MAGNETIC CONFINEMENT

PREDICTED AND VALIDATED THEORETICAL RESULTS FOR STELLARATORS IN THE FRAME OF EUROFUSION WPS2

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The main results of the work performed under EUROfusion for stellarator optimization are shown. Physics and engineering activities are undertaken in order that both are considered from the very beginning and the physics optimization takes into account the engineering constrains. are considered The HELIAS (W7-X like) configuration has been chosen as starting point and the physics criteria comprises minimization of NC transport, reduction of bootstrap current in order to have a feasible island-based divertor, reduction of turbulence and improving MHD stability and fast ion confinement. Coils are also simplified and breeding blanket studies together with the power balance of the device.

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INTRODUCTION

The stellarator theory and development EUROfusion workpackage comprises both physics and engineering activities in order that the optimization criteria provided by the two research lines are taken into account from the very beginning and the physics optimization takes into account the engineering constrains. In this way, it will be possible that a next step device has a design that is a balance between the physics optimization and the engineering requirements. The HELIAS (W7-X like) configuration has been chosen as a starting point for the optimization, taking advantage of its isodinamicty. A target of the research is to produce proxies for both the physics and engineering optimization criteria that allow one to perform a quick optimization process.

The physics criteria comprises reduction of neoclassical (NC) transport, minimization of bootstrap current to keep constant the edge value of the rotational transform in order to have a feasible island-based divertor, reduction of turbulent transport, improving the MHD stability and improving the fast ion confinement. All these criteria are evaluated with codes that can be validated in present devices, like TJ-II and W7-X.

The coils for the optimised configurations are designed using the NESCOIL code and they are optimized to reduce the manufacturing complexity using the ONSET code. The feasibility of electron cyclotron heating of the new configurations is explored using the TRAVIS code, which on top produces operation scenarios for W7-X. Electron Bernstein waves are explored as a method to heat high density plasmas. ICRH and NBI heating methods are also studied and, again, the predicted results will be validated on W7-X. A particular output of ion heating is the generation of fast ions, whose confinement will be explored in W7-X. The possible couple of ICRH power to Slow Wave, which will be absorbed in the edge, is also explored. The edge topology and transport are also studied to explore the properties of the island divertor configuration.

Regarding the engineering studies, the 0D PROCESS code has been modified to include specific stellarator modules and has been used to estimate the performance of the future stellarator reactors. Breeding blanket studies have been started by calculating the 3D-neutron flux on the wall of a HELIAS-like optimized configuration. This flux is taken as input for the breeding blanket design, which must be suitable for the complex stellarator geometry.

1. OPTIMIZATION TOOLS

We perform optimization by minimization a target function that gives the figure of merit of the different optimization criteria. Those criteria are included in the optimization process by using proxies or fast codes that can be run iteratively. The minimization algorithms can be based on chi-square minimization, can be genetic or based on the swarm search strategy. The main optimization tool is the code ROSE that includes all the former searching strategies. The main output of this work is to link several codes to ROSE in order that several criteria are included. For the moment, NC transport and bootstrap current reduction are included in the loop and here we report on the advances in other criteria, like the one of fast particle confinement. Fig. 1 shows an example of ROSE-optimized configuration with 5 field periods and an aspect ratio of A=12.2. Work is performed on turbulence to try to find out how to include it in the optimization, as well as we are developing strategies to explore the magnetic topology behaviour.

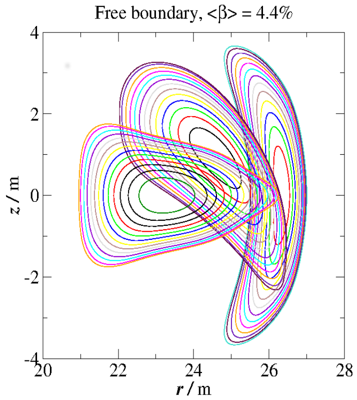

Fig 1. Magnetic surfaces of an optimized configuration

Coils are designed and optimized by the code ONSET [1] that calculates the currents needed to create the magnetic configuration and has common search strategy with ROSE. The Fig. 2 shows the coils that crate the configuration shown in Fig. 1.

The estimation of fast ion confinement is performed using the code ANTS [2] in order to optimize the configuration.

