change in the center, although the ι -profile seems to settle at the boundary, especially the minimum just above $\iota=5/13$, which is responsible for the meander structure in the flux surfaces, is no longer changing. However, there are still more studies to be done. Also the grid convergence has to be tested which is required by the build up of the steep space gradients in the pressure profile due to the Shafranov shift.

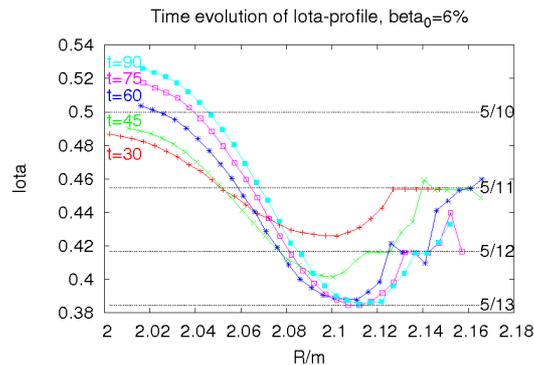


Fig.6: Profiles of the rotational transform at different time points in the calculation.

Summary

The new HINT2-code has been successfully applied to high- ι configurations of W7-AS which were used in HDH-mode discharges and in high- β experiments. The results presented are initial ones but give a good foundation for further studies as well as for comparisons with the experiment. So far, experimental trends are observed qualitatively. However, for quantitative comparison code improvements with respect to toroidal net-currents must be done as well as convergence studies concerning the grid spacing.

References:

- [1] S.P. Hirshman et al., Comput. Phys. Commun. **43**, 1986, 143-155
- [2] A. Reiman and H. Greenside, Compt. Phys. Commun. **43**, 157 (1986).
- [3] K. Harafuji, T. Hayashi and T. Sato, J. Comput. Phys. **81**, 169 (1989)
- [4] Y. Suzuki "Development and Applications of HINT2 code to Helical System Plasmas" in Joint Meeting of 2nd 21COE Plasma Theory Workshop and US-Japan JIFT Workshop on "Progress of Theoretical Analyses in Three-dimensional Configurations"
- [5] K.McCormick et al., Phys. Rev. Lett. **89**, 015001 (2002).
- [6] J. Geiger and T. Hayashi, Proc. 29th EPS Conf. on Plasma Phys. and Contr. Fusion (Montreux), 2002, 26B, P5.035, <http://epsppd.epfl.ch/Montreux/start.htm>
- [7] J.Geiger et al, Fusion Sci. Technol. **46**, 13 (2004)
- [8] A. Weller *et al*, 15th International Stellarator Workshop, Madrid, 2005 (to appear in Fusion Sci. Technol.).
- [9] Y.Suzuki et al., „MHD Equilibrium Calculations of Wendelstein 7-X“, P2.119, this conf.