Assessment of fatigue effects induced by fast beam transients in the IFMIF-DONES Li target

Journal:	*IEEE Transactions on Plasma Science*
Manuscript ID	TPS12479
Manuscript Type:	Special Issue - Selected Papers from SOFE 2019
Date Submitted by the Author:	19-Jul-2019
Complete List of Authors:	Bernardi, Davide; ENEA Brasimone Research Centre Arena, Pietro; ENEA Brasimone Research Centre, FSN-ING-PAN Di Maio, Pietro; University of Palermo Faculty of Engineering Gordeev, Sergej; Karlsruhe Institute of Technology North Campus, Institute for Neutron Physics and Reactor Technology and ; Nitti, Francesco; ENEA Brasimone Research Centre
Key Words:	Neutron sources, Fatigue, Finite element methods, Lithium
Specialty/Area of Expertise:	

Assessment of fatigue effects induced by fast beam transients in the IFMIF-DONES Li target

D. Bernardi, P. Arena, *ENEA*, P.A. Di Maio, *University of Palermo*, S. Gordeev, *KIT*, F.S. Nitti, *ENEA*

***Abstract*— As a crucial step of the EU fusion programme, the IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented NEutron Source) facility is currently being developed within the framework of the EUROfusion Consortium as the reference Li(d,nx) neutron source to qualify candidate materials under fusion-relevant conditions for the design and licensing of the future DEMO reactor. The heart of the IFMIF-DONES facility consists of a lithium target where a high speed jet of liquid lithium flowing on a steel backplate is struck by a 125 mA, 40 MeV deuteron (D+) beam supplied by a linear accelerator to generate a neutron flux of about 5x10^{18} m^{-2} s^{-1} with a broad peak at 14 MeV by means of D-Li stripping reactions. In this work, analysis of the fatigue effects generated on the backplate steel structure by repeated thermally-induced shock waves propagating in the lithium as a consequence of accelerator fast beam trips events has been carried out.**

***Index Terms*—IFMIF-DONES, Lithium Target, beam trips, fatigue**

I. INTRODUCTION

As a crucial step of the EU fusion programme, the IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented NEutron Source) facility is currently being developed within the framework of the EUROfusion Consortium as the reference Li(d,nx) neutron source to qualify candidate materials under fusion-relevant conditions for the design and licensing of the future DEMO reactor [1]. The heart of the IFMIF-DONES facility consists of a lithium target where a high speed jet of liquid lithium flowing on a steel backplate is struck by a 125 mA, 40 MeV deuteron (D+) beam supplied by a linear accelerator to generate a neutron flux of about 5×10^{18} m^{-2}s^{-1} with a broad peak at 14 MeV, by means of d-Li stripping reactions (Fig. 1). The design of the IFMIF-DONES lithium target is a challenging task since it has to deal with extreme heat fluxes (up to 1 GW/m^2) as well as many other issues induced by the presence of liquid metal, severe irradiation conditions, radioactive materials and so on. So far, a detailed investigation of the thermo-mechanical behaviour of the IFMIF-DONES target system has been accomplished for the case of steady state operation, considering the D+ beam steadily running at full nominal power (5 MW). However, the analysis of the effects generated in the lithium and in the surrounding steel structure during the unavoidable beam trips needs to be carried out as well. In fact, the sudden variation of the heating power deposited in the lithium when the beam is rapidly switched between ON and OFF states leads to the generation of thermally-induced shock pressure waves which propagate towards the backplate causing rapidly alternating stresses in the structure. This high frequency stresses might eventually determine the damage of the component by fatigue. A quantitative assessment of such fatigue effects has thus been performed in the present paper. To this purpose, a thermo-mechanical finite element model (FEM) has been used to calculate the stress/strain range on the backplate associated to the thermally-induced pressure field generated by a single beam trip, as obtained from a CFD transient model of the lithium jet subjected to an impulsive variation of the nuclear heating deposited in it. The calculated backplate stress/strain range has then been employed to determine the fatigue lifetime of the component, that is, the number of trips to failure. The results obtained are herein summarized and discussed.

