Physics and engineering design of the low aspect ratio quasi-axisymmetric stellarator CHS-qa

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Abstract. A low aspect ratio quasi-axisymmetric stellarator, CHS-qa, has been designed. An optimization code has been used to design a magnetic field configuration with evaluations of the following physical quantities: quasi-axisymmetry, rotational transform, MHD stability and alpha particle collisionless confinement. It is shown that the electron neoclassical diffusion coefficient is similar to that of tokamaks for the low collisional regime. A self-consistent equilibrium with bootstrap current confirms the global mode stability up to 130 kA for an $R = 1.5$ m and $B_t = 1.5$ T device. The neoclassical plasma rotation viscosity is greatly suppressed compared with that of conventional stellarators. The engineering design was completed with 20 main modular coils and auxiliary coils, which provide flexibility of configuration in experiments for confinement improvement and MHD stability.

1. Introduction

In magnetic fusion research, helical systems (stellarators) have made remarkable progress in the past two decades. The plasma parameters obtained in small sized devices have become comparable to those of tokamaks of similar size, and the initial results of LHD [1] showed prospective plasma qualities close to those of large sized tokamaks. Configuration design studies of helical systems have also been developed greatly, and a number of new configurations have been proposed owing to the great freedom in the geometry of 3-D helical system structures. In such new configuration developments, the primary objectives were:

(a) To improve neoclassical transport by reducing the orbit losses of helical ripple trapped particles,
(b) To explore high beta configurations, which are always favourable in reactor designs.

The concept of the quasi-axisymmetric stellarator, which has a magnetic field structure with tokamak-like 2-D symmetry [2, 3], is one of these new proposals. It can solve the essential problem of stellarator transport by strongly reducing the helical ripple structure itself. Another attractive feature of this concept is that a low aspect ratio design is easier for this concept than for conventional stellarators. From the tokamak point of view, because the rotational transform is provided by the external coils, it gives a new direction for improvements, such as avoidance of disruptions, avoidance of current drive and the creation of negative shear.

A low aspect ratio stellarator CHS-qa has been designed on the basis of such a quasi-axisymmetric concept [4, 5]. As well as good neoclassical transport characteristics, MHD stability for high beta equilibrium is very important in making the new concept promising for fusion reactors. We basically designed CHS-qa to realize these characteristics as the necessary basis for a new experimental device. On the other hand, it is well known that the transport phenomena occurring in current toroidal experiments are mainly dominated by anomalous transport. The optimization of the configuration must take great care with these features if there is to be hope of achieving good confinement in real experiments. The device design is also strongly related to the engineering problems that may arise at the manufacturing stage. We have tried to take all these aspects into account to achieve the best optimized design for the device.

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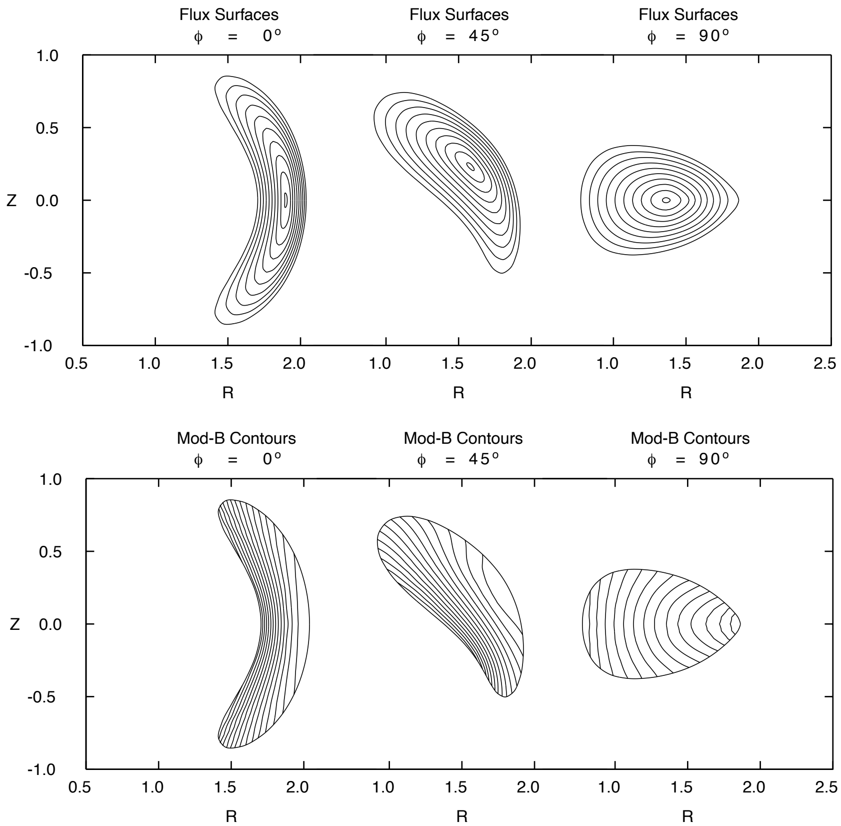

