New Classes of Quasi-axisymmetric Stellarator Configurations
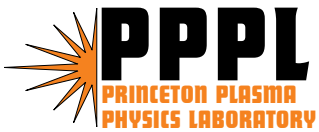
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New Classes of Quasi-Axisymmetric Stellarator Configurations

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Abstract

We have identified and developed new classes of quasi-axially symmetric configurations which have attractive properties from the standpoint of both near-term physics experiments and long-term power producing reactors. These new configurations were developed as a result of surveying the aspect ratio-rotational transform space to identify regions endowed with particularly interesting features. These include configurations with very small aspect ratios (~2.5) having superior quasi-symmetry and energetic particle confinement characteristics, and configurations with strongly negative global magnetic shear from externally supplied rotational transforms so that the overall rotational transform, when combined with the transform from bootstrap currents at finite plasma pressures, will yield a small but positive shear, making the avoidance of low order rational surfaces at a given operating beta possible. Additionally, we have found configurations with NCSX-like characteristics but with the biased components in the magnetic spectrum that allow us to improve the confinement of energetic particles. For each new class of configurations, we have designed coils as well to ensure that the new configurations are realizable and engineering-wise feasible. The coil designs typically have coil aspect ratios R/Δ_{min}(C-P) $\leq$ 6 and coil separation ratios R/Δ_{min}(C-C) $\leq$ 10, where R is the plasma major radius, Δ_{min}(C-P) and Δ_{min}(C-C) are the minimum coil to plasma and coil to coil separations, respectively. These coil properties allow power producing reactors be designed with major radii less than 9 meters for DT plasmas with a full breeding blanket. The good quasi-axisymmetry limits the energy loss of α particles to below 10%.

I. Introduction

Stellarators with quasi-axially symmetric (QA) magnetic field structure have attracted considerable interests in recent years. They are expected to have good particle orbits found in tokamaks and may be made passively stable to MHD perturbations found in conventional stellarators. A proof-of-principle device, the National Compact Stellarator Experiment (NCSX), is being designed and operation is expected to begin in 2008 [1, 2]. In parallel, a reactor studies project (ARIES-CS) is being conducted to examine critical issues of compact stellarators as power producing reactors [3]. It is under the auspices of this project that we made an extensive survey of the aspect ratio-rotational transform space to look for regions endowed with particularly interesting characteristics. We report in this paper the progress made in identifying new configurations with unique features of different emphasis that may be of interest from the standpoint of both power producing reactors and near term physics experiments.

NCSX is a highly optimized configuration in both physics and coil properties. The baseline plasma was chosen for its low aspect ratio (A~4.5), low non-axisymmetric residues in the magnetic spectrum (<2.5%), and good MHD stability characteristics in that it is calculated to be stable to the ideal infinite-n ballooning and external kink modes without close-fitting conducting walls at ~4% β based on the linear theories implemented in various computer codes [4]. The coils were designed with sufficient room to accommodate the scrape-off, vacuum vessel, diagnostics, etc., and with enough flexibility to accommodate a wide variety of operating scenarios. However, the configuration space is vast and complex. Possibilities exist that there are other configurations also having "good" properties. To look beyond NCSX, we asked ourselves: are there other configurations more attractive and what additional properties will make a quasi-axisymmetric stellarator (QAS) more attractive? We note that recent experimental results from W7AS and LHD showed that, while magnetohydrodynamic (MHD) activities apparently existed in these devices, 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 [5] and 4% in LHD [6], limited only by the available heating power and perhaps the integrity of the equilibrium flux surfaces. These results led us to focus particularly in three areas: minimizing the loss of α particles in a reactor, developing very compact devices and finding novel ways to assure integrity of equilibrium flux surfaces at high β.

It is known that the confinement of energetic particles in a QAS is sensitive to the ripple structure along magnetic field lines due to the long connection lengths. In a DT reactor, good confinement of α particles is of particular importance 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 they escape. While very low residues in the magnetic spectrum constitute a sufficient condition for good confinement, other constraints such as the local shear required for MHD stability may make the attainment of negligibly small residues impractical. We have found that by introducing a "designer's" principle mirror component in the magnetic spectrum of the magnitude ~1-2%, a QA configuration may be made much less susceptible to the loss of energetic particles and its ripple characteristics much improved. This leads to a new family of configurations similar in physics properties to those of NCSX but with significantly better particle orbits.

One of the advantages of QAS is that they can be designed with low aspect ratios. Lower aspect ratios generally lead to higher power densities and smaller sized devices. So the question is how low an aspect ratio a QAS can be? This investigation leads to the development of a new family of two field-period configurations, generally known as MHH2, in which the plasma aspect ratio A is only about 2.5 but they have superb quasi-axisymmetry. Moreover, a compact device requires not just the low plasma aspect ratio but also "compact" coils. We are able to design coils for some of these configurations that have the characteristics conducive to constructing compact reactors. The coil design optimization is made more challenging for MHH2 because the very low aspect ratio makes the real estate inside the donut hole more precious.

The integrity of equilibrium flux surfaces along with the MHD stability determines the attainable beta of a configuration. The formation of magnetic islands may short circuit confinement by allowing heat to flow along separatrix. If rational surfaces are too close together, the fields may also become stochastic. In a QAS, bootstrap currents of the magnitude comparable to those in tokamaks are expected, making the occurrence of these phenomena more likely. In this connection, we have devised configurations with carefully tailored rotational transform profiles to avoid the appearance of low order rational surfaces, leading to yet another new family of configurations whose rotational transforms are much like those in conventional stellarators.

