EUROfusion

WPPMI-CPR(17) 17484

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Investigation of plasma disruptions in DEMO reactor

Preprint of Paper to be submitted for publication in Proceeding of
13th International Symposium on Fusion Nuclear Technology
(ISFNT)

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Preliminary study of DEMO disruptions due to component failures

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Plasma disruptions represent the highest hazard for the integrity of plasma facing components in tokamak reactors. Several studies are performed in order to minimize their severity and occurrence or to mitigate their effects in case they happen despite the prevention carried out. In a power plant as DEMO, the disruptions should have low occurrence probability, relying on assumption that proper well qualified plasma scenarios and operative procedures will be identified and followed after ITER and other fusion facilities experimental campaigns. Anyway, the probability of technical failures of components leading to disruptions cannot be assumed low a priori. A specific study has been performed in order to have a first overview on this issue.

The applied methodology benefits from a large set of safety and reliability/availability analyses performed in the past for ITER and DEMO. Possible failure modes of the components of DEMO systems are investigated. The main objective has been to highlight the overall failure events that happening during the plasma operations could lead to plasma disruptions or requests of controlled plasma shutdown. Finally, a first estimation of the probability of occurrence of such failure events has been provided on the base of: component failure rates available in literature, estimation of number of similar components in the plant and yearly time of plasma operations.

Keywords: Plasma Disruption, Disruptivity, FMEA, Failure Rate, DEMO, Plasma Shutdown.

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1. Introduction

Plasma disruptions represent the highest hazard for the integrity of plasma facing components in tokamak reactors. In fact, some plasma disruptions could be very severe leading to large forces induced on the structures surrounding the plasma, to large heat loads applied on in-vessel components and to large amount of runaway electrons on the plasma chamber walls.

In a power plant as the European "Demonstration Fusion Power Plant" (DEMO), two kinds of reasons are expected to cause disruptions: physics reasons and technical failures of operating components and systems. Even if, at the time of DEMO operations, after ITER and other fusion facilities experimental campaigns, we should be able to rely on proper well qualified plasma scenarios and operative procedures, as well as in well qualified fusion components and systems, we cannot neglect the occurrence of plasma disruptions. This study is performed in order to have a first and very preliminary overlook on the overall technical failures occurring inside the different plant systems and leading to disruptions, i.e. the chains of causalities that starting from technical failures of components could cause disruptions.

As currently, four different concepts of breeding blanket (BB) are considered for the future reactor, the study interests all the four BB concepts. They are: the Helium-Cooled Pebble Bed (HCPB) [1], the Helium-Cooled Lithium Led (HCLL) [2], the Water-Cooled Lithium Led concept (WCLL) [3] and the Dual-Coolant Lithium Led concept (DCLL) [4]. The considered designs are the ones developed in 2015-2016.

2. Methodology of analysis

The applied methodology benefits from a large set of safety and reliability/availability analyses performed in the past for ITER and DEMO, as well as for power plant conceptual studies performed in the frame of different European programs (last published articles [5,6]).

A detailed plant breakdown structure (PBS) of DEMO systems is defined at first, taking into account the different options of DEMO design currently considered. Then, possible failure modes of the components at the PBS lower levels are defined investigating the Failure Mode and Effect Analyses (FMEAs) performed in the past both at component level and functional level for the various reactors. The main objective of this report is to highlight, with the help of the FMEAs, the overall failure events that happening during the plasma operations could lead to plasma disruptions or requests of plasma shutdown.

In most of the different FMEAs taken as reference for this study the following items were identified, analyzed and discussed:

- Systems and/or main equipment and/or components devoted to perform process and safety functions.
- Failure modes and causes of failures,
- Consequences for the plant, in terms of damage to the machine, radioactive inventory mobilization through the different containment barriers and to the environment, possible harm to workers and population and, finally, possible plasma disruption.
- Actions/means set to prevent occurrence of the initiator and to mitigate the consequences of the failure, e.g., detections and responses of the control system, such as plasma shutdown (PSD).

The effects of the failure on the plasma are checked in terms of

- plasma disruption induced by the initiating event (e.g. massive matter injection in plasma chamber, failure in magnet and power supply systems) or,
- the possibility that a fast PSD is required either for safety or investment protections (in ITER, the estimated time required for a fast PSD by a controlled injection of inert gas is 3 s) or,
- the possibility that a soft PSD is required either for safety or investment protections (in ITER, a soft PSD is in the order of 100 s) or,
- no direct plasma shutdown is required for the occurrence of the IE.

