The Helias Reactor Concept: Comparative Analysis of Different Field Period Configurations.

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1. Different options of the Helias configurations

The Helias reactor (HSR) is one of the favourite candidate for a steady state fusion power reactor. A straightforward extrapolation of the W7-X experiment towards a reactor leads to a 5-field period magnetic configuration, with the same optimised properties as in W7-X. These include reduced Pfirsch-Schlueter currents and the subsequencent reduction of the Shafranov shift. The dimensions of this type Helias reactor, HSR5/22, are determined by the need to accommodate a blanket and a shield between coils and plasma, to have a sufficient confinement time to ensure ignition and a tolerable magnetic field value to allow for NbTi-superconducting coils. Thermal fusion power should be about 3GW. The main data for HSR5/22 consistent with these requirements are: major radius 22 m, average plasma radius 1.8 m, magnetic field on axis 5 T, maximum field on coils 10 T. Islands at the plasma edge (m/n=5/5) can be utilized for divertor action. In order to reduce the size of the reactor, another option, HSR4/18, (major radius 18 m, plasma radius 2.0 m, B = 5 T), has been investigated [1]. The modular coil system comprises 40 coils, which are constructed using NbTi-superconducting cables. Efforts have been made to reduce the maximum magnetic field in the coils to 10.3 T by shaping the winding pack trapezoidally. For this reason the winding pack consists of 8 double pancakes, which are wound on a mould and then welded together. Stability limit and energy confinement times are nearly the same as in HSR5/22 and the same fusion power is expected in both configurations. Since self-sustained burn depends on the balance between alpha-particle heating and energy transport, current scaling laws of energy confinement have been tested with respect to their compatibility to ignition conditions. The required confinement time is in the range of 2.5-3s; three of the empirical scaling laws - Lackner-Gottardi scaling, W7-scaling and NLHD2-scaling - predict confinement times, which are larger than the required ones. There is no need to invoke any improvement factors or H-mode confinement in order to meet the ignition conditions. The start-up scenario has been studied using the empirical scaling laws of confinement; the net heating power to reach ignition is on the order of 50 MW. Self-sustained burn can be reached in the following parameter regime: Temperature T(0) = 11 keV, line-averaged density = $2.126x10^{20}$ [m^{-3}], averaged beta 3.6 %, fusion power 1600 MW. The design point has rather high density and low temperature in comparison to a tokamak experiment. The choice of the high-density regime is justified by recent results in Wendelstein 7-AS, where line-averaged densities of more than $3x10^{20}$ [m^{-3}] could be achieved. The Helias reactor is expected to operate at high density (central electron density of $3x10^{20}$ m^{-3}) and moderate temperature (central temperatures less than 15 keV). Under these conditions, neoclassical theory predicts that only the so-called 'ion-root' solution for the radial electric field exists, thus requiring strong optimisation of the magnetic field spectrum to minimize losses in the stellarator-specific $1/\nu$-regime. HSR4/18 is excellent in this regard, having an effective helical ripple considerably less than one per cent over the entire plasma cross-section. At this level, $1/\nu$-losses provide no threat to ignition.

The divertor concept in the Helias reactor follows the same concept which has been developed for Wendelstein 7-AS and Wendelstein 7-X. For an island divertor with the 5-fold periodicity of the machine the desired structure 5/5 ensures clear island structure. In 4-period case the structure of the magnetic field outside the last closed surface is stochastic, however there exists a separatrix region of the 4/4 islands, where a strong radial transport of the outflowing plasma arises. Heat load on the target plates is a critical issue; to keep the thermal load below the technical limits of 5 – 10 MW/m^2, up to 90% of the alpha-particle power must be radiated. This requirement remains one of the strict constrain, although similar to the tokamak-reactor. In 3-period case the stochastic region outside the last magnetic surface is impressed by the remnants of the 3/4 islands and the plasma flows along the certain channels towards the plates.

The high accuracy in manufacturing and assembling of the magnetic coils is required due to the high sensitivity of the Hellas magnetic configurations to resonance field errors. Field errors arise if the modules are not identical or are not properly positioned. This shows the experience with W7-X construction. The most important magnetic errors are the ones that resonate with a rational surface, ι=1. In standard operations of W7-X and its reactor prototypes this surface will be the only low order rational due to the smallness of the shear. In case of 3 period reactor configurations the sensitivity to the positioning error will probably not so large, while $\iota \neq 1$ at the edge.

