Investigation of plasma dynamics to detect the approach to the disruption boundaries

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*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

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Outline

• Introduction
  • APODIS predictor

• Trajectories in the plasma operational space

• Transit speed non-disruptive/disruptive regions

• Prediction credibility

• Plasma dynamics
Introduction

• So far, plasma theoretical models do not cope satisfactorily with the prediction of disruptions
• Nowadays, disruption prediction is carried out by means of machine learning methods that distinguish between disruptive and non-disruptive behaviours in the multi-dimensional operational space
• A training dataset made up of disruptive and non-disruptive examples allows determining the separation frontier between both zones

During the execution of a discharge, inputs are provided to the model on a periodic basis and an alarm is triggered when the output is ‘disruptive’

• Cyan curve represents a possible trajectory of the plasma behaviour in the operational space during a discharge
  • The trajectory summarizes the plasma dynamic

• Could be characterized the plasma dynamic in the operational space?
  • APODIS can help
The Advance Predictor Of DISruptions (APODIS) is in operation in the JET real-time data network

<table>
<thead>
<tr>
<th>#</th>
<th>Signal name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plasma current</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>Locked mode amplitude</td>
<td>T</td>
</tr>
<tr>
<td>3</td>
<td>Total input power</td>
<td>W</td>
</tr>
<tr>
<td>4</td>
<td>Plasma internal inductance</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Plasma density</td>
<td>m(^{-3})</td>
</tr>
<tr>
<td>6</td>
<td>Stored diamagnetic energy time derivative</td>
<td>W</td>
</tr>
<tr>
<td>7</td>
<td>Radiated power</td>
<td>W</td>
</tr>
</tbody>
</table>

APODIS basic computations are carried out in temporal windows 32 ms long

- Sampling frequency 1 kS/s (32 samples per window)
- 2 representations per signal in each time window
  - **Time domain**: mean value
  - **Frequency domain**: standard deviation of the power spectrum (removing DC component)
- Feature vectors \(\mathbf{x} \in \mathbb{R}^{14}\) are continuously generated every 32 ms when \(I_p > 750\) kA

The classifiers operate in parallel on consecutive time windows.

First layer:
- M1, M2 and M3 are 3 independent classifiers
- Train temporal segments (ms) w.r.t. disruption

Second layer:
- The three classifiers may disagree about the discharge behaviour

Decision Function: SVM classifier

**As a discharge is in execution, the most recent 32 ms temporal segments are classified as disruptive or non-disruptive**
Temporal evolution of the distance to the APODIS separating hyper-plane

Discharge 87287

Discharge 87493

Discharge 87377

Discharge 87355

12 ms in disruptive zone

474 ms in disruptive zone

224 ms 96 ms 25 ms in disruptive zone

22 ms from safe zone

256 ms
Some empirical facts about plasma dynamics

- In general, there is no erratic trajectories in the operational space
  - The plasma state remains at a ‘constant’ distance from the separating hyper-plane and the transit is fast
- It is possible to determine the transit speed between the non-disruptive and the disruptive zones
  - $V = \frac{\Delta d}{\Delta t} = (d(t+32) - d(t))/32$
- Sometimes the plasma transits and comes back to the non-disruptive state but there exist ‘no-return points’
  - Why this behaviour?
In general, the plasma evolves in a steady way during the plasma current flat top
  • The furthest the better

The trajectory remains parallel to the separating hyper-plane

Some events can push the plasma towards the hyper-plane
  • Most of times the plasma stays in the safe region and recovers the initial distance
    • What are the physics reasons for this?
  • Sometimes the plasma crosses to the disruptive zone and goes back
    • False alarms
    • Premature alarms
    • Near a disruption

The temporal evolution of the APODIS distance can be used for the creation of specialised databases to identify events that produce loss of stability
  • Data mining for physics studies
• The transit speed distribution follows a gamma probability distribution with *shape parameter* $t = 1.6274$ and *scale parameter* $\lambda = 3.0516$

• 292 discharges between shots 84628 and 87532
State transitions

- How can the plasma dynamics be interpreted with APODIS?
  - Multiple transitions between safe and disruptive states
  - APODIS does work for machine security: **real-time**
    - From an engineering viewpoint, in a first stage, identification of disruptive behaviours is more important than to know the physics causes
- How can be used APODIS predictions for physics analysis?: **off-line**
  - The analysis of disruption physics has to be concentrated around ‘no-return points’

- Distance fluctuations around $d = 0$, do they represent true switching between plasma states?
  - How reliable are the predictions?
- Can ‘no-return points’ be characterised in any form?
Predictor reliability: general ideas

- The closer the samples to the hyper-plane the lesser credibility for the prediction
  - The samples are ‘strange’ in relation to the training samples
    - They are far away from the training sets
    - They are very close to the separation frontier: the classification can depend on measurement error bars
- How can be quantified the ‘strangeness’?

Samples are feature vectors: $\mathbf{X} \in \mathbb{R}^n$
Measures to quantify ‘strangeness’ (credibility)

• With $n_1 = 14$, $n_2 = 18$
  - $s_1 = 1/32 = 0.03125$ (strange: low credibility in the prediction)
  - $s_2 = 2/32 = 0.0625$ (strange: low credibility in the prediction)
  - $s_3 = 25/32 = 0.78125$ (no strange: high credibility in the prediction)
  - $s_4 = 32/32 = 1$ (no strange: high credibility in the prediction)
Prediction credibility

Credibility vs. Distance

Separating hyper-plane

Discharge 87119

Time (s)

APODIS distance

Discharge 87119

Time (s)

Credibility

Discharge 87119

Time (s)
Distances and credibility are not completely equivalent

- APODIS distance is computed with a single dataset
  
  - Separating hyper-plane

- To compute the credibility, a conformal prediction framework is used
  
  - The first feature vector of a discharge uses the initial training dataset
  - After computing the credibility of the first feature vector, the vector is added to the training set
  - With each new feature vector, both the separating hyper-plane and the credibility are computed

- As new feature vectors are added, the hyper-plane can change
  
  - Separating hyper-plane

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Distances and credibility are not completely equivalent

- The credibility is more sensible than the APODIS distance to diagnose the plasma dynamics
Plasma dynamics

- A decreasing credibility means that the plasma approaches to the separating hyper-plane.
- An increasing credibility means that the plasma moves away from the separating hyper-plane.

![Graphs showing plasma dynamics](graph.png)
No-return points

Discharge 87119

$t_1$: no-return point

$t_2$: around the hyper-plane

$t_3$: around the hyper-plane

$t_4$: disruption

Mean: 749 ms
Std: 1060 ms

297 JET discharges in the range
84628 - 87532

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No-return points

Discharge 87119

$t_1$: no-return point
$t_2$: around the hyper-plane
$t_3$: around the hyper-plane
$t_4$: disruption

297 JET discharges in the range 84628 - 87532

$t_1 \rightarrow t_2$
Mean: 187 ms
Std: 447 ms

$t_2 \rightarrow t_3$
Mean: 243 ms
Std: 686 ms

$t_3 \rightarrow t_4$
Mean: 319 ms
Std: 529 ms
Summary

• The plasma maintains a parallel trajectory to the separating hyper-plane during a non-disruptive evolution

• It is possible to determine a transit speed

• The reliability of each prediction can be quantified through the credibility

• The plasma dynamics can be explained in terms of the temporal evolution of the credibility

• How can be characterize the no-return points?