For each of the new class of configurations, we have attempted to design coils as well to ensure that the configurations are realizable and engineering-wise feasible. The coil designs typically have coil aspect ratios $R/\Delta_{min}(C\text{-}P) \leq 6$ and coil separation ratios $R/\Delta_{min}(C\text{-}C) \leq 10$, where R is the plasma major radius, $\Delta_{min}(C\text{-}P)$ and $\Delta_{min}(C\text{-}C)$ are the minimum coil to plasma and coil to coil separations, respectively. The maximum magnetic field strength in the coil body is typically twice as large as the field strength on the magnetic axis for conductors having R~8 m and cross sectional areas 0.2 m^2. These coil properties should provide sufficient space for in-vessel components, instrumentation and diagnostics for near-term physics experiment. They should also allow designs of reactors of ~2 GW(th) with major radii < 9 meters when deuterium-tritium (DT) plasmas are used along with a full breeding blanket. The good quasi-axisymmetry typically limits the energy loss of α particles to below 10% for such reactors.

The configurations were developed and studied with the extensive use of numerical computation and optimization. In section II, we briefly discuss the approaches and optimization techniques for designing new configurations and coils. We discuss the three new classes of QA configurations in the remaining sections by showcasing selected examples for each. Section III presents a three field-period A~4.5 configuration with β~4% whose magnetic spectrum was chosen to improve the loss orbit of α particles. Section IV shows a two field-period configuration with A~2.65 at 5% β for which a set of modular coils have been carefully designed. It illustrates the feasibility of a very compact QAS. Section V presents a three field-period, A~6 configuration at 6% β whose shaping field is such that the rotational transform decreases rapidly away from the magnetic axis. Section VI gives a summary and conclusions.

II. Configuration Design and Optimization

Nuhrenberg et al. pioneered the stellarator configuration optimization [7]. In the development of NCSX, an efficient non-linear optimization package, STELLOPT [8], was developed. Configuration optimization may be made by either the Levenberg-Marquadt

algorithm or the genetic or the differential evolution techniques. VMEC [9] is used for the evaluation of equilibria. Function evaluations were made in parallel, in either the gradient calculations when the local gradient search algorithm is used or the "fitness" calculations when the genetic or differential evolution algorithm is used. We find that it is also very useful to examine plasma equilibria by the NSTAB code as well [10]. Optimization of plasma properties begins by an initial design of the last closed magnetic surface (LCMS). It is convenient to represent LCMS in the following form:

$$r + iz = e^{iu} \sum \Delta_{m,n} e^{-imu+inv} \tag{1}$$

.

where r and z are the radial and axial components of a cylindrical coordinate, *m* and *n* are the poloidal and toroidal mode numbers, *u* and *v* are the normalized poloidal and toroidal angular variables. The choices of the index *m*=1, 2 and 3 are associated respectively with helical, excursion, elongation and triangularity in the shape of the plasma, and *m*=-1 is associated with the crescent shape typically found in the Helias configurations [11]. In this notation the design of optimal configurations is facilitated by a more or less direct relationship between the quantities $\Delta_{m,n}$ and $B_{m,n}$ defined as

$$B(s) = \sum B_{m,n}(s) \cos(m\theta - [n - \iota m]\phi) \tag{2}$$

Here, ι is the rotational transform on a surface labeled by the normalized toroidal flux *s* and the Fourier decomposition is carried out in the Boozer coordinates [12].

The optimizer we built allows multiple "goodness" functions that can be "plugged-in" as individual modules. These modules include parameters concerning the basic properties (such as the desired amount of external rotational transform, the magnetic shear, magnetic well depth), measures of MHD stability (such as external kinks, infinite-n ballooning), and figures of merit for transport (such as effective ripples, diffusion coefficient evaluations, and collisionless loss of α particles). Typically, we evaluate the effective helical ripple to which the neoclassical transport is directly correlated by NEO [13], α-particle transport by the guiding center code ORBIT3D [14], the kink stability by Terpsichore [15], the ballooning stability by CORBA [16] and the thermal transport by TRANS [17].

Coils that reproduce the properties of the target plasma may be designed by requiring that the normal components of the magnetic field on the LCMS due to the coils cancel that due to the plasma current. Because of the discrete nature of coils, the normal field on the LCMS may not vanish exactly, but the errors may be minimized. Various techniques have been devised for this purpose [18, 19]. We used a three-stage approach: first, we solve for current potentials on a prescribed current carrying surface from which an initial set of coils is cut; second, we allow the winding surface geometry as well as the geometry of the coils wound on this surface to vary so as not only to minimize the field errors on the LCMS but also to enforce additional constraints, such as minimum separations to the plasma or to the neighboring coils, to optimize the engineering properties; and finally, we directly solve for the free boundary equilibrium and optimize both the physics properties (QA, α loss, etc.) and engineering properties aforementioned simultaneously instead of minimizing the normal field errors on the boundary defined by the original fixed boundary plasma to allow extra degrees of freedom to locate a "better" optimum using coil parameters obtained from step 2 as the initial condition. The last step is a complicated and difficult procedure, but it is necessary because of the complexity of

the coil geometry required to include all the essential harmonics of the magnetic field to yield needed plasma properties.

Typically, we represent coils parametrically as two dimensional Fourier series in terms of toroidal and poloidal angles on a winding surface. The winding surface itself in turn is represented as Fourier series in the toroidal and poloidal angles. This double representation has the advantage in that it allows one to choose the initial coil geometry in a more flexible and intuitive way. The initial choice of the winding surface is important since the optimization is highly non-linear and the configuration space is complex with many valleys and hills. The optimization is to find the "local" minimum of the penalty function we specified. There is no unique solution in this multi-dimensional optimization. An optimal solution is such that all constraints are satisfied and the penalty function is minimized.

