Progress in the Engineering Design of the National Compact Stellarator Experiment (NCSX)

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Abstract- The National Compact Stellarator Experiment (NCSX) is a proof-of-principle experiment whose objective is to demonstrate high beta operation in a quasi-axisymmetric stellarator.

NCSX will be housed in the Princeton Beta Experiment (PBX-M) test cell. Many of the existing site assets including the test cell, TF and PF coils, power supplies, neutral beam heating systems, and site utilities can be re-used, minimizing the cost of the project. Saddle coils are used in the reference design. The stellarator core is pre-fabricated and dropped into place on the PBX-M platform. The existing TF and PF coils are then reassembled around the stellarator core. Alternate coil topologies are also being explored.

INTRODUCTION

Compact stellarators have tremendous promise, combining the best features of tokamaks and stellarators:

- High beta (>4%) stability
- Excellent confinement
- No disruptions
- No current drive required for steady state operation
- No conducting wall or feedback system required to stabilize external kink modes
- Vertical stability without a conducting wall or feedback system, even in highly elongated plasma configurations
- Low aspect ratio resulting in high power density and improved economics

NCSX is a proof-of-principle experiment to demonstrate high beta operation in a quasi-axisymmetric stellarator. In this paper, we describe the present design concept for NCSX. Alternate coil topologies currently being studies are also described.

The proposed site for NCSX is in the Princeton Beta Experiment (PBX-M) facility. We plan to utilize existing assets including the test cell, toroidal field (TF) and ex-vessel poloidal field (PF) coils, power supplies, heating systems, diagnostic components, and site utilities, thereby realizing substantial cost savings.

PERFORMANCE REQUIREMENTS

NCSX is a proof-of-principle experiment to demonstrate high beta operation in a quasi-axisymmetric stellarator. To achieve high beta, the plasma must be stable to ballooning modes, external kink modes, and tearing modes. Ballooning mode stability is achieved by having strong axisymmetric shaping (high elongation and triangularity), like an advanced tokamak. External kink mode and tearing mode stability are achieved by having a monotonic, reverse shear iota profile, as shown in Figure 1.

In a quasi-axisymmetric stellarator (QAS), the magnitude of B is nearly independent of toroidal angle in Boozer coordinates. The magnitude of the magnetic field along a field line looks like a tokamak, increasing with decreasing major radius, as shown in Figure 2. Quasi-axisymmetry is desirable for providing good (tokamak-like) particle and energy confinement. Quasi-axisymmetry results in higher bootstrap currents than would be present in plasma configurations that are not quasi-axisymmetric. The rotational transform from the bootstrap current adds to the rotational transform from the external windings. However, the rotational transform from plasma current has positive (rather than negative or reverse) shear. Therefore, the external windings must provide sufficient reverse shear to assure that the rotational transform remains monotonic with adequate reverse shear.

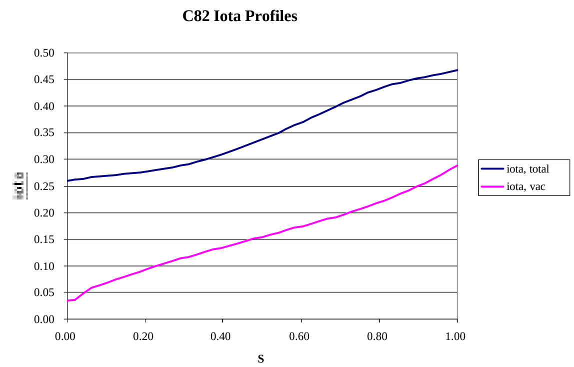

Figure 1 – Plasma rotational transform

NCSX plasma configurations are optimized by changing the plasma boundary to produce plasma configurations that are stable to ballooning, external kink, and tearing modes at a beta of 4% while preserving good quasi-axisymmetry. The plasma boundary was constrained to lie between radii of 1.05m and 1.85m, preserving the option of re-using the PBX-M TF coils.

