Reactor Configuration Development for ARIES-CS

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***Abstract*—New compact, quasi-axially symmetric stellarator configurations have been developed as part of the ARIES-CS reactor studies. These new configurations have good plasma confinement and transport properties, including low losses of α particles and good integrity of flux surfaces at high β. We summarize the recent progress by showcasing two attractive classes of configurations – configurations with judiciously chosen rotational transforms to avoid undesirable effects of low order resonances on the flux surface integrity and configurations with very small aspect ratios (~2.5) that have excellent quasi-axisymmetry and low field ripples.**

Keywords-stellarator; quasi-axisymmetry; fusion reactor; low aspect ratio; equilibrium flux surfaces

I. INTRODUCTION

Compact, quasi-axisymmetric (QA) stellarators, which combine features of good particle orbits typically found in tokamaks and MHD stable plasmas typically found in conventional stellarators, have attracted considerable interests in recent years. A proof-of-principle device, NCSX, the National Compact Stellarator Experiment, is being designed and operation is expected to commence in 2008 [1, 2]. A reactor studies project, ARIES-CS, is being conducted in parallel to examine critical issues of compact stellarators as power producing reactors and to find configurations that are optimized with respect to components critical to a reactor performance. [3]. One of the key elements in this project is to identify plasma engineering issues relevant to a compact stellarator reactor. These include plasma aspect ratios in relation to the attainable quasi-axisymmetry, α loss and its minimization, equilibrium and MHD beta limits and the quality of flux surfaces.

A design based on the NCSX physics but with coils re-configured to make it more attractive from the standpoint of a power reactor was reported in [4]. Methods to improve the confinement of energetic particles in NCSX-like configurations were discussed in [5]. We now have developed new classes of QA configurations after surveying the aspect ratio-rotational transform space to identify regions endowed with particularly interesting features. In particular, recent experimental results from stellarators W7-AS and LHD showed that, while MHD activities apparently existed and were active in some cases, the plasmas nevertheless were quiescent and remained quasi-stationary. The predicted MHD stability limits based on linear theories were surpassed. A beta of 3.5% was achieved in W7AS [6] and 4% in LHD [7], limited only by the available heating power and perhaps the integrity of the equilibrium flux surfaces. These results led us to design new configurations with more emphasis on the quality of flux surfaces and transport, particularly the confinement of α particles, than the limits placed upon them by the calculations based on linear MHD stability theories, as we have done before. The confinement of α particles is of importance in a fusion reactor because of its role in the power balance and because of the potential impact on the local heating and damage to the first wall, if escaped.

The integrity of equilibrium flux surfaces places a limit on the attainable beta because the Shafranov shift of the magnetic axis may cause flux surfaces to collapse if the pressure become excessive or the formation of magnetic islands may short circuit plasma confinement by allowing heat to flow along separatrix if low order resonances exist. If resonances are too close together, the fields may also become stochastic. The existence of rational surfaces can not be avoided in a stellarator. Most conventional stellarators are designed for the condition of zero net current, in which case the rotational transform at finite beta deviates from that in a vacuum only by the Pfirsch-Schluter current which is generally small. The vacuum transforms in these devices were normally chosen carefully to avoid low order resonances to guarantee good flux surfaces. In a QA stellarator, bootstrap currents of the magnitudes close to those in tokamaks are expected. Their presence modifies the overall rotational transform and the resulting shear that could be large would draw many of the resonances close to each other. The impact of the resonance on the flux surface integrity may be minimized by a carefully tailored rotational transform profile. In section II, we demonstrate the existence of such configurations that are also quasi-axially symmetric.

The fusion power output is proportional to $\beta^2B^4R^3/A^2$. A reactor with smaller aspect ratio allows for lower fields in coils and lower operating beta at a given power density. And for a given operating beta and magnetic field, a reactor of smaller aspect ratio will give higher power density, hence a smaller reactor for a given total power output. While the engineering constraints such as the neutron loading on the first wall may very well decide the most optimal plasma aspect ratio, the low plasma aspect ratio is always welcome from the power density standpoint. We have found a new class of configurations with two field periods whose aspect ratios are only ~1.3 per field period. Their low aspect ratios, good confinement of α particles and comparatively simple shape of the plasmas make this family of configurations the embodiment of the vision of compact stellarator reactors that could be economically competitive with other fusion confinement concepts. In section III, we show the characteristics of a family of such configurations, known as MHH2.

It is the purpose of this paper to show the existence of each respective class of configurations by showing specific examples in each class. In the process we hope to demonstrate the richness of the QA magnetic topology. These new configurations serve as the basis of systems studies from which optimal reactor parameters will be derived. Further configuration optimization, in terms of both physics and coils, will then be carried out for the reactor design based upon these optimal parameters.