For a DT reactor the tritium breeding and coil protection from radiation damage typically require a blanket and shield to have certain minimum thickness. We included the coil aspect ratio R/Δ_{min} (C-P) as a constraint in the design optimization, where R is the plasma major radius and Δ_{min} (C-P) is the minimum separation between the coils and the LCMS. In addition, we impose the constraints of coil separation ratio R/Δ_{min}(C-C), where Δ_{min}(C-C) is the minimum separation among coils, and the minimum radius of curvature in the coil optimization. We allow the coils to have different currents, but they have to maintain stellarator symmetry. Typically we search solutions for which the coil aspect ratio is <6, coil separation ratio < 12, and major radius to minimum radius of curvature <12. During the last stage of optimization in which free boundary equilibrium is solved, we vary the coil geometry as well as coil currents to minimize the non-axisymmetric "noise" in the magnetic spectrum, the effective ripples and the collisionless loss of α particles.

III. Configurations with Biased Magnetic Spectrum

In this section, we discuss a case where a bias is introduced in the magnetic spectrum. Fig. 1 shows the LCMS of a configuration with three field periods and A~4.5 in four equally spaced toroidal angles over half a period. The configuration has the characteristics of NCSX, i.e., contributions from the square and pentagon components in the plasma shaping which we find helpful in stabilizing MHD perturbations while at the same time maintaining good QA. It is characterized by $\Delta_{2,0}$=-0.25, $\Delta_{2,1}$=-0.41, $\Delta_{3,0}$=0.14, $\Delta_{-1,0}$=0.11, $\Delta_{3,1}$=0.15, $\Delta_{-1,-1}$= 0.17, $\Delta_{0,1}$=0.07, $\Delta_{3,2}$=0.06 and $\Delta_{4,0}$=-0.06, resulting an average elongation of ~1.7 and triangularity ~0.7. The rotational transform ranges from 0.44 on the magnetic axis to 0.48 on the LCMS, also similar to that of NCSX. The internal contribution due to the bootstrap current at 4% β makes the transform rise to ~0.67 near the boundary. The configuration is calculated to be marginally stable to the infinite-n ballooning modes and the external kinks at 4% beta, depending upon the pressure and current profiles.

The total non-axisymmetry measured by the square-root of the magnetic energy is ~3.6% at the edge of the plasma when normalized to the energy due to the axi-symmetric components. This is also similar to that of NCSX. But unlike NCSX in which the non-axisymmetry is primarily due to $B_{2,1}$ and $B_{3,2}$, here the main components are $B_{0,1}$ which amounts to ~1% near the core and ~2.5% at the edge and the helical term $B_{1,1}$ which is ~1.8% at the edge when normalized to $B_{0,0}$ at the magnetic axis, as shown in Fig. 2. The components $B_{2,1}$, and $B_{3,2}$ are now reduced to <1%. The presence of the mirror and helical terms does not make the ripple worse. The effective ripple calculated for this configuration is less than 0.6%, as shown in Fig.

3. A slowing down calculation for α particles indicates that this configuration has reduced the prompt losses considerably when compared to similar configurations without the biased mirror component. In Fig. 4 and 5 we show two typical characteristics of the lost α's: the cumulative fraction of the particle loss and the energy distribution of the escaped particles. These are derived from a Monte Carlo calculation using ORBIT3D with the conditions of 1000 m^3 volume, 6.5 T field, parabolic distribution for the background species, and the average collisionality parameter $nR/T^2 \sim 0.15$. Reactors based on this new configuration are likely to achieve α energy loss fractions $\leq 10\%$.

It appears there is a synergy of omnigeneity and QA in this class of configurations. $B_{0,1}$ plays a prominent role in the transport optimized devices W7X [20] and QPS [21], but in these quasi-omnigenous configurations the ratio of $B_{0,1}$ to $B_{1,0}$ is much larger, being 3-5 in W7X and greater than 1.5 in QPS. In our configuration $B_{0,1}/B_{1,0}$ is only about 0.2 for $r/a \geq 0.5$.
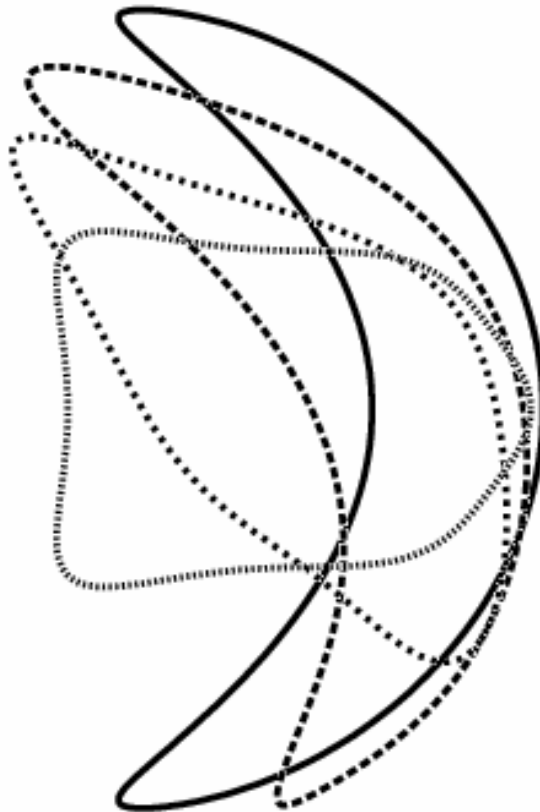

