Model based optimization and estimation of the field map during the breakdown phase in the ITER tokamak

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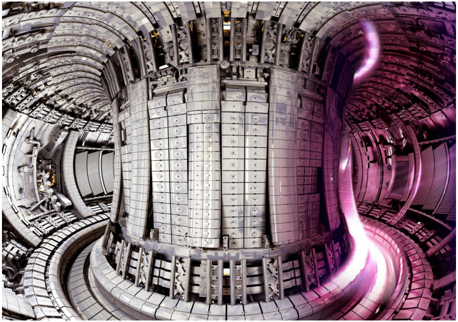
2015 IEEE Multi-Conference on Systems and Control
September 21–23, 2015, Sydney, Australia

Outline

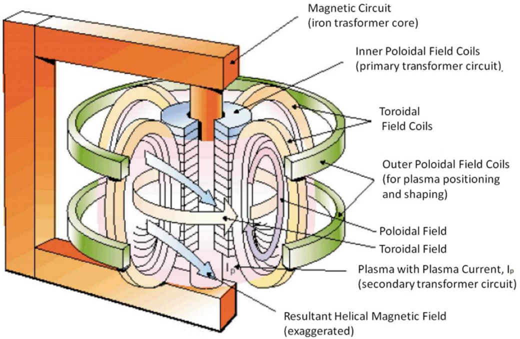
1. **Introduction**
2. **Plasma breakdown scenario**
3. **Breakdown scenario optimization**
4. **Field map estimation via Kalman filter**
5. **Simulation results**

Tokamak



A tokamak is an electromagnetic machine containing a fully ionised gas (plasma) at about 100 million degrees within a torus shaped vacuum vessel

Magnetic confinement in tokamaks



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

Plasma breakdown phase

- Plasma start-up in a tokamak is complex and calls on different control strategies during the early phases of **plasma formation** and current ramp-up
- The **breakdown (BD)** in a tokamak requires the establishment of a (poloidal) magnetic field null in a given region of the tokamak chamber
- BD conditions in terms of both electric and magnetic field should be reached within a given accuracy

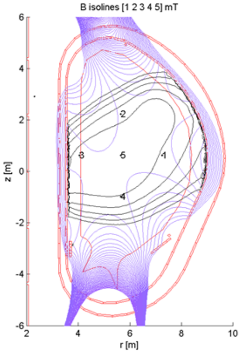


Figure: Example of isoflux (blue) and isofield (black) lines at the BD.

Plasma Breakdown in ITER

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  - Given this value of the electric field, *ohmic* BD is only possible over a narrow range of pressure and magnetic error field
  - Electron Cyclotron Resonance Heating (ECRH) may be necessary to provide robust and reliable plasma start-up in order to complete ionization of hydrogen

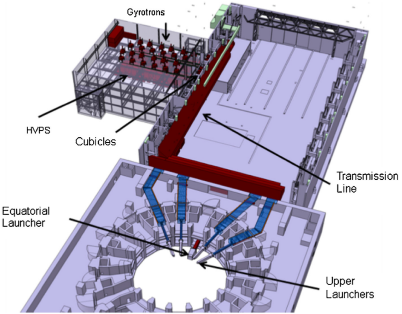


Figure: Layout of the ITER Electron Cyclotron plant.

Plasma Breakdown Optimization

- Feedforward control is maintained during the BD and the first plasma phases until sufficient plasma current I_p allows feedback control on both radial and vertical plasma position
- The optimization of the Poloidal Field (PF) voltages and currents involves a dynamic process with strong magnetic interactions among *active coils* and *passive structures*

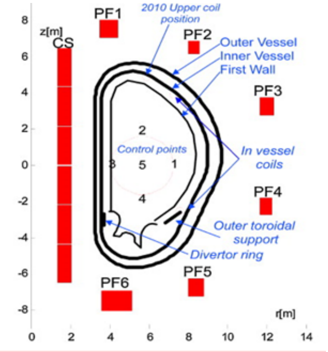
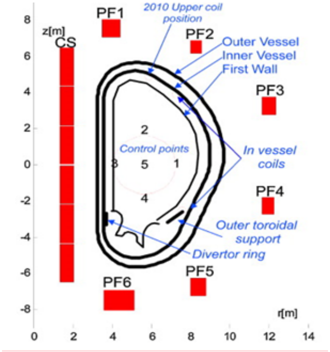


Figure: ITER Poloidal cross section.

