# Princeton Plasma Physics Laboratory

PPPL-4179 PPPL-4179

## Magnetic Alignment of NCSX and Control of Field Errors

M.C. Zarnstorff, N. Pomphrey,
and A. Brooks

June 2006

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

# PPPL Report Availability

## Princeton Plasma Physics Laboratory

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Fiscal Year 2006.

The home page for PPPL Reports and Publications is:

http://www.pppl.gov/pub_report/

## Office of Scientific and Technical Information (OSTI):

Available electronically at: http://www.osti.gov/bridge.

Available for a processing fee to U.S. Department of Energy and its contractors, in paper from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062

Telephone: (865) 576-8401

Fax: (865) 576-5728

E-mail: reports@adonis.osti.gov

# Magnetic Alignment of NCSX and Control of Field Errors

M.C. Zarnstorff, N. Pomphrey, and A. Brooks.

*Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA*

Careful elimination of magnetic field errors is crucial for optimum performance of stellarators and tokamaks. Resonant error fields produce islands in the magnetic topology, reducing confinement. Error fields also damp rotation and can cause MHD mode locking. In existing experiments, error fields due to millimeter-scale offsets between coils or misshaping of coils have produced measurable effects on the plasma confinement [1, 3]. Similar errors have been deliberately introduced to study their effect [2]. Low-order field errors are the most dangerous, due to their long radial decay lengths. To prevent them, coil positions and shapes are usually measured and aligned mechanically during construction. However, this may be inadequate due to the coil conductors being encased by insulation and support structures of variable thickness. In addition, tolerance errors can build up through multiple assembly steps, producing significant deviations. During operation, the magnetic field can be laboriously measured directly to search for errors [3] and, in stellarators, the resonant errors can be measured using electron-beam mapping [4]. However, once operation has begun, correcting coil misalignment may not be possible.

The National Compact Stellarator Experiment (NCSX) [5], currently under construction, is a three-period quasi-axisymmetric stellarator designed to study confinement and stability of high-beta plasmas. The helical field is created by 18 modular coils of three different shapes supplemented by 18 (weak) planar toroidal field coils and 6 pairs of poloidal field coils to provide shape control and experimental flexibility. A construction goal is that < 10% of the total flux be in magnetic islands. This requires accurate positioning of the coils taking into account their as-built shapes, particularly for the low order n=1-3 components of the magnetic field.

A novel technique has been developed to magnetically measure the relative deviations in the coils positions and shapes during assembly, when corrections are still possible. The general approach is to use field coils themselves as sensors by studying the mutual inductances between the coils and their self-inductances. If the mutual inductances were measured directly, the sensitivity would be limited by the ability to accurately measure and predict the absolute magnitude of the mutual inductances. Greatly increased sensitivity is available by measuring differences between mutual or self-inductances that should be identical due to design symmetries of the coil set. Measureing non-zero differences then directly indicates deviations in the location, orientation, or shape of the magnetic field from one or more coils and thus the coil conductors themselves. Since the number of mutual inductances and the null symmetric differences increases quadratically with the number of coils, this technique gives more information as the number of coils increases.

As an example, consider an array of $n$ toroidal field coils, as shown in Fig. 1. There are $n(n-1)/2$ independent mutual inductances and $n$ self-inductances. Each possible coil separation corresponds to a separate rotational symmetry group for the mutual inductances. For each group, there are $(n-1)$ linearly independent symmetric differences of mutual inductances of the logical form $M(i,j) - M(k,l)$ where $\text{mod}(j-i,n) = \text{mod}(k-l,n)$. If $n$ is odd there will be $(n-1)/2$ symmetry groups and a total of $(n-1)^2/2$ independent difference measurements. If $n$ is even there will be $n/2+1$ such symmetry groups and a total of $n(n/2-1)$ independent difference measurements, where the symmetry group of mutuals between opposing coils has a 2-fold degeneracy. For the array of Fig. 1, $M(4,6) - M(12,10)$ is one such symmetric difference. To achieve the highest sensitivity, a direct measurements of the combined inductance is desired. Since four coils are involved, the actual measuremets will a combination of four mutual inductances of the forms $M(i,j) + M(k,\bar{l}) + M(i,\bar{l}) + M(k,j)$ and $M(i,\bar{j}) + M(k,l) + M(i,l) + M(k,\bar{j})$, where the overbar indicates coil-reversal, the first coil in each combination is the drive coil, and the second coil is the detector. Together, these two phyical measurements provide both $M(i,j) - M(k,l)$ and $M(i,l) - M(k,j)$. The condition on $\text{mod}(k-l,n)$ ensures that both are symmetric differences. In addition, using an AC Whetstone bridge, the self-inductance of coils of the same shape can be compared to high accuracy, limited by the systematic uncertainty in balancing the bridge, providing $(n-1)$ additional independent difference measurements. Thus, if such a toroidal-field coil setassembly has more than 11 coils, the measured symmetric-differences between the mutual inductances in principle provide enough linearly independent constraints to determine the $6(n-1)$ relative separations and orientations of the coils. The differences of self-inductance and the additional mutual inductance differences if $n > 13$ provide information about differences between the coil shapes.

