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Physics and Engineering Studies of a Helias Reactor

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Abstract

The current Helias reactor is an extrapolation of the W7-X configuration to reactor dimensions. This paper summarizes the computational results of various activities to improve the concept of the advanced stellarator reactor: Forces and stress analysis of the coil system, self-consistent computation of plasma equilibria, a concept of divertor action on the basis of magnetic islands, neoclassical transport and investigation of alpha-particle confinement, start-up scenarios of the Helias reactor using ECRH and pellet injection and confinement studies using empirical scaling laws.

Keywords:

stellarator reactor, modular coils, ignition

1. Introducton

The main technical component of a Helias reactor is the magnetic system consisting of 50 modular coils. The magnet system comprises 5 field periods with 10 coils per period. In comparison to a previous design [1] the magnetic field on the coils has been reduced using a trapezoidal shape of the coil cross section and by reducing the average field by 5%. The winding pack is split into two parts in order to reduce the overall current density at the location of maximum magnetic field.

The maximum field on the coils is now 10 T which is in the range of NbTi-technology at a temperature of 1.8 K. Furthermore, slight modifications of the coil geometry have been made to account for the necessary space for blanket and intercoil support elements. Each coil is enclosed in a steel case, which is designed as a box-type profile with a central web for mechanical stiffening (Fig. 1).

HSR Coil Cross-Section

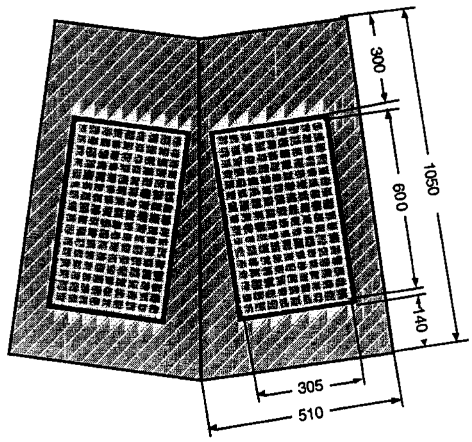

Fig. 1 Cross section of the modular coils.

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Table 1 Parameters of the HSR coil system

Major radius	22	[m]
Number of coils	50	
Average coil radius	5	[m]
Max. field on coils	10	[T]
Current density	29.5	[MAm $^{-2}$]
Windings per coil	288	
Current in winding	37.5	[kA]
Magnetic energy	100	[GJ]
Weight of one coil	300 - 350	[tonnes]
SC winding packs	4000	[tonnes]

A 0.04 T vertical field is provided by the modular coils and compensates the Shafranov shift at the outermost surfaces. The minimum bending radius of the superconducting cable is 1.4 m. Force and stress analysis of the Helias coil system have been reported in Ref. [2]. An optimized design of the intercoil support system is in progress.

2. Plasma Equilibrium

The magnetic field of a finite-beta-equilibrium is computed iteratively using the free-boundary equilibrium code NEMEC [3] inside the last magnetic surface and the code MFBE [4] in the region outside the plasma. Starting from a vacuum field with inward-shifted magnetic surfaces, a finite-beta equilibrium with $<\beta>=5\%$ was computed. As can be seen from Figs. 2 and 3 there is a finite Shafranov shift, however the radiating plasma center is still centered with respect to the first wall, thus avoiding large hot spots from neutron irradiation.

The Shafranov shift is in the expected range of Helias configurations. The effective plasma radius shrinks slightly at finite beta leading to a modification of the island region at the boundary. The remnants of the $\iota=1$ islands determine the pattern of plasma flow to the divertor plates. As shown in Fig. 3 by Monte-Carlo calculations of particle orbits, divertor target plates collect the out-streaming plasma. The finite beta-plasma at $<\beta>=5\%$ is stable according to both Mercier and resistive interchange criteria.

