Perspectives for operation of stellarators as fusion reactors

The distinctive characteristic of stellarator confinement devices is their use of external, non-axisymmetric helical fields rather than externally driven plasma currents to form closed magnetic surfaces and rotational transform (designated by $\iota = 1/q$, where q is the safety factor).

1. Essential results

Since 1970, there have been 30 stellarator experimental devices successful y and operated in seven countries, in sizes from R = 0.12 m to R = 3.9 m, magnetic fields of 0.1 T to 3 T, and heating powers from a few kW to 18 MW. Experiments on these devices and associated theory and analysis have established key findings about the behavior of stellarators.

Density limit

The maximum achievable plasma density in a stellarator is determined not by the onset of a macroscopic MHD instability (like a disruption in a tokamak), but rather by a soft radiative collapse when there is balance between the heating power radiation losses [1]. A fit to a wide range of experimental data gives the relation [2]

$$n_c = 14.6\left(\frac{P}{V_p}\right)^{0.48} B^{0.54} \qquad [10^{19}\ \mathrm{m}^{-3}, \mathrm{MW}, \mathrm{m}^{-3}] \tag{1}$$

where V_p is the plasma volume, P is the input power, and B is the magnetic field. The functional form of this result is remarkably close to that of a simple model [3] which gives $n_c \propto (PB/V)^{0.5}$.

Typically, the density limit for a stellarator is 3-5× larger than for a tokamak of comparable size, magnetic field, and rotational transform.

Beta limit and stability

In experiments to date [4,5], the achievable plasma beta in stellarators has been found to be limited by available heating power and confinement, and not by large scale plasma instabilities or disruption. At high density, some discharges end in soft radiative collapses. The best results so far (from the largest stellarator, LHD) are transient volume-averaged betas of 5.2% and sustained betas of 4.8%, which are roughly encapsulated as

$$\beta < 5\% \tag{2}$$

The global features of the 3-D equilibrium of finite-beta stellarators are broadly similar to what is expected from equilibrium calculations. More detailed reconstructions of experimental equilibria using multiple diagnostic inputs suggest that the outer flux surfaces may be breaking up as beta increases. At present this is the leading candidate for the decrease in energy confinement observed at high beta, and schemes for alleviating this problem by configuration design and/or the use of trim coils to compensate these effects are under investigation.

ELMs are sometimes seen in stellarator plasmas after transitions to the H-mode. However, ELMs appear in configuration "windows" with edge rotational transforms near rational values that are interleaved with windows where ELMs are absent. This behavior could be evidence that "ergodic" magnetic surface in stellarators suppresses ELMs in a way similar to that observed in the DIII-D tokamak.

Fast particle modes (TAE, GAE, etc.) in stellarators have been studied both theoretically and in low density experiments with neutral beam injection [6]. The three-dimensional flux surface geometry introduces new families of modes. However, the impact of fast-particle modes in stellarator reactors can can be reduced by operation at higher densities, which shorten slowing down times, reduce alpha pressure, and lower the energy with which lost alpha particles leave the plasma.

Energy confinement scaling

Database studies of all the readily available data sets from the world's larger stellarators have been used to develop the International Stellarator Scaling ISS04 (an update of the earlier scaling relation ISS95) [7]:

$$\tau_E^{ISS04} / f_{ren} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \bar{n}_e^{0.54} B^{0.84} \iota_{2/3}^{0.41} \qquad [\mathrm{s, m, m, MW}, 10^{19}\ \mathrm{m}^{-3}] \qquad (3)$$

Here $\iota_{2/3}$ is the rotational transform at the two-thirds plasma radius, and f_{ren} is a renormalization factor which correlates with the degree of orbit optimization in the magnetic configuration concerned.

Stellarators built prior to 2000 are referred to as *non-optimized* or *partially-optimized* because the helical ripples in the external stellarator field are such that trapped particles can stray significantly from flux surfaces or even suffer direct orbit loss. This can increase thermal losses at low collisionality, and enhance the loss of fusion-produced alpha particles in an actual reactor. Alteration of the geometric structure of the helical ripple (either by fundamental design or the use of external trim fields) is used to "optimize" the configuration to reduce (often to a very large degree) the ripple-induced losses.

The "new" stellarator configurations developed in recent years have been deliberately optimized by design. The large W7X (R = 5.5 m, operation in 2014) device in Greifswald. Germany is designed to have near-zero bootstrap current, very low ripple, and to have negligible Shafranov shift at betas up to ~ 5%. US optimization studies have used *quasi-symmetry* as their focus. These efforts led to the HSX device, now operating at the University of Wisconsin, which has already demonstrated experimentally some of the confinement benefits of quasi-helical symmetry, and to the NCSX (quasi-axisymmetry, i.e., quasi-toroidal symmetry) and the QPS (quasi-toroidal symmetry), both of which were canceled in 2008.

