Equilibrium control in Tokamaks

Sang-hee Hahn¹

Prepared for “Plasma Control Session”

in

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¹KSTAR research center / National Fusion Research Institute, Daejeon, Korea

Contact: hahn76@nfri.re.kr
• Essentials of Equilibrium control in tokamaks
  • Common requirements – start, build, ignite, maintain and shutdown
    • Definition
    • Conventional approaches
  • K-DEMO control requirements
    • Specifications, parameters and machine configurations
• Issues in DEMO equilibrium control
  • Pulse length vs economy – control of transients
  • Do we have suitable diagnostics?
  • Actuators
  • Exception handling issues
• Summary
Essentials of Equilibrium control in Tokamaks
Equilibrium control includes

- **Plasma current** \( I_p \)
  - an essential quantity for maintaining the tokamak confinement (nested flux surfaces)

- **Position and shape**
  - Radial force balance
  - Vertical position stabilization (VS) *for vertically elongated shape*
  - Location of plasma boundary defined by the *last closed flux surface (LCFS)*
    - Limited vs diverted
  - Shape of separatrix and divertor, position of the striking points

Figure: G. Ambrosino, R. Albanese, IEEE Control Syst. Mag. 25 (2005) 76–92.
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  - Shape of separatrix (X-point) and divertor, position of the striking points

**Figure:** A. Cenedese, A. Beghi, Advances in Real-Time Plasma Boundary Reconstruction: From gaps to snakes, IEEE Control Syst. Mag. (2005) 44–64.
Control actuators

- A set of devices which makes the desired control happen
- *magnetic flux change* by changing the coil current of surrounding magnets
- Driving force is $J_p \times B$

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Control actuators

• A set of devices which makes the desired control happen
• *magnetic flux change* by changing the coil current of surrounding magnets
• Driving force is $J_p \times B$ forces
• In-vessel vs Ex-vessel coils
  • In KSTAR all ex-vessel coils are contained in the He cryostat so that they maintain superconducting (SC) state
  • In-vessel coils are conventional copper (Cu) behind the first wall
Control actuators in superconducting devices

• Special remarks for Superconducting devices
  • Toroidal field coils (TF) are no more regarded as available actuator – stationary during the plasma pulse
  • Central Solenoid (CS) & Poloidal Field (PF) Coils are distant from the plasma due to structures
  • The vertical stabilization speed requirement is usually faster than the PF coils can deal with
    • need of in-vessel control coils until ITER
  • CS coils are not the OH coils
    • No hardwired ohmic field provision
    • due to the complexity of magnet manufacturing

Basic magnetic control in SC devices is more challenging due to reduced controllability

Figure reused from D. A. Humphreys et al, Talk at ITPA MHD Stability TG meeting (2015), Naples, Italy, 19-22 October 2015.
Use of Equilibrium control

- Equilibrium control is usually responsible for:
  - Magnetization of the CS&PF coils and plasma breakdown
  - *Any* Inductive sustainment of $I_p$ until ignition
  - Creating defined boundary or gaps from the first wall
  - Maintaining of boundary or gaps
  - Heat load control of the divertors (partially)
  - Shutdown of a pulse as a part of _exception handling_

![Diagram showing the time profile of $I_p$](image-url)
Use of Equilibrium control: a lifecycle of a pulse

- Equilibrium control is usually responsible for both *transient* and *stationary*:
  - Magnetization of the CS&PF coils and plasma breakdown
  - *Any* Inductive sustainment of $I_p$ until ignition
  - Creating defined boundary or gaps from the first wall
  - Maintaining of boundary or gaps
  - Heat load control of the divertors (partially)
  - Shutdown of a pulse as a part of _exception handling_
Example of fully non-inductive pulse in KSTAR

- **20s,** $f_{\text{NI}} \sim 1.0$ high $\beta_p$ achieved[*]
  - $V_{\text{loop}} \sim 0.0$ with NBI+ECH = 5.5MW
  - $\beta_p > 3.0$, $\beta_N \sim 2.0$

- Central EC heating is essential
  - At $B_T = 2.9$ T
  - EC 170GHz at the plasma center

- Similar characteristics as “high li” mode[**]
  - elongation~1.7, $q_{95} \sim 11$

- Pulse terminated by PFC overheat due to fast ion losses

[*] Y.M. Jeon et al., H-mode WS 2017

Feedback is necessary in steady-state pulses

- Plasma basic property changes with recycling
  - Striking point position moves in ~71s KSTAR discharges

![Graph showing plasma properties over time]

- $I_p$ (MA)
- $P_{NBI} = 3.8$ MW
- $P_{ECH} = 0.8$ MW
- $V_{loop}$ (V)
- $V_{loop}$ increase indicates $R_p$ increase
- $<n_{s,FR}>$ ($10^{19} \text{ m}^{-3}$)
- $W_{MHD}$ (MJ)
- $W_{MHD}$ decrease
- $\beta_p$
- $\beta_N$
- $D_{\alpha, Tor}$ (a.u.)