Plasma Breakdown Optimization

- The optimization problem is made more complex by the presence of hard constraints
    - current and voltage saturation limits
    - maximum fields
    - maximum vertical forces
- The need to ramp up I_p guaranteeing equilibrium conditions over a post-BD time interval, requires that voltages and currents optimization has to be performed over a sufficiently wide time window including transients



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Contribution

1. Formalization of the BD scenario optimization problem as a Quadratic Programming (QP) problem with linear constraints
    - The proposed QP problem is based on a two-dimensional axi-symmetric model and on the hypothesis that **plasma can be modeled as a circular massive conductor** with known resistance for a plasma current value up to about 500kA

Contribution

1. Formalization of the BD scenario optimization problem as a Quadratic Programming (QP) problem with linear constraints
    - The proposed QP problem is based on a two-dimensional axi-symmetric model and on the hypothesis that **plasma can be modeled as a circular massive conductor** with known resistance for a plasma current value up to about 500kA
2. Design of a Kalman Filter to reconstruct the field map in the plasma chamber also in the presence of uncertainties and noise

Deriving a state-space model - 1/2

- The starting point is the Grad-Shafranov equation (nonlinear PDE), which is recasted into a finite dimensional problem using a first order Finite Elements Method

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- Given a first order mesh of N elements, N *linear equations* can be derived to describe the behaviour of the (poloidal) fluxes $\tilde{\psi}$ in the N nodes

$$\tilde{\psi} = C_{PF} I_{PF} + C_{eddy} I_{eddy} + C_p I_p + C_{fil} I_{fil} \tag{1}$$

with

  - I_{PF} are the currents in the (active) PF coils
  - I_{eddy} are the *eddy* currents in the passive structures
  - I_p is the plasma current (which is *active* after the BD, i.e. $\forall\ t > t_{BD}$
  - I_{fil} are additional **static** filamentary currents used to simulate additional magnetic fields (e.g., busbar connections, ferromagnetic material from building)

Deriving a state-space model - 2/2

The dynamic of the currents in (1) is driven by the following circuit equation

$$\begin{pmatrix} L_{PF,PF} & L_{PF,eddy} & L_{PF,p} \\ L_{eddy,PF} & L_{eddy,eddy} & L_{eddy,p} \\ L_{p,PF} & L_{p,eddy} & L_{p,p} \end{pmatrix} \frac{dI}{dt} + \begin{pmatrix} R_{PF} & 0 & 0 \\ 0 & R_{eddy} & 0 \\ 0 & 0 & R_p \end{pmatrix} I = \begin{pmatrix} V \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

where

- $I = \left(I_{PF}^T \; I_{eddy}^T \; I_p \right)^T$
- During the first phase of the plasma current rise (soon after t_{BD}), plasma is modeled as a massive circular conductor with R_p of few $\mu\Omega$
- Plasma self-inductance L_p is one of the outputs of the electromagnetic model (computed under the assumption of circular massive conductor)

State-space model for BD optimization - 1

Letting $x = I$, $u = V$, $w = I_{fil}$, $y = \tilde{\psi}$, yields to the usual state-space representation

$$\dot{x} = Ax + Bu\,, \quad x(0) = x_0 \tag{3a}$$
$$y = Cx + Du + Fw \tag{3b}$$

Assuming u piecewise linear, system (3) can be augmented as follows

$$\dot{x} = Ax + Bs\,, \quad x(0) = x_0 \tag{4a}$$
$$\dot{s} = \dot{u}\,, \quad s(0) = u_0 \tag{4b}$$
$$y = Cx + Du + Fw \tag{4c}$$

State-space model for BD optimization - 2

Finally, letting $z = \left(x^T \; s^T\right)^T$, system (4) can be written as

$$\dot{z} = \tilde{A}z + \tilde{B}\dot{u}\,, \quad z(0) = z_0 \tag{5a}$$

$$y_{ct} = \tilde{C}_{ct}z + y_{ct_0} \tag{5b}$$

$$y_{cs} = \tilde{C}_{cs}z + y_{cs_0} \tag{5c}$$

with

- y_{ct} **controlled outputs**, e.g., magnetic (vertical and radial) field and flux in the control points
- y_{cs} **constrained outputs**, e.g., PF currents and voltages, vertical forces on coils
- $y_{ct_0} = F_{ct}w$ and $y_{cs_0} = F_{cs}w$.