Stellarator data, configuration optimization, and established reactor design criteria have been used to develop a reference quasi-axisymmetric reactor design, the ARIES-CS (compact stellarator), which is shown in Fig. 1, with its parameters shown in Table 1. Note that the required confinement enhancement is small (10%).

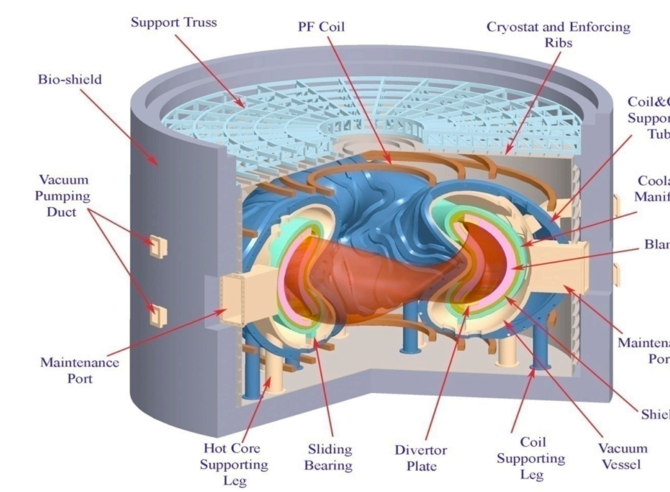

Fig. 1. ARIES-CS reactor

Table 1.ARIES-CS Parameters

NCSX-like (QA):	3 periods		
$\langle R \rangle = 7.75$ m	$\langle a \rangle = 1.72$m	$\langle R \rangle / \langle a \rangle \sim 4.5$	$\langle B \rangle_{axis} = 5.7$ T
$\langle n \rangle = 4.0 \times 10^{20}$ m^{-3}	$\langle T \rangle = 6.6$ keV	$\langle \beta \rangle = 6.4\%$	H(ISS04) = 1.1
P(fusion) = 2.364 GW	P(electric) = 1 GW	Fully ignited ($P_{ext} = 0$)	
$I_{plasma} = 3.5$ MA (*bootstrap, 25% of rotational transform)*			

2. Control of stellarator plasmas

Experience shows that the robust operational stability and soft operation boundaries of stellarators greatly lessen the need for powerful actuators and fast-acting feedback control developed for tokamaks. Feedback is used in some cases for control of gas and power input to achieve constant density and/or stored energy. Stellarator experiments have also used time variation of the magnetic configuration for pre-programmed changes of vertical field or trim coil currents to alter the high beta equilibrium, and to perform deliberate perturbation experiments, but a majority of stellarator experiments have operated with the magnetic figuration fixed for the duration of the discharge.

While it is likely that these overall plasma control techniques will become more sophisticated for a reactor (e.g., approach to ignition and subsequent burn), the greatest evolution in stellarator operational techniques will surely be in the area of control of the heat and particle flux in the divertor during steady-state operation. The longest high power stellarator discharge to date was a one hour, 750 kW rf heated plasma on the superconducting LHD device; the duration was determined by limits imposed by the local electric utility.

Stellarator divertors as presently conceived take advantage of the islated edge structure of the stellarator field to form helically diverted fields lines with long connection lengths. A schematic of the divertor used in the W7AS stellarator is shown in Fig. 2. The divertor plates are twisted, three-dimensional structures oriented so as to baffle the strike locations of the field lines.

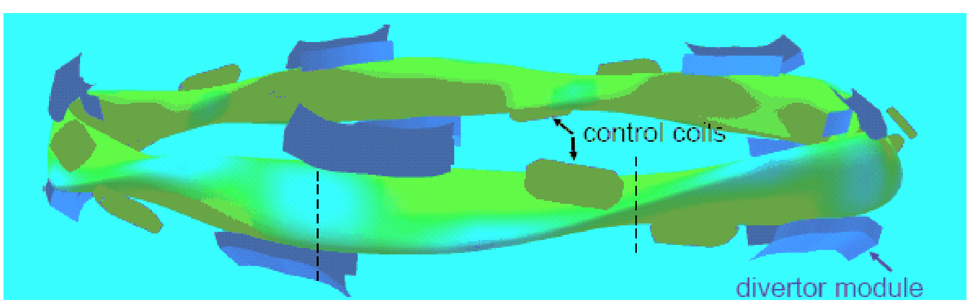

Fig. 2. Layout of the W7AS divertor

As in other magnetic confinement schemes, the peak power fluxes to the divertor in a stellarator reactor can be expected to be large, possibly exceeding 10 MW/ m^{-3}. Operation at the high densities accessible in stellarators will mitigate this somewhat, by reducing the kinetic energies with which particles strike plasma-facing materials. In addition, the island structures of the stellarator offer long connection and lengths and local confinement zones in the islands themselves. These structures can enhance radiation losses from exiting plasma before it strikes exposed surfaces.

References

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