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Quasi-Axisymmetric Stellarator CHS-qa

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Abstract

The physics aspects of CHS-qa, a quasi-axisymmetric helical device, which is being designed as the post-CHS device, are discussed. Its main objective is to improve the transport in helical systems by reducing the parallel viscosity and by applying max. J criterion to its design. The parallel viscosity is much reduced compared with that in CHS and the max. J criterion is fulfilled at the region near the edge in the typical CHS-qa configuration. As an experimental device, a variety of knobs for controlling magnetic field configuration are taken into consideration in the design to study transport-related physics subjects: bifurcation phenomena of radial electric field and max. J criterion. Other physics requirements which CHS-qa should satisfy as POP experiment, such as MHD characteristics, neoclassical transport aspects, are also discussed.

Keywords:

helical system, drift optimization, quasi-axisymmetry, improved transport, low viscosity, maximum J

1. Introduction

As is well recognized, helical systems are free from difficulties inherent of equilibria for which a plasma current is necessary: major disruptivity, recirculating power and elaborate current profile control. Conventional helical systems, in spite of these merits, have an inherent helical ripple, which has been believed to induce a particle loss and an enhanced neoclassical transport in the low collisionality regime. From the point of drift optimization, where the particle drift orbit coincides with the magnetic surface, Palumbo derived the so-called Palumbo condition, i.e. the concept of isodynamicity [1]. There, the diamagnetic current is divergence-free, i.e. there is no Pfirsch-Schlueter current, which leads to no neoclassical transport. The Palumbo condition, which is also equivalent to the statement that the magnetic field strength does not vary perpendicular to the field lines on magnetic surfaces, can unfortunately not be met in practical toroidal devices, then one possible solution according to this guiding principle is to realize quasi-symmetry in helical systems. QHS (quasi helical symmetric system) [2] and QAS (quasi-axisymmetric system) [3,4] concepts follow this principle. QOS (quasi-omnigenous or quasi-isodynamic system) of W7-X [5] relies on a

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generalization of the Palumbo condition, pursuing, in particular., the reduction in Pfirsch-Schlueter and bootstrap currents.

Lower aspect ratio (A_p), which is characteristic of CHS, is satisfied in QAS configurations more easily than in other configurations, although recent QOS design [6] can be of low A_p. Low A_p is practically important for an experimental device because it gives large plasma volume and accessibility to ports. As was shown in CHS experiment [7], helical ripples substantially reduce the toroidal rotation velocity induced by NBI. The central rotation velocity increases as the vacuum magnetic axis R_{ax} is shifted inward, where the central helical ripple is reduced from several % to almost zero with the shift. The velocity is mainly determined by the parallel viscosity except for the inward-shifted case. Low parallel viscosity is required not to damp the rotation velocity induced spontaneously, which should be one of necessary conditions to obtain the velocity shear for the transport improvement.

On the other hand, as was shown in FM-1 spherator experiment [8], where trapped particles were located in the good curvature region by controlling its magnetic field structure with the vertical field, the particle confinement time was strikingly improved because the max. J criterion was satisfied. The criterion is effective to reduce the growth rate of micro-instabilities, i.e. collisionless trapped particle instabilities, η_i modes and so on, and it is partially satisfied in the vertically elongated tokamaks where the triangularity makes the criterion to be satisfied more [9]. The confinement improvement in the reversed shear tokamak configuration may result from this criterion. Application of the max. J criterion to helical plasmas has been discussed in the design study of LHD [10]. Unfortunately it was not successful for the criterion to be realized in its design because of technical problems on computation time. Because this criterion has been shown to be effective for the confinement improvement in real experiments, the design effort incorporating the criterion in helical systems should be one of most important subjects for toroidal plasma confinement.

2. Physics Aspects of CHS-qa

Generally speaking, drift-optimized helical systems (QHS, QAS, QOS) inevitably require a rather long pitch in their magnetic field configurations compared with heliotron / torsatrons. This is because of the role of an $l = 1$ helical component which should be of long pitch, otherwise it becomes a simple solenoid. In QAS, the $l = 1$ component is inevitable for adjusting the magnetic field strength to realize quasi-axisymmetry of which basic magnetic field is given by an $l = 2$ toroidal helical component. By pursuing the low A_p guideline adopted in CHS, A_p lower than that of CHS is selected, i.e. about 3-4, which results in the toroidal period number N of 2 for CHS-qa according to the long pitch. The major radius and the magnetic field strength of CHS-qa are determined to be 1.5 m and 1.5 Tesla, respectively, mainly from facility constraints. Design studies have been done from physics and engineering viewpoints [11,12].