Figure 1. Magnetic surfaces and contours of magnetic field strength for the 2b32 configuration, for 3% average beta equilibrium.

In the quasi-axisymmetric configuration, a tokamak-like bootstrap current (increasing the rotational transform) is expected, especially for high beta and high temperature operation. It is always possible to design a device based on the existence of a large plasma current. However, in our present work, we have tried to achieve a design that is more flexible to a wide range of stellarator operation, from very low beta operation (no plasma current case) to high beta operation.

2. Configuration design

The configuration design was carried out with an optimization code containing 43 controlling variables for the boundary shape Fourier components. The equilibrium was obtained with the VMEC code [6] fixed boundary calculation. Optimization was achieved on the basis of evaluations of several physical properties. The basic optimization goals were to reduce the non-axisymmetric components of the Boozer spectra and to control the rotational transform bounded within the assumed range of values, avoiding dangerous low order rationals. MHD stability is evaluated using ballooning and/or Mercier criteria. The number of toroidal periods N is very important in determining the basic characteristics of the configuration. We selected $N = 2$, which allows a secure modular coil design for a low aspect ratio device, but with the disadvantage of accepting a relatively lower rotational transform.

After surveying various configurations, we obtained the 2b32 configuration, which has a rotational transform profile above a third at the centre and slightly increasing to the edge value of 0.4. The aspect ratio is 3.2. Figure 1 shows three poloidal cross-sections of the equilibrium magnetic surfaces and contours of magnetic field strength of the 2b32 configuration for 3% average beta with zero toroidal current. The evaluation of the MHD stability for this configuration was made on the basis of the local ballooning stability. The configuration 2b32 has a Mercier stability for more than 5% average beta and a local ballooning stability up to 3%. In most cases,

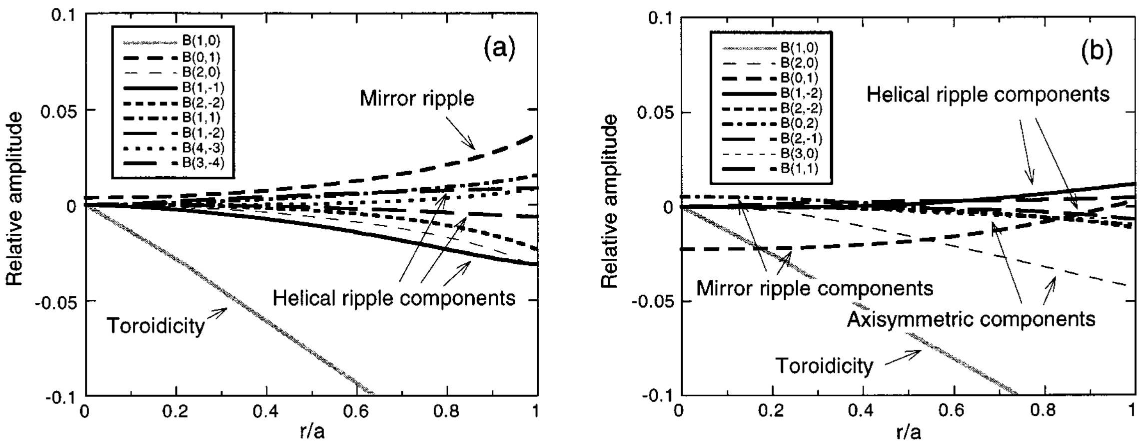

Figure 2. Boozer spectrum of magnetic field ripple components for (a) the 2b32 configuration and (b) the 2a36 configuration. $B(m,n)$ (m, poloidal mode number; n, toroidal mode number) is the amplitude relative to that of the toroidal field.

we evaluate the MHD stability with zero average toroidal current. The optimization procedure with the local ballooning stability gave an additional effect of strong reduction of the Shafranov shift for a high beta equilibrium.