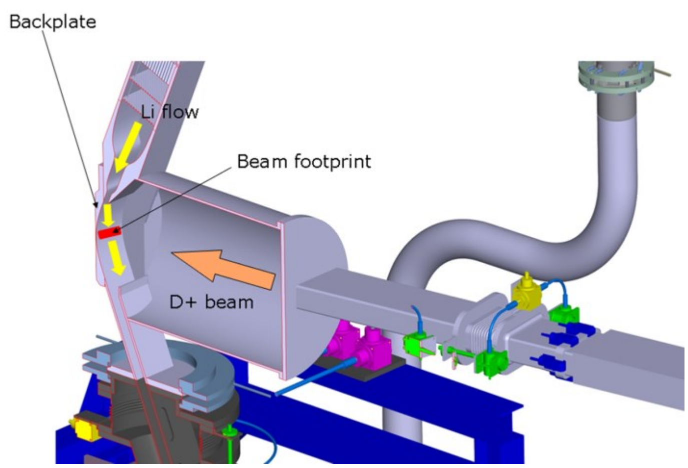

Fig. 1. Scheme of the IFMIF-DONES lithium target concept

II. THE IFMIF-DONES TARGET SYSTEM

In IFMIF-DONES, the target system is the system devoted to create and steadily maintain a liquid lithium screen with the required characteristics in front of the D+ beam. It is located inside the blind room called Test Cell (TC) which houses the high flux test module (HFTM) containing the material samples to be irradiated. A sketch of the most updated 3D model of the IFMIF-DONES target system is shown in Fig. 2. It is mainly

D. Bernardi, ENEA Brasimone, Italy (e-mail: davide.bernardi@enea.it)
P. Arena, ENEA Brasimone, Italy (e_mail: pietro.arena@enea.it)
P.A. Di Maio, University of Palermo, Italy (e_mail: pietroalessandro.dimaio@unipa.it)
S. Gordeev, Karlsruhe Institute of Technology, Karlsruhe, Germany (e-mail: sergej.gordeev@kit.edu).
F. S. Nitti, ENEA Brasimone, Italy (e-mail: francesco.nitti@enea.it)

composed of a target assembly (TA) with its related support structure and lithium inlet pipe, the quench tank (QT) and the lithium outlet pipe.

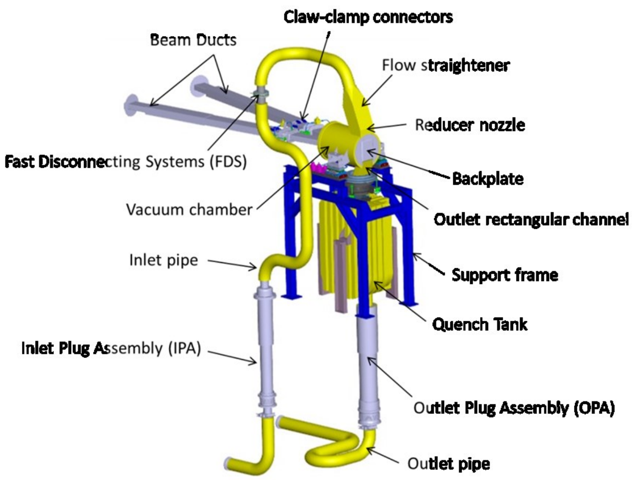

Fig. 2. Global view of the IFMIF-DONES target system

The Target Assembly (TA) is aimed at generating the high-speed liquid lithium jet and creating the vacuum environment in which the interaction between lithium and deuterons takes place. It is composed of an inlet pipe which routes the liquid lithium from the main lithium loop to the target area; a flow straightener with the function to smooth the incoming flow; a reducer nozzle which accelerates the lithium and shapes it into a jet with rectangular cross section; a backplate (BP) on which the free surface jet flows at a speed of about 15 m/s; and the outlet channel which evacuates the lithium from the TA. The free jet is exposed to low pressure conditions (10^{-3} Pa) created inside the vacuum chamber by means of a vacuum pump connected to the accelerator beam line. Inside the vacuum chamber, the D+ beam impinges on the liquid lithium jet over a footprint with nominal area of 20x5 cm^2 to produce a neutron yield of the order of 10^{17}n/s. The target chamber is connected to the accelerator high energy beam transport (HEBT) line by means of a beam ducts penetrating through the TC wall. The TA is entirely made of the reduced activation ferritic/martensitic steel EUROFER and it is supported by two arms laying on the support frame directly fixed to the TC floor by means of bolts. The target chamber and the outlet channel are connected to the beam duct and to the QT, respectively, by means of bellows.

The lithium inlet pipe is divided in two sections connected by means of a fast disconnecting system (FDS). One of these sections is made of EUROFER and is rigidly attached to the flow straightener and the BP assembly which are replaced annually during the scheduled maintenance of the facility. The other section is made of stainless steel 316L and it is not supposed to be replaced during the life of the plant unless it fails.

A quench tank (QT) collecting the lithium that exits from the TA is placed below the vacuum chamber. Its main function is to thermally homogenize and slow down the lithium flow before routing it back to the main lithium loop by means of the outlet channel. Both inlet and outlet pipes penetrate through the TC floor by means of plugs fitting in the respective openings in the concrete wall.