A typical plasma configuration is shown in Figure 3. It features three periods. Three periods were favored over two because of increased edge shear. Three periods were favored

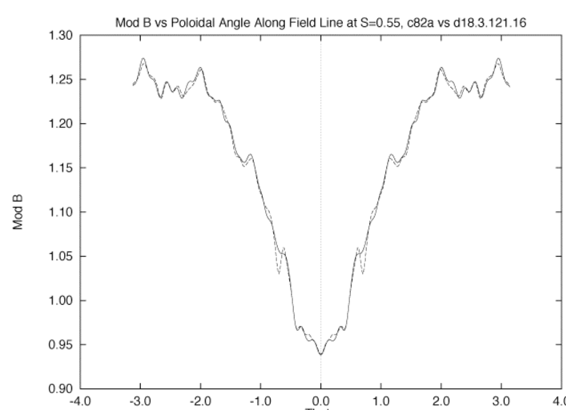

Figure 2 – Mod B versus poloidal angle

Figure 3 – NCSX plasma configuration

over four because of better quasi-axisymmetry. The nominal toroidal field is 1.2T at a major radius of 1.45m. This field is high enough to adequately confine PBX-M neutral beam ions. Yet, it is low enough for the plasma to be heated to 4% beta with only the PBX-M neutral beams (6MW at 50keV). For additional plasma heating, the device and facility are capable of being upgraded to accommodate 6MW of ion cyclotron resonant frequency (ICRF) power. A modest ECH system (0.1MW for 0.1s) is required for plasma initiation.

The nominal plasma current is 200kA. This is the bootstrap current that would be expected to evolve if the plasma collisionality was sufficiently low and the pulse length was sufficiently long. In practice, the plasma current will be inductively driven, allowing experimental flexibility in the magnitude of the plasma current and peakedness of the profile.

The experiment will be initially configured for a 0.5s pulse length. The limiting factor is the pulse length of the PBX-M neutral beams, which are limited to 0.3s. The experiment will be designed for a 3s pulse length, which would require an upgrade to the neutral beams. The 0.5s pulse length is adequate for the plasma to get to high beta. The 3s pulse length is required for profile relaxation.

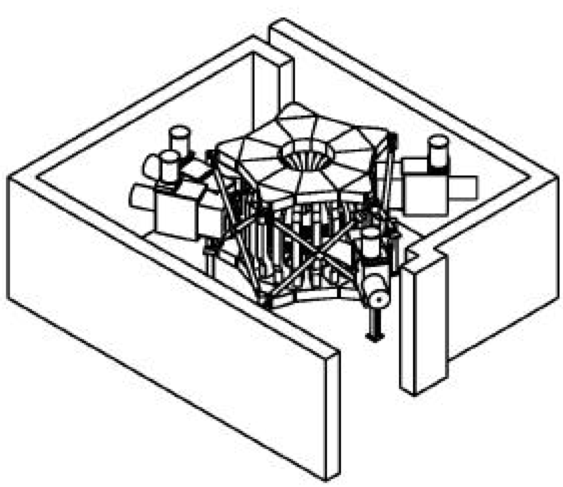

Figure 4 –NCSX in PBX-M facility

THE FACILITY

The PBX-M facility is the proposed site for NCSX because of the many site assets that could be utilized, resulting in substantial cost savings. The test cell itself is large enough to accommodate NCSX and four tangential neutral beams, as shown in Figure 4. The overhead crane has a capacity of 30 tons and can be upgraded to 50 tons without building modifications, if necessary.

The PBX-M tokamak has operated reliably with no areas of significant concern. PBX-M features 20 TF coils. These coils are capable of providing a toroidal field of 2T at 1.45m for 2s. At 1T, the flattop time would be 22s. Clearly, the TF coils provide ample field strength and pulse length.

