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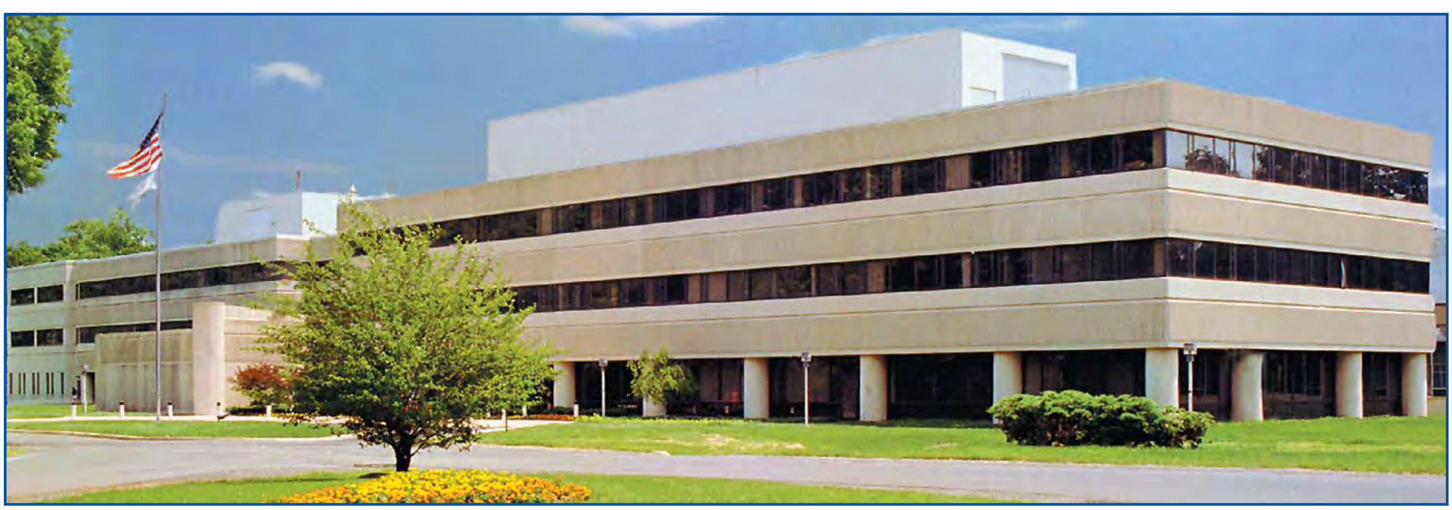

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Using e-beam mapping to detect coil misalignment in NCSX

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Following assembly of the NCSX device, a program of e-beam mapping experiments is planned to validate the accuracy of the construction and assembly of the NCSX coil systems. To aid in the development of requirements for the e-beam mapping hardware and machine requirements, simulations of the e-beam mapping experiments, including various coil misalignments, have been done. The magnetic flux surface configuration was constructed using a numerical code, based on the Biot-Savart law, to calculate the magnetic field components and trace the field line trajectory many times around the torus. Magnetic surfaces are then mapped by recording the field line intersections with toroidal cross-sections of the magnetic system, much as in an actual e-beam mapping experiment.

The NCSX coils were designed to provide good magnetic surfaces at high beta with significant bootstrap current. The coil set includes separately powered modular, toroidal, and poloidal field coils, and can produce a wide range of magnetic configurations. Many of the *vacuum* field configurations with low order rational surfaces have stellarator-symmetric islands present. In particular, configurations with an ι = 0.5 surface are found to be most sensitive to coil alignment errors and typically have a stellarator symmetric 3/6 island chain (the ι = 1/3 surface has been found to be much less sensitive to coil alignment errors). Nevertheless, despite the presence of these islands, configurations have been found which will allow, we believe, the identification of modular and poloidal field coil displacements of < 0.5 mm. In the course of these calculations, a catalogue of many hundreds of vacuum magnetic configurations was compiled, each with varying sensitivity to the coil displacements.

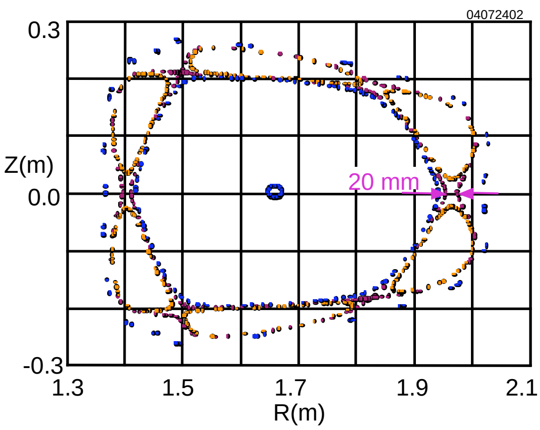

Fig. 1. K_{φ} *=1.05,* B_z*=6.47% (without PFC currents) Bo=1.7 T,* $\iota_0 = 0.448$, ι_{max}*=0.508, 1-st module displaced 1 mm.*

