Simulation NTM control

Below $w_c$

Low power
Confinement

\[ P = 6 \text{ l/s} \]

\[ W = 12 \text{ l} \]

\[ \tau = 2\text{s} \]
Tokamak turbulence

Toroidal ITG (n=20)
Positive magnetic shear

Vector potential

Potential
Streamers
Tokamak Operation Regimes

i) Advanced Operating Modes

ii) H-mode

Sawteeth

L-mode

Pedestal

Internal Transport Barrier (ITB)

Edge Localized Modes (ELMs)

Edge Transport Barrier (ETB) (H-mode)

Hybrid modes

Normalized radius r/a
Magnetic winding number $q$, and its derivative $s$

Mode damping at low $s/q$. How can we control $s/q$?

- Distributed control problem
- Multiple actuators
- Nonlinear (time history is important)
- Difficult to measure
- No “simple solution”
Citrin, NF 50 2010

**Figure 6.** Various plasma profiles for the optimized $T_{\text{ped}} = 5$ keV simulation at $t = 3000$ s: electron temperature, ion temperature and the electron density profiles (left panel); total current, bootstrap current, current driven by 33 MW neutral beams injection, and current driven by 17 MW electron cyclotron wave injection (central panel); evolution of the $q$-profile (right panel).
Closed loop flux control in Hybrid-mode

Reference

Controller

Multi beam ECCD

Plant Hybrid mode

Full state

RT Evolution
Current density
GS-constrained

RT Thermal Transport

Flux surface Layout

ρ_r, q_r, s_r

ε

θ_i, P_i
Control oriented modeling

\[
\psi(x, t) = \frac{1}{2\pi} \int B_{\text{pol}} dS.
\]

control-orientated model of the magnetic flux

\[
\frac{\partial \psi(x, t)}{\partial t} = \frac{\eta_{\parallel}(x)}{\mu_0 a_e^2} \left( \frac{\partial^2 \psi(x, t)}{\partial x^2} + \frac{1}{x} \frac{\partial \psi(x, t)}{\partial x} \right) + \eta_{\parallel}(x) R_0 j_{\text{ni}}(x, t),
\]

where \( j_{\text{ni}}(x, t) = j_{\text{bc}}(x) + j_{\text{nbi}}(x) + j_{\text{eccd}}(x, t) \) with the boundary conditions

\[
\frac{\partial \psi(0, t)}{\partial x} = 0 \quad \frac{\partial \psi(1, t)}{\partial x} = -\frac{R_0 \mu_0 I_p}{2\pi}
\]
Due to the fact that the parameters $\eta_\parallel(x)$, $j_{bc}(x)$, and $j_{nbi}(x)$ are space dependent parameters, the PDE model has to be discretized in order to evaluate the magnetic flux $\psi(x, t)$.

$$\frac{d\psi(x_i, t)}{dt} = \frac{\eta_{i,j}}{\mu_0 a_e^2} (c_1(i)\psi_{i+1} - c_2(i)\psi_i + c_3(i)\psi_{i-1}) + \eta_{i,j} R_0 (j_{bc}(x_i) + j_{nbi}(x_i) + j_{cccd}(x_i, t))$$

with the discretization coefficients

$$c_1(i) = 1/2 \frac{2x_i + \delta x}{\delta x^2 x_i}$$
$$c_2(i) = 2 \frac{1}{\delta x^2}$$
$$c_3(i) = 1/2 \frac{2x_i + \delta x}{\delta x^2 x_i}$$
- Calculates optimal inputs using a cost function
- Multiple constraints on inputs and states
- Sufficiently accurate dynamical input-out model required
• **Ohm’s law** can be used to derive a model in state space format as follows:
  - \( \varphi(t + T_s) = A \varphi(t) + B u(t) \)
  - \( \frac{1}{q}(t) = \iota(t) = C \varphi(t) \)
  - which relates the poloidal magnetic flux profile \( \psi(t) \) to the inverse safety factor profile \( \iota(t) \), where the input vector \( u(t) \) includes the non-inductive current drives such as NBI and ECCD
Minimize the following cost function $J$ over the prediction horizon $P$:

- $J = \sum_{i=1}^{P-1} W_e(y_i - r_i)^2 + W_{\Delta U} (\Delta u_i)^2$,

subjected to the constraints:

- $u_{\text{min}} \leq u \leq u_{\text{max}}$,
- $t(x) \leq 1$

and penalizing loop voltage gradient profile $\frac{\partial u_{pl}}{\partial x}$ at end of prediction horizon $P$. 
Model based controller
RT estimation $q$, $s$ and $\rho$: Boundary + MSE

Figure 4: Correlation of core elongation with $l_i$ for JET Hybrid regime.

JET shot #79630

- $q_{\text{OFIT}}$
- $q_{\text{CRONOS}}$
- $q_{\text{hybrid}}$

$\rho$ error [%] vs. time [s]

TU/e Technische Universität Eindhoven University of Technology
RT Estimation of thermal transport

Work in progress
Step 2: Add observer for current and thermal transport

F. Felici, NF 2011

Raptor
Combined current and thermal transport model  RAPTOR presently refined for real-time model update
F. Felici Originator of RAPTOR
Fast 1-D transport code for real-time implementation and fast optimization
- Evolves profiles of poloidal flux $\psi(\rho,t)$, and electron temperature $T_e(\rho,t)$
- Neoclassical resistivity, bootstrap current [Sauter PoP 1999,2002]
- Parametrized heating / current drive sources
- Includes nonlinear profile coupling, crucial for hybrid/advanced scenarios
Closed loop flux control in Hybrid-mode

DIFER
Dutch Institute for Fundamental Energy Research

Reference $\rho$, $q$, $s$

Controller $\varepsilon$, $\theta$, $P$

Multi beam ECCD

Plant Hybrid mode

Full state

RT Evolution
Current density
GS-constrained

RT Thermal Transport

Flux surface Layout
Conclusions

• The fusion plasma is highly non-linear. Our solutions are linear
• Controllers have been designed and tested for tearing modes, sawteeth (not shown), and for plasma performance
• Emphasis on
  – sensing (in-line ECE, OFIT, RT-HPP, RT-sawtooth detection)
  – Modelling
• With these controllers will give the community more stored energy, for less input power