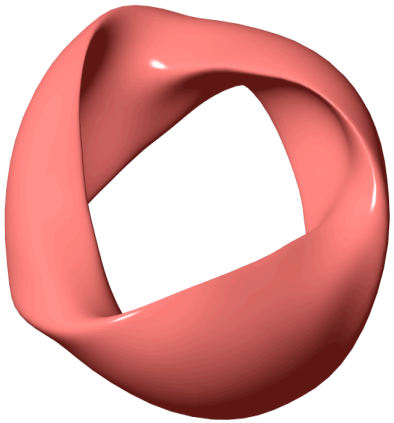
Design of Magnetic Equilibrium Diagnostics for NCSX



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presented by
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Motivation

- **Knowledge of the equilibrium is essential to understanding the underlying physical processes (stability, particle and energy transport). Also need the information simply to map other diagnostics to flux coordinates.**
- **Plasma control; as the current and pressure profiles evolve, the plasma boundary shape must be controlled so as to maintain stability and quasi-symmetry.**
- **The amount of detail in the internal profiles that can be extracted from external magnetics is not known. We want to explore this.**

Both of these are familiar problems in axisymmetric systems but they have not been explored to a great extent in stellarators. With the plasma current making a significant contribution to the transform and its shear and/or finite β these issues come to the forefront.

We expect that many of the magnetic diagnostics will be located in the space between the vacuum vessel and the coils. As such, they will need to be installed during the assembly of the device. Thus we need these diagnostics to be ready for installation prior to March 2006.

Outline of Design Process for Magnetics

- **Restrict ourselves to diagnostics that are nominally practical, e.g., their positions conform to physically realizable locations such as the vacuum vessel surface, the coils, the structural shell or the gap between the structural shell and the first-wall armor.**
- **Selection of Sensors**
  - » **Begin with a trial set of sensors and reduce the set to those of most importance.**
  - » **Transform to a linear algebra problem (Control Surface Problem) for choosing sensors from this set.**
- **Confirmation of Choices**
  - » **If we can reconstruct the equilibrium with sufficient accuracy, then plasma control can be done.**
  - » **Explicit control algorithms are not required to determine the sufficiency of the diagnostic set.**
  - » **The parallel issues of the redundancy needed and the detection of departures from stellarator and field periodicity symmetry will be considered separately from the choice of sensors.**
- **The issue of islands is not addressed in this work.**
  - » **I will briefly mention our plans in this area.**

Control Surface Problem

To choose diagnostics it is very convenient to formulate as a linear algebra problem. We create a database of VMEC free boundary equilibria that encompasses the range of plasmas that can be produced in the device.

A "control surface" (CS) is generated that surrounds the boundary of all equilibria in the database, with a minimum distance δ from the control surface to the nearest point on any of the equilibria.

The control surface is a vacuum surface. Thus the **B** field on this surface is completely specified if a single component is known.We choose $B_\perp$ the component perpendicular to the local normal and ϕ directions, i.e. B_θ in the axisymmetric limit.

Control Surface Problem (cont'd)

Next we need to produce a set of (s) of trial diagnostics. This includes:

1. An array of triple-axis B probes inside the vessel. The orientation is determined by the local normal to the surface (as if they were in a bracket that is to be affixed to the wall.
2. An array of saddle coils on the vessel surface.
3. An array of flux loops co-wound with the coil set.
4. An array of saddle coils on the structural shell (at each port penetration).
5. An array of toroidal flux loops outside the vessel.
6. An array of poloidal flux loops outside the vessel.
7. Rogowski coil and diamagnetic loop.