3. Particle transport

The boozer spectrum of the 2b32 configuration is shown in Fig. 2(a). The two largest non-axisymmetric components are the mirror component $B(0,1)$ and the helical ripple component $B(1,-1)$. The relative amplitudes of these terms are about 3% at the edge and 1.5% at the half-radius. As is described later, this level of residual ripples does not affect the neoclassical diffusion coefficient of the quasi-axisymmetric configuration so much. But such residual ripples cause stochastic ripple losses of toroidal banana orbits of highly energetic particles, for example, alpha particles in a reactor. The dependence of the banana particle losses on each non-axisymmetric Boozer component is not obvious. For example, the mirror term with zero poloidal mode number usually remains with an almost unchanged amplitude shape as a function of radius for many solutions of the optimization, although it is possible to shift it up or down by adjusting the bumpiness of the toroidal field. Fortunately, this component is not an important one in influencing the losses of high energy banana particles. A smaller component with higher poloidal mode number affects the losses more strongly.

Another new optimization procedure — the evaluation of high energy particle confinement — gave a new solution for the configuration, with a dramatically improved high energy particle confinement [7]. Figure 2(b) shows a Boozer spectrum of the 2a36 configuration obtained by the new optimization procedure. Although non-axisymmetric components (except for the mirror term) are suppressed below 1.5% at the edge in this new configuration, the special effect given by the combination of components with different mode numbers is a possible mechanism for such a large reduction (more than one order of magnitude) of the stochastic ripple losses of high energy banana particles.

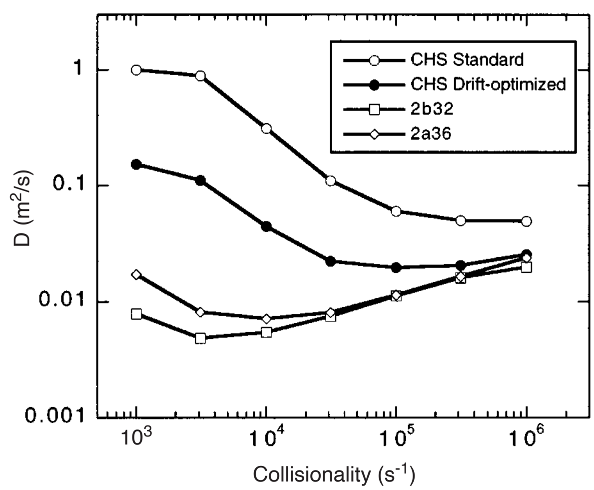

Figure 3. Neoclassical diffusion coefficients for CHS and CHS-qa. The electric field is not included.

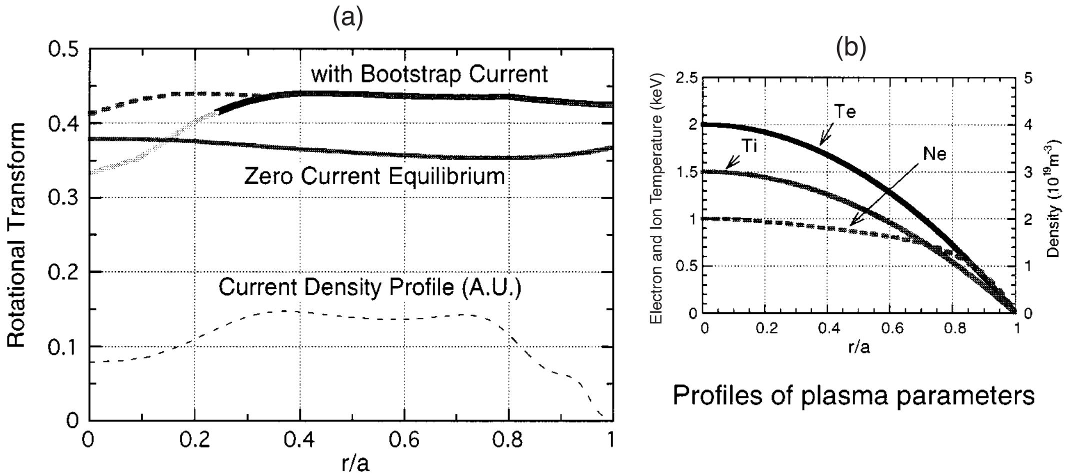

Figure 4. (a) Rotational transform profile with self-consistent bootstrap current. The current density profile is shown in arbitrary units. The rotational transform of the equilibrium with the assumption of zero average current is also shown for comparison. (b) Plasma profiles used in the calculation.

