ITER plasma current and shape control using MPC

Samo Gerkšič[1] Gianmaria De Tommasi[2]

[1]Jožef Stefan Institute, Ljubljana, Slovenia
[2]Università degli Studi di Napoli Federico II/CREATE, Napoli, Italy

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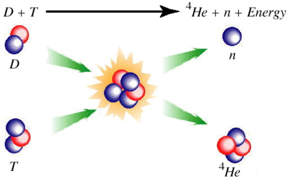
Outline

Nuclear Fusion for Dummies

Main Aim

Production of energy by means of a fusion reaction

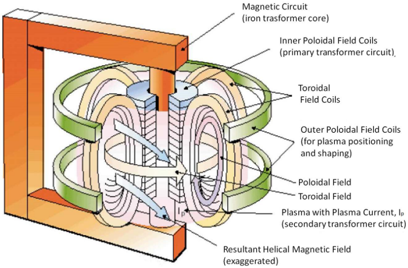
$$D + T \rightarrow {}^{4}\mathrm{He} + n$$



Plasma

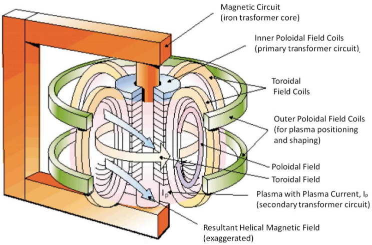
- High temperature and pressure are needed
- Fully ionised gas ↦ Plasma
- Magnetic field is needed to confine the plasma

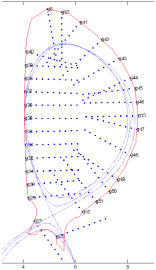
What is a Tokamak?



A tokamak is an electromagnetic machine containing a fully ionised gas (plasma) at about 100 million degrees within a torus shaped vacuum vessel. Poloidal and toroidal field coils, together with the plasma current, generate a spiralling magnetic field that confines the plasma.

Plasma current, shape and position control in tokamaks





- In tokamaks, **control of the plasma is obtained by means of magnetic fields produced by the external active coils**

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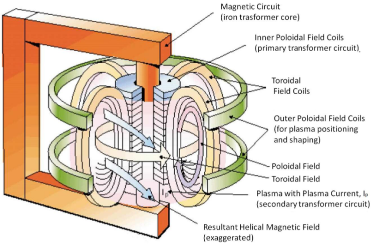

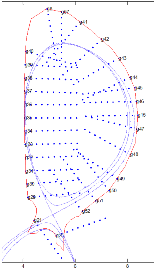

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- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section $\Rightarrow$ vertically unstable plasmas**

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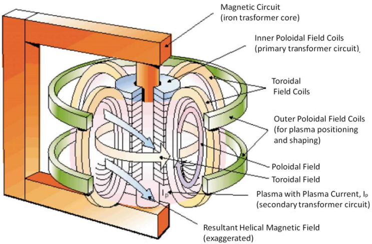

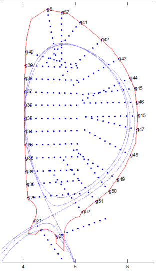

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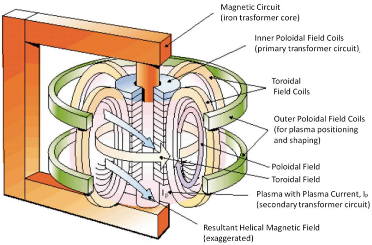
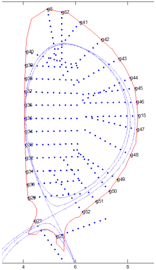
Plasma current, shape and position control in tokamaks





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- It is important to **maintain adequate plasma-wall clearance during operation**
- Plasma current must also be controlled

Motivations

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- For the ITER tokamak dealing with constraints it is particularly challenging
- MPC allows to explicitly take into account constraints on the PF currents and voltages