BD voltage optimization problem - 1

Problem statement

Given system (5), a desired value of the controlled outputs at the BD time t_{BD}, a desired time behavior of some of the controlled outputs y_{ct}, a set of constraints on output variables y_{cs}, a desired value of the flux state at t_{BD}, find:

- t_{BD} in which BD conditions are met with minimum loss of flux state
- the set of initial currents in PF and CS coils
- a piecewise linear time behaviour of PF and CS voltages from 0 to t_{BD}

BD voltage optimization problem - 2

- In order to formulate the BD voltage optimization problem, system (5) is **converted into a discrete-time model** (with constant sampling period T_s), under the assumption of piecewise linear input voltages u
- The **explicit response of the discrete-time model** is computed

$$\begin{pmatrix} y(k) \\ y(k-1) \\ \vdots \\ y(1) \end{pmatrix} = \Phi \begin{pmatrix} z_0 \\ \dot{u}(0) \\ \vdots \\ \dot{u}(k-1) \end{pmatrix} + \begin{pmatrix} y_0 \\ y_0 \\ \vdots \\ y_0 \end{pmatrix} \tag{6}$$

- By making the distinction between *controlled* and *constrained* outputs, it is possible to rewrite (6) as

$$Y_{ct} = \Phi_{ct} X + Y_{ct_0} \tag{7a}$$

$$Y_{cs} = \Phi_{ct} X + Y_{cs_0} \tag{7b}$$

QP problem

A solution to the BD voltage optimization problem can be obtained by solving the following QP problem

$$\min_{X} \left(\Phi_{ct} X + Y_{ct_0} - Y_{ct_d}\right)^T Q \left(\Phi_{ct} X + Y_{ct_0} - Y_{ct_d}\right) + X^T R X$$

subject to

- $\Phi_{cs} X + Y_{cs_0} < Y_{cs_M}$
- $\Phi_{cs} X + Y_{cs_0} > Y_{cs_m}$
- $X_m < X < X_M$

where Y_{ct_d} is the vector of the desired controlled outputs, while $Q > 0$ and $R \geq 0$ are *weighting matrices*.

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- Before plasma BD (i.e. when $I_p = 0$), assuming that I_{PF} and the static offsets are known, then the circuit equation (2) can be exploited to design a Kalman filter that reconstructs the eddy currents

Requirements for ITER plasma initiation at half toroidal field (2.7 T)

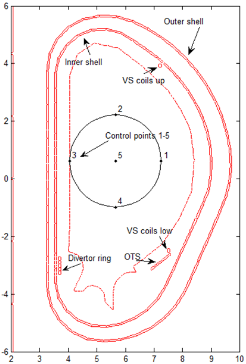

Figure: Control point considered for the BD optimization.

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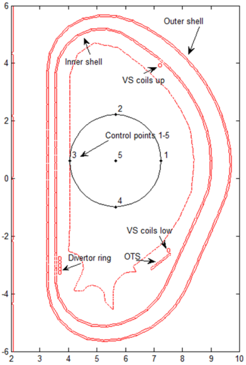

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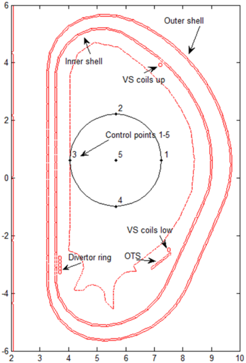

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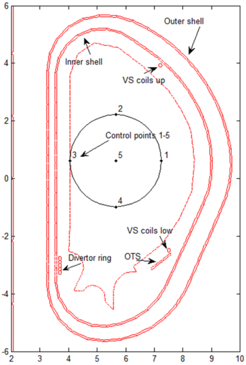

