Physics and Engineering Studies of a Helias Reactor

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Introduction

Helias (Helical Advanced Stellarator) configurations have been developed at the IPP Garching in a long phase of analytical and numerical studies to improve the reactor prospects of a classical stellarator. The current Helias reactor is an extrapolation of the W 7-X configuration to reactor dimensions. The basic physical features of a Helias configuration are: its capability to confine an MHD-stable plasma up to $\langle\beta\rangle=5\%$, the low neoclassical losses which are not prohibitive to ignition and the good confinement properties of highly energetic alpha-particles. The 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.

Coil system

The coil system of the Helias reactor consists of 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 in 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.

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 [2]. An optimized design of the intercoil support system is in progress.

Table 1: Parameters of the HSR coil system

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

Finite-beta-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 Fig. 1 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 irridiation. 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. 1 by Monte-Carlo calculations of particle orbits, divertor target plates collect the outstreaming plasma. The finite beta-plasma at $<\beta> = 5\%$ is stable according to both Mercier and resistive interchange criteria.

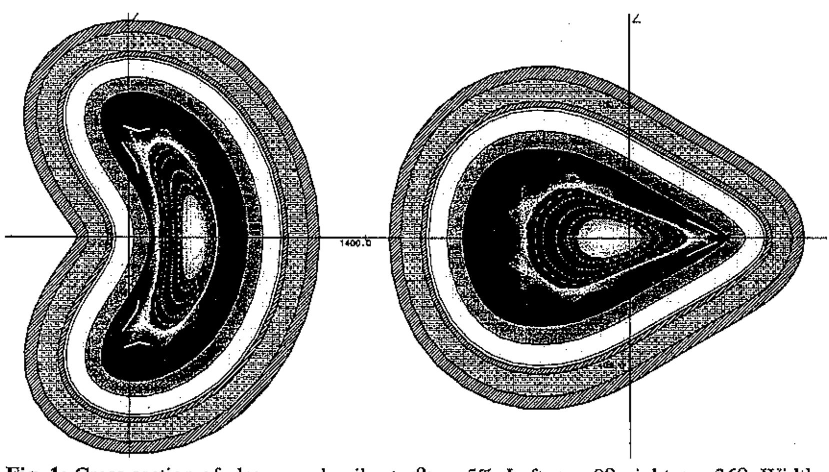

Fig. 1: Cross section of plasma and coils at $<\beta> = 5\%$. Left: $\varphi = 0^{\circ}$, right $\varphi = 36^{\circ}$. Width of blanket and shield is 1.2 m at all locations around the torus.

Neoclassical transport

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/ν-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-suface-averaged value of B. The first is 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.

Alpha-particle studies

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.

Ignition scenarios

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, $n(0) = 3 \times 10^{20}$ 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. Typical confinement times of 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 alpha-particles which must not surpass 5 - 6%.

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 the basis of ISS-scaling (International Stellarator Scaling which averages over all stellarator systems) ignition cannot be achieved; as with the LHD-scaling an improvement factor is needed. However, Lackner-Gottardi scaling and the W7-AS-scaling, which describe the data in Wendelstein 7-A and Wendelstein 7-AS, predict ignition without any improvement factor.

Table 2: Plasma parameters in a Helias reactor

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

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. 1) radiation by fast neutrons is rather weak at about 0.6 MWm^{-2}.

Conlusions

First results of finite-β-equilibria computations in a Helias reactor have verified that the Shafranov shift at $<\beta>$ =5% is acceptable and that neutron emission is distributed equally to the inboard and outboard sides. The magnetic field has been reduced slightly compared to previous concepts to accomodate the requirements of NbTi-superconductor. Ignition in the Helias reactor can be achieved on the basis of empirical scaling laws from present-day stellarator experiments; assumptions about improvement factors are not needed. In conclusion, Helias reactor studies made to date have confirmed the viability of the advanced stellarator reactor concept.

References :

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