Fig. 1. The last closed magnetic surface of a three field-period, A=4.5 configuration whose non-axisymmetric residue in the magnetic spectrum is biased to have a prominent principal mirror component, as shown in Fig. 2.
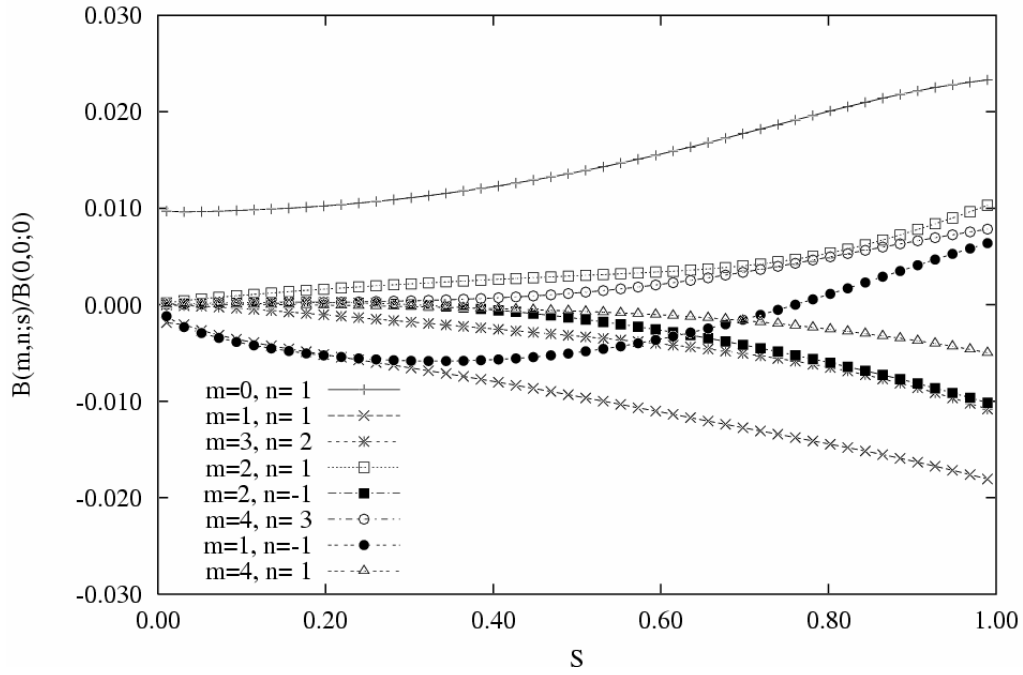
Fig. 2. Selected components of the magnetic spectrum plotted as function of the normalized toroidal flux for the configuration given in Fig. 1.
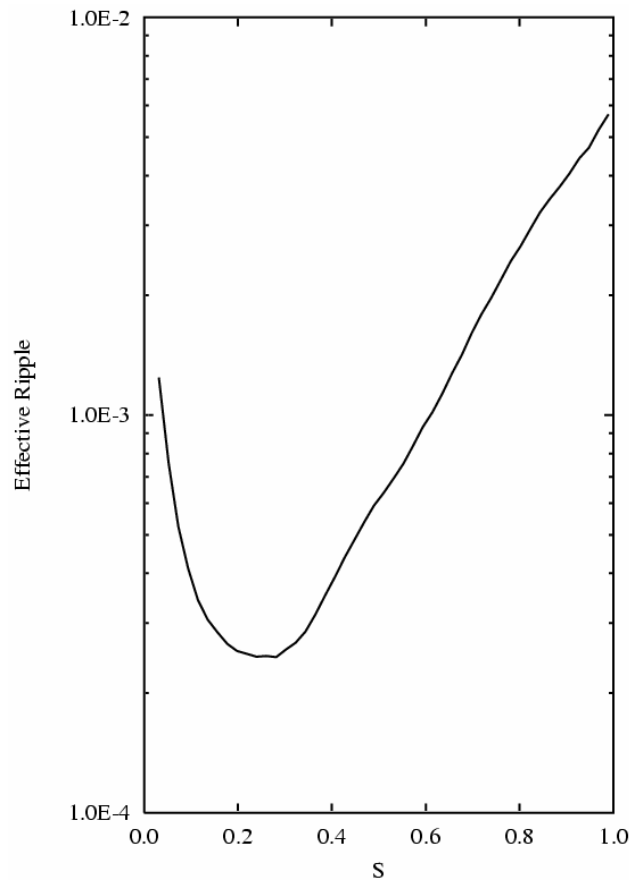