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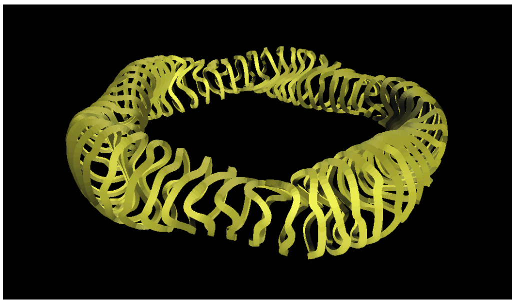

Fig. 2. Coils for the configuration of Fig. 1

Fig. 3 shows the alpha collisionless losses in this configuration. The properties of Alfvén modes as fast-ion transport drivers are also explored, especially for the isomon (m=n modes), which happen to have strong impact on fast ion transport (see Talk I-04).

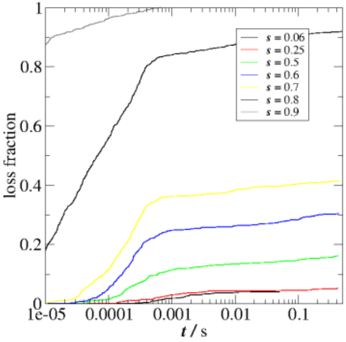

Fig. 3. Losses of fusion alpha particles losses launched on selected flux surfaces

2. HEATING AND CD

2.1. ECRH AND ECCD

The ray tracing code TRAVIS is customarily used to estimate ECRH and ECCD in W7-X plasmas, together with the equilibria calculated with VMEC and the plasma profiles.

High density plasmas can be achieved in ECRH regimes by using Bernstein waves. The new 3D full-wave code CUWA based on a Graphic Processing Unit (GPU)-accelerated finite-difference time-domain (FDTD) technique has been developed. Additionally, the code has an interface with the ray-tracing code TRAVIS applied for preliminary calculations (entrance conditions, polarization, etc.) and to reduce the full-wave calculations, using the WKB approach when possible. Fig. 4 shows the first results of CUWA.

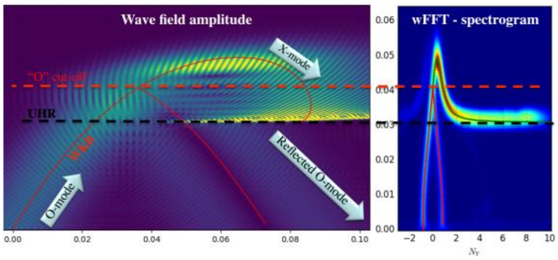

Fig. 4. Left: Example of O-X conversion in a W7-X plasma at the O-mode cut off layer. Right Spectrogram of the modes after the conversion

On top of that, the relativistic dispersion relation valid for any value of the wave vector, which is mandatory to estimate the properties of Bernstein modes (see Talk O2), has been obtained.

Current drive is usually studied in collisionless approximation (see e.g. Ref [3]). Nevertheless, it is desirable to account for collisional effects when the current is driven close to the plasma edge. Numerical tools suitable for investigations of the finite collisionality effects on ECCD are developed, including the fully relativistic approach for the generalized Spitzer function. The model was successfully benchmarked and applied for several ECCD scenarios for W7-X. Fig. 5 shows the current calculations for several collisionalities [4].

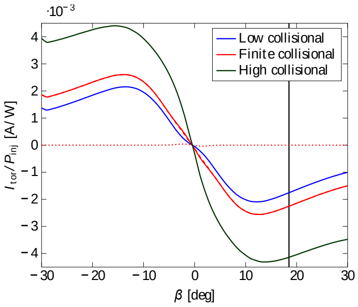

Fig. 5. Current drive efficiency as a function of the launched angle for three different collionalities

2.2. ICRH AND FAST ION GENERATION

Modelling wave propagation in 3D devices like stellarato, is a challenging task and, moreover, high density plasma operation requires the development of suitable heating scenarios that can provide a population of fast ions to explore the confinement properties of these particles. The SCENIC package [5] has been used to simulate the performance of multiple ion heating schemes, including ICRH, NBI and combined NBI-ICRH, in various W7-X magnetic geometries (low, moderate and high mirror). The advantages of each equilibrium type for each heating type (NBI, minority ICRH and 3-ion species) have been investigated (Fig. 6).

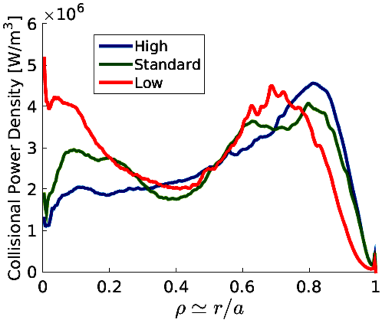

Fig. 6. Comparison of ICRH collisional power density profiles for low, standard and high magnetic mirror configurations

A novel heating scheme of high potential both for tokamaks and stellarators has been developed: the 3-ion species scheme. This scheme has the particular characteristic of being able to create high-energy ions even at high density (Fig. 7). This heating method has been demonstrated in JET tokamak [6].

The undesired Slow Wave coupling to the plasma edge is explored for W7-X configuration, which was integrated into a ray tracing code. ICRF antenna spectrum was analyzed for calculations of rays. The first calculations have shown that: the slow wave propagation and absorption in the peripheral plasma of Wendelstein 7-X does not depend on [^{3}He]; the collisional absorption and Landau damping is very weak; the absorption of SW by ^{3}He ions is absent [7].

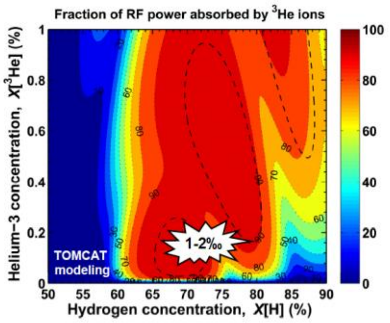

Fig. 7. Predicted absorbed power fraction as a function of the ^{3}He and H concentrations in a H-(^{3}He)-D mixture

3. BASIC TRANSPORT THEORY

Analytical calculation of NC transport of optimized stellarators based on Hamiltonian techniques has been performed [8]. Based on these techniques, the familiar analytical expression for the stellarator bootstrap current at low collisionality, valid in the $1/\nu$ regime and in the large aspect ratio approximation, has been generalised to the ν and sqrt(ν) regimes. It is well-known that, in tokamaks, the finite collisionality correction to the bootstrap current due to the effect of the collisional layer at the boundary between trapped and passing particles is quantitatively important. In stellarators, this collisional layer also exists but it is different to the tokamak case. The layer has been worked out, showing that its size scales with a different power of the collisionality. A fast NC code called KNOSOS (KiNetic Orbit-averaging-SOlver for Stellarators), based on those analytical expressions has been developed [9]. This code was improved by introducing the component of the electrostatic potential that is non-constant on the flux surface, φ_1, since it is relevant for impurity transport. Previously, we included the effect of the tangential magnetic drift on the particle trajectories for magnetic configurations that can be written as an omnigeneous field plus a perturbation. Comparisons between φ_1 calculated by the gyrokinetic code EUTERPE and by KNOSOS have also been carried out (Fig. 8). The importance of the tangential magnetic drift is shown.

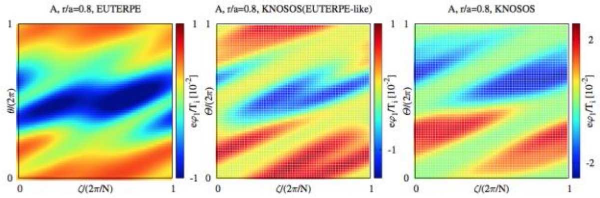

Fig. 8. Comparison of φ_1 as given by EUTERPE (left), KNOSOS without the tangential magnetic drift (center) and KNOSOS including the tangential magnetic drift (right) in an LHD plasma

The calculations of φ_1 become especially large in plasma regimes in which the tangential magnetic drift counts. If the collisionality and radial electric field are such that the tangential magnetic drift is important, the NC equations remain radially local only if the stellarator is sufficiently optimized; i.e. if it is close enough to being omnigeneous.

4. EDGE PHYSICS AND MAGNETIC TOPOLOGY

The properties of magnetic topology are crucial in stellarators for both the internal transport and the stability and performance of the island based divertor. Edge transport must be investigated in configurations with island based-divertors.

4.1. EDGE PHYSICS

The EXTENDER code has been created to describe the geometry of edge plasma and SOL, including the presence of magnetic islands [10]. The code allows the introduction of several reactor configurations and different beta and plasma current values. Configuration studies at standard-iota (5/5) (high-mirror configuration) were performed to assess a candidate configuration with the aim to combine the low-bootstrap current property of the HM-config. and the load pattern of the standard-ref.-config. for good SOL-diagnostic coverage. Result was a high-mirror config. with narrow mirror form. VMEC-EXTENDER calculation comparing net-toroidal current changes with iota-changes in the vacuum field configuration have been performed for later comparison with experiments. Particle flux on the divertor plates have been estimated in these three configurations (see Fig. 9) to detect the strike points.