To reduce the aspect ratio further, a configuration of the Helias type with 3 periods, HSR 3/15, was been recently investigated. This device has a major radius of 15m, a minor radius of 2.5m and an aspect ratio of 6. HSR3/18 providing at least 3 GW of fusion power and the second option is the ignition experiment HSR 3/18/i aiming at a minimum of fusion power and the demonstration of self-sustaining burn. With 10 coils per period the total number of modular coils is 30. The stochastic region outside the last magnetic surface is dictated by the remnants of the 3/4 islands and the plasma flows along the distinct channels towards the plates. Although iota per period is in the same range as in HSR 4/18 the total value is significant smaller and results in a higher ratio of the Pfirsch-Schlüter currents to diamagnetic currents. The neoclassical transport characterised by the effective ripple coefficient ε_{eff} is very small and amounts to about 0.65% at half radius. The energy loss of fast α-particles is calculated to be about 6%. The main problem occurs due to the high value of the magnetic field at the coils; further optimisation is required. The data for different options of the Helias reactor are listed in Table 1. Here an ignition experiment is also considered (HSR4/18i, HSR 5/15i), where a breeding blanket is not required and were the distance between plasma and coils is smaller than in a power reactor .

	HSR5/22	HSR4/18i	HSR 3/15i
Major radius [m]	22	18	15
Av. minor radius [m]	1.8	2.1	2.5
Plasma volume [m3]	1410	1560	1600
Av. field on axis [T]	4.75	4.4	4.4
Max. field on coils [T]	10	8.5	8.3
Number of coils	50	40	30
Magnetic energy [GJ]	100	76	72

Table I. Main parameters of HSR5/22, HSR4/18i and HSR3/15i configurations.

Further optimisation of HSR3/15 configuration will include the minimization of the bootstrap current and improvement of the alpha particles confinement. The engineering tasks mainly concern the magnetic coil design and support structure. The W7-X construction experience in assembly of the magnet system will be particularly taken into account.

2. Equilibrium and stability analysis.

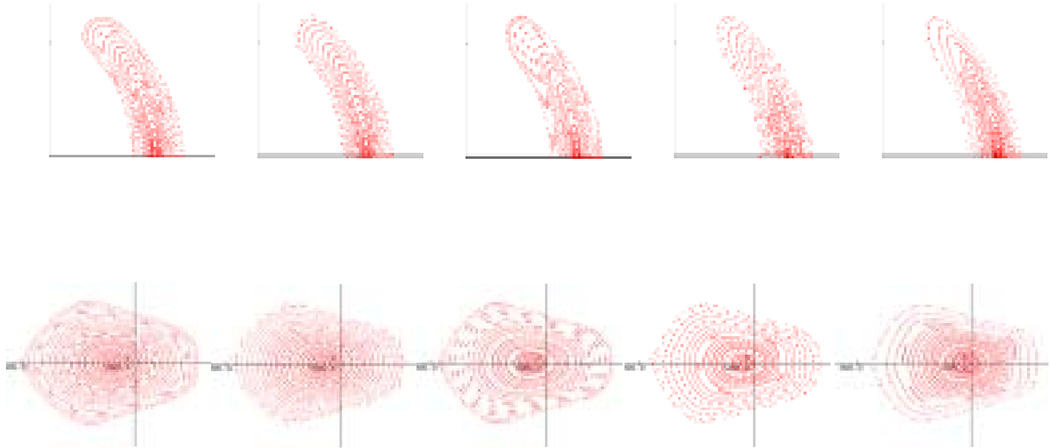
Here we will discusse equilibrium and stability properties with respect to the Mercier and resistive interchange criteria have been considered for HSR3 and HSR4 devices for different pressure profiles and several β values. Simulation has shown that the Shafranov shift is sufficiently small for both, 3- and 4-period, configurations. The maximum β limit is around 4%. In figures 1 and 2 the simulated rotational transform value and magnetic well profiles versus magnetic surface label are shown for different values of β. At β=3% for the peaked pressure profile 3/5-resonances appear inside the LCMS. With the increase of the plasma pressure the rotational transform at the centre drops significantly and the range of possible rotational transform values becomes larger. These features are more pronounced for the peaked pressure profile than for the parabolic one. The magnetic well deepens with the increase of β from 4 to 12,5% at the boundary for the peaked pressure profile and from 3,2 to

10% for the parabolic one. Figure 3 demonstrates that the Shafranov shift is rather small for HSR3/15 configuration. These are Poincaré plots at the bean-shaped and triangular cross-sections obtained for the peaked pressure profile. For the parabolic pressure profil the numbers for the. Shafranov shift are 20% smaller. Stability analysis has shown that Mercier and resistive -interchange criteria for both pressure profiles are satisfied up to β=3%.

