# DEVELOPING ISOFLUX SHAPE CONTROL AND REAL TIME EQUILIBRIUM RECONSTRUCTION

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## A plan to achieve accurate discharge control for all plasma conditions

1. Real time EFIT algorithm for equilibrium reconstruction.
   - Provides identification of actual plasma shape.
   - Calculates the shape error:
     difference between actual shape and desired shape.
2. Shape error from rtEFIT is input to the shape controller.
   - Short term:
     - Proportional, integral, differential (PID) controller.
     - Empirically determined gain matrix.
   - Long term:
     - Multiple-input, multiple-output (MIMO) controller.
     - Systematic design techniques.
3. Other complex controlled parameters are possible in the future, e.g. current profile.

## Motivation: shape control is critical to many physics experiments.

1. Control of shape in discharges with the broad pressure and current profiles characteristic of low aspect ratio devices will be a new area of research.
2. Rapid changes in the discharge stored energy or internal inductance, such as those common in high beta experiments, can result in significant changes in the discharge shape unless controlled properly.
3. The high harmonic fast wave RF heating technique depends on close coupling between the plasma and the antenna requiring good control of the plasma/antenna gap.
4. Shape control flexibility is required to produce a variety of double-null divertor, single-null divertor, and elongated limited shapes.
5. Single-null divertor discharges required for helicity injection experiments will be challenging to control because of the low internal inductance and unusual current profiles.

## Real time equilibrium reconstruction provides the basis for accurate discharge shape and profile control

- A solution to the Grad-Shafranov tokamak equilibrium relation is calculated which is consistent with measured diagnostic data.
- Shape identification is robust to changes in $\beta_p$, $\ell_i$ and edge current density.
- Accuracy of discharge shape identification is comparable to that obtained with between-shot analysis.
- "Real time" reconstruction produces equilibrium solutions rapidly enough for feedback control of discharge parameters.
- Used routinely for DIII-D.
- The spatial distribution of toroidal current and poloidal flux are available in real time for evaluation of discharge parameters.
- Future inclusion of motional Stark effect data allows determination of the q profile.

# Differences between the real time and standard off-line EFIT algorithms provide for a practical calculation speed

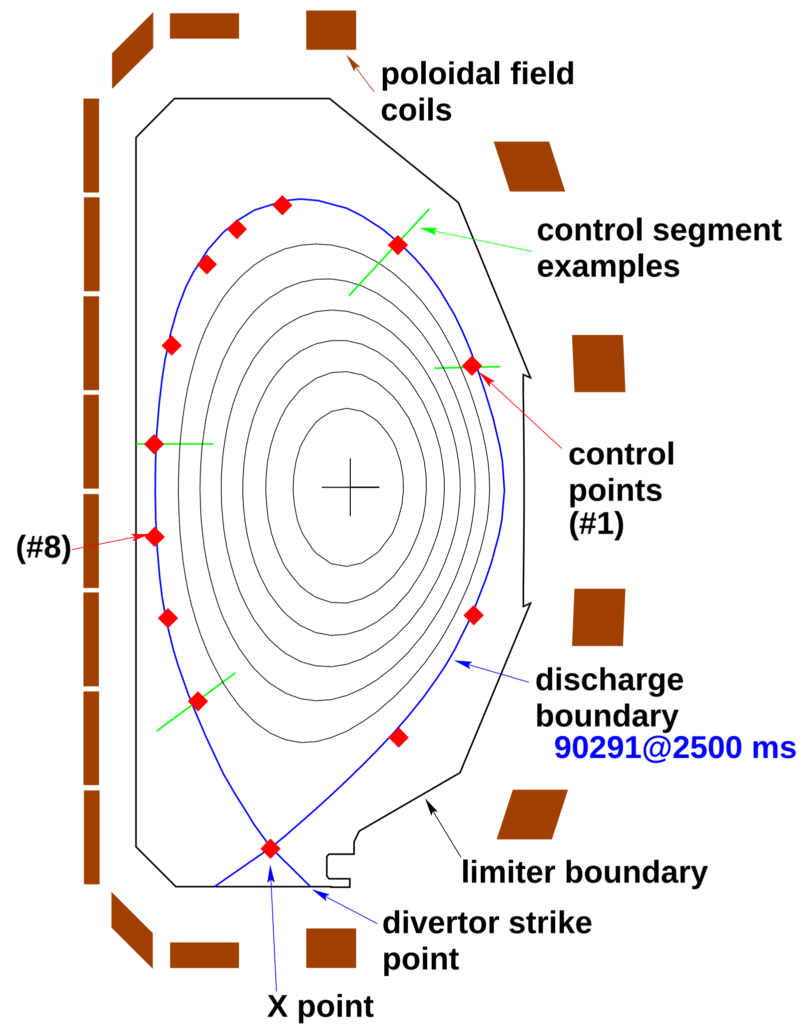
- Effect on calculated boundary location is small.