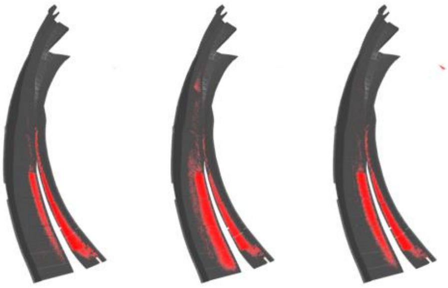

Fig. 9. Strike pattern calculations for HM-configuration (left), the SC (middle) and the new configuration with narrow mirror form (right)

The calculation of kinetic 3D transport is a computational-expensive task, so we are developing the multifluid code FINDIF that can perform quickly such a calculations. FINDIF can solve T_i and T_e, density and parallel momentum transport equations and is being applied to interpret W7-X data.

4.2. MAGNETIC TOPOLOGY

The effect of magnetic islands must be explored both in the edge and in the plasma centre. In particular, the 1.5D transport codes in stellarators assume a topology of nested magnetic surfaces with constant plasmas magnitudes, but this magnetic topology is broken when magnetic islands or ergodig zones appear in the plasma. A code is developed that modify the metric of the transport equations to take into account the appearance of these zones where the nested surfaces topology is broken. The effect ECCD deposited on X or O point of externally imposed magnetic islands has been explored on LHD plasmas with the n=1, m=1 and the n=1, m=2 externally imposed islands. The magnetic calculations show that the current tends to restore the vacuum position of the island when it is deposited on the O point of the island, while tends to increase the separation of the vacuum when the current is deposited close to the X point. Nevertheless, the influence of ECCD is not strong enough for the current reached here (up to Ip≈ -14 kA). This procedure could be used for shifting the island chain position on demand, provided that enough value of the current is achieved.

Experimental results found in stellarators like TJ-II show long lasting stable MHD modes that break the periodic symmetry. A theoretical study has been performed to explain such symmetry breaking, showing that the most stable equilibria are not the periodic ones. The free boundary equilibrium code VMEC has been used for this purpose, introducing a perturbation parameter δi that breaks the externally imposed symmetry (Fig. 10) [11].

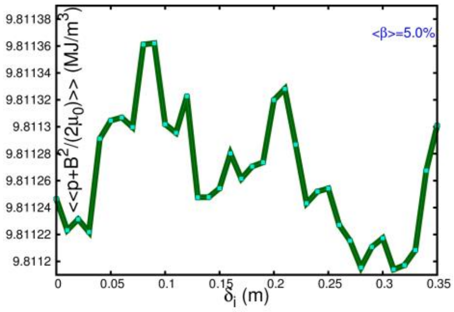

Fig. 10. Magnetic plus kinetic energy of the equilibrium plasma as a function of the perturbation parameter δi

Experiments in LHD have shown that plasma detachment can be reached in the presence of magnetic islands close to the separatrix, in such a way that the fluxes onto the wall are reduced and the radiated power increases. The detachment appears when the plasma conditions are such that they imply healing of the island, accordingly to what it is known in the centre of the plasma column [12]. So it is deduced that plasma detachment happens when the island is not healed and is able to reduce the fluxes on the wall. Therefore, the understanding and controlling of island healing is a primary tool to reach plasma detachment. Fig. 11 shows the attached/detached plasma states in the beta-collisionality space for several values of the current in the resonant coils. (the larger the current the stronger the perturbation to the nested flux surface topology).

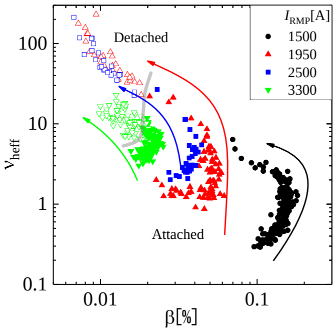

Fig. 11. The attached/detached plasma states in the beta-collisionality

5. TURBULENCE OPTIMIZATION AND ASSESSMENT

Although turbulent transport is less relevant in stellarators than in tokamak plasmas, NC optimised configurations can present a relevant level of turbulent transport, so we must try to optimize stellarators to minimize turbulent transport. NC-optimised Helias-like configurations were optimised against ITG modes introducing a proxy for the transport value driven by such modes [13]. These configurations are supposed to be optimised against ETMs, since the unfavourable curvature happens where the fraction of trapped particles is smaller. Non-linear calculations have been performed in W7-X like plasmas, showing that the elongated configurations present larger level of turbulence (Fig. 12).