Fig. 3. Effective ripples, ε-eff, calculated by NEO as function of the normalized toroidal flux for the configuration with biased $B_{0,1}$. For bulk of the plasma (r/a<0.8) ε-eff is less than 0.1%.
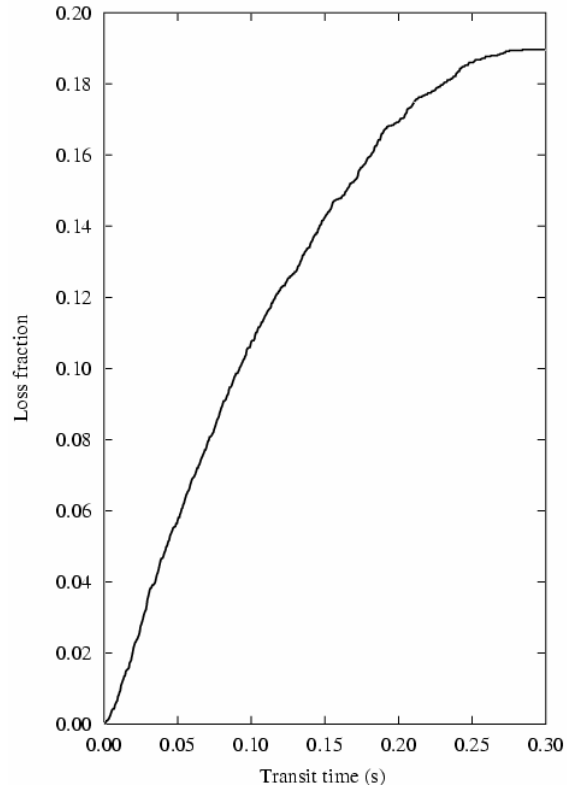
Fig. 4. Cumulative loss fraction of α particles in the model calculation for the configuration given in Fig. 1 plotted as function of transit times.
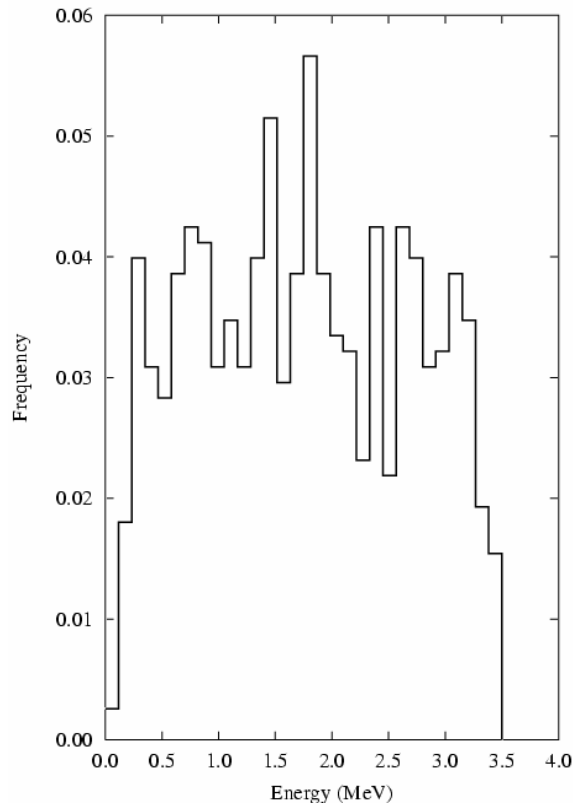

Fig. 5. Distribution of the energy of escaped α particles in the model calculation for the configuration given in Fig. 1, showing most losses are collisional.

IV. Configurations of Very Low Aspect Ratios

One of the advantages of quasi-axially symmetric configurations is their potential of being designed with low aspect ratios. It is not clear, however, how quasi-symmetry and the amount of desirable rotational transform relate to the lowest aspect ratio one can achieve. We have identified a class of 2 field-period configurations, generally known as MHH2, that have aspect ratios of only ~2.5 yet they possess excellent quasi-axisymmetry and very low field ripples. Fig. 6 shows the LCMS of an 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 may be described by $\Delta_{2,0}$=-0.12, $\Delta_{2,1}$=-0.42, $\Delta_{-1,0}$=0.15, $\Delta_{-1,-1}$=0.20, $\Delta_{0,1}$=0.025, $\Delta_{1,1}$=0.08, $\Delta_{1,-1}$=0.05, $\Delta_{2,2}$=-0.07 and $\Delta_{3,2}$=0.08. It is optimized such that it has good quasi-axisymmetry at 5% β with a rising rotational transform when taking into account the contribution of the bootstrap current. The non-axisymmetric terms in the magnetic spectrum are less than 1.5% with the principal mirror $B_{0,1}$ being the largest. The effective ripple (ε-eff), to which the neo-classical transport in the 1/ν regime is directly correlated, is less than 0.8% so that the neo-classical thermal transport should be negligible when compared to the anomalous. The configuration is expected to be stable to the ballooning modes at β~5%. More detailed discussions of the MHH2 configuration may be found in [22].

The attractiveness of this "ultra-low" aspect ratio MHH2 as a small-sized, compact device can be realized, especially for power producing reactors, only if coils can also be designed with sufficient compactness and with good engineering properties. For a DT reactor, sufficient space between the plasma and coils must be provided to accommodate the blanket for tritium breeding. Radiation shielding must also be in place for the protection of coils. If the ratio of the plasma major radius to the minimum separation between the plasma and coil winding gets too small, the shape of coils may become too complex. If the ratio gets too large, the size of the device may have to be increased to provide an adequate space and the device may become too big to be compact, irrespective of the compactness of the plasma itself. Fig. 7 illustrates a design of modular coils obtained by the three steps of optimization technique discussed in section II. There are four distinct types of coils in each of the half periods for a total of sixteen coils. R/Δ_{min}(C-P) of these coils is only ~5.5 and R/Δ_{min}(C-C) ~10. The ratio of the plasma major radius to the minimum radius of curvature is ~13. These coils are reasonably smooth but in the in-board region near the crescent at the beginning of a field period they are twisted to provide the shaping along the ridges. Our study seems to indicate that the coil aspect ratio of ~5 may be achievable, although the design is still being optimized.