Contributions

- An MPC-based architecture for ITER plasma current and shape control is proposed
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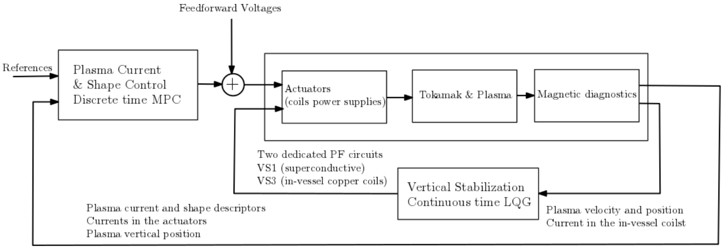
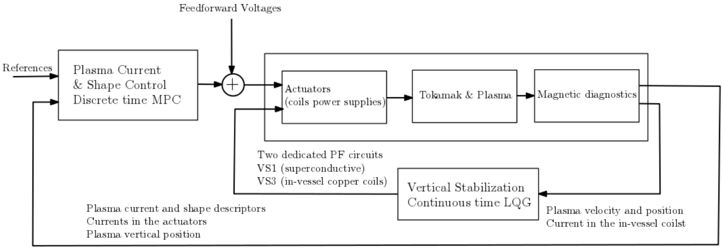
  - the requirements on control sampling frequency
- This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018

Proposed architecture 1/2



- LQG control to **vertically stabilizes the plasma**
  - The design is based on a **reduced version of the plant model (third order is good enough)**
  - The constraints on the control variables are fulfilled by tuning the LQG weights
  - Continuous time design (real implementation is straightforward)

Proposed architecture 2/2



- MPC control has been used to control plasma current and shape
  - Discrete time version of the plant (including VS loop) has been used for the design, assuming a sampling time of 100*ms*

MPC design

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- The plant has been first augmented in order to include integral actions and achieve offset-free control at steady state
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- The MPC controller was designed using the output-cost formulation with the *Multi-Parametric Toolbox*
- The prediction horizon was set to $N = 30$
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- The prediction horizon was set to $N = 30$
- Amplitude constraints on the PF voltages and currents were set
- The control law is computed solving a QP problem
- To reduce the computational demand, the number of free control moves was reduced from 30 to 3 by *grouping* them

Validation of the proposed architecture

- The the proposed architecture has been validated in simulation considering different scenarions (VDE, H-L transitions, Minor disruptions, etc.)
- The behaviour has been compared with the one proposed in [1] (a combination of SISO and SVD-based design techniques)
- In general, for the considered scenarios (see the paper for the details), the proposed MPC achieves faster suppression of disturbances on plasma current and shape control
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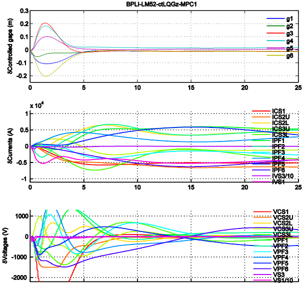
- The improved tracking performance comes at the price of a slight increase of the PF voltages and/or currents
- **However, the greatest benefit of the proposed MPC compared to Ambrosino et al., MSC 2015, is that is possible to explicitly include the constraints in the design**

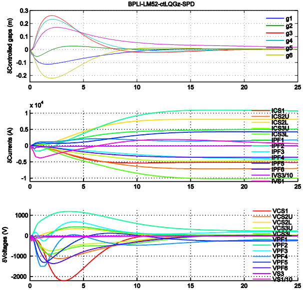
R. Ambrosino et al.
Design and nonlinear validation of the ITER magnetic control system
2015 IEEE MSC, 2015

The H-L transition

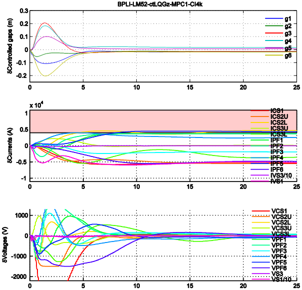
MPC architecture without constraints on I_{PF}



Architecture proposed in Ambrosino et al., MSC 2015



MPC architecture with $|I_{PF_i}| \leq 4kA$ soft constraint $\forall\ i$



Complexity reduction

- $N_x \sim 60$ (after model reduction), $N_u = 11$, $N_y = 20$, $N = 30$, soft output constrints→ computation is too slow (sampling time should be 100ms)!