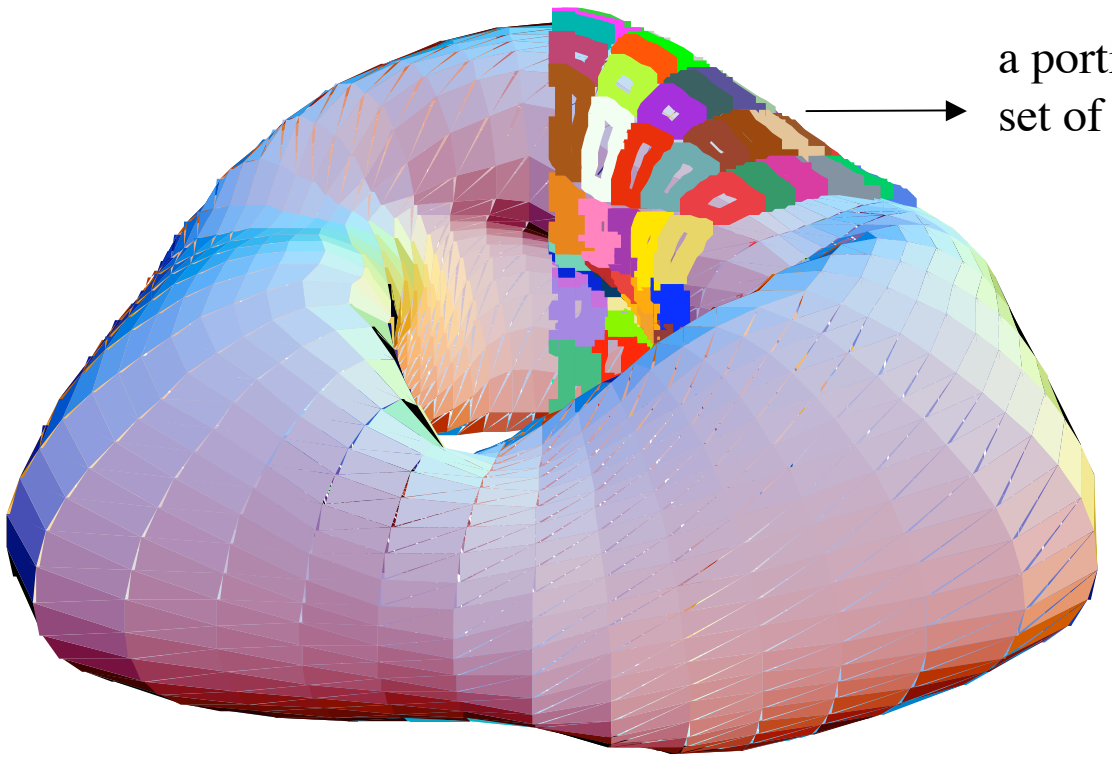
Our trial set has about 400 sensors and we need to develop a selection process to eventually reduce this by 50 or 75%.

Control Surface Problem (cont'd)

- The adequacy of a given diagnostic set (s) is determined by linear analysis. Considering some large set of equilibria, there is a matrix **S** of $B_\perp$ values on the control surface and a matrix **D** of magnetic measurements and these are linearly related: $\mathbf{S} = \mathbf{C}^{(s)}\,\mathbf{D}^{(s)}$ in a least-squares sense.

- For particular diagnostic subset, s=s1, $\mathbf{D}^{(s1)}$ is a good predictor of the expected range of equilibria if, for the given **S**, a matrix $\mathbf{C}^{(s1)}$ can be found such that the norm, $|\mathbf{S} - \mathbf{C}^{(s1)}\,\mathbf{D}^{(s1)}| \equiv \varepsilon^{(s1)}$, is not too large compared with $\varepsilon^{(s)}$. Note the solution to the problem gives us information about what linear combinations of diagnostics are important. The elimination of actual diagnostics involves looking in detail at the structure of these eigenfunctions.

An example - the array of saddle coils on the vessel surface.