| | rtEFIT | off-line EFIT |
|---|---|---|
| Computation grid | $33 \times 33$ | $65 \times 65$ |
| Convergence | One iteration starting with the result from the previous time step | Iterate until the solution converges |
| External currents | Some coil and/or vessel current measurements treated as having zero uncertainty | True uncertainty used for all coil and vessel currents |
| Boundary tracing | No real time tracing of plasma boundary | |

- Reference: Ferron, J.R., et al., "Real Time Equilibrium Reconstruction for Tokamak Discharge Control," Nucl. Fusion 38, 1055 (1998).

# Shape control is implemented by requiring equal flux at points on the desired boundary

- Operator specifies the required boundary shape.
- The "control points" for the boundary are at the intersection of the desired boundary and a set of preselected line segments ("control segments").
- Coil currents are adjusted to make the flux at each control point equal to be flux at the reference control point ("isoflux control").
- Reference control point:
  - Desired or actual limiter touch point (for limited shapes).
  - Computed X point position (for divertor shapes).
- X Point: R, Z position computed in real time and controlled to be at the location specified by the operator.
- Divertor strike point controlled by specifying a control point at the desired position on the limiter.



# The shape controller calculates the commands to the poloidal field coil power supplies

$\vec{E}$ = [control point flux errors, X point position errors]

Coil commands $= [\vec{G}_p \vec{E} + \vec{G}_i \int \vec{E} dt + \vec{G}_d d\vec{E}/dt] \times$ [gain matrix]

- PID gains ($G_p$, $G_i$, $G_d$) and gain matrix can evolve with time to match the desired plasma shape or plasma parameters.
- Primary experimental task in implementing isoflux shape control algorithms is determination of PID gains and the gain matrix.

# Upcoming tasks focus on isoflux control with a PID controller

- Preparation:
  - Complete implementation of the rtEFIT code on the NSTX PCS.
  - Offline testing by simulating several past discharges to evaluate performance.
  - Complete implementation of new data acquisition on the PCS.
    - Provides the necessary diagnostics for rtEFIT.
- Testing with plasma:
  - Basic testing of new PCS hardware and data acquisition.
  - Piggyback testing of real time equilibrium reconstruction.
  - Testing of each isoflux control algorithm.
    - Separate algorithm, PID gains and gain matrix for each shape (double-null, lower X point single-null, upper X point single-null, inside wall limited).
    - Start by using isoflux control during a short portion of the discharge.
    - Gradually lengthen the isoflux control portion.
    - Requires dedicated experiment time (a few days).

# A multiple input/multiple output (MIMO) controller includes the effect of actuator changes on all controlled quantities

- A controller is designed using plant models.
  - Power supplies, coils etc. must be modeled.
    * Initial task for FY02.
    * Plan is to use existing data.
  - Plasma response model required (linear or nonlinear).
    * Requires some plasma data in which the discharge shape is perturbed.
    * Planned for FY03.
- Dynamic response can be specified.
- Controller design is automatic.
- Improvement on:
  - Empirical determination of controller gains and time constants.
  - Proportional/integral/differential (PID) controllers.

## Model-based MIMO controller design is a key technology for high and low aspect ratio toroidal systems

- Systematic design method for new plasma configurations.
- Explicit means for trading off conflicting control demands (e.g. relative accuracy of gap and X point control).
- Methods for dealing with hardware constraints (e.g. giving up control accuracy as coil currents approach 0 or the maximum level).
- Integrated controllers are required for internal profile control.
  - Profile and shape control are coupled.
- Model-based MIMO controller design is a research topic with widespread interest and application throughout the fusion program.
  - Used extensively in design of ITER plasma controllers throughout EDA.