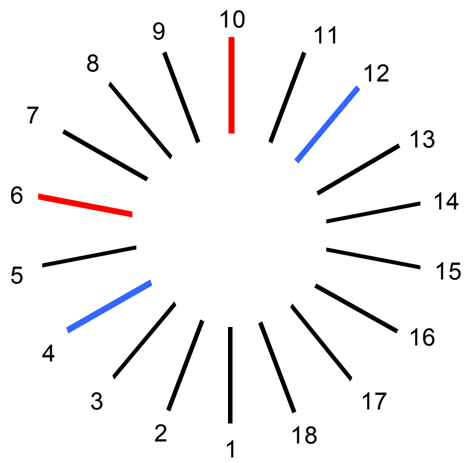

Figure 1. Array of 18 toroidal field coils.

For more complicated coil assemblies, careful counting of the symmetry groups is required to determine how much information is available. For example, in a tokamak with $p$ pairs of poloidal field coils, there are $p(p-1)$ linearly independent symmetric differences of mutual inductances between them, $p$ differences of self-inductance, and $2pn$ null mutuals between the poloidal and toroidal field coils. In a stellarator, each half-period is mirror symmetric to the next (stellarator symmetry). For modular coils, there are $2l$ coils of each shape (excepting any on the symmetry planes), where $l$ is the number of periods. Thus, most symmetry groups will have $(2l-1)$ linearly independent symmetric differences. The exceptions are groups that involve mutuals between mirror-symmetric coils or between coils on the symmetry planes, which have a 2-fold degeneracy and only $(l-1)$ members.

For the fully assembled NCSX, there are 48 field coils and 1002 linearly independent symmetric inductance differences, which provide constraint equations on the possible geometric deviations. Measuring the difference of these symmetric inductance differences from zero is sufficient to determine, in principle, the 270 relative location and orientation parameters for the coils and 732 relative coil-shape moments (~15.3/coil). The constraint equations can be inverted by linearizing around the design shapes and positions, assuming small deviations. Expanding the deviations in a Fourier series, or other representation, and linearizing, the matrix coupling the deviations to the expected change in the symmetric mutual inductance measurements can be calculated. For a truncated representation, this matrix can be directly inverted. More generally, the coupling matrix is analyzed using singular value decomposition to determine the number of moments that can be resolved with a given signal to noise level. If the perturbations in coil shape or location are large, the changes in the mutual inductances may no longer be linear, and a non-linear fitting procedure will be needed for accurate inversion.

In order to measure mutual inductances or differences between mutual inductances, one or more coils are excited by an time-changing current, and the induced voltages are measured on one or more coils. At high frequencies, eddy currents in surrounding structures (e.g. the modular coil structural shell) will modify the inductances. For NCSX, eddy current analysis of the structural shell found that the longest-lived eigenfunction had a lifetime (at LN temperatures) of 0.017 sec. The resistivity of stainless-steel does not depend strongly on the temperature. So, measurements at frequencies near or above ~60 Hz may be influenced by shell eddy currents. To measure the properties of the winding alone will require measurements at frequencies well below 60 Hz.

At frequencies where the impedence of the driven coils is dominated by the inductance ($f > 1$ Hz), the ratio of the detected voltage to drive voltage is $V_{out} / V_{drive} = M / L_{drive}$, where $L_{drive}$ is the self-inductance of the drive coil(s) and $M$ is the mutual inductance to the sense-coils. Since the general strategy is to measure deviations of $V_{out}$ and $M$ from zero, sensitivities of $V_{out} / V_{drive} \sim 10^{-6}$ appear easily accessible. Direct calculations of the linearlized coupling matrix for the NCSX coils indicate that 1 mm perturbations of the coil locations or shape cause changes in $M / L \sim 10^{-5} - 10^{-4}$. Thus, this method is expected to be able to measure relative deviations of the spatial allignment and shape with a resolution of 0.01 – 0.1 mm. The calculations indicate that this resolution can be achieved for either a modular stellarator or a tokamak coil set (toroidal and poloidal field coils alone). At this level of sensitivity, finite imperfections will likely be detected in all coils. Procedures to correct the alignment and positioning of the coils can be developed, but strategies for accomodating small higher order shape deviations remain to be investigated.

The assembly of the NCSX coil system will proceed in stages, starting with separate half-period modular coil sub-assemblies. It would be helpful to learn as much as possible about the shape, symmetry, and alignment of the coils at this early stage, while re-alignment is easy. Unfortunately, at this stage only six modular coils are available, providing only six linearly independent symmetric inductance differences. This is insufficient to determine the relative spatial separation and orientation of the coils. To provide additional information, a test jig, see Fig. 2, is introduced containing two arrays of saddle coils symmetrically mounted on a large G10 (or other insulating) cylinder, which is in turn symmetrically mounted on a G10 plate bolted between the field coils. The goal is to have the two ends of the cylinder be identical, with $n \sim 10$ identical coils each, arrange circumferentially. In addition, there should be a circular sense coil on the plate, concentric with the cylinder, for testing the alignment of the cylinder. Ideally, this coil should be located in the center of the plate, i.e. at the symmetry plane of the whole arrangement. Other equivalent locations for this coil are also possible.