No explicit controls for strike points applied

Figures from S. Hahn et al., IAEA TM SSO (2017)
Y.M. Jeon et al., H-mode WS 2017
Examples of control design of a discharge

- Role of each actuator is NOT assigned to a single role:
  - Responsible for both transient and stationary
  - Stationary movement must be optimized after ignition, for longer pulse length:
    - \textit{(superconducting constraint)} AC loss minimization

\textbf{Figure 3.} Timeline of a typical NSTX-U discharge showing algorithms associated with each coil set during the major phases of the discharge.

Known diagnostics of Equilibrium control

- Plasma current ➔ magnetic diagnostics
  - By direct measurement or reconstructions
- Position or gap measurement ➔
  - modeled approximations using magnetic diagnostics (JET descriptor)
  - Optical detection like IR polarimetry/reflectometry (see Dr. Wiel’s morning talk)
- Plasma surface, separatrix geometry and flux error ➔
  - equilibrium reconstructions using magnetic diagnostics and MSE (EFIT$^1$, LINQE$^2$, CCS$^3$ ...)
  - Image reconstructions (fast CCD camera $^4$ or IR)
  - Tomographic reconstructions on radiation $^5$ or x-ray spectroscopy

Two options of DN shape are suggested [1,2] with full SC magnet equipment.

Table 2
Parameters and operational capabilities of K-DEMO.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
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<tbody>
<tr>
<td>Major radius, $R_0$ (m)</td>
<td>6.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Minor radius, $a$ (m)</td>
<td>1.8</td>
<td>2.0</td>
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<tr>
<td>Aspect ratio, $A$</td>
<td>3.33</td>
<td>3.25</td>
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<tr>
<td>Triangularity, $\delta$</td>
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<td>0.4</td>
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<tr>
<td>Normalized beta, $\beta_N$ (%)</td>
<td>4.2</td>
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<tr>
<td>Safety factor, $q_{95}$</td>
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<td>Energy confinement time, $\tau_E$ (s)</td>
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<td>Bootstrap current fraction, $f_{bs}$</td>
<td>0.6</td>
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<tr>
<td>Averaged electron temperature (keV)</td>
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<td>Averaged electron density ($10^{20}$/m$^3$)</td>
<td>1.08</td>
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<td>Total fusion power (MW)</td>
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K-DEMO requirements: shape specifications

- Two options of DN shape are suggested with full SC magnet equipment

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K~2.0, DN, d~0.4 Shape assumed for conceptual K-DEMO divertor design [*]

Fig. 2. Diagram of K-DEMO plasma power flow in Phase I operation (unit in MW).

K-DEMO requirements: actuator specifications

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Conceptual K-DEMO magnet design [**]: 16 TFs, 8 Central Solenoid (CS), 12 PFs

A certain pressure & current profile is suggested for the “steady-state” scenario \cite{1} under available H&CD \cite{2}.

\begin{table}[h]
\centering
\caption{K-DEMO steady-state scenario parameters.}
\begin{tabular}{lccc}
\hline
 & 1st phase & 2nd phase (\(f_{GW} = 110\%\)) & 2nd phase (high \(T_{ped}\)) \\
\hline
\(P_F\) (MW) & 2070 & 3050 & 2950 \\
\(Q\) (fusion gain) & 19.7 & 23.4 & 22.7 \\
\(I_P\) (MA) & 15.5 & 17 & 17 \\
\(f_{BS}\) & 77\% & 81\% & 78\% \\
\(P_{NB}\) (MW) & 105, 500 keV & 130, 650 keV & 130, 600 keV \\
\(I_{NB}\) (MA) & 4.0 & 4.2 & 5.2 \\
\(\beta_N\) & 2.8 & 3.2 & 3.1 \\
\(H_{98\%2}\) (keV) & 1.2 & 1.17 & 1.17 \\
\(T_{ped}\) (keV) & 8.3 & 8.3 & 8.9 \\
\(n_{ped}\) (m\(^{-3}\)) & \(9.9 \cdot 10^{19}\) & \(11.2 \cdot 10^{19}\) & \(10.9 \cdot 10^{19}\) \\
\hline
\end{tabular}
\end{table}


See the talk by K. Kim for more K-DEMO details (this afternoon)
Issues on DEMO equilibrium control
Important questions

• How long we’ll run for a pulse?
  • Tokamak is regarded as a pulsed machine
  • Maintenance & restart & exception handling

• Do we have suitable diagnostics with meaningful calculation time?
  • Transient phase
  • Stationary phase
  • Shutdown seq. for exception/maintenance
  • Computation requirement

• Do we have all necessary actuators feasible?
  • Degree of freedom
  • Feasibility of installation
  • Additional component
  • (superconducting case) frequency separation for Ip / shape / VS
How long we’ll run?

