Mapping of the ASDEX Upgrade Operational Space for Disruption Prediction

R. Aledda, B. Cannas, A. Fanni, G. Sias
Department of Electrical and Electronic Engineering
University of Cagliari
Cagliari, Italy

G. Pautasso, the ASDEX Upgrade Team
Max-Planck-Institüt für Plasmaphysik
EURATOM Association
Garching, Germany
Summary

✓ Introduction
✓ Self Organizing Map
✓ The Database
✓ Mapping of AUG operational space
✓ Disruption Prediction
✓ Conclusions
Introduction

*Self Organizing Map* as a Tool for:

- visualization and analysis of the AUG operational space
- disruption prediction
Self Organizing Map (SOM)

- Mapping from an $nD$-space to a regular array of neurons (clusters)
- **Topology preservation**

Cluster barycentre

Data close in the input space

Data close in the SOM

3D Input Space

2D Output Space SOM
The Database

<table>
<thead>
<tr>
<th>DB</th>
<th>disruptions</th>
<th>range</th>
<th>Time period</th>
<th>use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>disrupted</td>
<td>safe</td>
<td></td>
<td>Training and Validation</td>
</tr>
<tr>
<td>DB1</td>
<td>149</td>
<td>80</td>
<td>16200-19999</td>
<td>2002–2005</td>
</tr>
<tr>
<td>DB2</td>
<td>81</td>
<td>537</td>
<td>20000-22146</td>
<td>2005–2007</td>
</tr>
<tr>
<td>DB3</td>
<td>118</td>
<td>534</td>
<td>22162-25665</td>
<td>2007–2009</td>
</tr>
</tbody>
</table>

All the disruptions except those:
- in the ramp-up phase
- in the ramp-down phase if \( t_D > t_{\text{ramp-down}} + 100 \text{ ms} \);
- caused by massive gas injection
- following a VDE
<table>
<thead>
<tr>
<th><strong>Signal</strong></th>
<th><strong>Acronym [unit]</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current</td>
<td>$I_p [A]$</td>
</tr>
<tr>
<td>Safety factor at 95% of poloidal flux</td>
<td>$q_{95}$</td>
</tr>
<tr>
<td>Input power from Neutral Beam Injection</td>
<td>$P_{NBI} [W]$</td>
</tr>
<tr>
<td>Input power from Electron Cyclotron Radio frequency Heating</td>
<td>$P_{ECRH} [W]$</td>
</tr>
<tr>
<td>Input power from Ion Cyclotron Radio frequency Heating</td>
<td>$P_{ICRH} [W]$</td>
</tr>
<tr>
<td>Ohmic input power</td>
<td>$P_{OH} [W]$</td>
</tr>
<tr>
<td>Total input power</td>
<td>$P_{inp} = 0.9 P_{NBI} + P_{ECRH} + P_{ICRH} + P_{OH} [W]$</td>
</tr>
<tr>
<td>Locked Mode signal</td>
<td>$LM [V]$</td>
</tr>
<tr>
<td>Radiated power</td>
<td>$P_{rad} [W]$</td>
</tr>
<tr>
<td>Radiated fraction of the input power</td>
<td>$P_{frac}=P_{rad}/P_{inp}$</td>
</tr>
<tr>
<td>Plasma density divided by the Greenwald limit</td>
<td>$ne_G$</td>
</tr>
<tr>
<td>Internal inductance</td>
<td>$l_i$</td>
</tr>
<tr>
<td>Poloidal $\beta$</td>
<td>$b_p$</td>
</tr>
<tr>
<td>Loop Voltage</td>
<td>$U_{loop} [V]$</td>
</tr>
</tbody>
</table>
Mapping of AUG 7D-operational space

\[ \{q_{95}, P_{\text{inp}}, P_{\text{frac}}, li, LM, \beta p, ne_G\}_{t1} \]

\[ \{q_{95}, P_{\text{inp}}, P_{\text{frac}}, li, LM, \beta p, ne_G\}_{t2} \]

\[ \{q_{95}, P_{\text{inp}}, P_{\text{frac}}, li, LM, \beta p, ne_G\}_{t18} \]

\[ \{q_{95}, P_{\text{inp}}, P_{\text{frac}}, li, LM, \beta p, ne_G\}_{t90} \]

7D-Plasma parameter space

2D-Output Space (2D-SOM)
Mapping of AUG 7D-operational space

**Disruptive discharges**

- $t_{\text{FLAT-TOP}}$  
- $t_{D} - 45\text{ms}^{(*)}$  
- $t_{D}$

Safe phase

**Safe discharges**

- $t_{\text{FLAT-TOP}}$  
- $t_{\text{END}}$

2D mapping colored on the basis of clusters type

<table>
<thead>
<tr>
<th>Clusters</th>
<th>safe discharge</th>
<th>Disruptive discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>green</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>grey</td>
<td>X</td>
<td>&lt;85%</td>
</tr>
<tr>
<td>red</td>
<td>-</td>
<td>≥85%</td>
</tr>
<tr>
<td>white</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Disruption Prediction:
Performance indexes and results

\[ PD = \frac{n^o \text{ Premature Decisions}}{n^o \text{ disruptive shots}} \times 100 \]

\[ SP = \frac{n^o \text{ Successful Predictions}}{n^o \text{ disruptive (or Safe) shots}} \times 100 \]

\[ TD = \frac{n^o \text{ Late Decisions}}{n^o \text{ disruptive shots}} \times 100 \]

\[ MA = \frac{n^o \text{ Missed Alarms}}{n^o \text{ disruptive shots}} \times 100 \]

\[ FA = \frac{n^o \text{ False Alarms}}{n^o \text{ safeshots}} \times 100 \]