Fig.4 *HSR3,* Poincaré plots

φ=0°

φ=60°



β=1 % **β=2 %** **β=3 %** **β=4%** **β=5%**

Δ_1=0.05a Δ_2=0.1a Δ_3=0.15a Δ_4=0.21a Δ_5=0.26a

Simulation for HSR4, provided for the indicated pressure profiles, also revealed a drop of the β value at the magnetic axis with the increase of the plasma pressure (fig.4), but the range of possible values is not as broad as in the HSR3 case. The magnetic well changes from 2,8 to 9,2% for peaked and from 2,2 to 7,5 % for the parabolic pressure profile. A small Shafranov shift was found for β values from 1 till 5% for both parabolic and peaked pressure profiles. It was found that the Shafranov shift is sufficiently small for HSR3 and HSR4 configurations. The range of rotational transform values increases for $\beta = 1\%$ higher beta, so

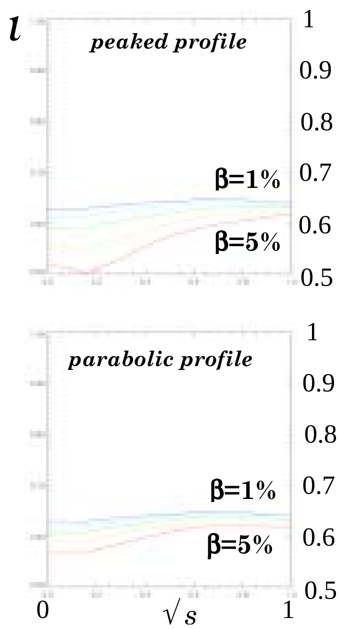


Fig.2 HSR3,
Rot. transform

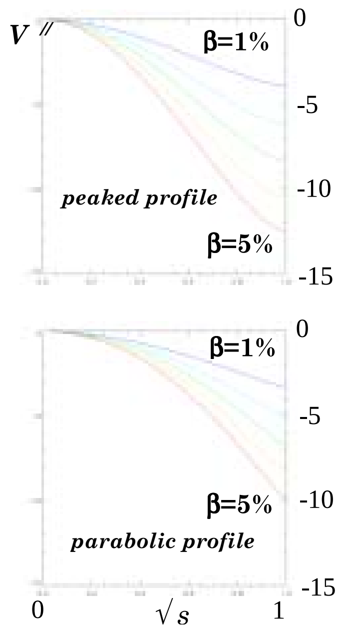


Fig.3 HSR3,
Magnetic well

that low-order resonances appear inside the LCMS. To investigate an equilibrium with islands, other numerical tools are required. For HSR3, Mercier and resistive-interchange stability criteria for the chosen pressure profiles are satisfied for β=3% and the maximum β is around 4%. HSR3 needs further optimisation with respect to the bootstrap current, α-particle confinement and rotational transform profile. Simulation for HSR4, provided for the different pressure profiles, also reveales a drop of the β value at the magnetic axis with the increase of the plasma pressure (see fig.5), but the range of possible values is not as broad as in the HSR3 case. The magnetic well, shown in fig. 6, changes from 2,8 to 9,2% for peaked and from 2,2 to 7,5 % for the parabolic pressure profile. A small Shafranov shift was found for β values from 1 till 5% for both parabolic and peaked pressure profiles.