The study is completed with the estimation of the occurrence of failure events. It has been provided on the base of: component failure rates available in literature, estimation of number of similar components in the plant and yearly time of plasma operations.

3. Plant breakdown structure (PBS)

The DEMO PBS is outlined for the purpose of the study. The hierarchical structure of components and items has been as much as possible detailed to enable the identification of failures impairing the operations of the considered system and the operations with plasma. The first level of the DEMO PBS is the one currently defined in the EUROFusion Work Programme (see first two columns of Table 5). Table 1 exemplifies the achieved level of detail in components/items identification, based on last available design updates. Items reported in Table 1 relate to First Walls, Caps, Side Walls, Stiffeners, Breeding zone grids, Backplate, Manifolds, Back supporting structure, in-Vacuum Vessel (In-VV) distributors and collectors identified for the four BB concepts. The total length or the quantity of the different items is also reported.

Table 1. Example of items identified for the four breeding blanket concepts

Items		HCPB	HCLL	WCLL	DCLL
Cooling channels/small pipes in BB modules	[m]	2,470,817	847,209	630,596	213,830
Welds in BB modules acting as seals against in-box coolant leak	[m]	168,984	594,080	429,768	108,608

Welds in BB modules acting as seals against in-VV leak (coolant, purging gas and/or LiPb)	[m]	22,680	20,288	74,880	18,880
Distributors and collectors inside VV (coolant, purging gas and/or LiPb pipes)	[m]	1,620	640	1,620	640
Pipe-F/Ts (feedthroughs) in the VV boundary	Qty	540	320	540	320
F/Ts in BB modules acting as seals against in-VV leak	Qty		38,340		

4. Failure rates

The likelihoods of single component failures were estimated by data extracted from the fusion component failure rate database (FCFRDB), which collects data useful for probabilistic assessment in nuclear fusion and fission field [7-9]. Due to the heterogeneity of FCFRDB data sources, for almost all components, more than one failure rate data was available to be taken as reference in defining the component failure rates. Then, on the basis of the available data sets (e.g. one set for each failure mode of the different components), a sensitivity analysis has been done providing results for two scenarios: 1) results based on the lower failure rates between the sets of available reference data and 2) more conservative results based on the mean values of the failure rates of the same sets of data. The selection of the most optimistic failure rate, practically, gives credit to the high quality of the components and items eventually selected for DEMO. While, the selection of less optimistic failure rates allows to gain insight about the possible range of occurrences of the single events and of the consequential effects on the plasma. Example of failure rates used for this study is reported in Table 2.

To be noted that such failure rates have to be considered only indicative for a reactor that will be built in tens of years. In fact, the failure rates coming from fission, even if quite consolidated, refers to nuclear components (e.g. classified in quality class 1) manufactured and operated up to few years ago and, the failure rates coming from fusion are relevant to components often prototypes. So, some improvements (reduction of failure rates) might be expected for future and new DEMO components, particularly for components that will use advanced technologies.

5. Occurrence of failure events

Once the list of components/items of the plant with the related possible failure modes and failure rates of the single elements are identified the occurrence of failure events is calculated.

Single failures are combined to evaluate the occurrence of the elementary events in the whole plant. The occurrence of each event was evaluated considering the following data: failure rate of components; yearly hours of plasma operations; number of components interested in the failure and their reliability wise correlations, i.e. series and/or parallel configurations in defining effects on the plasma in terms of disruption or requests of fast or soft PSD.

The yearly hours of plasma operations has been assumed as 2890 h [DEMO Power Plant Requirements Document (PRD) (2MG7RD v2.4)].

