Marco de Baar,¹,³ Federico Felici,² Matthijs van Berkel,¹,³ Bert Maljaars,³ Timo Ravenbergen,¹,³ Thomas Blanken³
Tokamaks are atypical from Control Perspective

- Distributed, Equilibrium dependent
- Task shared
- Close to variable constraints

Close to varying performance, operational, machine integrity limits
- ODEs to non-linear, coupled PDEs
- Off-normal events, Repetitive

\[ Y_r \xrightarrow{C} A \xrightarrow{P} Y_m \]

Distributed, Equilibrium?
- Limited scope for sensing
- Bandwidth, Latency
- Degradation
Control of MHD using CO-LOCATED actuator-sensor

A line-of-sight electron cyclotron emission receiver for electron cyclotron resonance heating feedback control of tearing modes, JW Oosterbeek et al., Review of Scientific Instruments 79 (9), 093503 (2009)
Sensor model: Radial location tearing mode
Closed-loop control of MHD in TEXTOR

Detailed knowledge of state is key in modern methods.
Concept Kalman observers

Plant

Model

Kalman update of x

u → Plant → $Y_{me}$

$Y_{mo}$ → Model → Kalman update of x

u → Plant → $Y_{me}$

$Y_{mo}$ → Model → Kalman update of x
Unscented Kalman filter for mode frequency and phase

Kalman filters for real-time magnetic island phase tracking, DP Borgers, et al., Fusion Engineering and Design 88 (11), 2922-2932 (2013)
Observer for control of distributions of $n_e$, $j$ and $T_e$

- Discretized coupled nonlinear diffusion PDEs
- Nonlinear state observation: Extended Kalman filter

Core plasma described by 1D transport equation

Artefacts in measurements (fringe jumps) rejected
Observer for electron density distribution

T.C. Blanken et al., Fusion Engineering and Design, 126, 87-103 (2018)
Closed loop density control in TCV
Simultaneous control of $4 \ j_{ECCD}$ sources + $I_p$

Control of the tokamak safety factor profile with time-varying constraints using MPC.
E. Maljaars et al., Nucl. Fusion 54 (2014)
Profile control simulations and experiments on TCV: a controller test environment and results using a model-based predictive controller, E Maljaars et al., Nuclear Fusion 57 (12), 126063 (2017)
How to determine when to allocate the actuators to specific control tasks?
Finite state modeling of plasma implemented on TCV

FSMs implemented in MATLAB Stateflow

Modelled supervisory controller

Plasma states

Control task priorities

Only two control tasks may be simultaneously executed due to actuator constraints

Tasks: Central heating, NTM stabilization and $\beta$ control
Decision chain: NTM presence $\rightarrow$ Control task priorities $\rightarrow$ EC launcher allocation
MANTIS realized at TCV.
Real-time capability up to 400 Hz.

10 Ximea MX031MG-SY-X2G2-FV
Adapted OFIT to identify divertor leg + Radiation front
Sensors for RT control at 450 Hz
Sensor model + RT front location detector in TCV
System identification approach

- Less experimental time
- Quantify robustness
- One controller for multiple regimes
# System Identification Approach

<table>
<thead>
<tr>
<th>Feature</th>
<th>Status</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-time (RT) diagnostic</td>
<td>✔️</td>
<td>MANTIS</td>
</tr>
<tr>
<td>RT analysis/measurement</td>
<td>✔️</td>
<td>EUROfusion MST1</td>
</tr>
<tr>
<td>Dynamic characterisation</td>
<td>Near future</td>
<td>EUROfusion MST1</td>
</tr>
<tr>
<td>RT (feedback) controller</td>
<td>Near future</td>
<td>EUROfusion MST1</td>
</tr>
<tr>
<td>RT Model ('Advanced' control)</td>
<td>ongoing</td>
<td>Mathematics dept. TU Eindhoven</td>
</tr>
</tbody>
</table>

![Diagram of plasma flux and diagnostic system](image)
Conclusions and Observations

Control of the distributions of \( n_e, j \) and \( T_e \) as well as the suppression of neoclassical tearing modes

Model-based controllers for these control tasks have been developed and implemented MPC to deal with (varying) limits and constraints.

Can we use event predictors to identify the plasma limits and use these in the MPC cost-function?

Supervisory controller determines in real-time the priority of the control tasks and the actuator allocation

Consistent estimate of the plasma state: EKF and UKF approach → Models for plasma dynamics + sensor models required

Machine learning is very cool, but .... don’t forget well established methods such as System Identification

ITPA diagnostics initiative to

- 1- Top-down: Ensure availability of the sensor models for first plasma & first campaign
- 2- Bottom-up: Set-up Inventory of existing models in community
Systems and control theory

1940-1960  Classical control engineering (SISO)
1960-1980  State space,
           Large scale systems (MIMO),
           Kalman observation
1980-1990  Robust control
           System identification
1990-2000  Model predictive control
2000-2010  Hybrid (event-driven) system theory
2010-2018  Network control,
           Distributed control,
           Iterative Learning Control