The optimization process on CHS-qa has been done by using 43 variables (R_{mn} and Z_{mn}) to adjust the outermost magnetic surface. The rotational transform ι, QA-ness, magnetic well, local ballooning stability criterion and α particle confinement are taken into account in the process. Up to now the configuration called 2b32, where the priority in the process was put on the local ballooning stability, is considered to be most preferable from the purpose of CHS-qa experiment because the optimization is also directed to the max. J criterion. Fourier components of its magnetic field strength are shown in Fig. 1 as a function of the normalized minor radius r/a. As is seen from the figure the B_{00} component, the measure of vacuum magnetic well, is several % at the boundary, and B_{10} showing the toroidicity is the dominant one. Typical cross-sections of the magnetic surfaces along with the averaged magnetic surface are shown in Fig. 2. It might be said that the cross-sections are decomposed into the axisymmetric one and 3D shaping applied to it. The axisymmetric shape in the figure looks like a typical tokamak cross-section with moderate elongation and triangularity, which are favorable for max. J criterion. It can also be seen from the vertically and horizontally elongated cross-sections that the outermost magnetic surfaces are strongly affected with elongation and triangularity. The 3D shaping determines physics characteristics of optimized stellarators. It should be noted that the comet-like cross-section [13] is derived by taking primary account of the max. J criterion.

Neoclassical transport calculations on CHS-qa without the radial electric fields show tokamak-like behavior in the low collisionality regime [12,14], which is much better than that of drift-optimized configuration of CHS where the bottom of helical ripple has the same value by shifting the position R_{ax} inward. The α particle confinement is estimated in the reactor-relevant CHS-qa configuration (5 Tesla, plasma volume of 1000 m^3) [15],

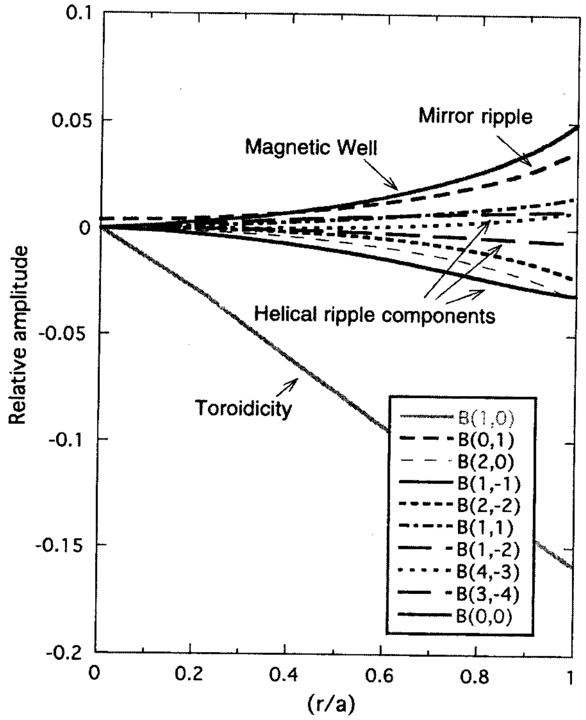

Fig. 1 Fourier components of the magnetic field strength of 2b32 configuration in the Boozer coordinate.

