ENERGY CONFINEMENT IN W 7-AS AND EXTRAPOLATION TO A HELIAS REACTOR

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The energy confinement time in Wendelstein 7-AS shows a strong dependence on the rotational transform, which makes it difficult to establish a universal scaling laws for energy confinement. Under optimum conditions the scaling of confinement follows Lackner-Gottardi scaling with an improvement factor of 1.2. This holds in the very neighbourhood of low order rational surfaces ($\iota = 0.34$ and $\iota = 0.52$). The scaling law together with other ones published in the literature are applied to the Helias reactor HSR4/18 ($R = 18$ m, $a = 2$ m, $B = 5$ T) showing that the conditions of self-sustained bum can be satisfied. In a second part the one-dimensional heat conduction equation is solved for the temperature profile taking into account alpha-particle heating and bremsstrahlung losses. The non-linearity of the equation leads to multiple solutions, the scaling of the stable solution is studied in detail.

1 Introduction

Energy confinement in Wendelstein 7-AS is dominated by anomalous transport, and in particular in the boundary region the losses are considerably larger than predicted by neoclassical theory. Empirical scaling laws for the energy confinement have been established and these provide the only basis for extrapolating plasma performance to future devices as Wendelstein 7-X and the Helias reactor. In a previous investigation [1] several scaling laws of energy confinement have been derived for stellarators. Experiments in LHD, which in contrast to Wendelstein 7-AS is a high shear configuration, have extended the confinement times in stellarators into the 100 - 300 ms regime, a scaling law of τ_E has been reported at the IAEA-conference in Sorrento [2]. The general form of scaling laws for τ_E is given in the following equation

$$\tau_E = C R^{a1} a^{a2} B^{a3} n^{a4} \iota^{a5} P^{a6} \text{ [s] } (\mathrm{m}, \mathrm{T}, 10^{20}\,\mathrm{m}^{-3}, \mathrm{MW}) \tag{1}$$

(C=const., R=major radius, a=av. plasma radius, B=magnetic field, n=line averaged density, P=external heating power). The coefficients are listed in Table 1.

The former version of the Lackner-Gottardi-scaling (LGS) has a smaller coefficient than given in the list, the coefficient of LGS is 0.175. LGS1 in Table 1 is essentially the Lackner-Gottardi scaling except for the coefficient C=0.21, which has been introduced to give a better fit to the ECRH-data. NLHD1 is the scaling based on experimental data from LHD and CHS. The ISS 95-scaling (International Stellarator Scaling) uses all available data from stellarator and torsatron experiments and derives one scaling law from these data. Taking into account only data from Wendelstein 7-A and Wendelstein 7-AS yields the W 7-scaling. Since major radius is the same in Wendelstein 7-A and Wendelstein 7-AS the dependence on major radius is assumed to be the same as in the ISS-scaling.

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		LHD	ISS 95	W7	LGS1	LGS	NLHD1
C		0.166	0.255	0.36	0.21	0.175	0.269
a1	R [m]	0.75	0.65	0.74	1.0	1.0	0.64
a2	a [m]	2.1	2.2	2.2	2.0	2.0	2.59
a3	B [T]	0.84	0.83	0.73	0.8	0.8	1.01
a5	ι (2/3)	0	0.4	0.43	0.4	0.4	0
a4	n [10^{20} m^{-3}]	0.69	0.51	0.5	0.6	0.6	0.59
a6	P [MW]	-0.58	-0.59	-0.54	-0.6	-0.6	-0.58

Table 1: Coefficients of empirical scaling laws

2 Confinement in Wendelstein 7-AS

In the low-shear stellarator Wendelstein 7-AS (major radius 2 m, av. plasma radius 0.18 m, magnetic field on axis 2.5 T, rotational transform $\iota = 0.2 - 0.65$) energy confinement depends strongly on the choice of the ι-regime. Highest confinement times could be achieved in the region around $\iota = 0.34$, while in the "H-mode-regime" at $\iota = 0.52$ the confinement time is smaller, which is mainly attributed to the smaller plasma radius. ECR-heated discharges in Wendelstein 7-AS were mainly carried through at B=2.5 T and a frequency of 140 GHz. Maximum heating power was 1.2 MW. The energy confinement time in ECR-heated discharges reaches 35 ms under optimum conditions, the distribution is depicted in the next figure.