To minimize the ripple from discrete coils, we initially prescribe the outer winding surface at a distance about twice the average minor radius. This enlarged space should help providing rooms needed for instrumentation, diagnostics, and remote handling and maintenance in the case of a reactor. Fig. 8 shows the selected components in the magnetic spectrum of the free-boundary equilibrium constructed using the VMEC code with 7 poloidal modes and 8 toroidal modes per period. Except for $B_{0,1}$, the maximum non-axisymmetric component has a magnitude of only ~1.1%. The energy loss of α particles at 5% β is ~5%, depending on the size, magnetic field strength and collisionality with the background electrons and ions. The magnetic field strengths along field lines, an example of which is given in Fig. 9, indicates tokamak-like characteristics with only minor secondary ripple wells on the high field side of the field lines.
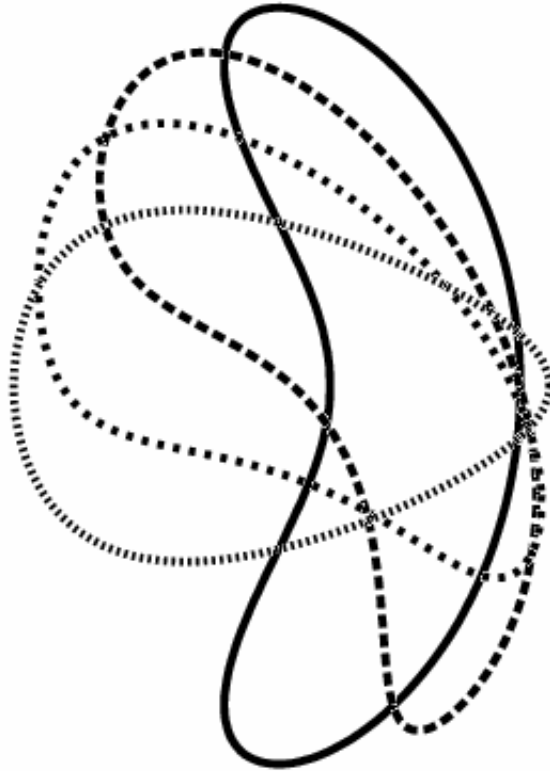
Fig. 6. The last closed magnetic surface of a MHH2 shown in four cross sections equally spaced over half a period.
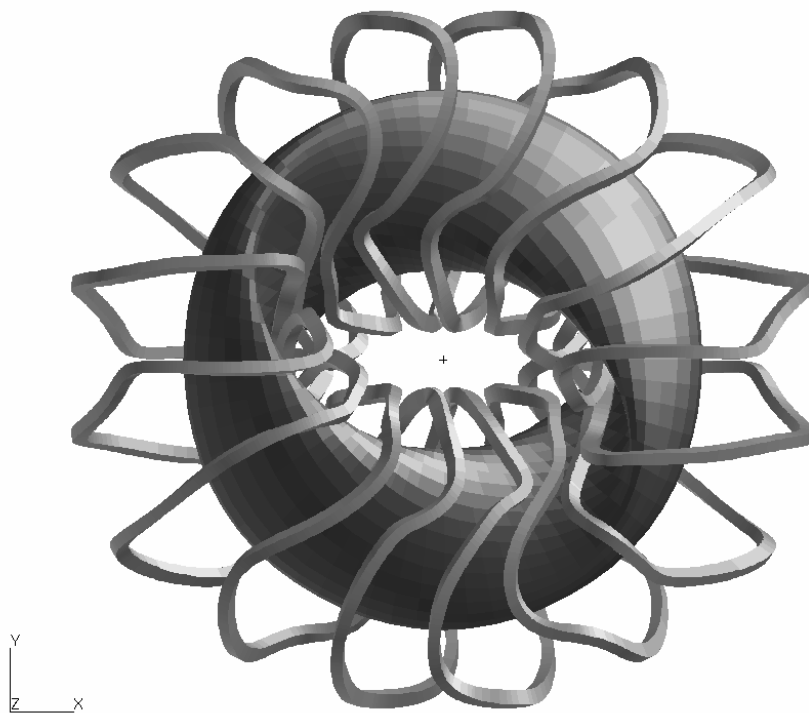

Fig. 7. Top view of a modular coil design for the MHH2 in Fig. 6 with coil aspect ratio 5.5.There are four distinctive types of coils for a total of 16 coils in two field periods.
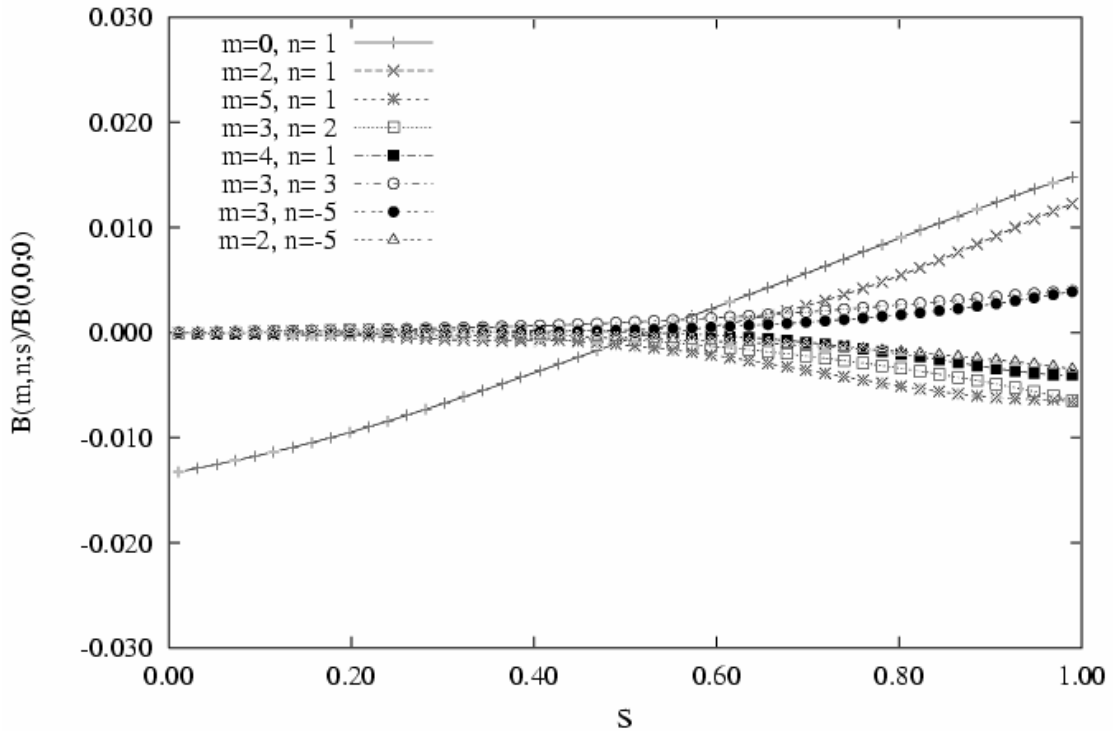
Fig. 8. Selected components in the magnetic spectrum of the free-boundary equilibrium constructed from the coils shown in Fig. 7 plotted as function of the normalized toroidal flux, S.
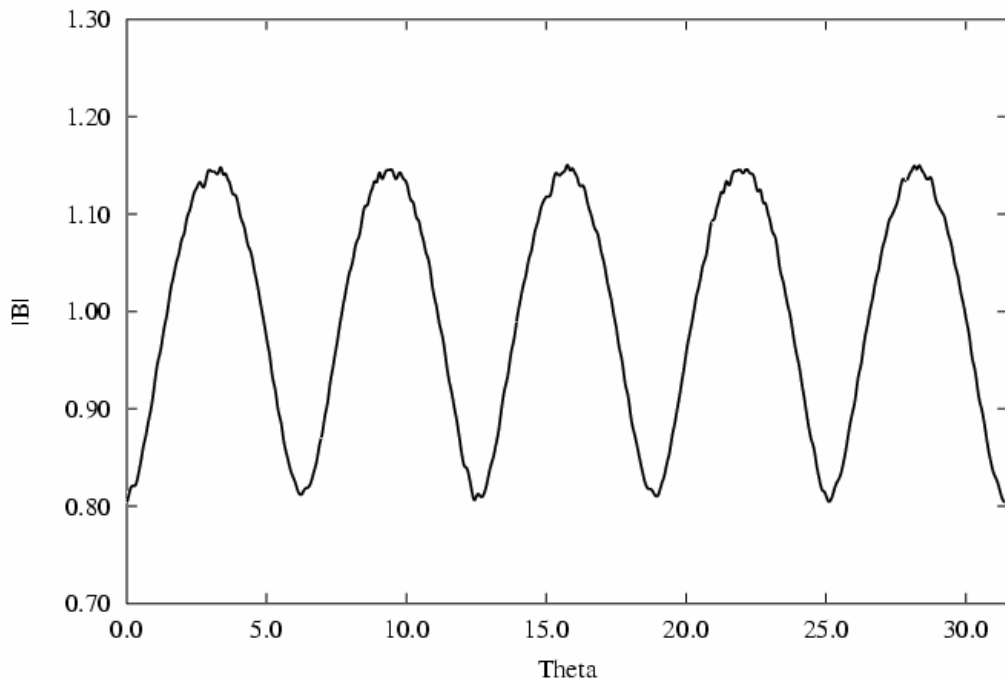

