PHYSICS CONSIDERATIONS FOR THE DESIGN OF NCSX[1]

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Stellarators have several potentially significant advantages over tokamaks. These include: steady state operation without the need for current drive (with its large recirculating power requirement) and disruption free operation. However, present day and planned stellarators have very large aspect ratio and thus suffer an economic penalty due to low wall loading. In addition, due to ripple transport, conventional stellarators should be subject to very large energetic particle losses in the reactor regime.

A new experiment, the proposed National Compact Stellarator Experiment (NCSX), hopes to surmount these two deficiencies in stellarators. NCSX overcomes the deleterious ripple transport usually associated with stellarators in the reactor relevant regime by use of the quasi-axisymmetric configuration[1]. A quasi-axisymmetric configuration is one in which the Fourier spectrum of the magnitude of the magnetic field in so-called Boozer coordinates is dominated by the toroidal angle averaged ($n = 0$) components. The transport of particles depends only on the Fourier spectrum in Boozer coordinates and thus quasi-axisymmetric stellarator configuration have transport properties nearly identical to tokamaks (they would be identical if the $n \neq 0$ components were zero).

Overcoming the second deficiency, large aspect ratio, is related to the problem of MHD stability. W7-X, also a new concept stellarator, presently being construction at Greifswald, Germany, has an aspect ratio of ten. One of the reasons for this large aspect ratio is that ideal MHD instabilities limit the achievable β to below 5% as the aspect ratio is lowered below ten. Ideal stability is an even worse problem for conventional stellarators, ballooning stability in particular, limiting the β to something less than 2%.

The low aspect ratio NCSX uses a novel idea to overcome the ideal MHD limitations. It was realized that the configuration we would be seeking is, in Boozer coordinates, very close to a tokamak configuration, the main difference is that it would have no current drive. Thus, a good configuration to use to start our search would be a tokamak configuration, with a high ballooning β and well aligned bootstrap current. One well known configuration that satisfies

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these conditions is the ARIES-RS tokamak. ARIES-RS, was optimized using shape and pressure profile parameterization. It has a ballooning β = 7.5% and 90% bootstrap alignment. With this knowledge it is now quite simple to find a low aspect ratio stellarator with selfconsistent bootstrap current that is stable at high β to ballooning modes. An optimizer coupled with a 3-D equilibrium solver is asked to start with the ARIES-RS configuration and add non-axisymmetric components to the boundary in such a way that $|\mathbf{B}|$ spectrum in Boozer coordinates is mostly quasi-symmetric. To keep the optimizer from finding the tokamak solution, the current and pressure profile, and the $n = 0$ boundary harmonics are kept fixed and the optimizer is requested to find an solution whose surface transform is different from the tokamak's surface transform.

Figure 1 shows the outer boundary of a configuration produced using this procedure. The optimizer strategy that produced this configuration asked for 40% of the transform to come from the external coils. This configuration has the following properties: a stellarator aspect ratio of $R/ < a >= 2.1$, a ballooning beta limit of 5.3%, a maximum $n \neq 0$ spectrum in Boozer coordinates of less than 3.5% of the main toroidal field. The neoclassical energy confinement times are several times the ISS95 empirical international stellarator scaling for the ions.

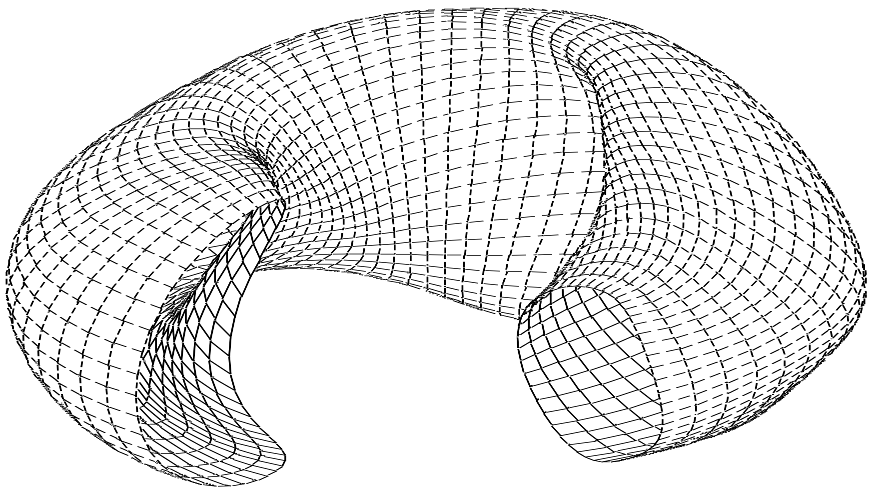

Figure 1. Last closed flux surface of a low aspect ratio, quasi-axisymmetric stellarator with 40% of the transform produced by external coils

At this point one might ask; What is the advantage of this configuration, when in fact the starting tokamak had a higher β limit? There are several significant advantages that stellarators, like the one shown in Figure 1, have over the ARIES-RS tokamak.

- The stellarator might be able to operate disruption free. Experiments have shown that when the externally generated transform is as low as 20%, disruptions can be avoided. When viewed as stabilizing coils added to a tokamak it is important to realize that they have been added in a way that does not spoil the good neoclassical confinement properties of the tokamak. We have found high β ballooning stable, quasi-symmetric configurations with external transform as high as 50%.
- The current drive in the outer portion of the stellarator plasma can be turned off, while

retaining good ballooning stability and quasi-symmetry. Current in the outer region is costly to drive and is necessary in the tokamak configuration.

- We have produced quasi-symmetric stellarator configurations that have monotonic negative shear profiles throughout the plasma. Negative shear is known to stabilize neoclassical tearing modes. These are instabilities which have been determined to be the cause of performance degradation in long pulse tokamak discharges. Monotonic negative shear can not be produced in an axisymmetric tokamak and instabilities, such as infernal modes, occur at the shear reversal layer in tokamaks with negative central shear.
- The ballooning instability is localized to the outside of the device and thus there is considerable headroom in the interior to allow an increase in the pressure gradient in there, and hence to increase β. We have also been able to go to higher β by flattening the pressure profile in the region of the ballooning instability.
- By adjusting the shear at the edge of the plasma, we have found that the configuration can be made stable to kink modes, with a wall one minor radius from the plasma edge. It is believed that stability with a wall at this distance means that the wall can be removed and stability retained. The ARIES-RS tokamak has a low critical β of about 2.5% to free boundary kink modes. Thus, a reactor based on the quasi-axisymmetric stellarator configurations under discussion here could dispense with the tight fitting shell and feedback schemes envisioned to stabilize kink and resistive wall modes in a reactor based on the ARIES-RS concept.

There are a number of issues that have to be addressed in order to arrive at a reference design for NCSX. A major issue is development of a configuration that can fit into the PBX-M device at PPPL. Because we must mount interior coils in PBX-M, the aspect ratio, must be larger than the configuration mentioned above. We have found it more difficult to find larger aspect ratio solutions that have all the desired properties: quasi-symmetry, negative shear, good volume utilization, bootstrap consistency and stability at high β to kink and ballooning modes. Our high β mark has been lowered to about 4% at the larger aspect ratio. However, we have recently found that addition of corrugation coils on the outside of the plasma greatly increases the stability with respect to the kink modes[2]. Since kink stability is one of the most difficult issues for us to deal with, the development of these corrugation coils has made us hopeful that a fully consistent solution can be found. Other issues we must resolve are those of startup and coil design modifications for the PBX-M device. The resolution of these issues is an area of intense activity for the NCSX physics design team.

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References

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