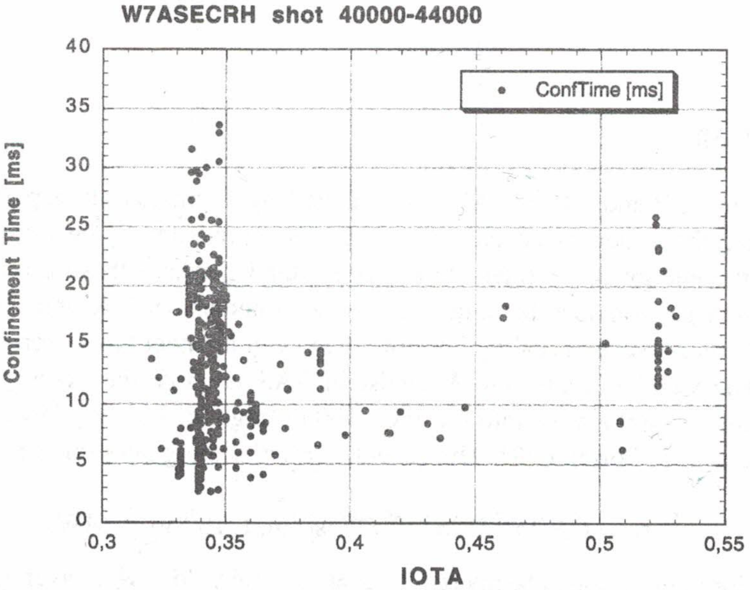

Figure 1: W7AS/ECRH-discharge. Confinement time vs rotational transform. (Courtesy of Dr. R. Brakel)

For reasons unknown so far confinement is poor in the region between $\iota = 0.35 - 0.5$. However, as already found in Wendelstein 7-A, optimum confinement has been achieved in the very neighbourhood of low order rational surfaces, in particular around $\iota = 1/3$ and $\iota = 1/2$. Since the standard configuration of Wendelstein 7-X has a ι-profile close to $\iota = 1.0$, similar conditions as in Wendelstein 7-AS can be expected and for this reason it is justified to extrapolate the optimum confinement data towards Wendelstein 7-X and a Helias reactor.

The data in Fig. 1 are compared with the scaling laws. LG-scaling in its former version (C = 0.175) does not fit to these data; raising the factor C to $C = 0.21$ gives a better fit to the experimental data. The lower curve is obtained by the LHD1-scaling and it shows that this curve does not fit to the experimental data of W7-AS. Evaluating the scaling laws in the density regime of Fig. 1 shows that the LGS1-scaling and the W7-scaling, proposed by Stroth et al. yield nearly the same confinement times. Taking into account that the modified LG-scaling fits into the dimensional constraints, this approximation to τ_E has a better physics basis than the other empirical scaling laws; except for the NLHD1-scaling law, which also satisfies the dimensional constraints.

The next figure includes all ECRH-data at $\iota = 0.34$ and $\iota = 0.52$ and compares it with the LGS1-scaling.

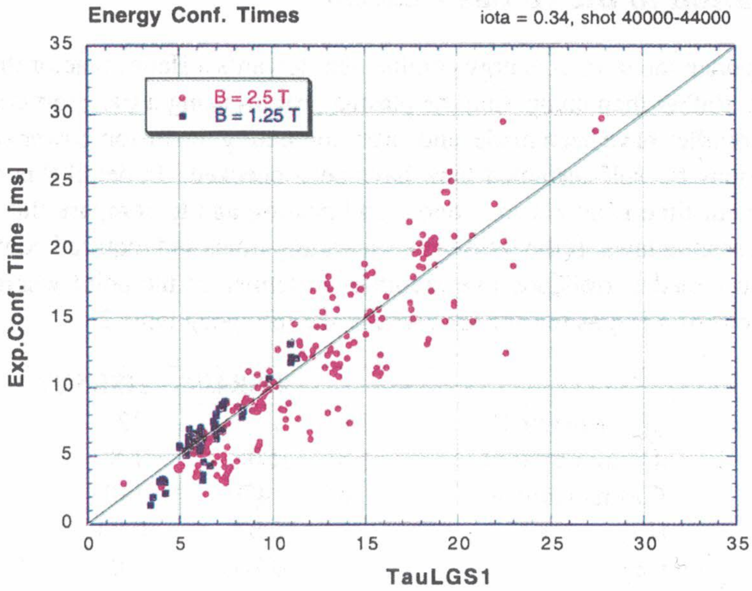

Figure 2: W7AS/ECRH-discharge. Confinement time vs LGS1-time. Magnetic field 2.5 T, 1.25 T, $\iota = 0.34$ and $\iota = 0.52$