Table 2. Example of component failure rates used in the study

Component	**Failure mode**	**Failure rate**		
		Min	**Max**	**Unit**
Accelerator grid	Leak/Rupture	1.0E-6	2.0E-6	/h
Bellow	Leak/Rupture	3.0E-8	3.7E-7	/h
Busbar ac	Short	1.0E-7	6.7E-7	/h
Busbar dc	All failure modes	2.9E-7	5.2E-7	/h
Capacitor	All failure modes	5.6E-6	3.9E-5	/h
Centrifugal pump	All failure modes	1.8E-6	3.8E-6	/h
Circuit breaker Low Voltage	Failure to remain in position	1.1E-7	1.3E-6	/h
Coil conductor	All failure modes	1.0E-7	4.5E-6	/h
Coil jacket	Leak/Rupture	1.2E-8	2.5E-6	/h
Coil termination joints	Short	2.7E-8	3.0E-7	/h
Compressor	Failure to function/operate	3.0E-5	1.0E-4	/h
Condenser	Loss of vacuum	1.0E-5	2.3E-5	/h
Cryo pump	All failure modes	2.0E-6	2.0E-5	/h
Electromagnetic pump	Failure to function/operate	1.0E-6	3.4E-6	/h
F/T - electrical	Leak/Rupture	1.0E-7	2.0E-6	/h
F/T - pipe	Leak/Rupture	6.0E-8	5.0E-7	/h
Filter	Clogging	2.1E-6	3.0E-6	/h
Flowmeter	Failure to function/operate	2.7E-6	1.7E-5	/h
Generator	All failure modes	4.5E-7	2.0E-5	/h
Transformer	All failure modes	3.2E-7	1.0E-6	/h
Heat Exchanger	All failure modes	3.1E-7	6.9E-6	/h
Heater	Failure to function/operate	5.6E-7	8.6E-7	/h

Helium channel	Clogging	8.5E-10	2.0E-9	/mh
Instrumentation channels 2oo3	All failure modes	3.8E-10	6.1E-9	/h
Insulator	All failure modes	1.0E-8	6.0E-7	/h
Mechanical supports	All failure modes	1.0E-8	3.0E-8	/h
Mirror	Rupture	5.7E-7	1.1E-6	/h
Pipe	Leak/Rupture	2.5E-11	8.5E-10	/mh
Port seal	Leak/Rupture	3.0E-8	6.0E-8	/h
Power cable	Short	1.0E-8	1.0E-7	/h
Pressurizer	Leak/Rupture	1.0E-10	1.0E-8	/h
Relief Valve	Spurious opening	1.6E-6	1.0E-5	/h
Resistor	All failure modes	1.0E-7	6.4E-7	/h
Rupture disk	Spurious opening	5.9E-7	3.0E-6	/h
Switchgear	Failure to remain in position	1.7E-6	3.4E-6	/h
Tank	Leak/Rupture	1.0E-8	4.0E-7	/h
Turbine	All failure modes	1.9E-5	2.1E-4	/h
Turbine bypass valve	Failure to remain in position	1.1E-6	4.6E-5	/h
UPS	All failure modes	3.0E-6	6.0E-6	/h
Vacuum pumping system	Failure to function/operate	5.6E-9	7.5E-8	/h
Vacuum switch	Failure to remain in position	1.1E-5	2.2E-5	/h
Vacuum Transmission Line	Leak/Rupture	5.6E-9	7.6E-8	/h
Valve - motor actuator	Leak/Rupture	1.0E-8	2.7E-8	/h
Valve - pneumatic actuator	All failure modes	1.8E-6	6.9E-6	/h
Valve - pneumatic actuator	Failure to remain in position	3.0E-7	3.0E-6	/h
Water channel	Clogging	8.5E-9	2.0E-8	/mh
Weld	Leak/Rupture	1.8E-9	2.6E-8	/mh
Window	Leak/Rupture	1.4E-6	3.4E-6	/h

6. Results

The total amount of different failure modes identified with this study is reported in Table 3 by allocating the events for concept of blanket module. The events have been distinguished between events either inducing plasma disruptions or, requiring a fast PSD or a soft PSD, or events that do not require a direct PSD.

Table 3. Total amount of different failure modes allocated for the four breeding blanket concepts

Type of failure consequence	HCPB	HCLL	WCLL	DCLL
Disruptions	316	316	317	314
Fast PSD	45	45	48	45
Soft PSD	314	330	312	328
No direct PSD	490	502	487	502
Total	1165	1193	1164	1189

In Table 4, the expected yearly frequencies of disruptions, fast PSD and soft PSD is reported with values range depending on whether the minimum or maximum component failure rate is considered, as explained in section 4 above.