Figure 3 shows the diffusion coefficients of 1 keV electrons for two types of helical device. CHS is a low aspect ratio heliotron/torsatron type conventional stellarator. Two magnetic configurations are calculated for CHS, which are obtained by shifting the magnetic axis position. The CHS drift optimized configuration has an inward shifted magnetic axis position in comparison with the standard one, where the drift orbits of helically trapped particles approximately coincide with the magnetic surfaces [8]. The $R_{ax} = 3.6$ m configuration of LHD [9] is similar to this drift optimized configuration of CHS.

The neoclassical diffusion coefficient D is calculated using the DCOM code [10] with no electric field effect. The Monte Carlo method is used to follow test particle orbits in the Boozer co-ordinates under the influence of pitch angle scattering. The value of D is determined from the radial distribution of test particles at the minor radius, $r/a = 0.5$, after taking sufficient time for the Monte Carlo run. The parameters in the calculations are chosen from the real device dimensions: the magnetic field is 1.8 and 1.5 T and the major radius 1 and 1.5 m for CHS and CHS-qa, respectively. The diffusion coefficients for 1 keV (mono-energetic) electrons are plotted as a function of collisionality (by varying the electron density) for the $1/\nu$ regime. The CHS case clearly shows the increased diffusion coefficient in the $1/\nu$ regime. The drift optimization yields an improvement in the neoclassical diffusion property, but the increase in diffusion coefficient for the low collisionality regime still exists. On the other hand, the diffusion coefficient falls in CHS-qa, which is similar to the tokamak cases.

It is noted that the difference between the neoclassical diffusion coefficients for the 2b32 and 2a36 configurations of CHS-qa is not significant in this calculation. The 2b32 configuration is even slightly better than 2a36, which is the opposite result from the alpha particle confinement characteristics. The key difference could be the mirror ripple amplitude, which is larger for the 2a36 configuration. The relatively larger mirror component in 2a36 might improve alpha particle confinement but decrease bulk neoclassical confinement.

4. Bootstrap current and global kink stability

The assessment of the importance of bootstrap current is one of the most difficult problems in this design work. Because the bootstrap current depends largely on the transport process, which cannot be predicted reliably at present, bootstrap current effects will be a major area of investigation in the experiment. However, theoretical model calculations have been made for limited cases of the

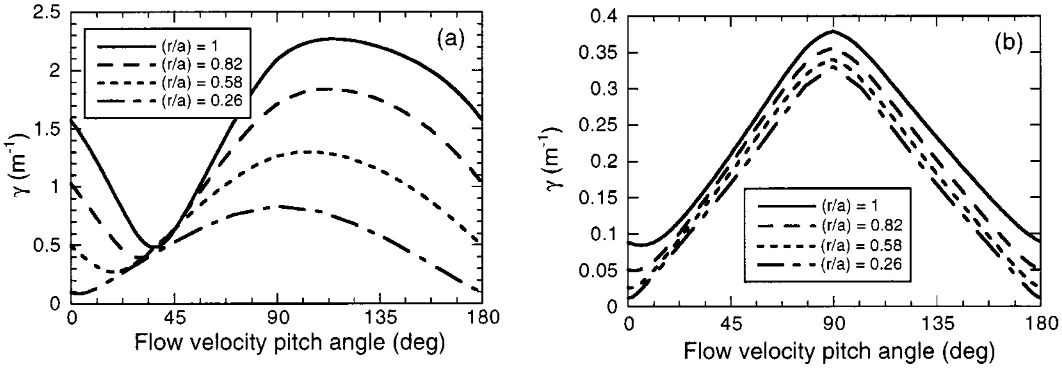

Figure 5. Comparison of magnetic field variation γ for (a) CHS and (b) CHS-qa (the 2b32 configuration). γ is calculated for four selected magnetic surfaces. As for the flow velocity pitch angle, 0° corresponds approximately to the toroidal direction and 90° to the poloidal direction.