3. Plasma Confinement

The neoclassical transport charactristics of the new configuration are very similar to those of its predecessors. To summarize briefly, the vacuum magnetic field has an effective helical ripple (for $1/\nu$ transport) of 2.5% or less over the entire plasma cross section. Neoclassical electron losses are thereby small enough to allow ignition even for the "ion root" solution of the ambipolarity constraint. This is a critical point as the envisaged plasma parameters do not allow operation at the more favourable "electron root". Finite plasma pressure introduces two transport-relevant changes of the magnetic field spectrum: the reduction of the mirror term on the magnetic axis and a significant radial variation of the flux-surface-averaged value of B. The first is

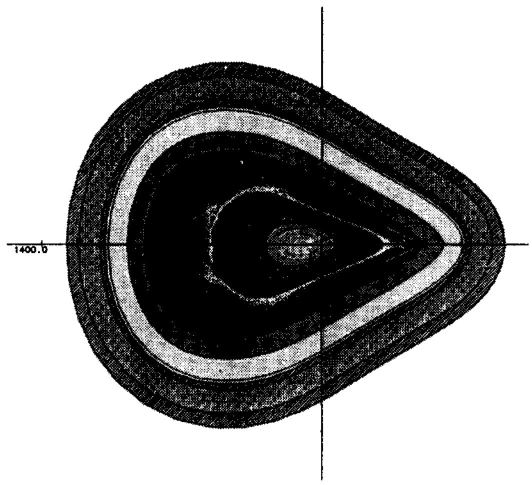

Fig. 2 Cross section of plasma and coils at $<\beta>=5\%$, $\varphi=36°$. Width of blanket and shield is 1.2 m at all locations around the torus.

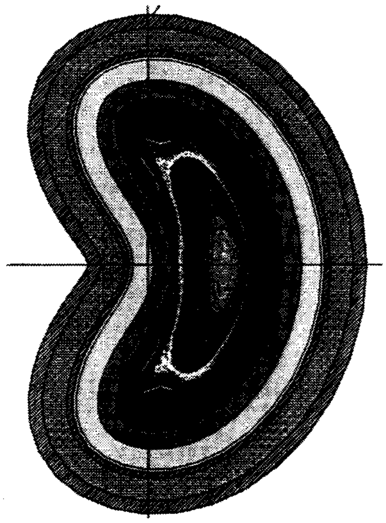

Fig. 3 Cross section of plasma and coils at $<\beta>=5\%$, $\varphi=0°$.

a relatively modest effect and actually reduces the effective helical ripple to 2% and less by means of improved drift optimization. The second is critical for the confinement of highly energetic α-particles but of only minor importance for bulk plasma transport.

Confinement of trapped α-particles is a critical issue in HSR, however, finite plasma pressure produces a true minimum-B-configuration in which the majority of reflected α-particles are confined for at least one slowing-down time [5]. Nevertheless, modular-coil ripple leads to a small fraction of "very prompt" losses (with confinement times less than 10^{-3} sec), potentially resulting in "hot spots" on the first wall of the reactor. To estimate the severity of the problem, the α-particle birth profile is combined with the fraction of phase space in which the birth takes place in a modular ripple. For the $<\beta>=5\%$ case, the total heat load on the first wall due to very prompt losses is estimated to be ≤ 2.2 MW.

4. Ignition Conditions

The ignition phase of the Helias reactor has been computed using the 1-D time-dependent ASTRA-code [6]. The transport model uses the neoclassical model including the non-diagonal transport coefficients and the anomalous thermal conduction corresponding to ASDEX-L-mode scaling. The radial electric field results self-consistently from the ambipolar condition. In the envisaged parameter regime (T=14 keV, $n(0)=3\times10^{20}$ m^{-3}) the ion root determines the electric field. Fuelling of particles is provided by D-T-pellet injection. The results of the computations show that ignition can be achieved within 10 seconds using a net heating power of 70–80 MW. Density and temperature profiles are shown in Fig. 4. Typical confinement times for steady-state operation are 1.6–1.8 s which coincides very well with the predictions of Lackner-Gottardi scaling. A critical parameter is the fraction of cold α-particles which must not surpass 5–6%. These computations assume that the particle transport is also anomalous and the diffusion coefficient is 1/5 of the anomalous thermal conductivity. If one assumes reduced anomalous particle diffusion the neoclassical particle transport leads to hollow density profiles.