The ex-vessel PF coils can be re-used in their present positions and should provide ample capability for inductive current drive and plasma position control. These PF coils were used on PBX-M for plasmas with higher current (600kA versus 200-400kA) and comparable beta (>5%) with an equivalent square wave (ESW) time of 1.5s. The OH coils (OH 1-9) provide 3 V-s of inductive current drive. The vertical field coils (EF 21-22) provide vertical field for radial position control. Although NCSX appears robustly vertically stable, radial field coils (EF-SOL, NF-12) are available for vertical position control. In-vessel PF coils can be re-positioned if desired, for axisymmetric shaping. All PBX-M coil power supplies are operational. If additional power supplies are required, TFTR power supplies from D-site could be utilized.

The four neutral beam lines can provide 6MW of heating to the plasma at 50keV for 0.3s. (The highest achieved output is 7MW.) These beams heated PBX-M to a beta of 6.8%. All beams will be oriented for tangential injection at an increased tangency radius of 1.5m (versus 1.3m).

There are currently six 2.5MW 30MHz 3s RF sources located at C-site. Although these are not used in the initial configuration of NCSX, they could be effectively used for the 6MW upgrade in ICRF power.

THE STELLARATOR CORE

The plasma is surrounded by a vacuum vessel that conforms to the shape of the plasma, as shown in Figure 5. The plasma facing surface is covered with carbon tiles to prevent the influx of high-Z impurities to the plasma. Low-Z vessel coatings are also being considered. In order to facilitate rapid recovery from vacuum openings and disruptions, the vacuum vessel will be bakeable to 350ºC.

Figure 5 – Vacuum vessel conformal to plasma

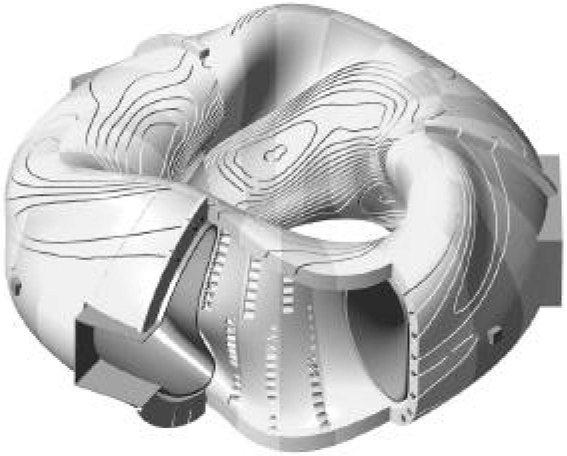

Figure 6 – Saddle coils wound in conformal shell

Several options have been identified for forming the Inconel vacuum vessel. These include brake forming, press forming, and explosive forming. All three options are being pursued to determine which is the lowest cost option with acceptable risk.

The helical fields are provided by saddle coils, as shown in Figure 6. The saddle coils are wound in grooves in a bronze shell. Bronze was chosen for its high strength; thermal and electrical conductivity properties; well-matched coefficient of thermal expansion to copper; and ease of casting and machining. The bronze shell is segmented with insulating breaks at the bolted joints to reduce the time constant of the lowest order eigenmode to approximately 20ms.

The grooves are pre-machined into the shell segments, which are then bolted together around the vacuum vessel to form a continuous shell. Cabled copper conductor with a rectangular cross section is would in grooves. Cabled conductor was chosen for ease of winding. The conductor is conduction cooled to the shell.

Each winding is a double pancake, as shown in Figure 7. The double pancake winding puts each turn in direct thermal contact with the shell. Concerns about field errors drove the winding concept. Numerous turns (typically 10 per coil) are used to keep the conductor current low, below 5kA. This is a double win. The low conductor current keeps the field errors small. The low conductor current also results in small conductor cross-sections, which keeps the field errors from joggles and transitions small.