Fig. 9. Magnetic field strength plotted along a segment of field line on the surface at r/a=0.7 starting at ϕ=0, and θ=0, where ϕ and θ are toroidal and poloidal angles, respectively in Boozer coordinates.

V. Configurations Designed for Good Flux Surfaces

The integrity of equilibrium flux surfaces places a limit on the attainable beta of a configuration. The presence of bootstrap currents in a QA stellarator modifies the overall rotational transform which potentially could result in a large shear drawing many of the resonances close to each other. One way to avoid low order rational surfaces and to maintain proper spacing is to make the profile of rotational transform for plasma shaping a strongly decreasing function of minor 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 also be made small enough to maintain an adequate spacing among remaining resonances to assure an ordered field line topology. The positive shear should ensure stability again tearing modes as well. A three field-period example having an aspect ratio ~6 and optimized at 6% β is given in Fig. 10 and its rotational transform profiles are given in Fig. 11. This configuration is characterized by $\Delta_{2,0}$=-0.33, $\Delta_{2,1}$=-0.41, $\Delta_{-1,0}$=0.20, $\Delta_{-1,-1}$=0.18, $\Delta_{0,1}$=0.06, $\Delta_{1,-1}$=0.08, $\Delta_{1,2}$=-0.08, $\Delta_{2,2}$=-0.07, $\Delta_{3,0}$=0.17, $\Delta_{3,1}$=0.06 and $\Delta_{3,2}$=0.06. It has an average elongation of ~2, which is quite large. The external transform decreases rapidly away from the magnetic axis with $1/\iota \cdot \delta\iota/\delta s$~-0.5. The shear for the total transform, on the other hand, is only ~0.05. The equilibrium flux surfaces at the triangular cross section calculated by the PIES code [23] which does not presume the existence of nested flux surfaces is shown in Fig. 12, where we see the quality of the equilibrium surfaces is excellent, as expected.

The non-axisymmetric residues in the magnetic spectrum of this configuration are small. The main components are helical terms having magnitudes less than 1.8%. This stands in contrast to configurations with high positive shears where most often the dominant non-axisymmetric terms are $B_{2,1}$ and $B_{3,2}$. The effective ripple, which is a measure of the effect of helical ripples on the neo-classical transport in the $1/\nu$ regime, is less than 0.5%. 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 perturbation.