With three coil sets, connecting a measured field error to a specific coil misalignment is a challenge. Some progress in this regard has been made through the recognition that many useful vacuum configurations may be created by energizing only a subset of the field coils, *e.g.*, many configurations with good surfaces may be created using only the modular and toroidal field coils. This allows us to test first the alignment of the the modular and toroidal field coil systems without introducing potential error fields from the poloidal field coils. The situation is further improved in that most configurations are relatively insensitive to even moderately large toroidal field coil alignment errors. Thus, the e-beam mapping experiments are envisioned to begin with a vacuum configuration using only the modular and toroidal field coils.

An example of the potential sensitivity to coil alignment errors is the configuration shown in Fig. 5. In this configuration, the toroidal field coils provide roughly 5% of the toroidal field, just enough to introduce an $\iota = 0.5$ surface. In this calculation, a single module has been linearly displaced by 1 mm. The 3/6 islands have a width of about 80 mm, but with the shift of the module, at four of the six island X-points, the island separatrix is separated by approximately 20 mm. In a similar calculation for a displacement of 2 mm, the separatrix is displaced by ≈ 28 mm, following the qualitatively expected square root scaling. Following this scaling, a 0.5 mm displacement should result in an easily detectable 14 mm displacement of the separatrix near the island X-point. Previously achieved spatial resolution with the luminescent rod method[1] of the e-beam mapping were of order 5 mm.

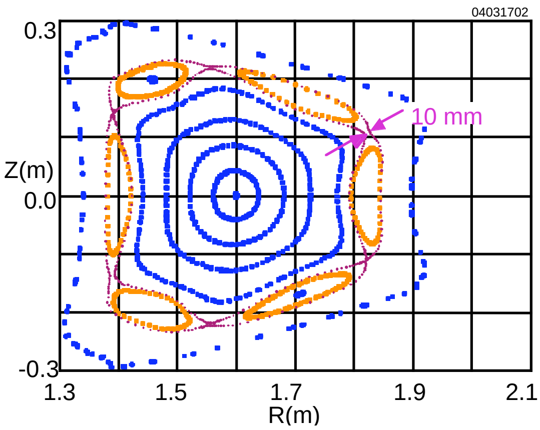

Fig. 2. $K_\varphi = 1.13$, $B_z(1.4) = 10.5\%$, $\iota_0 = 0.454$, $\iota_{max} = 0.52$, Toroidal Coil 1 tilted with angle 24'.

The e-beam mapping is similarly sensitive to displacements of the poloidal field coils. In Fig. 2 is shown a Poincaré plot for a configuration which is sensitive to poloidal field coil misalignments. For illustration, in this calculation the toroidal field coil was tilted by 24' (which corresponds to approximately a 7mm displacement). The flux surface near the separatrix is displaced by about 10 mm at four of the island X-points. For comparison, in Fig. 3 is shown the same configuration, but instead with the poloidal field coil tilted by only 2' (about 1.2 mm). In this example, the island separatrix is displaced by about 25 mm. In general, displacements of the poloidal field coils by less than 1 mm should be readily detectable.

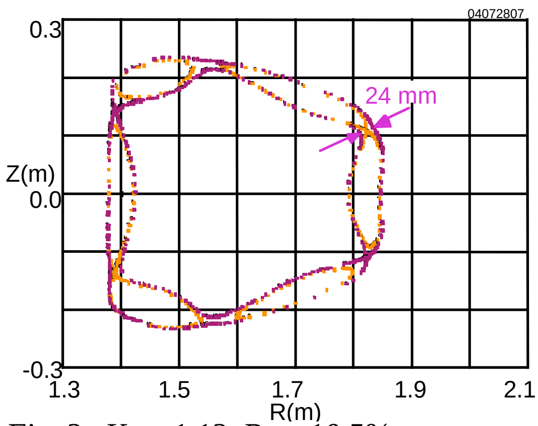

Fig. 3. $K_\varphi = 1.13$, $B_z = 10.5\%$, $\iota_0 = 0.454$, $\iota_{max} = 0.52$. PF6(upper) tilted with an angle of 2'.

The PF5 and PF6 coil pairs (the larger poloidal field coils) can be studied separately (without the PF3 and PF4 coils energized), and with even a single PF6 coil, a configuration can be created which has closed flux surfaces sensitive to coil misalignments. However, the misalignment of the PF3 and PF4 must be studied in conjunction with PF5 and/or PF6. Thus the e-beam mapping experiments will first verify the alignment of the modular coils, then PF5 and PF6, followed by PF4 and PF3. Then configurations will be studied to document the toroidal field coil alignment accuracy.