In the search for fast estimate of turbulence properties, linear simulations of zonal flow (ZF) relaxation have been performed in optimized configurations using flux tube (GENE) and global simulations (EUTERPE), finding important differences between the two techniques.

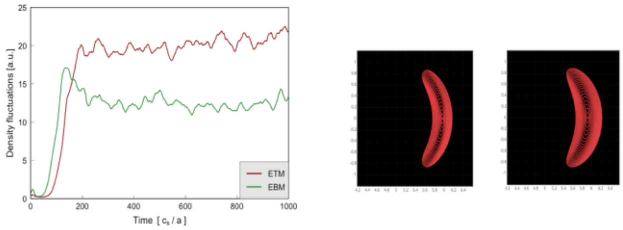

Fig. 12. Comparison of density fluctuations generated by ITGs in two magnetic configurations with different elongations and iota values: ETM, left: higher iota, more elongated; EBM, right: smaller iota, less elongated and with lower turbulence level

This work has motivated a longer-term comparison between simulations in different simulation domains. Previous ZF relaxation simulations in TJ-II [14,15] have been improved, including light impurities and considering the contribution of kinetic electrons, thus reaching a quantitative agreement with experimental measurements. A study of the generation of ZF oscillation by fast particles has been initiated with promising results: ZF oscillations are generated, with frequencies in the low frequency ranges. The study of non-linear saturation of turbulence in stellarators and the influence of the electric field and the properties of ZFs on it is being revised because of the large ZF component found in the non-linear simulations with EUTERPE. (Fig. 13). The role of collisions in the damping of oscillations is being analysed presently.

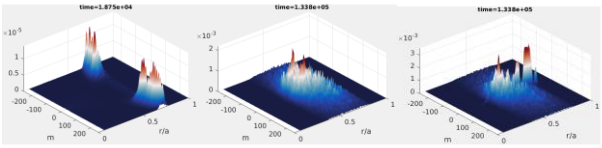

Fig. 13. Wave number spectrum of potential fluctuations vs poloidal mode number and radial position (r/a) in the linear phase (left) and the non linearly saturated phase (middle and right) of a simulation in W7-X. The ZF (m=0, n=0) Fourier component has been suppressed in the middle figure and is retained in the right one

6. ENGINEERING

The inclusion of engineering results in the optimization process provides the capability of finding a balance between the physics optimization and the capability of design a feasible stellarator.

6.1. PERFORMANCE CALCULATIONS

A stellarator module has been implemented in the 0D system code PROCESS to maximize synergy effects with the existing tokamak models [16]. The PROCESS code has undergone significant development dedicated to its overall modernisation, including heating systems, coils and divertor, for the moment.

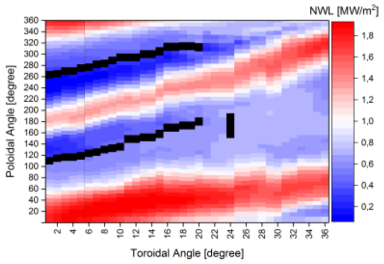

Fig. 14. Poloidal-toroidal distribution of the Neutron Wall Loading (NWL) calculated with DAGMC

6.2. NEUTRONICS AND BREEDING BLANKET

We are carrying analysis of an appropriate configuration of a Breeding Blanket for the HELIAS power reactor based on 3D neutronics, thermal hydraulics and structural mechanical calculations taking into account possible maintenance schemes.

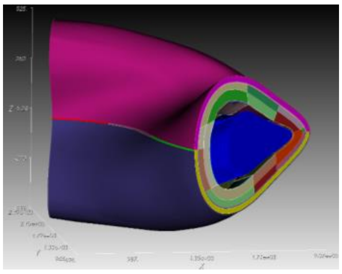

Fig. 15. Poloidal-toroidal distribution of the Neutron Wall Loading (NWL) calculated with DAGMC

A first neutronics model of HELIAS, suitable for use with the DAGMC Monte Carlo code [17], has been generated and applied in neutronics simulations (Fig. 14). The model includes a simplified representation of a HCPB blanket with first wall, breeder zone, back support structure and radiation shield described in coarse layers with homogenized material mixtures. These results are a solid starting point for further investigations and considerations towards the design optimization and integration of engineering components such as a breeder blanket: a first segmentation strategy for the inclusion of breeding blankets in HELIAS has been proposed. A 3D FEM model is being developed in order to assess if the assumed gaps between the blanket modules is sufficient to ensure, under simplified thermomechanical loads, a thermal expansion of the modules without overlapping (Fig. 15).