The magnitude of the negative shear from plasma shaping would have to depend on the amount of bootstrap currents. For different β or pressure profiles one would choose profiles of vacuum transform differently. We have shown that configurations having such characteristics exist for both 2 and 3 field periods and in ranges of 4 to 6% β [24]. For a given configuration, however, one must demonstrate 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 sequence. The start-up aspect of the configuration design is to be studied.
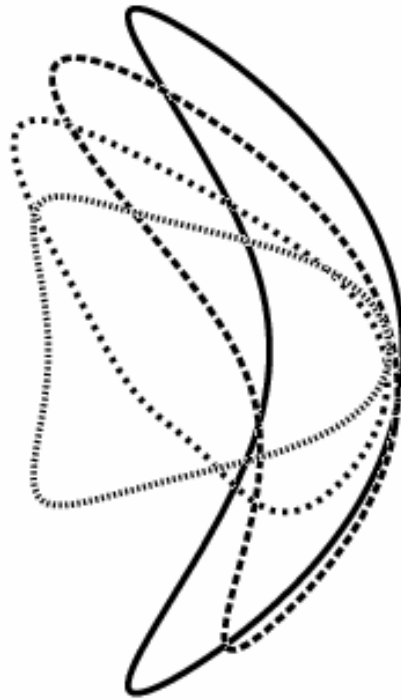
Fig. 10. LCMS of a 3 field-period, A~6 configuration. The shaping is such that the rotational transform decreases rapidly as the minor radius increases as shown in Fig. 11.
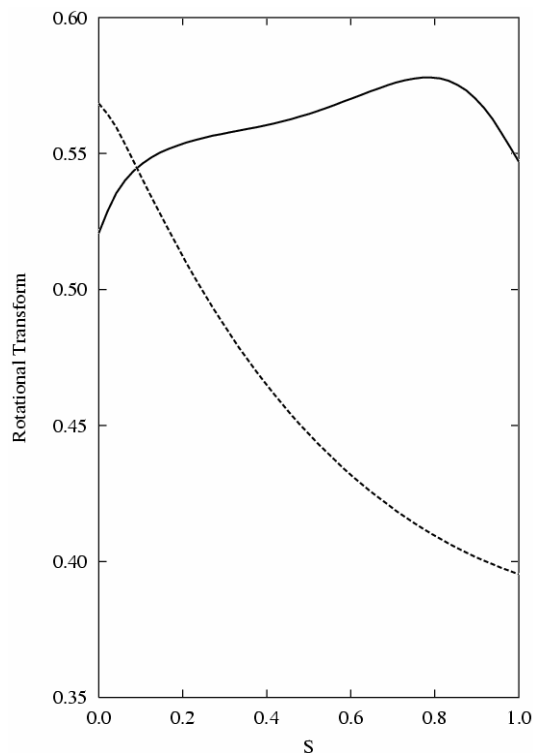

Fig.11. External (dotted) and total (solid) rotational transform as function of the normalized toroidal flux S ($\sim r^2/a^2$) for the configuration given in Fig. 10. The total transform includes the internal contribution due to bootstrap currents equivalent to a magnitude of 0.043 MA/T-m expected at 6% β.
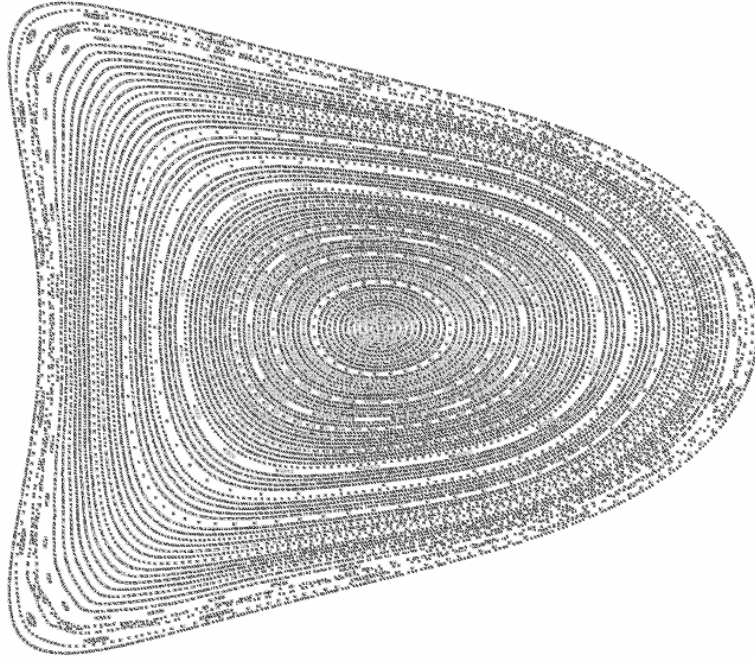
Fig. 12. Equilibrium flux surfaces calculated by PIES at 6% β viewed at the toroidal plane corresponding to the half period cross section for the configuration shown on Fig. 10.

VI. Summary and Conclusions

We have identified and developed new classes of quasi-axially symmetric configurations with attractive properties. We've showcased configurations whose rotational transforms have small but positive shear even in the presence of a large amount of bootstrap current, making the avoidance of low order rational surfaces possible. We have also found configurations in two field periods with very low aspect ratios, making reactors of higher power density and smaller sizes likely. We have found configurations in which the mirror term plays a profound but not yet fully understood role in improving the confinement of energetic particles. We hope that our studies of the configuration space have brought to light the richness of the QA magnetic topology and the flexibility in the configuration optimization.

Our focus has been to optimize configurations at a given state. There are many other important issues which are yet to be addressed. These include the startup and plasma control, beta limit and its optimization with respect to the temperature and density profiles, the effects of collisionality on the particle confinement, and the sensitivity and robustness of a configuration to the various assumptions in numerical calculations. And despite the progress we've made, there are still needs to further reduce the loss of α's in a QAS reactor and to make the integrity of flux surfaces more robust. We've found in many occasions that the ability to better meet these goals in configuration optimization is often compromised by other constraints such as satisfying the stability criteria based on the linear, ideal MHD theory. The fact that discrepancies have been observed in stability β between experiments and theoretical calculations may point to the issues of numerical methods in the linearized theory assuming the existence of simply nested flux surfaces. Experiments in coming years should be able to establish a physics data base that will enable further development of better QAS.

Finally, our methods of three-dimensional analysis are equally applicable to the analysis of non-axisymmetric perturbations of tokamak equilibria [25]. To this end, we are looking into the ramifications of various field errors on the confinement physics of the International Thermonuclear Experimental Reactor (ITER).

Acknowledgment

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