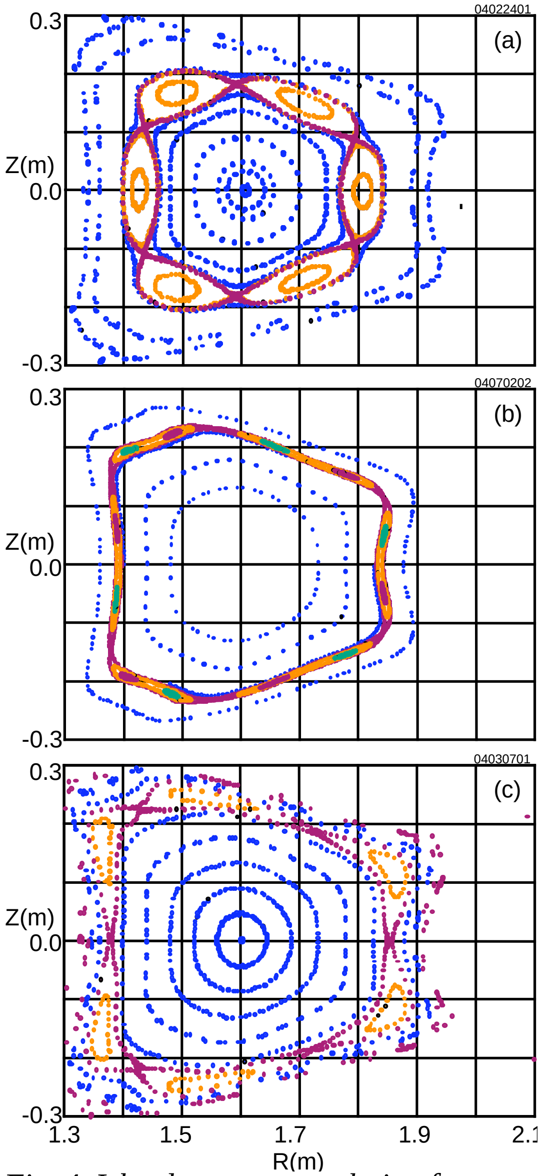

Fig. 4. Island structure evolution for vertical field strength of a) 9.84%, b) 10.06 and c) 10.2% of the toroidal field.

There is generally less sensitivity to displacements of the toroidal field coil, which is advantageous for both the study of poloidal and modular coil displacements, as well as for plasma operations. A novel approach to improve the sensitivity to toroidal field coil alignment errors is to energize a subset of the toroidal field coils at higher current. By using half of the toroidal field coils, at twice the current, it is possible to detect alignment errors of less than approximately 1 mm.

To further improve the e-beam mapping sensitivity to toroidal field coil alignment errors, a configuration where the vacuum islands are absent, and which contains an $\iota = 0.5$ surface has been identified. In Figs. 4a-c are shown three Poincaré maps illustrating the dependence of the 3/6 island phase on vertical field. The vertical field strength for each of these three calculations is a) 9.84%, b) 10.06% and c) 10.2% of the toroidal field. As the vertical field is increased, first the 3/6 island chain disappears, leaving behind a 6/12 island chain, then the 3/6 islands reappear, but shifted in phase by 180º.

The configuration in Fig. 4b with the relatively small islands would appear to be attractive for e-beam mapping experiments. In Fig. 5a is shown this configuration with one of the eighteen toroidal field coils tilted by 12’. In this example the flux surface is displaced by an undetectable amount. Increasing the poloidal field slightly, and using only nine toroidal field coils at twice the current, Fig. 5b, however results in a configuration sensitive to the toroidal field coil tilt. The flux surface in this case is displaced by ≈ 20 mm. Assuming the square root scaling, then a deflection of a toroidal field coil of less than 1 mm should give greater than 10 mm displacement of the flux surface.

The island-null configuration less sensitive to poloidal field coil tilts than the configuration in Fig. 3. As seen in Fig. 5c where a PF6 coil was tilted by 6’, the result was a 1/2 island with a width of about 33 mm. While this is acceptable sensitivity, recall that in the previous configuration, a tilt of only 2’ resulted in a 25 mm flux surface displacement.

This configuration has a second fault (besides low sensitivity), the island configuration is extremely sensitive to the vertical field. Very good current regulation of the field coil power supplies would be needed to avoid oscillation in time between the two anti-phase 3/6 island chains. The effect would be to blur this region in the e-beam mapping experiments.