**Prediction performance:**
- \( t_{\text{alarm}} < t_{D} - 160 \text{ms} \)
- \( t_{D} - 160 \text{ms} \leq t_{\text{alarm}} < t_{D} - 2 \text{ms} \) or Safe shots predicted as safe
- \( t_{D} - 2 \text{ms} \leq t_{\text{alarm}} \leq t_{D} \)
- \( t_{\text{alarm}} > t_{D} \)
- Safe shots predicted as disruptive

<table>
<thead>
<tr>
<th>Disrupted discharges</th>
<th>Safe discharges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PD[%]</strong></td>
<td><strong>SP[%]</strong></td>
</tr>
<tr>
<td><strong>DB1</strong></td>
<td>9,40</td>
</tr>
<tr>
<td><strong>DB2</strong></td>
<td>9,88</td>
</tr>
<tr>
<td><strong>DB3</strong></td>
<td>16,95</td>
</tr>
</tbody>
</table>
Disruption Prediction: Analysis of results

- The large majority of correct alarms is triggered in the presence of an increase of $P_{rad}$.
- 73.5% of FAs and 50% of PDs correspond to a peak in the $P_{frac}$ signal due to the shutdown of one or more AHS.

Discharge #21011 on the 2D-SOM.
Disruption Prediction: 2D Map of 8D operational space

Inputs: \( \{q_{95}, P_{inp}, P_{rad}, P_{frac}, li, LM, \beta p, ne_G\} \)

Algorithm to limit FAs and PDs

The alarm is inhibited when following conditions are simultaneously satisfied:

1. \( \frac{dP_{inp}}{dt} \leq \frac{dP_{inp}}{dt} \bigg|_{THR} \) At least once in the 20ms preceding the alarm time
2. \( P_{rad} \leq P_{rad} \bigg|_{THR} \)
3. \( \frac{dP_{rad}}{dt} < \frac{dP_{rad}}{dt} \bigg|_{THR} \)
Disruption Prediction: 2D Map of 8D-operational space

\[
\frac{dP_{inp}}{dt} \bigg|_{THR} = -1.2 \text{ GW/ms}
\]
Is the minimum value assumed by \( P_{rad} \) at the alarm time, for all the correct predictions in the presence of an increase of \( P_{rad} \).

\[
P_{rad} \big|_{THR} = 1.3 \text{ MW}
\]
the minimum value assumed by \( P_{rad} \) at the alarm time, for all the correct predictions in the presence of an increase of \( P_{rad} \).

\[
\frac{dP_{rad}}{dt} \bigg|_{THR} = 11 \text{ MW/ms}
\]
is the minimum value assumed by \( dP_{rad}/dt \) at the alarm time, for all the correct predictions in the presence of an increase of \( P_{rad} \).

**Prediction performance:**

<table>
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<th>Safe discharges</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>PD[%]</td>
<td>SP[%]</td>
</tr>
<tr>
<td><strong>DB2</strong></td>
<td>9.88</td>
<td>69.14</td>
</tr>
<tr>
<td><strong>DB3</strong></td>
<td>8.47</td>
<td>69.50</td>
</tr>
</tbody>
</table>
Conclusions

The SOM of the 8D-AUG operational space provides:

I. 2D-Map where regions with different risk of disruption can be identified

II. Disruption predictor
The $K$ output neurons are fully connected to the inputs via the weights $w$.

- $O_j = \sum_{i=1}^{n} w_{ji}x_i$ is the output of $j$th neuron, $j=1,\ldots,K$

- A competitive learning rule is used, choosing the winner $j^*$ as the output neuron with weight vector $w$ closest to the input $x$:

\[ \Delta w_j = \eta \cdot \Lambda(j, j^*) \cdot (x - w_j) \quad j = 1, \ldots, K \]

- The neighborhood function $\Lambda$ is equal to 1 for $j=j^*$, and decreases with the distance between neurons $j$ and $j^*$ in the output lattice. Thus, neurons close to the winner have their weights updated, while those further away, experience little effect.

Self Organizing Map (SOM)
Disruption Prediction: 
Alarm criteria

1. \( k = \frac{(101.11 - ds_\%)}{0.7} \) if \( 85 \leq ds_\% < 100 \)

   The value \( k \) is updated only if the trajectory moves into clusters with higher \( ds_\% \).

2. \( k = 2 \) if \( ds_\% = 100 \)