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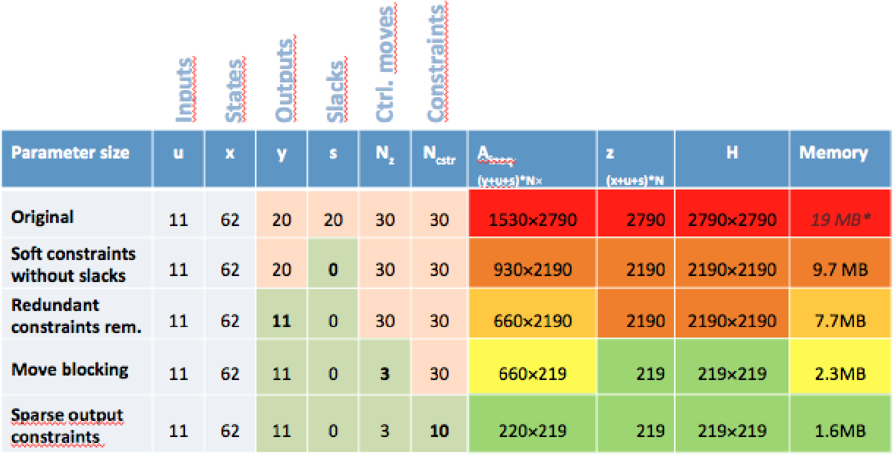
- $N_x \sim 60$ (after model reduction), $N_u = 11$, $N_y = 20$, $N = 30$, soft output constrints→ computation is too slow (sampling time should be 100ms)!
- Complexity reduction techniques have been considered (see Gerkšič et al, 2016)
  - Control move blocks
  - Sparse placement of output constraints
  - Elimination of redundant constraints
  - QP reduction via nullspace
  - . . .

S. Gerkšič et al.
Plasma current and shape control for ITER using fast online MPC
20th IEEE NPSS Real-Time Conference, Padova 2016

Reduction of the optimization problem

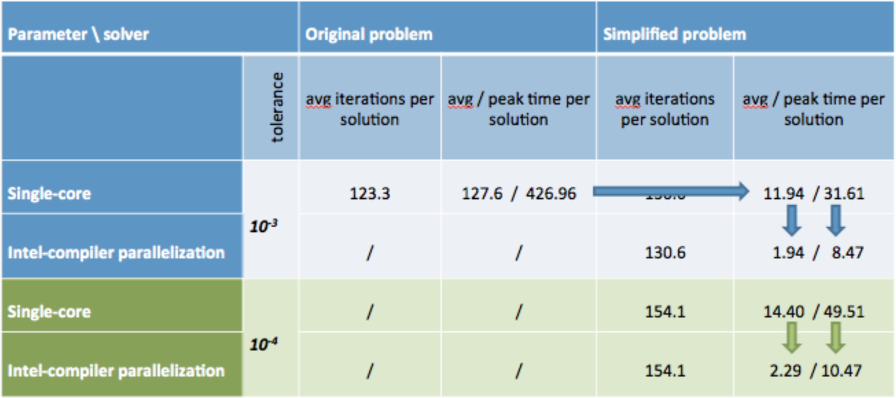


	Inputs	States	Outputs	Slacks	Ctrl. moves	Constraints				
Parameter size	**u**	**x**	**y**	**s**	**N_z**	**N_{cstr}**	**A_{ineq}** (y+u+s)*Nx	**z** (x+u+s)*N	**H**	**Memory**
Original	11	62	20	20	30	30	1530×2790	2790	2790×2790	*19 MB**
Soft constraints without slacks	11	62	20	**0**	30	30	930×2190	2190	2190×2190	9.7 MB
Redundant constraints rem.	11	62	**11**	0	30	30	660×2190	2190	2190×2190	7.7MB
Move blocking	11	62	11	0	**3**	30	660×219	219	219×219	2.3MB
Sparse output constraints	11	62	11	0	3	**10**	220×219	219	219×219	1.6MB

Choice of the optimization solver

Parameter \ solver		Original problem		Simplified problem	
	tol.	*avg iter. per solution*	*avg time per solution [ms]*	*avg iter. per solution*	*avg time per solution [ms]*
CPLEX	*10^{-3}*	2000	1332	326	48.7
QPgen, ADMM, SVD null-space		108	171	177	8.7
QPgen ADMM, DS null-space		110	100	1000	30.4
QPgen, FGM dual, SVD null-space		113	160	80	5.9
QPgen FGM dual, DS null-space		113	100	200	10.1

HW parallelization



Parameter \ solver		Original problem		Simplified problem	
	tolerance	avg iterations per solution	avg / peak time per solution	avg iterations per solution	avg / peak time per solution
Single-core	10^{-3}	123.3	127.6 / 426.96	[illegible]	11.94 / 31.61
Intel-compiler parallelization		/	/	130.6	1.94 / 8.47
Single-core	10^{-4}	/	/	154.1	14.40 / 49.51
Intel-compiler parallelization		/	/	154.1	2.29 / 10.47

Conclusions

- An MPC architecture for plasma current and shape control at ITER has been presented
    - It allows to explicitly take into account different types of constraints (on control and controlled variables)
- The performance are comparable with other proposed approaches for ITER magnetic control
- Further investigation aiming at the practical implementation of the proposed architecture is giving promising results

Thank you!