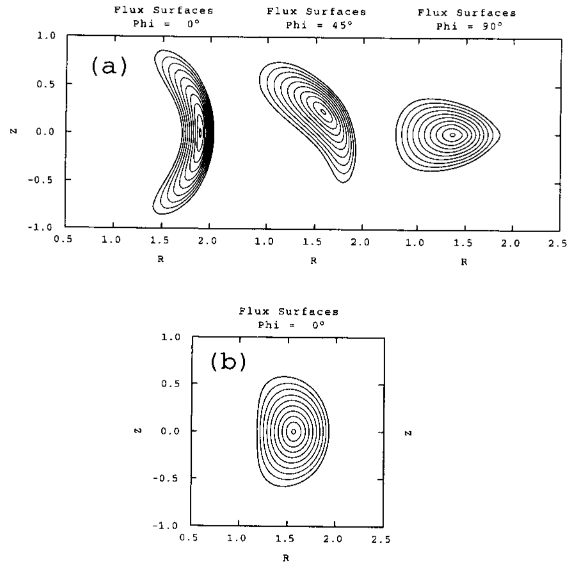

Fig. 2 Magnetic surfaces of 2b32 configuration at three typical toroidal cross-sections. (a) $\phi = 0$, (b) $\phi = \pi/4$, (c) $\phi = \pi/2$. The averaged cross-section is shown in (d). It is seen that the axisymmetric cross-section is composed of elongation and triangularity.

although it is different from the configuration of 2b32. By shifting the residual ripples into the high field side, α particle confinement is improved. This might be because the banana tip has less possibility to encounter the residual ripples. Compatibility with the 2b32 configuration awaits a future work.

The Pfirsch-Schlueter current can not be eliminated in QA configurations. Nevertheless, the associated problem of the Shafranov shift is eliminated by plasma shaping: the configuration 2b32 shows a nearly vanishing Shafranov shift compared with other CHS-qa configurations. The strong reduction in the parallel viscosity in the toroidal direction, described later, is selected at the expense of P.S. current in CHS-qa. By using 3D MHD equilibrium code HINT [16] where the existence of magnetic surfaces is not assumed a priori, the fragility of magnetic surfaces is examined. It is shown that up to the volume averaged beta $<\beta>$ of about 3% clean magnetic surfaces are kept under the condition of no net current and rather flattened pressure profile. The calculation taking account of net current due to the bootstrap and Ohkawa currents is under way. It is expected that rotational transform profile shaping by the net current may help to avoid resonances.

In QA configuration, the bootstrap current flows in the direction to augment the external rotational transform like in a tokamak. The increase in ι brings about a favorable effect on MHD properties, however care should be taken for ι not to cross the dangerous low order rational surface. The current is estimated with the NIFS bootstrap code under the temperature and density profiles plausible for the experiment and the resultant ι profile for $<\beta>$ of 1.3% is shown in Fig. 3. At present the calculation is reliable up to $<\beta>$ of about 1.5%. When the rotational transform has the positive shear ($d\iota/d\Psi > 0$, Ψ: the normalized toroidal flux) shown in the figure, the bootstrap current, which is supposed to preferentially flow at the node of island, creates the radial magnetic field of which direction is to cancel the perturbing radial magnetic field producing the island; it stabilizes the neoclassical tearing mode.

MHD calculation on the Mercier criterion gives stability $<\beta>$ of about 5% under the pressure profile of $(1-\Psi)^{1.5}$. In CHS and LHD, $<\beta>$ values obtained in the real experiments are higher than those predicted by the criterion [17-19]. However, in the CHS configuration shifted more inward than the optimized one, where the magnetic hill is even enhanced, MHD instabilities limiting the stored energy have been observed, showing that the Mercier criterion is valid as a rough guideline of the achievable $<\beta>$ prediction. Because min. B is