Partly motivated by these observations, we have also investigated the possibility of performing the initial e-beam mapping (and possibly start-up) studies in NCSX using two or fewer power supplies for the coils in the magnetic system (18 MC + 6 PFC + 18 TFC). For example, the configurations studied so far used a separate power supply for each of the three types of modular coils. There is a potential advantage of minimizing the complexity and cost of the initial mapping phase. More importantly, reducing the number of power supplies reduces uncertainties in the field mapping introduced by ripple from current regulation in the power supplies. We find that good configurations may be found using a single source to power all of the modular coils in series. However, to include the most sensitive $\iota = 0.5$ rational surface it is necessary to add some current to the toroidal field coils (Fig. 6). In

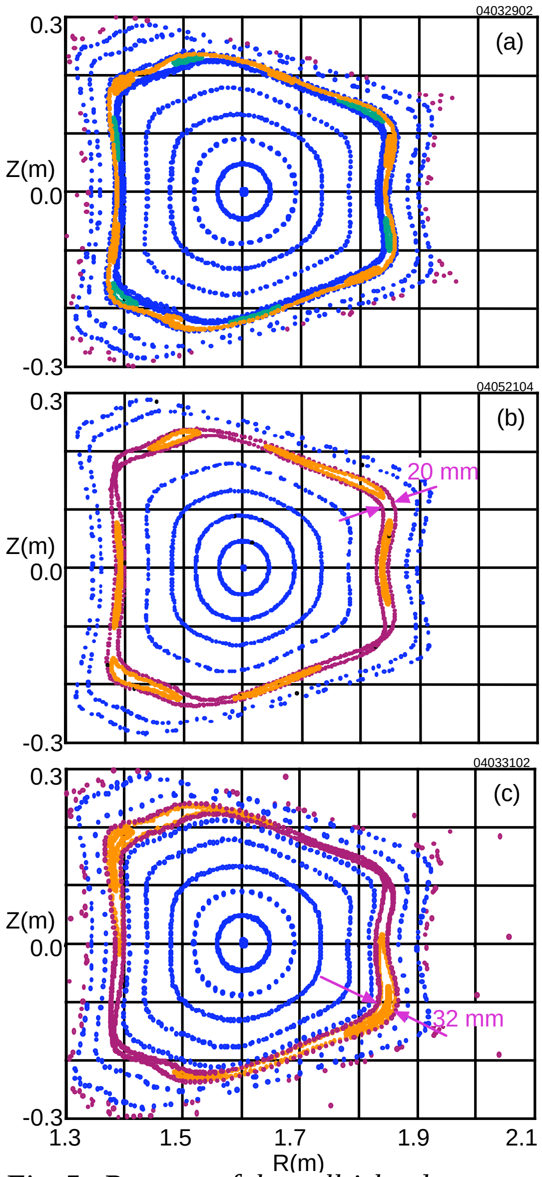

Fig. 5. Resonse of the null-island configuration to coil tilts: a) TF coil tilted by 12’, b) TF coil tilted by 12’, 9 TF coils at twice the current, c) PF6 tilted by 6’.

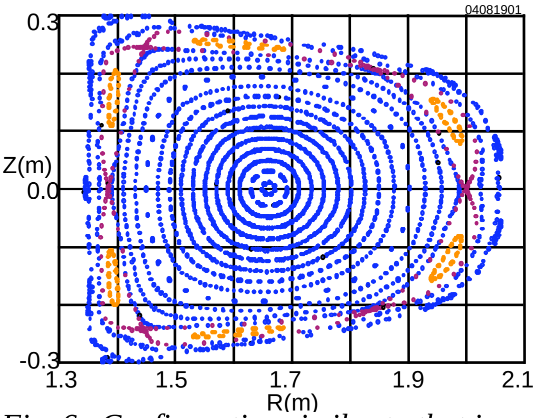

Fig. 6. Configuration similar to that in Fig. 1, but using same current in all modular coils. No current in the PF coils.

these configurations the previous sensitivity to coil displacements of order 1 mm is recovered. Future work will focus on developing methods to identify specific types of coil misalignments.

More extreme possibilities have also been explored. For instance, a reasonably large volume of good flux surfaces can be found using just one of the PF6 coil pair. The configuration is asymmetric, but does contain low order rational surfaces useful for testing of coil alignments.

In summary, configurations have been found which are sensitive to displacements of modular coils, poloidal field coils and toroidal field coils at the sub-millimeter level of precision (assuming that e-beam mapping can provide 5 to 10 mm accuracy in the flux surface measurements). Further, it seems possible to isolate the source of error field to at least the level of a particular coil set (MC, PFC or TFC), and for the PF coils, perhaps to individual coils. Further investigations will attempt to identify approaches to further isolate the source of error.

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