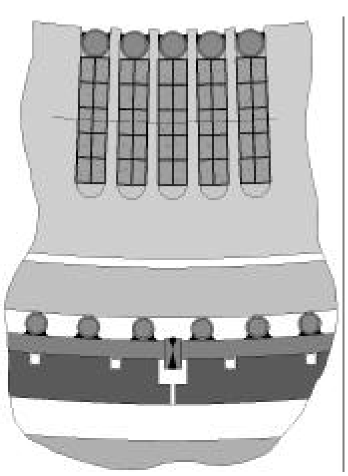

Figure 7 – Double pancake winding used in saddle coils

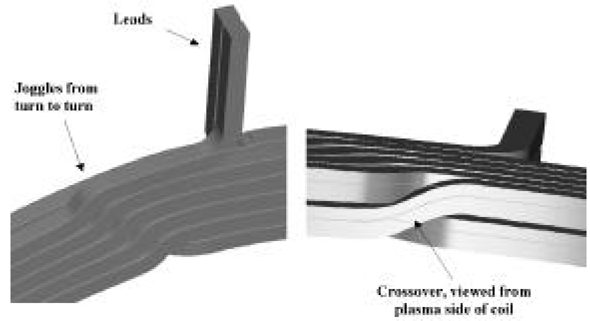

Figure 8 – Crossovers and turn-to-turn transitions in saddle coil winding

The double pancake coils are wound from the bottom with joggles to transition from turn to turn, as shown in Figure 8. Winding the coils in this fashion brings the leads together where they exit the coil, avoiding field errors due to uncompensated leads. Upon exiting the coil, the leads are joined to coaxial leads (to minimize field errors) which run along the shell to the outboard side of the stellarator core. Access to the leads from outside the machine provides flexibility for reconfiguring circuits.

The bronze shell and conductor are pre-cooled to LN_2 temperature (80K) between shots. The current density in the copper conductor is high, typically greater than $10kA/cm^2$. If the allowable temperature rise in the conductor is 50K, the ESW for water-cooled conductor would only be on the order of 1s. For LN2-cooled (adiabatic) conductor, the ESW is increased to 4s, as shown in Figure 9. R&D is underway to determine the maximum allowable temperature rise for the cabled conductor.

In order to prevent moisture from condensing on the cold shell and saddle coils, the shell and saddle coils are surrounded by a cryostat. The cryostat is sealed to the vacuum vessel to prevent the influx of moist air. The cryostat is currently envisioned to be a thin fiberglass structure with foam insulation operating with a 1 atmosphere dry nitrogen environment, as shown in Figure 10. However, a vacuum cryostat is also being considered.

Prior to constructing NCSX in the PBX-M test cell, equipment on the periphery of the tokamak would be cleared

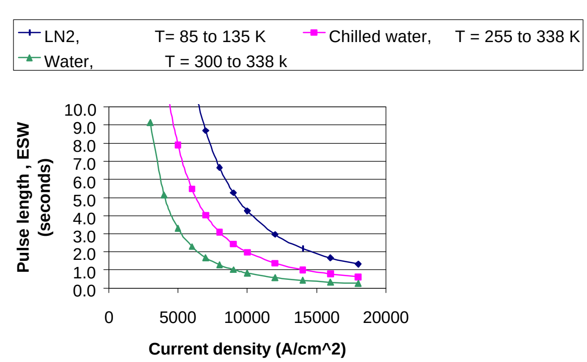

Figure 9 - Pulse length v. copper current density

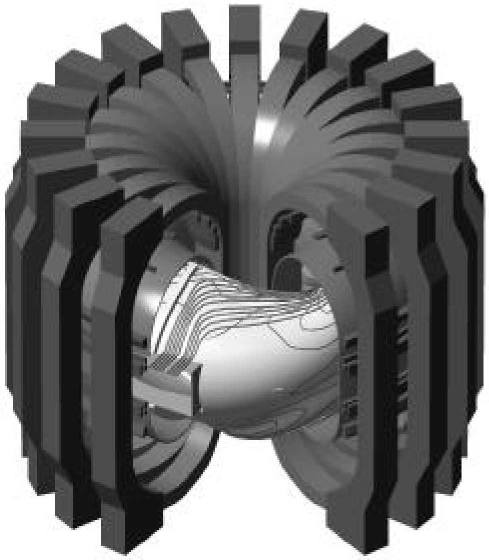

Figure 10 – TF and PF coils re-assembled around stellarator core

from the test cell. The upper shelf would be removed and the TF coils would be disassembled. The upper PF coils would then be removed followed by the vacuum vessel and internal hardware. The platform would then be ready for installation of the stellarator core.