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REFERENCES

1. M. Drevlak. Automated Optimization of Stellarator Coils // *Fusion Technology*. 1998, v. 33, p. 106-117.
2. M. Drevlak et al. // *Plasma Physics and Controlled Fusion*. 2011, v. 35.p. 429.
3. F. Castejón et al. // *Physics of Fluids*. 1992, v. B 4, p. 3689.
4. W. Kernbichler et al. // *21th International Stellarator-Heliotron Workshop*. 2017, p.1-49.
5. J.M. Faustin et al. // *Plasma Phys. Control. Fusion*. 2017, v. 59, p. 084001.
6. J. Ongena et al. // *Proc. 22nd Top. Conf. on RF Power in Plasmas*, *EPJ Web of Conferences*.2017, v. 157 , p. 02006.
7. D. Grekov, K. Tretiak, V. Nemov // *Report O-5 of 21th ISHW*, (Kyoto, October, 2017).
8 I. Calvo, F.I. Parra, et al. // *Plasma Phys. Control. Fusion*. 2017, v. 59, p. 055014.
9. J.L. Velasco et al. Large tangential electric fields in plasmas close to temperature screening // *Plasma Phys. Control. Fusion*. 2018, v. 60, p. 074004.
10. J. Geiger et al. // *Plasma Phys. Control. Fusion*. 2015, v. 57, p. 014004.
11. A.W. Cooper et al. Stellarator nonlinearly saturated periodicity-breaking ideal magnetohydrodynamic equilibrium states // *Nuclear Fusion*. 2018, p. 58(12), p. 124002.
12. Narushima et al. Detachment transition occurring with amplification and suppression of resonant magnetic perturbation field caused by plasma response in LHD // *Nuclear Fusion*. 2018, v. 17.
13. P. Xanthopoulos et al // *Phys. Rev. Letters*. 2014, v. 113, p.15.
14. P. Moneal et al. // *Plasma Phys. Control. Fusion*. 2016, v. 58.
15. E. Sánchez et al. // *Plas. Phys. Controll. Fusion*. 2018.
16. F. Warmer et al. // *Fusion Engineering and Design*. November 2017, v. 123, p. 47-53.
17. 6X-5 Monte Carlo Team, MCNP - A General Monte Carlo N-Particle Transport Code, ver. 5, v. I / *MCNP Overview and Theory*, LA-UR-03-1987, Los Alamos National Laboratory, 24 April, 2003; G. Bongiovi et al. Preliminary structural assessment of the HELIAS 5-B breeding blanket. Submited to SOFT-2018.

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ПРОГНОЗИРОВАННЫЕ И АПРОБИРОВАННЫЕ ТЕОРЕТИЧЕСКИЕ РЕЗУЛЬТАТЫ ДЛЯ СТЕЛЛАРАТОРОВ В РАМКАХ ЕВРО-ТЕРМОЯДЕРНОЙ ПРОГРАММЫ ВПС2

F. Castejón and the EUROfusion WPS2 Team

Показаны основные результаты работы в рамках ЕВРО-термоядерной программы для оптимизации стелларатора. Физическая и инженерная деятельности приведены для того, чтобы оптимизация физики учитывала инженерные ограничения. Конфигурация ГЕЛИАС (подобная) была выбрана в качестве отправной точки, а физические критерии включают минимизацию транспорта, уменьшение бутстрэп-тока, чтобы иметь возможный островной дивертор, снижение турбулентности, улучшение МГД-стабильности и удержание быстрых ионов. Катушки упрощены и размножены с использованием баланса мощности устройства.

ПРОГНОЗОВАНІ І АПРОБОВАНІ ТЕОРЕТИЧНІ РЕЗУЛЬТАТИ ДЛЯ СТЕЛАРАТОРІВ У РАМКАХ ЄВРО-ТЕРМОЯДЕРНОЇ ПРОГРАМИ ВПС2

F. Castejón and the EUROfusion WPS2 Team

Показано основні результати роботи в рамках ЄВРО-термоядерної програми для оптимізації стеларатора. Фізична та інженерна діяльності наведені для того, щоб оптимізація фізики враховувала інженерні обмеження. Конфігурація ГЕЛІАС (подібна) була обрана в якості відправної точки, а фізичні критерії включають мінімізацію транспорту, зменшення бутстреп-струму, щоб мати можливий острівний дивертор, зниження турбулентності, поліпшення МГД-стабільності і утримання швидких іонів. Котушки спрощені і розмножені з використанням балансу потужності пристрою.