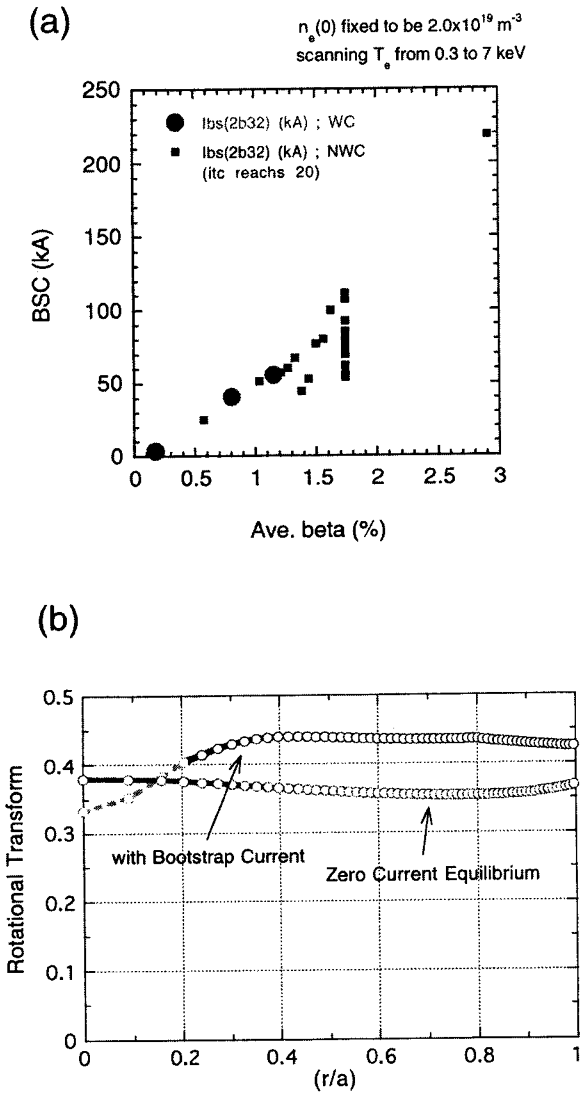

Fig. 3 Iota profiles for vacuum magnetic field and that with finite beta of $<\beta>$ = 1.3%. At the finite β positive shear of $d\iota/d\Psi > 0$ is realized.

satisfied in a sense of the average in CHS-qa, the stability against local ballooning modes is examined by TERPSICHORE code. The local ballooning mode stability, which should be more pessimistic than real plasmas, gives $<\beta>$ stable up to 3%. Ideal kink modes are also estimated by TERPSICHORE under the plasma current of which value is 100 kA and of which profile is elaborately tailored, and it is shown that 3D shaping of CHS-qa stabilizes the modes although the modes are unstable for the averaged cross-section without the 3D shaping. Ideal kink modes are examined by using CAS3D code, too. Here is assumed the current profile to be the bootstrap current one obtained from the pressure profile giving $<\beta>$ of 1.3%. Beyond the current of around 150 kA corresponding to $<\beta>$ of about 4%, ι crosses over 0.5 and the m/n=2/1 external kink mode gets unstable. In the experiments in JIPP T-II and W7-A, no current disruption was observed when the external ι is larger than 0.14 [20,21]. The external ι is shown to enlarge the stability window [22] and to produce the restoring force against the displacement of the current-carrying plasma column, irrespective of the displacement direction. These have been considered to be the cause of no disruption, however, recent W7-AS experiments [23] show that major disruptions occur occasionally. The situation, where the disruption is avoided even when the total ι crosses over 0.5, is also studied in W7-AS, and it gives us the clue to operate CHS-qa by controlling ι profile with Ohkawa and OH currents when the total ι exceeds 0.5 because of the bootstrap current as $<\beta>$ increases up to 4 or 5%, although more calculation studies on external kink and tearing modes are needed.

The velocity shear is known to be one of the stabilizing mechanisms of micro-instabilities. The motivation of the QA concept is in obtaining a strong toroidal rotation velocity. Actually in CHS-qa the toroidal velocity will be determined primarily by the anomalous perpendicular viscosity as in a tokamak and will be up to the level where VH-mode and H-mode are observed in DIII-D [24] and JFT-2M [25], respectively. The poloidal viscosity is also calculated for CHS-qa and is shown to be determined mainly by its high effective A_p, i.e. relatively small B_{10} component [26]. The low toroidal and poloidal viscosities will be helpful for achieving transport improvement. The H-mode in W7-AS is correlated with the reduction in the poloidal viscosity [27]. Bifurcation phenomena observed in tokamaks can be expected to occur in CHS-qa, and ITB observed in CHS [28] is also expected to occur by increasing the mirror ripple which is to be controlled by changing the current ratio of two groups of main modular coils [29,30]. In Fig. 4 the particle flux determining the radial electric field is schematically shown as a function of the helical ripple. Here, the flux due to the bulk viscosity is also shown as an example other than the neoclassical flux. It is shown that the radial electric field is uniquely determined by the neoclassical non-ambipolar diffusions when the ripple is about 10%, under which situation the bifurcation with positive radial electric field is expected as in CHS. When the ripple is reduced to about 1%, the fluxes due to such as bulk viscosity, loss-cone loss and charge