- **We expect from the control surface problem to find which in this saddle array contribute to our knowledge of the plasma.**
- **Based on this some will be eliminated and others combined into larger saddle loops.**

Database of Equilibrium

- We need # equilibria >> #candidate diagnostics ~ 400 to allow selection of diagnostics.
  - Since this is a major undertaking, we decided this was the point at which we should switch to the M50 coil set. (The one actually being built.).
  - We began with the set of equilibria from the flexibility studies and modeling of discharge evolution done with an older coil set. This gives us quite a variation in pressure and current profiles and boundary shapes. About 30 of each are combined in a random fashion to create targets for STELLOPT runs. We also add random multipliers to plasma current and β.
  - We are using the multifilament coils file (c08r01) to get a more accurate calculation of the coil contribution to the signals.
- Jobs are run continuously on ~~Seaborg~~ and the Petrels to generate equilibria. Each case is about 24 hours using 14 processors.
  - At present we have generated 505 equilibria of which 292 are acceptable (fit in the vacuum vessel). We need several thousand.
  - Results are kept in an SQL database and are expected to be more widely useful than this design process; it will encompass virtually every plasma that can be created in the device.
  - The scripts to keep all this going are pretty well debugged and at this time.
  - The creation of the database will require ~ 10^6 cpu-hrs

Much progress has been made.
Lots still to be done.

- While the critical tasks require a large database of equilibria for the final (M50) coil set, we have been able to develop our tools on a trial database of ~110 equilibria that resulted from the flexibility studies and the discharge evolution modeling, using an older (M45) coil set.
- New additions to STELLOPT that allow generation of the M50 database are complete
- V3RFUN and V3POST (response functions and signals) and have been tested with magnetic diagnostics generated for the M45 coil set.
- STELLOPT is running on the Beowulf cluster generating the M50 database
- Programs for generating magnetic diagnostic arrays in the local coordinates of the device have been written and tested.
- Tools for generating solutions to the CS problem have been tested.

Equilibrium Reconstruction

- Having obtained one or a few reduced sets, the ultimate test is can we reconstruct the equilibrium to acceptable accuracy.
  - » Defining acceptable here is not yet clear, but perhaps the first and second moments of the pressure and current density will suffice along with the plasma boundary.
  - » From our discharge evolution studies we do know the required accuracy, but not how to parameterize it.
- The ultimate test of the adequacy of a reduced set of magnetic diagnostics is adequate reconstruction
- We can initially do this work by incorporating the response function formalism into STELLOPT. (Coding has been done.) This may not be computationally efficient, but we are confident it will work.

Summary

- Dynamic control of the 3D plasma shape will be required for NCSX to meet its mission.
- To proceed towards solution of this problem, codes have been developed to compute magnetic signals using a response function formalism.
- The critical path item is the creation of the database for the M50 coil set.
- Linear analysis of the field on a control surface will be used to select a set of sensors.
- The selected set of sensors will be evaluated by its capability to provide accurate reconstruction of the equilibria in our database.

V3FIT Status

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OAK RIDGE NATIONAL LABORATORY