A large amount of NBI-heated discharges in Wendelstein 7-AS has been evaluated in a paper by M. Kick et al. [3]. In NBI-heated discharges higher densities can be achieved, which allows one to establish scaling laws in those regimes, which are not accessible by ECRH. NBI, (P 3.5 MW, 50 keV) give access to net current free plasmas in a wide range: electron densities, $n(0) \leq 3 * 10^{20}$ m^{-3}. Optimum (neoclassical) confinement discharges with energy confinement times up to 50 ms has been reached, which is of more than 2.5 times larger than predicted by the International Stellarator Scaling, ISS95. The maximum ion temperature is 1.5 keV in NBI-discharges and maximum beta around $<\beta>= 1.8\%$.

The density limit in Wendelstein 7-AS can be understood on the basis of power balance between heating power and losses by impurity radiation. Since the power balance also depends on transport processes the maximum achievable density is a function of the magnetic field strength. The first density limit in stellarators was discussed by Sudo et al.[4]. Recently Giannone et al.[5] have analysed data from Wendelstein 7-AS resulting in an empirical density limit given by

$$n_c = 1.46 \left(\frac{P}{V_p}\right)^{0.48} B^{0.54}\ [10^{20}\,\mathrm{m}^{-3}]\ (\mathrm{m}^3, \mathrm{MW}, \mathrm{T}) \qquad (2)$$

V_p is the plasma volume in [m^3]. The extrapolation for a Helias reactor is $n_c = 2.2 * 10^{20}$ m^{-3}. However, it should be noticed that the coefficient depends on the impurity content and the exponent may depend on the profiles of the radiating impurity. A theoretical analysis [6] has shown that, in general, the critical density is a function of heating power, plasma volume and magnetic field. The exponents are determined by the profile functions and thus a general scaling law valid for all devices cannot be expected. A large amount of NBI-heated discharges in Wendelstein 7-AS has been evaluated in a paper by M. Kick et al.

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3 Extrapolation to the Helias Reactor

On order to extrapolate the laws of energy confinement towards a Helias reactor the following procedure has been adopted: Rather than computing the plasma profiles using a transport code, some assumptions about the plasma profiles have been made, and, after computing the fusion power and the internal heating power, the conditions for self-sustained burn have been checked. In detail this means to compute the required confinement time from plasma energy and heating and to compare this with the confinement time predicted by scaling laws. If the ratio between scaling times and required confinement time is larger than one, a self-sustained burn is possible. Ignition is defined as the point where this ratio is equal to one. The dimensions of a Helias reactor are given in the following table 2.

		HSR4/18	HSR5/22
Major radius R	[m]	18	22
Av. minor radius a	[m]	2.0	1.8
Plasma volume	[m^3]	1420	1407
$\iota(0)$		0.83	0.84
$\iota(a)$		0.96	1.0
Magnetic field on axis	[T]	5.0	5.0
Magnetic field on coils	[T]	10.0	10.3
Number of coils		40	50
Magnetic energy	[GJ]	95	100

Table 2: Main parameters of HSR4/18 and HSR5/22

The plasma profiles are modelled as functions of the average plasma radius, which serves as a label of the magnetic surface. All plasma parameters are assumed to be constant on magnetic surfaces. The average plasma radius can be defined uniquely be the following procedure: Every magnetic surface encloses a volume V and together with the major radius R one defines a plasma radius r by $V = 2\pi^2 R r^2$. a is the radius of the last magnetic surface. The shape of the density and temperature profiles is descibed by

$$T(r) = \frac{T(0)}{1+\left(\frac{r}{r_T}\right)^{2\alpha_T}} \quad ; \quad n(r) = \frac{n(0)}{1+\left(\frac{r}{r_n}\right)^{2\alpha_n}} \tag{3}$$

Several options of these profile parameters have been investigated, the standard case has the following data: $T(0) = 15$ keV, $r_T = 0.5$, $\alpha_T = 2$, $N(0)_D = 1.3 * 10^{20}$ m^{-3}, $r_n = 0.7$, $\alpha_n = 5$. The plasma parameters computed for these profiles are shown in the following table The line averaged density is higher than the Sudo-limit, however, it is smaller than the density limit derived from Wendelstein 7-AS data [5]. The fraction of the Helium atoms is 3.5%, which leads to a Z_{eff} of 1.12. The averaged beta is 3.6%, which is close to but still below the stability limit of ideal MHD. The fusion output computed with these profiles is 3095 MW. A detailed list is shown in the Table 3. Cyclotron radiation losses are rather small, which is the result of the low temperature. It is too low to have an effect on the power balance.

For self-sustained burn an internal heating power of 522 MW is available. This heating power is the alpha-particle heating power reduced by 2% loss, which is due to lost orbits of highly energetic particles. Furthermore, 84 MW bremsstrahlung and 1.7 MW cyclotron radiation has been subtracted from the

Line Average Density	$1.986*10^{20}$	$[m^{-3}]$
Sudo-Limit	$1.505*10^{20}$	$[m^{-3}]$
WAS-Limit	$2.161*10^{20}$	$[m^{-3}]$
Electron Density $n(0)$	$2.840*10^{20}$	$[m^{-3}]$
Temperature $T(0)$	15.0	[keV]
Deuterium Density $n_D(0)$	$1.300*10^{20}$	$[m^{-3}]$
Tritium Density $n_T(0)$	$1.300*10^{20}$	$[m^{-3}]$
Alpha Fraction na/ne	3.521	[%]
Beta(0)	13.42	[%]
Average Beta	3.63	[%]
Plasma Energy	770	[MJ]
Average Z_{eff}	1.123	[ ]
Bremsstrahlung	84.12	[MW]
Fusion Power	$3.095*10^{3}$	[MW]
Internal Heating Power	$5.222*10^{2}$	[MW]
Energy Conf. Time	1.475	[s]
Alpha Conf. Time	6.68	[s]
En. Conf.Time (LHD)	1.37	[s]
En. Conf.Time (LGS1)	1.95	[s]
En. Conf.Time (W7)	2.23	[s]
En. Conf.Time (ISS)	1.05	[s]
En. Conf.Time (NLHD)	2.02	[s]

Table 3: Plasma data of the standard model

alpha-heating power. The total plasma energy is 770 MJ, which implies an energy confinement of 1.47 s. This is the required confinement time, any confinement time derived from scaling laws must be larger than this time otherwise the condition for self-sustained burn cannot be satisfied.

The required energy confinement time is 1.47 s. As shown in Table 3 this number can reached by empirical confinement times: LGS1-scaling, W7-scaling and NLHD1-scaling. There are no assumption about improvement factor, also an isotope effect has not been assumed. From current stellarator experiments there is no indications that an isotope improvement factor exists. The alpha-particle confinement time of 6.7 s is the result of the alpha production rate and the assumed alpha fraction of 3.5%. Doubling the alpha fraction would lead to 13.4 s confinement time and an increase of $<\beta>$ to 3.8 %.

The ignition margin is defined as the ratio between scaling time and required confinement time, if this number is larger than 1, ignition and self-sustained burn is possible. To compute this ratio the temperature has been varied while keeping the density and the profile functions fixed. The curves are computed using the W7-scaling, the NLHD1-scaling and the LG-scaling. Self-sustained burn is already possible at $T = 10$ keV.

Density profiles depend on refuelling and transport mechanism. Since both effects are uncertain, a broad density profile has been chosen to illustrate how the performance depends on the shape of the profiles. The density in the plasma centre had to be lowered in order to remain below the W7-density limit. This reduction also leads to smaller fusion power and therefore the temperature had to be raised to 17 keV. In both cases the line-averaged density is $<n>= 2*10^{20}$ m^{-3}. This density is in the density regime achieved in Wendelstein 7-AS, here even much higher densities can be reached.

The preceding examples demonstrate how sensitive the fusion power depends on the shape of the density profile. The following figure summarizes the results and shows the fusion power as function of averaged plasma beta. To reach the goal of 3000 MW fusion power the averaged beta must be around 4%, under optimistic conditions with the peaked density profile the averaged beta is 3.6%. This value is compatible with the MHD-stability limit [7], which has been investigated using the CAS3D-code [8].

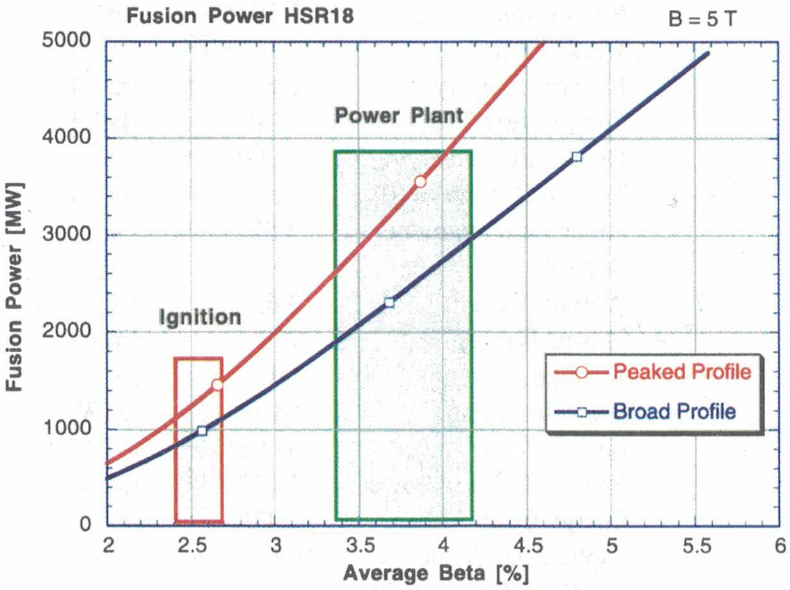

Figure 3: Fusion power vs averaged beta. Upper curve: peaked density profile, lower curve: broad density profile.

4 Conclusions

Energy confinement times in Wendelstein 7-AS confirm the Lackner-Gottardi-scaling as a favourite scaling law to describe the global energy confinement. Under optimum condition in the region around $\iota = 0.34$ (close to $\iota = 1/3$) and $\iota = 0.52$ the confinement is improved by roughly 25% compared to standarg LG-scaling with the factor $C_0 = 0.175$. The constant is increased from $C_0 = 0.175$ to $C_0 = 0.21$. Since in a Helias reactor the rotational transform is close to $\iota = 1$ a similar improvement factor can be expected. Using the empirical scaling laws for modelling a stellarator reactor leads to the issue of how to replace the external heating power, which enters the scaling laws as an external variable. Unlike the situation in an experiment, the heating power in the reactor depends on the reactor parameters, which are the result of transport processes and the heating mechanism. In the present analysis we adopted the standard procedure and replaced the external heating power by the difference of alpha heating power minus the bremsstrahlung loss. Taking the parameters of the Helias reactor HSR4/18 this method verified that some of the empirical scaling laws (LG1-scaling, NLHD1-scaling and W7-scaling) predict confinement times, which are larger than the required ones. Any further improvement factor or H-mode operation need not to be invoked.

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УТРИМАННЯ ЕНЕРГІЇ В W7-AS ТА ЕКСТРАПОЛЯЦІЯ НА ГЕЛІАС-РЕАКТОР

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Час утримання енергії у стелараторі Вендельштайн 7-AS сильно залежить від обертального перетворення, що перешкоджає встановленню універсальних законів подібності для утримання енергії. За оптимальних умов утримання плазми описується формулою Лакнера-Готтарді з фактором покращення 1.2. Це знаходиться дуже близько до раціональних поверхонь найменшого порядку ($\iota = 0.34$ та $\iota = 0.52$). У роботі цей закон подібності разом з іншими опублікованими у літературі застосовувалися при розрахунках Геліаса-реактора HSR4/18 (R = 18 м, a = 2 м, B = 5 Тл), які показали, що задовольняються умови самопідтримання горіння. У другій частині роботи розв'язується одновимірне рівняння теплопровідності з урахуванням нагрівання альфа-частинками та втрат на гальмівне випромінювання. Нелінійність рівнянь приводить до існування кількох розв'язків; детально вивчаються закони подібності стійкого розв'язку.