Finally, Table 5 shows the different yearly events of disruptions, fast and soft PSD allocated by systems (PBS level 1). The events related to the different blanket concepts for the reactor are identified in the specific PBS lines. The following acronyms are used in the Table: Primary Heat Transfer System (PHTS), Tritium Extraction and Removal (TER), Vacuum Vessel Pressure Suppression System (VVPSS)

It is important to specify that evaluating the failure of the BB only failures as clogging of cooling channels, leak/rupture of sealing welds (butt, fillet and lip welds) have been considered. For the lack of statistical data, failures of the machined or hipped cooled plates used to manufacture the BB have not been considered. Deformations or cracks of the plates, swelling of the cooling channels, rupture of the boundaries between adjacent channels have not been estimated. Therefore, higher values for the number of events caused by failures in BB modules (PBS 14, 15, 16 and 17 in Table 5) could result when considering possible additional failures of the cooled plates used for BB First Walls, Caps, Side Walls, Stiffeners, Breeding zone grids.

The Table 5 shows that the main systems responsible of plasma disruption and soft PSD are the BB systems. Also the auxiliary systems, particularly the electrical power supply systems, provide a not negligible contribution.

Table 4. Yearly frequencies of disruptions, fast PSD and soft PSD *induced by technical failures in the plant*

Type of failure consequence	HCPB		HCLL		WCLL		DCLL	
	Max	Min	Max	Min	Max	Min	Max	Min
Disruptions / year	26	5	912	111	30	5	21	5
Fast Plasma Shutdown / year	2	0	2	0	1	0	2	0

Soft Plasma Shutdown / year	49	8	2776	332	621	91	54	7

7. Conclusion

It's clear that this is a very premature study on the subject treated, particularly, because the very premature level of available DEMO design. Nevertheless, fixing a possible methodology to evaluate the influence of component failures on plasma pulses, it gives a picture on some concerns that could be critical for the EU DEMO plant. If further similar studies will accompany the progress of the design, they could provide useful metrics to achieve design optimisation, e.g. sensitivity analysis on key parameters (besides failure rates, other parameters as amount of welds, F/Ts, valves, pipes and channels could be considered) related to the plasma events would further give useful input for designers in orienting their efforts in developing design solutions.

About the results obtained by this study, it is clear that the design shall be deeply optimized because the quite high number of yearly disruptions and requests of PSD, summarized in Table 4 and related to technical failures, cannot be accepted for a machine having the goal to demonstrate feasibility of energy production by a fusion reactor. Furthermore, it is important to note that other plasma disruptions or requests of plasma shutdown could be added to the technical failures identified by this study. Other events induced by uncertainties in the physic regimes, by failure in the application of procedures and/or in setting sequence parameters could increase the frequency of events impairing plasma operations.

Another important note is that this study only deals with direct effects on plasma operations but does not address all the issues related to availability of the systems and of the overall plant. For all the concepts of BB adopted, all the identified faults concern the reliability and availability issues of DEMO, then also the about 500 events of Table 3 leading to "No direct PSD". A lot of failures interest in-vessel components and require long machine shutdown due to, for example, waiting time for dose rate reduction in maintenance area, fault identification, preparatory activities in the interested component and in the interfacing components, repairing and restoring time, recommissioning in the operating phase. Such long out-of-service time and the likelihood of the occurrence of the failures might bring to a low availability of DEMO. The identification of simple and robust BB design towards the operating conditions, the manufacturing problems, the controls of anomalies in the operating conditions, as well as the strong reduction of different numbers of items and components used in the plant are necessary, both passive and, above all, active components. Some effort should be also devoted to other systems as pointed out in Table 5.

Therefore, even if nowadays, the design (particularly BB modules design) gets already significant improvements and further changes are going on to greatly reduce the alarming results presented here, on the basis of this study, we can say that one of the **must** for the future of fusion power plants shall be the simplification of the design solutions pursued.

Acknowledgments

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Table 5. Yearly events of disruptions, fast and soft PSD allocated by systems (PBS level 1)