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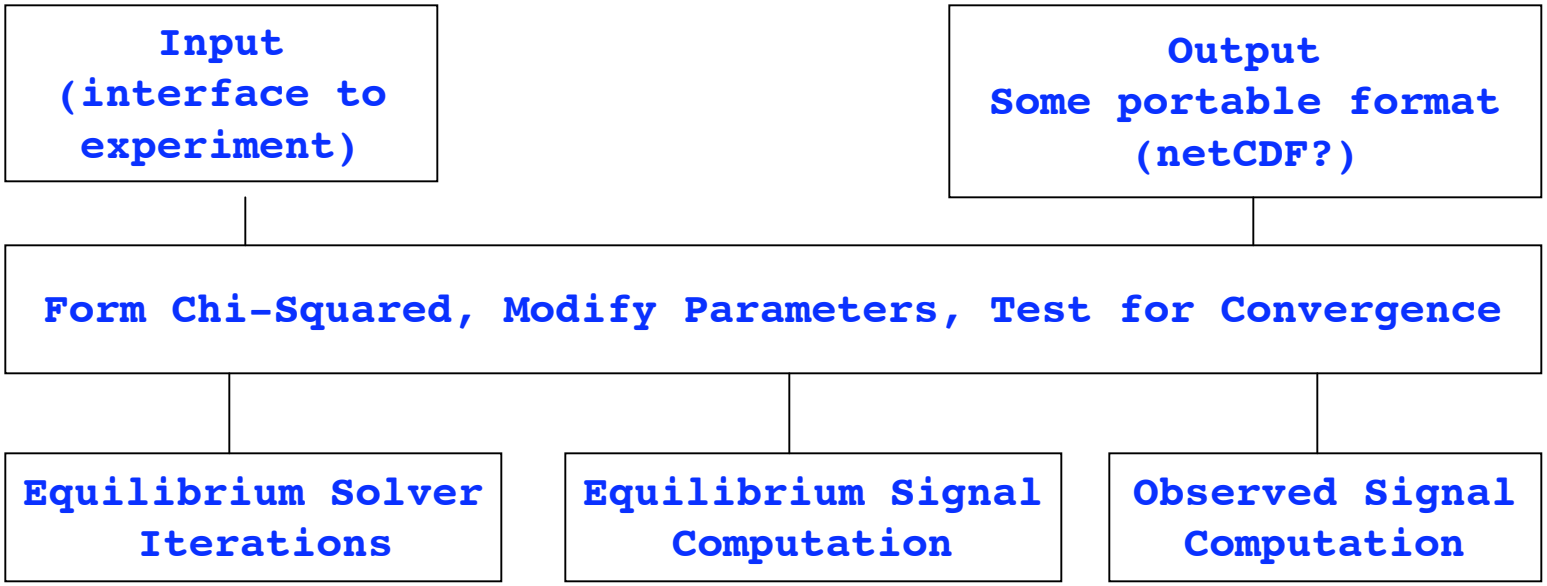
GENERAL ATOMICS

V3FIT

The overall structure of V3FIT is pretty well in hand.
The hooks into VMEC have been agreed upon.



- Tightly coupled reconstruction/equilibrium calculation.
  - » Designed for ease of future modification. Makes use of Structures and Modules.
  - » Utilize VMEC as 3D MHD equilibrium code, but allow for different MHD equilibrium solvers in the future.
  - » Initially write code for magnetic diagnostics. Coding has started.
  - » A highly modular approach will readily for other diagnostics in the future.

V3FIT - Current Activity

We are considering, and will test a variety of techniques for the regression analysis

- Levenberg-Marquardt (like STELLOPT)
- Conjugate Gradient (Hirshman used this for PBX and TFTR)
- Linearization (Like EFIT.) Avoids explicit computation of the Jacobian as the regression is linear at each step. The form of the problem looks similar to the Picard iteration scheme used in EFIT.

- We will explore convergence issues using a modified STELLOPT - This is likely to be used for the second part of our defining diagnostics for NCSX (reconstruction tests).

V3FIT Summary

- We are making progress on the mathematical approach for V3FIT
- Coding begun in June
- We are optimistic about obtaining a linearized minimization scheme
  - » Expect this to provide robustness and speed
- Next steps is convergence studies using STELLOPT
  - » Provide guidance for coding
  - » Study the amount of profile detail contained in external magnetics. (More than what can be deduced for a shaped tokamak.)
  - » Provide benchmarks for linearization testing
  - » Gain insight into interleaving of regression and equilibrium convergence
  - » Study sensitivity to initial conditions
- First real tests of V3FIT expected on CTH

Issues

- In a general sense, we are doing something that has not been done in stellarators. It is difficult to anticipate difficulties.
- The serious work on selecting diagnostics will not begin until we have built the database.
- Computer time is a problem. By the time we select out the good cases we are getting 4 or 5 per day from the Petrels and we need thousands.
- Islands - Future work
  - » Given that we are already in uncharted territory, I am not too concerned that we do not have a prescription for dealing with islands.
  - » The first plan is to build the analog of a tokamak filament code and a very fast (parallel) boundary tracer. Code needs to be built and then benchmarked against PIES.
  - » This remains in the category of future work.
  - » Investigate magnetic diagnosis of islands.
  - » Investigate how the existence of islands would affect the reconstructions done with VMEC, i.e. how islands affect the chosen magnetic diagnostics set.