2b32 configuration. Figure 4(a) shows the rotational transform profile of the self-consistent plasma equilibrium for a plasma beta of 1.3%. The rotational transform profile for the zero current equilibrium with the same beta value is also plotted for reference purposes. The plasma parameters assumed are $n(0) = 2 \times 10^{19}$ m^{-3}, $T_e(0) = 2$ keV and $T_i(0) = 1.5$ keV for a magnetic field of 1 T. Profiles are shown in Fig. 4(b). The resultant total current is 56 kA. The current density profile is also plotted in arbitrary units.

The effect of toroidal current in degrading the quasi-axisymmetry was generally very small. Although we found examples where an addition of a positive current (in the direction of increasing rotational transform) improves the local stability, a global stability such as a kink stability generally becomes worse with a plasma current present. For this example, we have examined the global MHD stability (external kink mode) using the CAS-3D code [11]. The rotational transform is modified to the one shown by the dashed curve in Fig. 4(a) in order to exclude the resonance effect in the plasma. We think such a modification is reasonable if the beam driven current of co-injection NBIs is considered (Section 6). The CAS-3D analysis shows that all low mode perturbations are stable for this configuration. We made a similar stability analysis with model rotational transform profiles for larger plasma current cases with the same beta value to check the effect of current on stability. Stability was obtained for the 130 kA case but it was lost for the equilibrium with a current above 185 kA.

5. Neoclassical viscosity for plasma rotation

When we consider the scenario of obtaining improved confinement, one of the most important keys is the plasma rotation and its radial structure. We have many experimental examples of the formation of transport barriers in both tokamaks [12] and helical systems [13]. Since the structure of plasma rotation is determined by the balance between driving force and viscosity, there are various types of transport barrier depending on these components. For example, the plasma rotation in helical systems is mainly caused by the strong driving force of non-ambipolar diffusion, while the rotation in tokamaks is maintained by the low rotation viscosity of the axisymmetric configuration with a relatively weak driving force. The clear difference between these two types of barrier formation appears as the polarity of the potential at the internal transport barrier: in most cases, positive in helical systems and negative in tokamaks.

The CHS-qa configuration is a good one with which to experimentally study these important issues. Because it has a quasi-axisymmetric configuration, the neoclassical rotation viscosity is very low compared with that of a conventional stellarator. Figure 5 shows the averaged magnetic field variation γ on the magnetic surfaces along a streamline in the CHS and CHS-qa 2b32 configurations ($\gamma^2 \equiv \langle[(dB/ds)/B]^2\rangle$). The neoclassical viscosity is approximately proportional to γ^2 [14]. A streamline is defined as a line which has a constant angle to the toroidal axis of Boozer co-ordinates (a constant

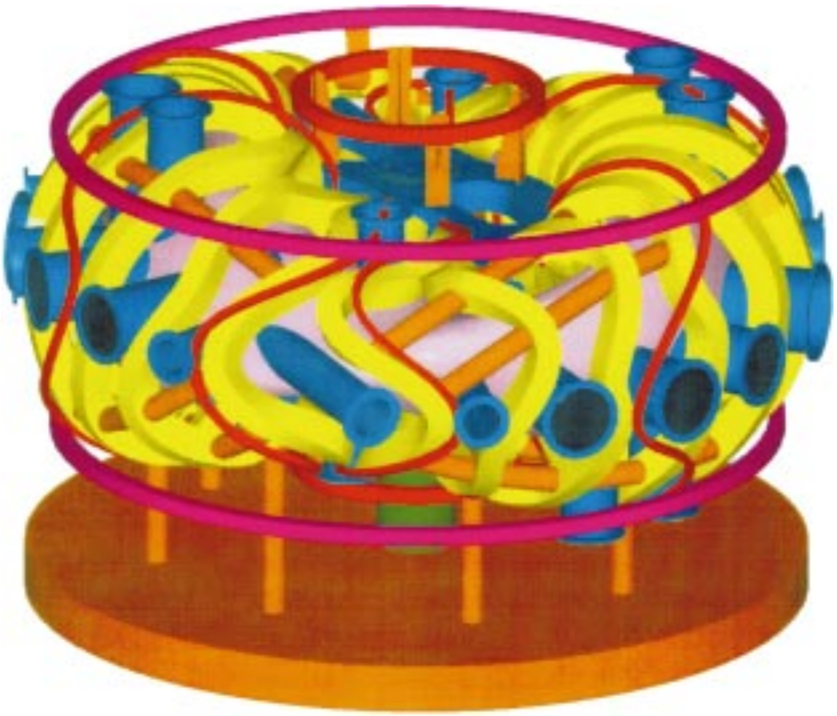

Figure 6. Schematic view of the CHS-qa engineering design.