II. CONFIGURATIONS DESIGNED FOR GOOD FLUX SURFACES

One way to avoid low order rational surfaces in a QA stellarator is to make the profile of the rotational transform due to plasma shaping a strongly decreasing function of radius so that when the internal transform is superimposed at a finite plasma pressure, the total transform will have a small but positive slope. When choosing properly, the total transform could be in a region free of low order resonance. The shear may be made small enough to maintain adequate spacing among remaining resonances to assure the ordered field line topology. The positive shear would ensure stability against tearing modes. One example of such configurations with aspect ratio 6 and three field periods is given in Fig. 1, where the shapes of the last closed magnetic surface are shown. The rotational transform profile is given in Fig. 2. When combined with the internal transform from bootstrap current at 6% β the total transform is expected to be 0.53 on the magnetic axis and 0.55 at the boundary with an overall shear of only about 5%. Here we assume an NCSX-like pressure profile [1]. There are essentially no low order resonances in this region. The second and third order resonances are near the magnetic axis which are unimportant for the quality of the flux surfaces. A calculation using the PIES code [8] which does not assume the existence of nested flux surfaces is given in Fig. 3. It illustrates the integrity and excellence of the flux surface at 6% β.

One of the pre-requisite of a QA configuration is, of course, the low non-axisymmetric residues in the magnetic spectrum

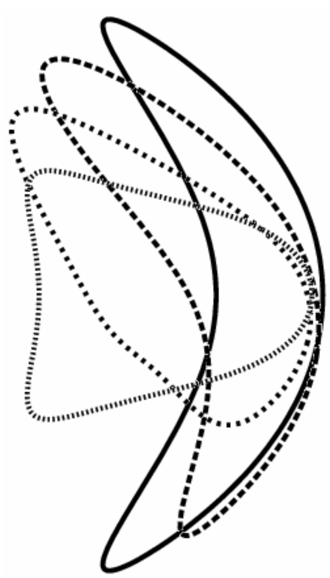

Fig. 1. The Last Closed Magnetic Surface (LCMS) shown in four equal toroidal sections in half a period for a three field-period, aspect ratio 6 configuration whose total rotational transform is designed to be nearly flat to avoid low order resonances, as shown in Fig. 2.

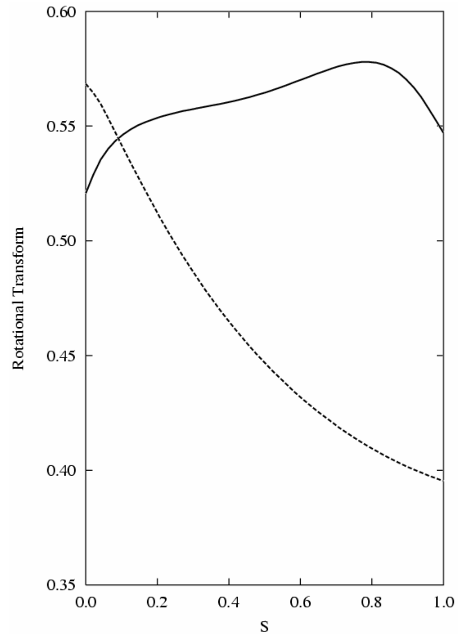

Fig. 2. External (dashed) and total (solid) rotational transform as function of the normalized toroidal flux S ($\sim r^2/a^2$) for the configuration given in Fig. 1. The total transform includes the internal contribution due to bootstrap currents equivalent to a magnitude of 0.043 MA/T-m expected at 6% β. Note that the total rotational transform lies between 0.5 and 0.6. The lowest order resonances are m=11, n=2, m=16, n=3 and m=17, n=3 per field period. They mostly appear near the axis where the size of islands will be negligibly small.

(the Fourier decomposition of the magnetic field strength in aspecialized straight field line coordinate-the Boozer coordinates [9]). Fig. 4 shows the radial profile of the eight components in the residue having the largest magnitudes. It is seen that all components are less than 1.8% and the non-axisymmety is mostly due to the helical terms, i.e., m/n=1/1 and 1/-1. Here, n is the toroidal mode number and m is the