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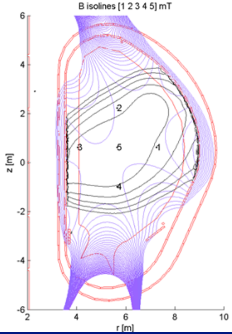
- For $t > t_{BD}$, the vertical field B_z should vary according to the Shafranov vertical field formula
- For $t > t_{BD}$, the decay index of the vertical magnetic field should be close to 0.5

BD optimization

- The presented BD optimization approach has been applied to the 2.7 T, early machine operation scenario, using a sampling $T_s = 90\ ms$.
- BD conditions have been achieved at $t_{BD} = 1.09\ s$, enforcing all the constraints
- **In order to obtain BD conditions Switching Network Units, i.e. bank of resistors in series to the CS/PF coils were needed to increase the current slew rate and satisfy the requirement on the loop voltage/electric field**



Isoflux **(blue)** and isofield **(black)** lines at t_{BD}. The control points 1-5 fall within a region inside the isofield line at 3 mT

Flux map reconstruction from noisy measurement

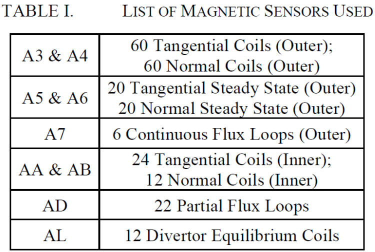


TABLE I. LIST OF MAGNETIC SENSORS USED

A3 & A4	60 Tangential Coils (Outer); 60 Normal Coils (Outer)
A5 & A6	20 Tangential Steady State (Outer) 20 Normal Steady State (Outer)
A7	6 Continuous Flux Loops (Outer)
AA & AB	24 Tangential Coils (Inner); 12 Normal Coils (Inner)
AD	22 Partial Flux Loops
AL	12 Divertor Equilibrium Coils

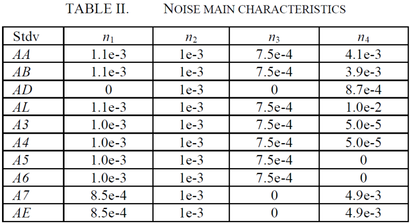


TABLE II. NOISE MAIN CHARACTERISTICS

Stdv	n_1	n_2	n_3	n_4
AA	1.1e-3	1e-3	7.5e-4	4.1e-3
AB	1.1e-3	1e-3	7.5e-4	3.9e-3
AD	0	1e-3	0	8.7e-4
AL	1.1e-3	1e-3	7.5e-4	1.0e-2
A3	1.0e-3	1e-3	7.5e-4	5.0e-5
A4	1.0e-3	1e-3	7.5e-4	5.0e-5
A5	1.0e-3	1e-3	7.5e-4	0
A6	1.0e-3	1e-3	7.5e-4	0
A7	8.5e-4	1e-3	0	4.9e-3
AE	8.5e-4	1e-3	0	4.9e-3

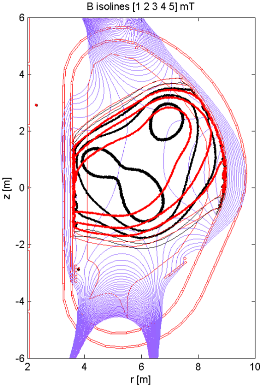
Noise on the measured output has been modeled as

$$y_m(t) = y(t)\left(1 + n_1 + n_2(t)\right) + n_3(t) + n_4(t)$$

where

- n_1 - constant multiplicative action
- $n_2(t)$ - multiplicative noise
- $n_3(t)$ - additive noise
- $n_4(t)$ - drift

Field map reconstruction - Simulation results



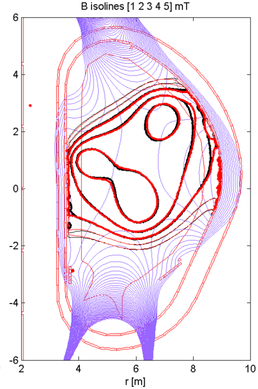


Figure: Comparison between the optimized field map **(red)** and the actual one **(black)**.

Figure: Comparison between the reconstructed field map and the actual one.

Conclusions

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Thank you!