poloidal co-ordinate line). The lowest γ is obtained in CHS for a flow angle of about 40° to the (Boozer) toroidal direction, which corresponds to the pitch angle of the helical coil windings. We have observed experimentally that, in a particular plasma condition, an electric field appeared spontaneously so as to make the plasma rotation flow along this direction [15]. On the other hand, the CHS-qa configuration has the lowest neoclassical viscosity in the toroidal direction. The ratio of minimum values of γ for CHS and CHS-qa is about 7 at the plasma edge and 20 at a quarter of a radius. We hope that such a reduction of neoclassical viscosity will be a good condition for tokamak-like internal transport barrier formation.

When non-axisymmetric ripple components are reduced to the order of 1%, the non-ambipolar current due to residual ripples becomes comparable to the effective radial current of the bulk rotation viscosity for typical rotation speeds in tokamaks. A new branch of plasma rotation physics might appear in such an intermediate configuration region. An important key to experiments is to provide various controls with which to vary the configuration and the physical characteristics. We designed CHS-qa with a large configuration flexibility for the purpose of studying confinement physics in this new area of magnetic field configuration.

6. Engineering design with configuration flexibility

The engineering design is for a medium sized device with 1.5 m major radius and 1.5 T magnetic field. Figure 6 shows a schematic view of the whole device with the main modular coils and auxiliary coils. The main coil system was designed with 20 modular coils for two toroidal periods. The distance of the coils from the plasma surface is about 0.4 m, which was determined by considerations of divertor space and an acceptable shape for the windings of the modular coils. The most difficult point of the modular coil design is at the inboard side of the bean shaped cross-section. The distance between adjacent coils is at an acceptable level from the viewpoint of device manufacture. A mechanical support structure for the modular coils was also designed. It is composed of individual modular coil support frames and connecting rods between the coils. This design gives fully open spaces on the outboard side of the torus allowing the installation of more than 50 ports. Two tangential ports are installed for two co-injection neutral beams which are designed to drive a strong plasma toroidal rotation with a good heating efficiency.

Although the target magnetic configuration is created by the main modular coils by themselves, various additional coils are installed to provide flexibility of field configuration control. Three sets of poloidal field coils allow plasma positional and shaping control which can be the method of controlling residual ripple structures. A combination of these poloidal coils also works as an ohmic coil by ramping currents within 0.1 s. Control of plasma currents up to 100 kA is available. Auxiliary modular coils (the eight small coils in red in Fig. 6) [16] give external control of the rotational transform, which is one of the most important controls to deal with bootstrap current effects on stability and confinement in the experiment.

References

[1] Fujiwara, M., et al., Nucl. Fusion **41** (2001) 1355.
[2] Nührenberg, J., et al., in Theory of Fusion Plasmas (Proc. Workshop Varenna, 1994), Editrice Compositori, Bologna (1994) 3.
[3] Garabedian, P., Phys. Plasmas **3** (1996) 2483.
[4] Matsuoka, K., et al., Plasma Phys. Rep. **23** (1997) 542.
[5] Okamura, S., et al., J. Plasma Fusion Res. SERIES **1** (1998) 164.
[6] Hirshman, S.P., et al., Comput. Phys. Commun. **43** (1986) 143.
[7] Nührenberg, J., et al., Plasma Phys. Control. Fusion **43** (2001) 137.
[8] Okamura, S., et al., Nucl. Fusion **39** (1999) 1337.
[9] Murakami, S., et al., Nucl. Fusion **39** (1999) 1165.
[10] Wakasa, A., et al., in Plasma Physics and Controlled Nuclear Fusion (Proc. 11th Int. Conf. Toki, 2000), National Institute for Fusion Science, Toki (2000) paper PII-10.
[11] Nührenberg, C., et al., Phys. Fluids B **5** (1993) 3195.
[12] Fujita, T., et al., Phys. Rev. Lett. **78** (1997) 2377.
[13] Fujisawa, A., et al., Phys. Rev. Lett. **82** (1999) 2669.
[14] Ida, K., Plasma Phys. Control. Fusion **40** (1998) 1429.
[15] Ida, K., et al., Phys. Rev. Lett. **86** (2001) 3040.
[16] Drevlak, M., Nucl. Fusion **38** (1998) 1409.

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