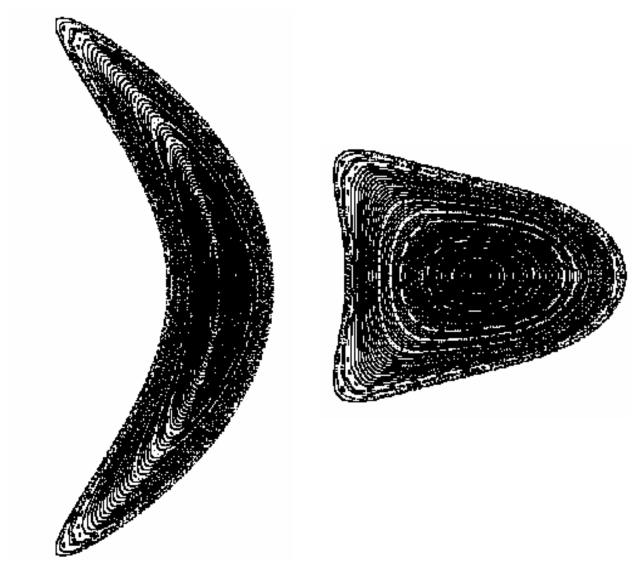

Fig. 3. Equilibrium flux surfaces at 6% β calculated by PIES viewed at the toloidal planes corresponding to the full and half period for the configuration given in Fig. 1, illustrating the excellent integrity of the flux surfaces.

poloidal mode number. This stands in contrast to configurations with high shears where the non-axisymmetry is mainly due to m=2, n=1 and m=3, n=2 terms. Indeed, the calculation of the so-called effective ripple as a measure of the effects of helical ripples on the neo-classic transport in the 1/ν regime [10] shows that it is less than 0.5%. As a result, the energy loss of α particles in a DT reactor is expected to be less than 10%, depending upon the size, magnetic field and operating temperature and particle density distributions.

The configuration is also designed to have a vacuum magnetic well on the order of 4%. A magnetic well is welcome for it tends to stabilize the interchange modes, making the configuration more robust to the MHD stability. The configuration may be further shaped such that it is stable to the calculated ballooning and external kink modes based on the linear theory predictions with some deterioration in the quality of QA [11].

The magnitude of the negative shear depends on the bootstrap current under consideration. For different beta or pressure profiles one would choose profiles of vacuum transform differently. We've shown that configurations, both in 2- and 3-field period, in ranges of 4 to 6% beta, of good QA exist in which low α loss may be achieved. For a given configuration, one must demonstrate, however, that it is possible to adjust the vacuum transform during plasma ramp-up, perhaps by auxiliary coils, to ensure the avoidance of low order rational surfaces throughout the entire discharge. The start-up aspect of the configuration design is to be studied.

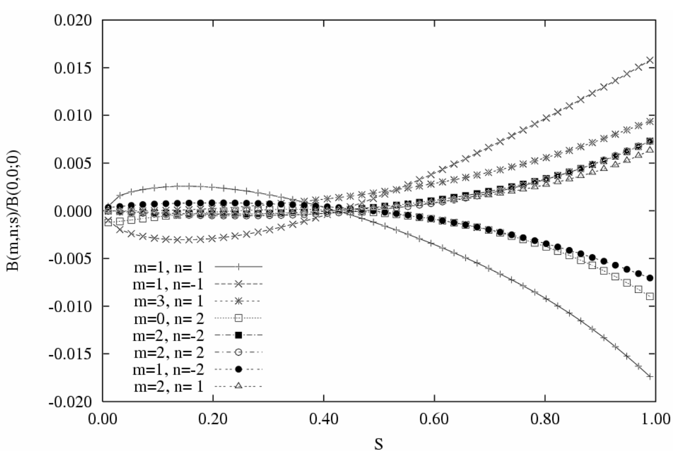

Fig. 4. Magnetic spectrum plotted as function of the normalized toroidal flux for the eight components having the largest magnitude for the configuration given in Fig. 1. Note that the maximum non-axisymmetric components are the helical terms and all are less than 1.8%.

III. CONFIGURATIONS OF VERY LOW ASPECT RATIOS

One of the advantages of quasi-axially symmetric configurations is that they can be designed with smaller aspect ratios. The low aspect ratios are not necessarily consistent with good QA, however. We have identified a class of 2 field period configurations, generally known as MHH2, that have aspect ratio of only 2.5, yet they possess excellent quasi-axisymmetry and very low field ripples.

Fig. 5 shows the LCMS of a typical example which is designed to have a nearly flat but slightly negative rotational transform profile ranging from 0.4 on the magnetic axis to 0.35 at the boundary. The configuration is also optimized such that it has good quasi-axisymmetry at 5% β with a rising rotational transform when taking into account the contribution from the bootstrap currents. Here we assume a linear iota profile increasing from 0.32 on the axis to 0.58 at the boundary without considering any specific pressure profile and collisionality upon which the bootatrap current, and therefore the total transform, will depend.