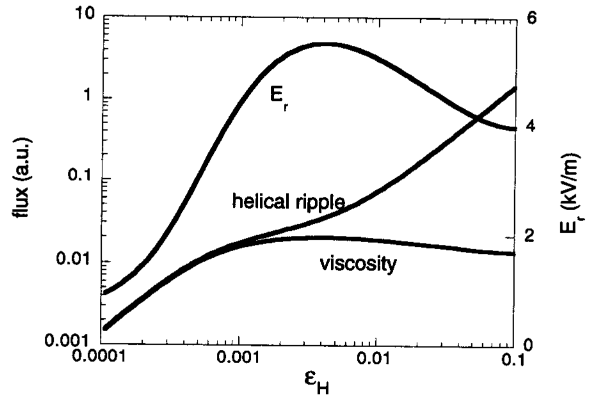

Fig. 4 The particle flux as a function of helical ripple. When the ripple is large (about 10%) the radial electric field is uniquely determined by the neoclassical fluxes. At the reduced ripple (about 1%) the flux due to the bulk viscosity becomes comparable to the neoclassical one. The fluxes due to such as bulk viscosity, loss cone loss and charge exchange loss, will also play an important role in determining the radial electric field.

exchange loss become comparable to the neoclassical one. There the bifurcation with negative radial electric field seen in tokamaks is expected.

The max. J criterion is satisfied in the magnetic configuration with the magnetic well and the shear of $d\iota/d\Psi > 0$ [9]. Collisionless trapped particle instabilities are excited when the toroidal drift velocity of ion (electron) banana is parallel to the toroidal component of ion (electron) diamagnetic drift velocity. The criterion is satisfied more for barely trapped bananas than for deeply trapped ones, because the former experiences the good curvature region more than the latter. In usual tokamak configurations without the reversed shear, it is difficult for banana particles to satisfy the drift reversal because of the negative shear of $d\iota/d\Psi < 0$. However, in CHS-qa the magnetic field configuration has a favorable characteristics that the average magnetic well in vacuum and the positive shear (stellarator shear) of $d\iota/d\Psi > 0$ due to the bootstrap current are satisfied as is shown in Fig. 1 and 3, respectively. Recent detailed calculation shows that because of small non-axisymmetric Fourier components growing outwards shown in Fig. 1 the parallel velocity for max. J calculation gets reduced near the boundary, which results in max. J configuration there. The extent of the region where the criterion is satisfied can be changed, for example, by controlling the vacuum magnetic axis position R_{ax} [31]. Controllability of max. J with other means, for example the mirror ripple, awaits a future work.

Finally, the flexibility is important for an experimental device; the current ratio not only of 3 pairs of poloidal field coils (for R_{ax} shift, quadrupole magnetic field, OH current) but also of main and additional modular coils (for mirror ripple and ι controls, respectively) can be controlled in CHS-qa. In addition to this, Ohkawa current will play an important role in controlling the ι profile. Further, a divertor study which also is of great experimental importance awaits future work.

3. Discussion and Conclusion

So-called optimized stellarators might be characterized by a variety of 3D shaping which is applied to an axisymmetric magnetic field configuration. It should be necessary for the axisymmetric shape to have one with both of elongation and triangularity for good confinement properties, which has been well established in tokamak experiments. If the omnigeneity is not lost by the 3D shaping, it might bring about good effects on toroidal plasma confinement. One example is the stabilizing effect on MHD modes related to the net plasma current. Among knobs for flexible experiments the most important one should be the mirror ripple, because this is related to conflicting requirements. For the α particle confinement it might be necessary to shift the residual ripples to the high field side, on the other hand, to satisfy max. J criterion the banana has to experience some bumpiness at the low field side [31] to reduce its parallel velocity.

In conclusion, by keeping advantages of compactness, low disruptivity, low recirculationg power CHS-qa can place itself in a unique position to study the confinement improvement among a variety of toroidal plasma confinement devices. This experiment will elucidate the role of magnetic field structures on the plasma confinement.

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