- 24h/7days may be ideal, but
  - Until the poloidal flux consumption runs out
    - startup flux consumption
    - (SC) AC loss
    - Can the auxiliary heating last 24/7?
  - Planned maintenance may require plasma shutdown & restart
  - Concept of Steady-state has “the daily rhythm of the electric supply on demand”. What’s the requirement then?
    - Concerned to the question of durability

Example of inductive ITER pulse
Do we have suitable diagnostics with meaningful calculation time?

- Calculation time might not be a big issue (Moor’s law, FPGA, GPU, ...)
- Diagnostics for **transient** and **stationary** phase can be different

<table>
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<tr>
<th></th>
<th>CCD / IR imaging</th>
<th>Magnetic diagnostics</th>
<th>Polarimetry / interferometry</th>
<th>Reflectometry</th>
</tr>
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<tr>
<td><strong>PRO</strong></td>
<td>Direct and intuitive</td>
<td>Best accuracy for transient</td>
<td>No drift issues</td>
<td>Best for the stationary?</td>
</tr>
<tr>
<td><strong>CON</strong></td>
<td>Window coating / Moderate Accuracy</td>
<td>Integrator drift / difficulty on maintenance</td>
<td>Limited sight / weak signal at transient</td>
<td>Less useful before the ref. shape</td>
</tr>
<tr>
<td>Plasma current</td>
<td>(Can’t)</td>
<td>Best so far...</td>
<td>Measurable by scaling?</td>
<td>(Can’t)</td>
</tr>
<tr>
<td>Position</td>
<td>Measurable but moderate accuracy</td>
<td>- VS for both phases</td>
<td>- Useful for VS detector</td>
<td>Measurable but accuracy in question for transient</td>
</tr>
<tr>
<td>2D Shape</td>
<td>Good for transient</td>
<td>Reconstructions well known, weak to defect of sensors</td>
<td>Auxiliary signal for reconstructions</td>
<td>Good for measuring deviances out of midplane</td>
</tr>
</tbody>
</table>
Issues on the magnetic diagnostics

- Drift from the integrator
  - Long pulse operation burden: inaccuracy increases
  - Invention of alternative implementations:
    - digital integrator development
    - EAST ~400s discharge used 4 different integrator sets per 1 sensor, 100s each

- Algorithms for automatic detection & amendment of errors due to sensor problems
  - Automatic exclusion of defective sensors by Chi^2 (D3D rtEFIT)
  - Automatic inference of malfunctioning sensors[*] by recent Machine Learning techniques

[*] Semin Joung et al., 22nd HTPD 2018
Even in magnetics + reconstruction scheme, sensitivity for measuring the separatrix requires extreme accuracy

- Fluctuations larger when the pedestal is steeper
- The main reason of difficulties when we maintain the balanced Double Null
- Is the mentioned optics able to discern the X-point?
- **Accuracy requirements**: how much errors we’ll allow for inboard / outboard / separatrix locations?

See poster P13 (David Eldon, Wed) for DN&SN configuration considerations for DEMO stability
Do we have all necessary actuator feasible?

• (SC) No hardware separations exist between OH and shape control coils
  • Many SC machines accomplished practical workaround by elaborate MIMO design
• VS feedback may have a very different timescale from Ip/Shape
  • VDE growth rate usually faster depending on the elongation (even in ITER)
  • (SC) Tradeoff on available power supply voltage / AC loss / cost
  • Reduction of elongation reduce the demand
    • how much can it be tolerable?
    • It is difficult to install & maintain in-vessel active control coils!
• Can we adjust the VDE growth rate down?
  • Passive structure at ASDEX-U
  • Conformal wall (aka passive stabilizers) at KSTAR
  • Caveat: Additional shielding, breakdown and startup

KSTAR in-vessel structure

Gap resistors btwn Cu plates (red circle) determine the VDE growth rate
Essentials of tokamak equilibrium control are summarized
- Ip, position, shape, and vertical stabilizations
- A typical lifecycle of tokamak discharge is reviewed – transient and stationary
- Some superconducting-specific remarks are done
- K-DEMO design

DEMO issues
- Trade-off on the economic pulse length vs Fusion power production
  - Main constraint for durable diagnostics, reliability and reproducibility
  - There seems to be no single type of all-purpose diagnostics for the lifecycle of pulse
    - Combinations of magnetic/optical methods
    - Identify the best working diagnostics in each phase (even sacrificial after the run)
- Practically essential but seldom-addressed questions:
  - Vertical stabilization
  - Exception handling / startup issues may be addressed at the earlier stage of design
    - increases machine requirement (dealing with lower performance plasmas)