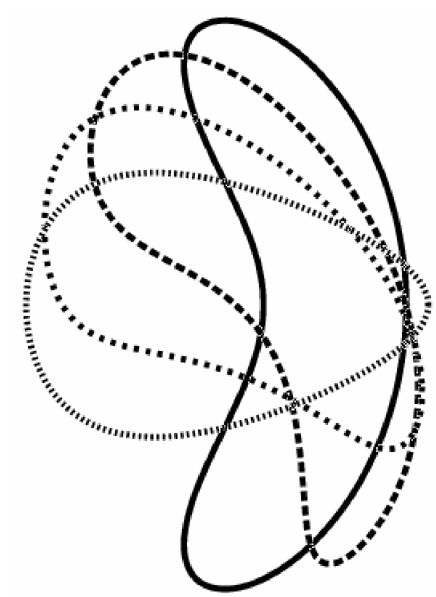

Fig. 5. The Last Closed Magnetic Surface (LCMS) in four equal toroidal cross sections over half a field period for an MHH2 whose aspect ratio is only 2.65.

The largest non-axisymmetric component (~1.7%) in the magnetic spectrum is the principal mirror, i.e., m/n=0/1. As observed in many of our configurations, the mirror term plays an interesting but not yet fully understood role in helping reduce bad orbits of α particles. Its presence does not make the overall ripple worse so that the neo-classical transport is very small compared to the anomalous. Examining the field line topology with an example shown in Fig. 6 suggests that the configuration has the desirable quality of QA. The so-called effective ripple, to which the neo-classical transport is directly correlated in the 1/ν regime, is less than 0.8% everywhere in the plasma. The model calculation of the energy loss of α particles is ~5% assuming a peaked birth distribution in a ~1000 m^3 reactor with 5 T field on axis in about one slowing down time, acceptable from the power balance as well as engineering design point of view. The flux surface quality is reasonably good at 5% beta, but the islands of intermediate mode numbers do show up and are made worse by the high magnetic shear from the bootstrap currents (spacing of neighboring resonance gets closer together). The rotational transform profile may be modified by the strategic use of external current drives to optimize the flux surface quality. The modified iota profile may also make QA better. An example along with the discussion of thermal transport and MHD stability may be found in [12].

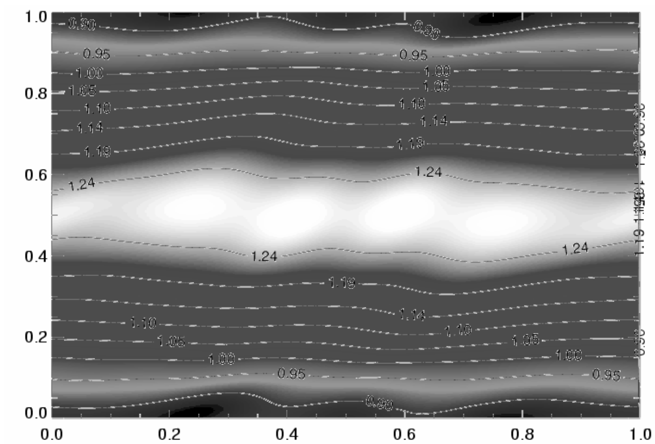

Fig. 6. Contours of magnetic field strength on the LCMS viewed on the normalized U-V plane, where $U=\theta/2\pi$, $V=2\phi/2\pi$, and θ and ϕ are poloidal and toroidal angles, respectively, for the configuration shown in Fig. 5. The contours show the quasi-axisymmetric characteristic of the magnetic field, but the effect of m=0, n=1 term is clearly visible in the inboard section.

IV. SUMMARY AND CONCLUSIONS

We have identified and developed new classes of quasi-axially symmetric configurations with attractive properties from the standpoint of power producing reactors for ARIES-CS. Taking advantage of recent experimental results which generally showed that the stellarator plasmas are more resilient to MHD perturbations than predicted by the linear theories, we searched the rotational transform-aspect ratio space for configurations endowed with better quasi-axisymmetry, lower α-particle loss and better integrity of flux surfaces at high equilibrium beta. We have found configurations whose rotational transform have small but positive shear even with a large amount of bootstrap current, making the avoidance of low order rational surfaces possible. We have also found configurations in two field periods having very low aspect ratios, making reactors of higher power density and smaller sizes likely. We showcased typical examples in this paper illustrating the general features characteristic to each class of configurations.

In addition, NCSX-like configurations with better quality of flux surfaces and confinement of α particles are also being developed [13]. Our extensive studies of the configuration space bring to light the richness of the QA magnetic topology and the flexibility in optimizing configurations to improve the plasma engineering performance. The most attractive configurations will ultimately be determined by results of systems optimization and constraints arising from engineering designs in addition to the physics and configuration considerations. To this end, we have included in our effort also the initial coil designs to ensure the realizability of the configurations we found (e.g., see [14]) and have provided configuration and coil parameters to the systems study to allow a better understanding of the optimal parameters for a competitive power plant [15].

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