The stellarator core would be fabricated and tested on site in the RESA building. Upon completion, the stellarator core would be transported to the PBX-M test cell for installation on the machine platform. The upper PF coils, TF coils, and upper shelf would be re-installed followed by the peripheral equipment. The completed assembly is shown in Figure 10.

ALTERNATE COIL TOPOLOGIES

Alternate coil topologies are being explored. The motivation for exploring alternate topologies is as follows:

- Lower current density (longer pulse length, higher field)
- Improved access
- Better surface quality
- Improved flexibility
- Simpler design, less risk, and lower cost

Candidate design options include:

- Fewer PBX-M TF coils
- Modular coils
- Helical coils
- Tilted TF (plus saddle) coils

Fewer TF coils should improve access for neutral beams and diagnostics, and eliminate symmetry conflicts. (PBX-M features 20 TF coils which do not have 3-fold symmetry.) Helical coils are the classical approach. Modular coils may be more reactor relevant. The most appealing option may be tilted TF coils.

Re-using the PBX-M TF coils in their present configuration results in a 1/R toroidal field. The saddle coils' job is to make the normal field on the plasma surface zero. The 1/R field from the TF coils results in large non-zero normal fields that the saddle coils have to null out. By tilting and interlocking planar TF coils, we should be able to reduce these normal fields substantially, thereby reducing demands on the saddle coils. It might even be possible to eliminate the need for saddle coils with the right plasma configuration. This concept is illustrated in Figure 11. Three planar TF coils actually form an l=3 helical winding! Each TF coil closes on itself with one poloidal transit per toroidal transit.

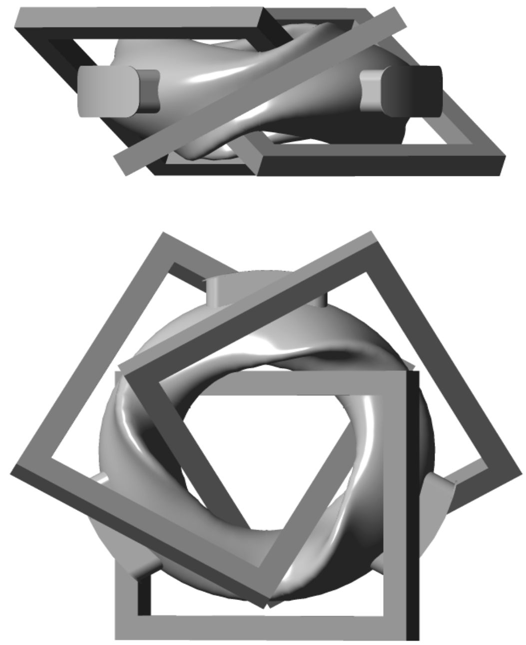

Figure 11 – Tilted and interlocked planar TF coils forming a helical winding

For all of these options, a vertical field will be required. We have been using the PBX-M ex-vessel PF coils for this function. However, the plasma is not circular. There may be substantial benefits in using wavy PF coils, either with varying Z and constant R or varying R and constant Z. These too, are being explored.

CONCLUSION

Compact stellarators have tremendous promise, combining the best features of tokamaks and traditional stellarators. NCSX is a proof-of-principle experiment to investigate quasi-axisymmetric compact stellarators. The initial design concept has been developed around the re-use of the PBX-M TF and PF coils with new saddle coils. Alternate coil configurations are being explored to reduce the current density in the new coils, improve access, provide cleaner magnetic surfaces, and improve flexibility.

The parameter space for compact stellarators is vast and relatively unexplored. NCSX is developing the tools and exploring the landscape to fully exploit the promise of compact stellarators.

ACKNOWLEDGEMENTS

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