3. Transport properties.

Neoclassical transport levels have been found to be very small in all cases considered (effective helical ripples of less than 1% at all radii). The confinement of fusion α particles is also satisfactory from the point of view of the power balance, although further optimization is desirable. The bootstrap current is significantly reduced compared to the equivalent axisymmetric device, however it is not yet clear whether the reduction is sufficient to insure a divertor compatible edge topology, especially for the 3-period case. The α particles confinement is a major concern. Calculation show that there is no direct losses but the stochastic diffusion leads to a lost energy fraction of about 2.5% in HSR4/18. This is tolerable with respect to the energy balance of the reactor; however, the wall loading by highly energetic α particles may be a matter of concern. Energetic α particles can excite Alfven instabilities, which may cause enhanced losses of these particles and thus reduce the heating effciency. Therefore the structure of the Alfven continuum in HSR4/18 was studied. It was found that the largest losses can result from destabilizationof mirror induced Alfven eigenmodes (MAE) and helicity induced Alfven eigenmodes. It was shown that the destabilization of certain Alfven eigenmodes affects

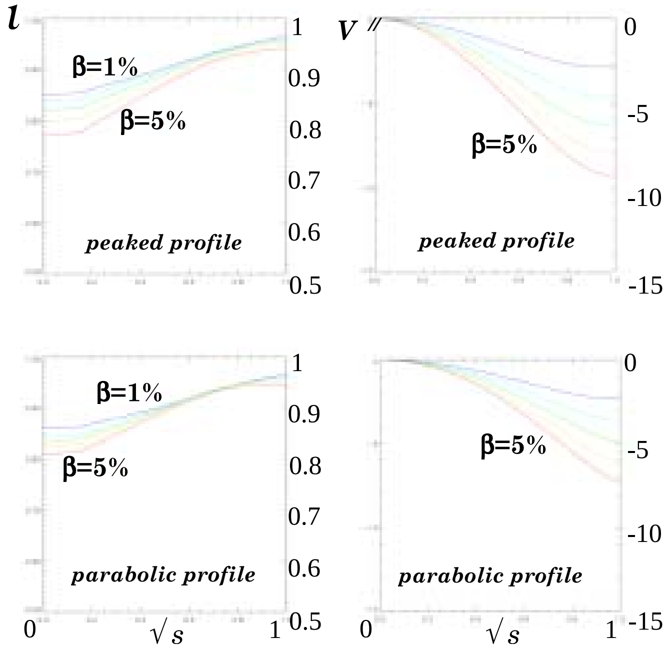


Fig.5 HSR4, Rot. transform

Fig.6 HSR4, Magnetic well

transport of the partly slowed down α particles, thus promoting the removal of helium ash from the reactor.

4. Conclusions.

A straightforward extrapolation of the W7-X towards a power reactor leads to a 5-field period magnetic configuration, HSR5/22. Islands at the plasma edge (m/n=5/5) can be utilized for divertor action. Thermal fusion power should be about 3GW. This configuration, however, is not cost optimised machine.

The more compact 4-period configuration, HSR4/18, may lead to a 20% cost reduction for the reactor core, because the reduction of field periods lowers the aspect ratio and reduces the size of the reactor. At the same time the plasma volume even increases ensuring better confinement time. The magnetic field of HSR4/18 has been optimized with respect to plasma equilibrium and neoclassical transport, which is extremely low. Fast α particle losses could be reduced to 2.5% of the heating power. Empirical scaling laws predict ignition in HSR4/18. However, further theoretical studies are needed to clarify the confinement at the beta limit, which is expected to be around 4.3%. The average neutron wall load will increase to $1.2 MW/m^2$ at a fusion power of 3GW. Since in HSR4/18 the maximum magnetic field is 10 T, this is still in the range of NbTi technology at 1.8 K.

The most compact Helias type 3 period configuration, HSR 3/15, shows the stochastic region outside the last magnetic surface which is dictated by the remnants of the 3/4 islands and the plasma flows along the distinct channels towards the plates. Although iota per period is in the same range as in HSR 4/18 the total value is significant smaller and results in a higher ratio of the Pfirsch-Schlüter currents to diamagnetic currents. The neoclassical transport is very small. The energy loss of fast α-particles is calculated to be about 6%. The Shafranov shift is also sufficiently small for HSR3 configuration. The range of rotational transform values increases for higher beta, so that low-order resonances appear inside the LCMS. For HSR3, Mercier and resistive-interchange stability criteria for the chosen pressure profiles are satisfied for β=3% and the maximum β is around 4%. The main problem here occurs due to the high value of the magnetic field at the coils. Further optimisation of HSR3/15 configuration will include the minimization of the bootstrap current and improvement of the α-particles confinement.

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