PBS		Disruptions		Fast		Soft		Total	
		Min	Max	Min	Max	Min	Max	Min	Max
11	Magnet system	0.1	**2.9**	0.1	0.8	0.6	**9.0**	0.8	**12.7**
12	Vacuum Vessel (VV)	0.0	0.1			0.0	0.1	0.0	0.2
13	Divertor	0.0	0.5			0.1	0.1	0.1	0.6
14	BB (HCPB)	0.4	**6.6**			**4.1**	**19.7**	**7.7**	**42.5**
15	BB (HCLL)	**106.7**	**892.1**			**328.1**	**2746.3**	**434.8**	**3638.4**
16	BB (WCLL)	0.7	**10.1**			**85.2**	**566.7**	**85.9**	**576.9**
17	BB (DCLL)	0.1	**1.4**			**3.0**	**24.8**	**3.1**	**26.2**
20	Cryostat	0.0	0.0			0.0	0.3	0.0	0.3
21	Thermal Shields					0.2	**1.2**	0.2	**1.2**
22	Tritium, Fuelling, Vacuum (TFV)	0.4	**2.4**	0.0	0.0	0.2	**2.1**	0.6	**4.5**
23	Remote Handling								
25	TER system for HCPB								
26	TER system for HCLL								
27	TER system for WCLL								
28	TER system for DCLL								
30	Electron Cyclotron (EC) system	0.3	0.8			0.6	**4.5**	1.0	**5.3**
32	Neutral Beam Injection system	0.5	**2.8**			0.2	**1.5**	0.7	**4.3**
40	Plasma Diagnostic & Control system	0.2	**1.6**					0.2	**1.6**
50	BB PHTS (HCPB)			0.1	**1.1**	0.2	**1.4**	0.3	**2.5**

51	BB PHTS (HCLL)			0.1	**1.1**	0.2	**1.4**	0.3	**2.5**
52	BB PHTS (WCLL)			0.1	0.3	0.0	0.3	0.1	0.6
53	BB PHTS (DCLL)			0.1	**1.1**	0.2	**1.4**	0.3	**2.5**
54	Vacuum Vessel (VV) PHTS					0.0	0.2	0.0	0.2
55	Divertor (DIV) PHTS			0.0	0.1	0.0	0.1	0.0	0.3
56	VVPSS (HCPB)	0.0	0.1			0.1	0.2	0.1	0.3
57	VVPSS (HCLL)	0.0	0.1			0.1	0.3	0.1	0.4
58	VVPSS (WCLL)	0.0	0.1			0.0	0.1	0.1	0.2
59	VVPSS (DCLL)	0.0	0.1			0.1	0.2	0.1	0.3
60	Remote Maintenance (RM) system								
61	Assembly								
63	Radwaste Treatment and Storage								
70	Balance of Plant (HCPB)			0.0	0.1	0.2	**2.3**	0.2	**2.3**
71	Balance of Plant (HCLL)								
72	Balance of Plant (WCLL)								
73	Balance of Plant (DCLL)								
80	Site Utilities					0.0	0.2	0.0	0.2
81	Cryoplant & Cryodistribution					0.8	**2.2**	0.8	**2.2**
82	Electrical Power Supply systems	**3.0**	**8.3**	0.0	0.1	0.5	**2.6**	**3.5**	**11.0**
83	Buildings								
85	Plant Control system								
87	Auxiliaries								

References

[1] F.A. Hernández González, Q. Kang, B. Kiss, H. Neuberger, P.Norajitra, G. Nadási, P. Pereslavtsev, C. Zeile; DDD 2015 for HCPB (Update of DDD 2014); EFDA_D_2MRQ4E v.1.1, 04-Jul-2016

[2] G. Aiello, J. Aubert, T. Barret, J-C Jaboulay, B. Kiss, J. Konys, A. Morin, M. Utili; HCLL Blanket Design Description Document; EFDA_D_2MAW5H v.1.0, 30-Jan-2015

[3] A. Del Nevo, E. Martelli; Design Description Document 2015 for WCLL (update of DDD 2014); EFDA_D_2MU9XC v.1.1, 15-Jun-2016

[4] D. Rapisarda; DCLL Blanket 2014 Design Description Document; EFDA_D_2MKUUT v.1.0, 4-Aug-2015

[5] T. Pinna et al, Identification of accident sequences for the DEMO plant, Fusion Engineering and Design (2017), https://doi.org/10.1016/j.fusengdes.2017.02.026

[6] D.N. Dongiovanni, T. Pinna, D. Carloni, RAMI analysis for DEMO HCPB blanket concept cooling system, Fusion Engineering and Design 98-99 (2015) 2125-2129, https://doi.org/10.1016/j.fusengdes.2014.12.035

[7] T. Pinna and L.C. Cadwallader, Component Failure rate data base for fusion applications, Fusion Engineering and Design 51-52 (2000) 579-585.

[8] T. Pinna et al, Fusion Component Failure Rate Database (FCFR-DB), Fusion Engineering and Design 81 (2006) 1391–1395.

[9] T. Pinna et al, Operating experiences from existing fusion facilities in view of ITER safety and reliability, Fusion Engineering and Design 85 (2010) 1410–1415.