Another approach to ignition is the extrapolation on the basis of empirical scaling laws [7] which are deduced from the international stellarator data base. On the basis of the International Stellarator Scaling, which averages over all stellarator systems, ignition cannot be achieved; as with the LHD scaling an improvement factor would be needed. However, Lackner-Gottardi scaling and the W7 scaling, which systematically lies above the ISS scaling, describe the data in Wendelstein 7-A and Wendelstein 7-AS. They predict ignition in HSR without any improvement factor.

The wall loading by 14 MeV neutrons has been computed taking into account the geometry of the finite-β plasma. Consistent with the data in Table 2 the peak neutron wall load is 1.6 MWm^{-2} and the average value 0.8 MWm^{-2}. In the region of the divertor plates (see Fig. 3) irradiation by fast neutrons is rather weak at about 0.6 MWm^{-2}.

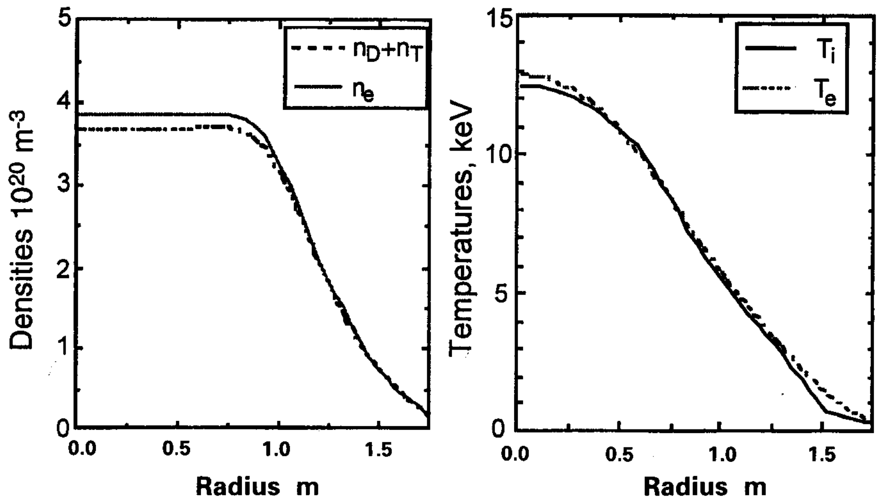

Fig. 4 Density profile (left) and temperature profiles (right) in HSR. Result of ASTRA-code.

Table 2 Plasma parameters in a Helias reactor

Major radius	22	[m]
Average plasma radius	1.8	[m]
Field on axis	4.75	[T]
Temperature T(0)	14	[keV]
Av. temperature	4.9	[keV]
Electron density n(0)	3.15	$10^{20}m^{-3}$
Max. beta	15.6	[%]
Average beta	4.6	[%]
Alpha power	608	[MW]
Fusion power	3040	[MW]
Confinement time τ_E	1.8	[s]
Fraction of α-particles	5	[%]

First results of finite-β-equilibria computations in a Helias reactor have been obtained. It has been verified that the finite Shafranov shift at $<\beta>=5\%$ is acceptable and that the emission of 14 MeV neutrons is distributed equally to the inboard and outboard sides of the torus. Because of the large area of first wall the average neutron power is rather low and below 1 MW/ m^2. Compared to previous concepts the magnetic field has been reduced slightly to 4.75 T on axis to accomodate the requirements of NbTi superconductor. The maximum magnetic field on the coils is now 10 T. Ignition in the Helias reactor can be achieved on the basis of empirical scaling laws from Wendelstein 7-A and Wendelstein 7-AS experiments; assumptions about improvement factors or isotope factors are not needed. The modular ripple of the coil system may lead to prompt losses of highly energetic α-particles however with 10 coils per period these can be kept below a critical level.

In conclusion, Helias reactor studies made to date have confirmed the viability of the advanced stellarator reactor concept.

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