For a test-jig assembly with 10 saddle coils/array and one circular loop, there are 241 linearly independent symmetric inductance differences between the sense coils. These are used to self-align and characterize the relative location and orientation of the sense coils and ~6 moments of their shape deviations. When the test-jig is combined with two half-period

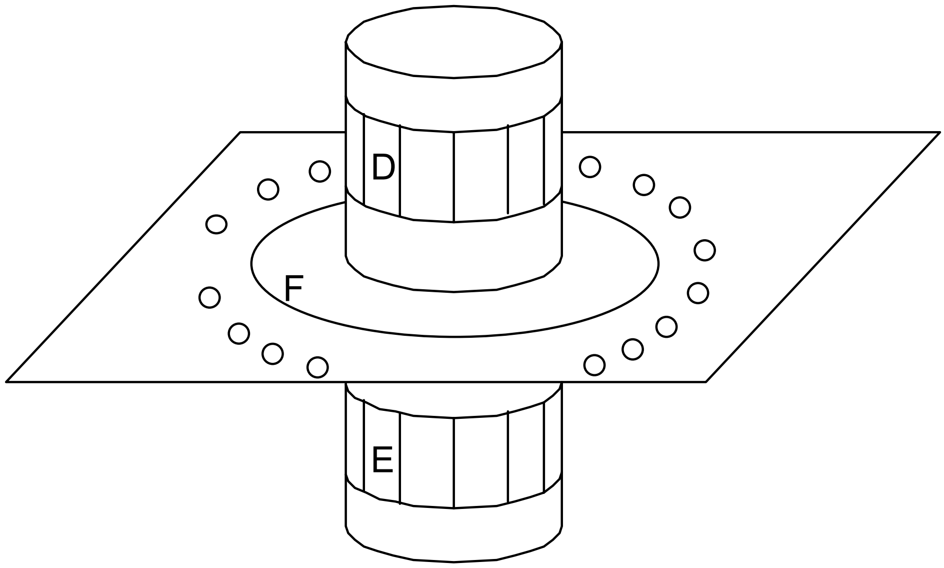


Figure 2. Test jig for aligning modular coil sub-assemblies. The jig contains two arrays of ~10 saddle coils (D and E) and one perpendicular loop (F) near the symmetry plane. The plate (with bolt holes) is for mounting the assembly between the modular coil sub-assemblies.

sub-assemblies of modular coils (six coils), there are an additional 72 symmetric inductance differences involving the modular coils. This is sufficient to determine the relative location and orientation of the modular coils and ~12 moments of relative shape deviation. If possible, each half-period set of modular coils will be compared to a fixed canonical set, to ensure proper alignment before full torus assembly. Linearized calculations of the coupling matrix between candidate test-jig arrangements and the NCSX modular coils again gives $M/L \sim 10^{-5} - 10^{-4}$ for the symmetric inductance differences and 1 mm perturbations, driving the modular coils. Thus, the sensitivity of the method for aligning the sub-assemblies is again in the 0.01 – 0.1 mm range.

Thus, analysis of symmetric differences of coil inductances appears to be a very powerful technique for determining the alignment, shape, and symmetry of arrays of magnetic field coils. Very high resolution is readily accessible. Straight forward methods can be used to extend the technique to align sub-assemblies during machine fabrication. This technique will be used to document the coil shapes for NCSX and optimize their alignment during assembly.

[1] J.T. Scoville and R.J. La Haye, Nucl. Fusion 43 (2003) 250.
[2] T.C. Hendler et al., Nucl. Fusion 32 (1992) 2091.
[3] J.L. Luxon et al, Nucl. Fusion 43 (2003) 1813.
[4] R. Jaenicke et al., Nucl. Fusion 33 (1993) 687.
[5] M.C. Zarnstorff et al., Plasma Phys. and Contr. Fusion 43 (2001) A237.

# External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Science Center, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, Hungarian Academy of Sciences, Central Research Institute for Physics, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Institute for Plasma Research, India
Dr. Pandji Triadyaksa, Fakultas MIPA Universitas Diponegoro, Indonesia
Professor Sami Cuperman, Plasma Physics Group, Tel Aviv University, Israel
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Instituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Laboratory for Complex Energy Processes, Institute for Advanced Study, Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Professor Toshitaka Idehara, Director, Research Center for Development of Far-Infrared Region, Fukui University, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Mr. Adefila Olumide, Ilorin, Kwara State, Nigeria
Dr. Jiangang Li, Institute of Plasma Physics, Chinese Academy of Sciences, People's Republic of China
Professor Yuping Huo, School of Physical Science and Technology, People's Republic of China
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Librarian, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Kazi Firoz, UPJS, Kosice, Slovakia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Dr. Rasulkhozha S. Sharafiddinov, Theoretical Physics Division, Insitute of Nuclear Physics, Uzbekistan
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Director, Research Division, OFES, Washington, D.C. 20585-1290

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov