Quasi-symmetry in Stellarator Research 2. New Trend of Hellcal System Research

journal or publication title	プラズマ・核融合学会誌
volume	Vol.78
number	No.3
page range	pp.200-204
year	2002-03-01
URL	http://hdl.handle.net/10655/2215

doi: <doi>info:doi/10.1585/jspf.78.200</doi>

Special Topic Article
Quasi-Symmetry in Stellarator Research

2. New Trend of Helical System Research

MATSUOKA Keisuke
National Institute for Fusion Science, Toki 509-5292, Japan

(Received 26 December 2001)

Abstract

New trend is described on the basis of previous and on-going achievements. Magnetic shear is effective to stabilize ideal interchange modes, on the other hand magnetic well is needed for stabilization of resistive modes and micro-instabilities. Owing to recent developments in numerical tools on optimization of magnetic surface quantities it is now possible to construct magnetic surfaces that can satisfy requirements from reactor considerations. Confinement improvement and divertor capability might be an important theme in the near future.

Keywords:
magnetic shear, magnetic well, drift orbit, neoclassical transport, optimization, helical ripple, parallel viscosity, divertor

Research activities on toroidal helical magnetic confinement have been devoted to develop the configuration fulfilling the following requirements toward a helical reactor : 1) clean and robust magnetic surfaces with external rotational transform, 2) good α-particle orbit and good neoclassical transport, 3) high equilibrium- and stability-β values, 4) good energy confinement, 5) adequate divertor function. Nowadays much attention has been paid to the reduction in the anomalous transport and to the divertor function. To discuss the new trend of helical system research, it would be better to look back the history of the concept development because the next step should proceed step by step on the basis both of previous achievements from theory and experiment and of those from other confinement concepts. Toroidal helical configuration is of 3-dimension, which brings about much freedom in the magnetic configuration, although resultant complexity had made the progress delayed in comparison with tokamaks. Key parameters for the configuration optimization are the profiles of rotational transform ι, magnetic shear and magnetic well.

The worldwide research activities of stellarators have been summarized occasionally: summary reports were published three times by stellarator community appearing as the supplement of journals [1-3] and sometimes appeared as review papers [4-6]. The starting point of the research was the Prof. Spitzer's pioneering work of Figure-8 stellarator in 1950's [7]. The idea to create the rotational transform was based on the torsion of the magnetic axis. Soon this idea to create ι was replaced with the conventional l = 2 or l = 3 helical windings having the planar magnetic axis. After the declassification of US fusion activities in Geneva IAEA Conference in 1958 the stellarator research was extended to Germany, Japan, USSR and UK. These worldwide theoretical and experimental activities of about 30 years ago formed basic concept on the confinement. The followings were pointed out. From the viewpoint of stabilization of ideal interchange modes the magnetic shear was necessary because Figure-8 stellarator had no shear. An l = 3 helical winding has the

author's e-mail address: matsuoka@nifs.ac.jp

parabolic profile of ι, the shear, however it turned out to be insufficient for the equilibrium because of very small ι in the core region. An $l = 2$ helical winding with a short pitch can bring about both the rotational transform and the magnetic shear. On the other hand, in Wendelstein stellarators, an $l = 2$ winding with a rather long pitch has been adopted avoiding low-order rational surfaces: there is almost no shear and the magnetic well is needed for the interchange-mode stability. However, much attention was not paid to the magnetic well in the conventional $l = 2$ and / or $l = 3$ helical winding machines with the planar magnetic axis at that time. On the other hand, it was pointed out theoretically that the magnetic well and short connection length are necessary to stabilize resistive interchange modes and ballooning modes, and in this connection the configuration that is called heliac later was invented [8]. Magnetic well is also effective to suppress the micro-instabilities, e.g. universal instabilities and η_i modes. The magnetic well is one of the most important ingredients in the recent optimization of stellarators, so heliacs having the torsion of the magnetic axis ($l = 1$ component) are explained in more detail here. The magnetic surface of heliac is a kind of island, which is produced by the resonance between the $\iota = N$ (toroidal period number, for example) rational surface of the supposed tokamak and a helical distorsion of Toroidal Field (TF) coils with the same pitch as the rational surface, i.e. the perturbing radial magnetic field produced by the torsion of TF coil. The sufficiently large current in the central toroidal ring produces the poloidal field of the supposed tokamak. The null (stagnation) point of the island thus produced makes large negative gradient of the integral of $1/B$ that contributes to the magnetic well. Heliacs [9] have a magnetic well even at the infinite aspect ratio. Here a large rotational transform and shorter connection length are realized, and a large local magnetic shear is also provided. However, the drift orbit of helically trapped particles was pointed out to be a problem. This problem holds for whole helical systems at that time meaning that the neoclassical transport in the collisionless regime resulting from helically trapped particles is much worse than that of tokamaks [10,11]. This had been one of the reasons why major activities of toroidal plasma confinement was concentrated on tokamaks. So, the magnetic well and good particle orbit were the concern. Note that medium-sized heliacs with the major radius of about 1 m were put into operation about 30 years after the reference [8]. Improvement of the drift orbit was originated in Palumbo's paper [12], where the drift surface of particles including passing and trapped particles coincides with the magnetic surface, i.e. no neoclassical transport (or no j_{para}) or the diamagnetic current j_{perp} is divergence-free. The Palumbo condition is reduced such that the equi-magnetic field strength surface coincides with the magnetic surface, i.e. it is a function of only one variable, e.g. the poloidal or toroidal flux, or the volume inside the magnetic surface.

The first summary report appeared in 1981 [1], putting a major emphasis on experimental results from major devices that were rather conventional. Most important result was less disruptivity of current-carrying stellarator plasmas in JIPPT-II [1] and W7-A [1], owing to the restoring force against plasma displacements due to the external rotational transform. Another important research trend was the optimization in W7-AS from the viewpoint of the reduction in Pfirsch-Schlueter (PS) current, or j_{para}, for improvement of the neoclassical transport and the reduction in the Shafranov shift induced by j_{para}. Reduced Shafranov shift is favorable for a high equilibrium β_{eq}. W7-AS was also designed to have a magnetic well, although not so deep, because the equilibrium satisfying the Palumbo condition was MHD unstable. For low β and small ι the ratio of j_{para} / j_{perp} is given by the variation of Q that is the line integral of dl/B on the magnetic surface where the integration is performed along the vacuum magnetic field over one field period. The reduced variation of Q means the reduction in unbalance of charge accumulation on the magnetic surface resulting in the PS current. In designing the W7-AS configuration the vacuum magnetic field is composed of analytical harmonic fields [13] to search the configurational space instead of trimming external coil distributions. This method made the search much easier. This vacuum field configuration is then used as an initial value for finite β calculations by using 3-D equilibrium codes to test MHD characteristics. In the course of the optimization process several components of polarity (l) were introduced as a result. The effect of the toroidal curvature is compensated with the large $l = 1$ field for the reduction in j_{para} / j_{perp}. As a result, the reduction of factor 2 was realized in W7-AS in comparison with conventional stellarators with the same ι. The $l = 1$ component also increases the local curvature. However, care should be taken not to increase the locally trapped particles as was described in heliacs. Then, deeply trapped particles are to be located in the small toroidal-curvature region, which leads to the idea of the toroidally linked mirror configuration of W7-X. On the other hand, the current

j_{para} is discussed from the viewpoint of island formation [14] and it is shown that the large toroidal period number N is favorable. The PS current is also discussed in the low collisionality regime [15]. W7-AS had another purpose of making use of poloidally closed modular coils [16, 17] in real experiments. In the meanwhile the analytical method for optimization made an advance; Representation of the vacuum magnetic field by using Dommaschk potential [13, 18] was replaced with the method of trimming the outermost vacuum magnetic surface. This is based on the fact that the equilibrium is completely determined as the Neumann problem when the derivative of flux function, i.e. the magnetic field is specified on the plasma boundary. All information on the magnetic field configuration, e.g. ι, magnetic shear, magnetic well, are included in the boundary shape, and in the present optimization process those quantities are controlled by the method. The modular coils could be derived from bunching the surface current on some surface that flows not to produce the magnetic field outside of the surface [19]. Remarkable progress was done on the magnetic coordinate [20] and it was found that the guiding center motion could be discussed only by the magnetic field strength B by using the Boozer coordinate [21]. The next-step compromise of the Palumbo condition might be the configuration with some symmetry in B. The strength B in the quasi-axisymmetric configuration like tokamak is of two-dimension and it is suggested that the particle orbit can be confined within the finite deviation from the magnetic surface, i.e. the banana orbit at worst. If the toroidal-angle-like variable of the Boozer coordinate is approximated by the usual toroidal angle it is not difficult to understand how quasi-axisymmetric helical configurations [22, 23] can be formed. By adjusting the following contributions to B, i.e. toroidicity, magnetic axis torsion (l = 1) and l = 2 component that is the main contributor to ι, the B profile proportional to $1/R$ can be imagined rather easily. The quasi-helical symmetry [24] having the finite aspect ratio is also understandable, where an l = 1 component mainly produces ι.

The summary reports [2, 3], that were motivated by the renewed interest in stellarators especially in U.S.A., appeared about 10 years after the first one. Heliotron-E [25] was the leading machine and its experimental results had motivated the construction of ATF [26]. ATF, CHS [27] and W7-AS [28] started their operations successively in a year. Along with these planar axis stellarators, heliacs, TJ-II [3] and H-1 [3], were under design. These devices were designed as a flexible heliac, where ι and magnetic shear can be controlled in a wide range by controlling the current of the additionally installed helical winding around the center ring. However, so-called advanced stellarators were of minority in respect of experiments and of designs of next-generation machines except the Wendelstein line. ATF aimed at realization of the second stability against ideal interchange modes [29] by selecting the moderate aspect ratio of 8 lower than those of W7-A and H-E. CHS made its aspect ratio 5, exploring physics of the low aspect ratio helical plasma. The second stability was also confirmed later in CHS [30] and LHD [31]. Important point is that the confinement does not degrade in the parameter region where the Mercier criterion predicts instability of ideal interchange modes. Investigation on the ballooning mode on the performance will be a future work. MHD stabilities of helical plasmas can now be well predicted by several 3-D codes, e.g. CAS3D [32] and Terpsichore [33] and it is possible to find the configuration stable against various MHD modes. With respect to confinement improvement present-day helical devices have shown promising results. In W7-AS [34] and CHS [35] H-modes were observed. Importance of the reduction in the poloidal viscosity was pointed out in W7-AS [36]. However, the improvement factor has not still been large. The relation between the parallel viscosity and the toroidal rotation velocity was clarified experimentally in CHS [37], indicating that the helical ripple should be reduced for obtaining a low parallel viscosity. However, in W7-AS the new H-mode regime has been found with the improvement factor of 2 over the ISS95 scaling at ι of around 5/9 where the poloidal viscosity has a maximum [38]. On the other hand, helical ripples in conventional helical devices induce the electric potential in the plasma due to the ambipolarity condition on the non-ambipolar diffusion of electrons and ions. The successive bifurcations between equilibrium states accompanying the transition of potential profiles were discovered in CHS [39]. The improved mode based on the potential bifurcation was discovered in CHS: the Neoclassical Internal Transport Barrier (NITB) for the electron energy [40]. It results from the bifurcation between equilibrium states with positive potentials. Recently NITB was observed in LHD, too. Preliminary result showing the transport barrier for ion in NITB was obtained in CHS. For realization of the improved ion energy confinement that is observed in tokamaks, where the ion pressure and the negative potential have the positive feedback relation, it is necessary to have a large shear of negative radial electric field. From this viewpoint the parallel viscosity should be reduced as much as possible to keep the rotation velocity large. However, it may be expected that the ion energy confinement should be improved in NITB modes of conventional helical machines. In respect of the α heating, instabilities induced by energetic particles, e.g. TAE and GAE modes, are investigated both theoretically and experimentally. Experiments have not shown the detrimental effect on the plasma performance because of these modes [41, 42]. It seems that there is no restriction on the ι profile from these instabilities. The important issue in the near future is the divertor. High/moderate aspect ratio l = 2 configurations have a clear divertor trace because of no strong sidebands, however, so-called advanced configurations consisting of l = 1, l = 2 and l = 3 components have no clear divertor trace. The island divertor scenario should be considered there. Local island divertor concept was verified in CHS [43] and is now adopted in LHD. Full helical divertor experiment in LHD is scheduled in the near future. The island divertor has been discussed from the point of compatibility between ELM free H-mode and detachment in W7-AS [38, 44]. The connection length around the island that governs the balance between the parallel and perpendicular diffusions will be a key parameter from the configuration consideration. The research in helical systems should be complementary to tokamaks. In this respect, quasi-axisymmetric configurations, NCSX and CHS-qa, could give an answer on Neoclassical Tearing Mode (NTM) and Resistive Wall Mode (RWM). These problems will be discussed in Chap. **5**.

In summary, it is now possible to construct the helical magnetic field configuration that satisfies almost all requirements mentioned in the beginning on the basis of the well advanced numerical techniques. Quasi-symmetric configurations could be the consequence of the research made so far on the helical plasma confinement. The research in the near future should be directed to the reduction in micro-instabilities by taking full advantages of the vacuum magnetic well and the stellarator shear, and the divertor issues.

References

[1] L. Spitzer, Jr. *et al.*, IEEE Trans. of Plasma Sci. (1981) Vol. PS-9, No 4.

[2] B.A. Carreras, G. Grieger *et al.*, Nucl. Fusion **28**, 1613 (1988); J.F. Lyon, G. Grieger *et al.*, Nucl. Fusion **30**, 1695 (1990).

[3] J.F. Lyon *et al.*, Fusion Technol. **17**, No.1 (1990).

[4] K. Miyamoto, Nucl. Fusion **18**, 243 (1978).

[5] V.D. Shafranov, Nucl. Fusion **20**, 1075 (1980).

[6] L.M. Kovrizhnykh, Plasma Phys. Control. Fusion **30**, 67 (1988).

[7] L. Spitzer, Phys. Fluids **1**, 253 (1958).

[8] H.P. Furth, J. Killeen, M.N. Rosenbluth and B. Coppi, *Plasma Physics and Controlled Nuclear Fusion Research 1965* (Proc. 2nd Int. Conf. Culham, 1965) Vol.1, IAEA, Vienna, (1966) p.103.

[9] S. Yoshikawa, Nucl. Fusion **23**, 667 (1983).

[10] B.B. Kadomtsev and O.P. Pogutse, Nucl. Fusion **11**, 67 (1971).

[11] A. Gibson and D.W. Mason, Plasma Phys. **11**, 121 (1969).

[12] D. Palumbo, Nuovo Cimento **53B**, 507 (1968).

[13] W. Dommaschk, Z.f. Naturforschung **36a**, 251 (1981).

[14] A.H. Reiman and A.H. Boozer, Phys. Fluids **27**, 2446 (1984).

[15] L.M. Kovrizhnykh, Nucl. Fusion **25**, 1391 (1985).

[16] H. Wobig and S. Reker, *Proc. of the Symp. on Fusion Technology*, Grenoble 1972, p.345, Max-Planck-Institute for Plasmaphysics, Report IPP 2/215 (1973).

[17] T.K. Chu, Nucl. Fusion **22**, 871 (1982).

[18] W. Dommaschk *et al.*, Nucl. Fusion **24**, 794 (1984).

[19] P. Merkel, Nucl. Fusion **27**, 867 (1987).

[20] A. Boozer, Phys. Fluids **24**, 1999 (1981).

[21] A. Boozer, Phys. Fluids **23**, 904 (1980).

[22] P. Garabedian, Phys. Plasmas **3**, 2483 (1996); Phys. Plasmas **4**, 1617 (1997).

[23] J. Nuehrenberg *et al.*, *Theory of Fusion Plasmas* (Varenna, 1994), Editrice Compositori, Bologna (1994).

[24] J. Nuehrenberg and R. Zille, Phys. Lett. A **129**, 113 (1988).

[25] K. Uo *et al.*, *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 11th Int. Conf. Kyoto, 1986, IAEA, Vienna) (1987) Vol.2, p.355.

[26] M.J. Saltmarsh *et al.*, *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 12th Int. Conf. Nice, 1988, IAEA, Vienna) (1989) Vol.2, p.349.

[27] K. Matsuoka *et al.*, *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 12th Int. Conf. Nice, 1988, IAEA, Vienna) (1989) Vol.2, p.411.

[28] H. Renner *et al.*, *Plasma Physics and Controlled*

Nuclear Fusion Research (Proc. 13th Int. Conf. Washington, 1990, IAEA, Vienna) (1991) Vol.2, p.439.
[29] J.H. Harris *et al.*, Phys. Rev. Lett. **63**, 1249 (1989).
[30] S. Okamura *et al.*, Nucl. Fusion **35**, 283 (1995).
[31] S. Sakakibara *et al.*, Nucl. Fusion **41**, 1177 (2001).
[32] C. Schwab, Phys. Fluids B **5**, 3195 (1993).
[33] D.V. Anderson *et al.*, Int. J. Supercom. Appl. **4**, 34 (1990).
[34] V. Erckman *et al.*, Phys. Rev. Lett. **70**, 2086 (1993).
[35] K. Toi *et al.*, Plasma Phys. Control. Fusion **38**, 1289 (1996).
[36] M. Hirsch *et al.*, *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 16th Int. Conf. Montreal, 1996, IAEA, Vienna) (1997) Vol.2, p.315.
[37] K. Ida *et al.*, Phys. Rev. Lett. **67**, 58 (1991).
[38] K. McCormick *et al.*, Plasma Phys. Control. Fusion **41**, B285 (1999).
[39] A. Fujisawa *et al.*, Phys. Rev. Lett. **81**, 2256 (1998).
[40] A. Fujisawa *et al.*, Phys. Rev. Lett. **82**, 2669 (1999).
[41] A. Weller *et al.*, Phys. Rev. Lett. **72**, 1220 (1994).
[42] K. Toi *et al.*, Nucl. Fusion **40**, 1349 (2000).
[43] A. Komori *et al.*, Fusion Eng. Des. **39**, 241 (1998).
[44] R.W.T. Koenig *et al.*, J. Nucl. Mater. **290–293**, 882 (2001).