III. Thermomechanical Model

A. FE model description

A 3D finite element (FE) thermomechanical model of the IFMIF-DONES target system has been recently developed [2]. The model reproduces the TA, its support structure and the inlet pipe up to the FDS connection. The QT and the outlet pipe have not been included as they are connected with the rest of the structure by means of a bellow that allows the mechanical decoupling of the system. The two FDS flanges on the inlet pipe were considered as tied. The beam ducts have not been directly modelled, but their presence in terms of thermal and mechanical effects on the TA have been properly taken into account through a simplified 1D model. A FE mesh consisting of ∼930k tetrahedral and hexahedral linear elements with max element size of ∼1 cm, connected through ∼500k nodes has been set up as the optimal discretization scheme to obtain grid-independent results allowing a reasonable calculation time. A linear elastic model has been employed for the structural materials. Temperature-dependent mechanical and thermo physical properties of EUROFER and AISI 316L steels have been considered. The presence of the liquid lithium through its thermal interactions with the wetted surfaces of the TA was also taken into account in the FE model.

B. Loads and boundary conditions

A set of loads and boundary conditions has been applied in the FE model of the IFMIF-DONES target system in order to simulate as much realistically as possible its behaviour under typical working scenarios. To reproduce the steady state nominal conditions, the 5 MW D+ beam power has been supposed to be deposited in the lithium within the footprint volume of 200×50×25 mm^3. The spatial distribution of neutron and gamma volumetric heating calculated from previous neutronics studies [3] has been applied in the TA structures. For the inlet pipe and the support frame where nuclear heating data were not available, a spatial distribution with a $1/r^2$ dependence (being r the distance from the centre of the BP) has been assumed.

Other thermal boundary conditions have been imposed as follows. Both radiative and convective heat transfer have been imposed on all non-insulated surfaces. In particular, radiation towards an infinite medium with temperature of 50 °C and emissivity of 0.3, reproducing the inner conditions of the TC volume as seen by the target system, has been assumed while natural convection with the TC atmosphere (He at 50 °C and 5 kPa) has been considered. Because of the narrow thickness of the He gap existing between the BP and HFTM external surfaces facing each others (for which a very low Rayleigh number of $\sim 5\times10^3$ is predicted), a pure diffusive heat transfer between them has been assumed with a sink temperature of 50 °C and a heat transfer coefficient calculated as the ratio between He thermal conductivity and gap thickness. Thermal radiation exchanged between inner surfaces of the TA has been taken into account as well. All thermal interactions between components in mutual contact have been simulated by imposing a thermal conductance of 2000 W/m^2 °C. Finally, the forced convection between flowing lithium and the TA wetted surfaces has been simulated by adopting a heat transfer coefficient of 34000 W/m^2 °C.

For what concerns mechanical boundary conditions, they have been applied as follows. The contacts between TA and its support structure, considered as dry lubricated, as well as between the lithium inlet pipe and the plug penetrating the TC floor have been simulated through mechanical contact models envisaging Coulombian friction interactions with a uniform friction factor of 0.03 and 0.74, respectively. Thermal deformations caused by non-uniform temperature fields have been taken into account. A pressure of 5 kPa has been applied to all external surfaces of the model, while a non-uniform distribution of internal pressures, as calculated in [4], has been applied on lithium wetted surfaces. For studying the beam transient scenarios with thermally-induced pressure waves a pressure field has been applied on the BP inner surface as calculated by a preventive CFD analysis (see Sect. IV-A)

Concerning mechanical constraints, displacements along vertical direction have been prevented on specific points on the TA arms to simulate the effect of their fixation pins on the support. Moreover, all displacements have been prevented for the support feet surfaces attached to the TC floor, as well as for the nodes on the fixed inlet pipe flange outside the TC.

IV. Fatigue Analysis

A. Input data from CFD calculations

In order to perform the fatigue analysis of the BP, the time evolution of the pressure distribution on the component following a fast beam trip event is needed. To this purpose, a CFD calculation of the fluid dynamic conditions in the lithium during various type of beam transients have been preventively carried out by KIT [5] and then provided as input to the thermomechanical model for fatigue assessment.

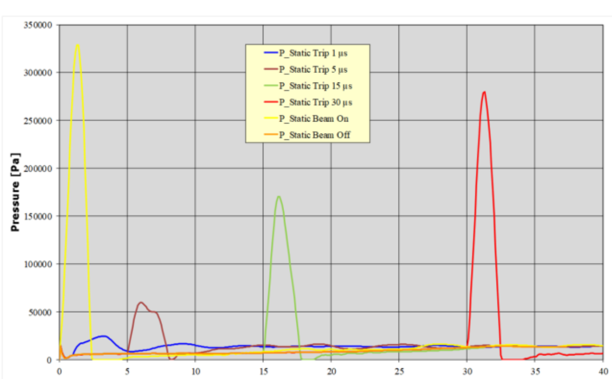

Fig. 3. Time evolution of peak pressure on the BP footprint for different beam transient scenarios

In particular, Fig. 3 shows the time evolution of the peak pressure developed on the BP footprint (the point in which the peak pressure is achieved is moving during the transient as the shock wave propagates) for three different beam transients: sudden beam OFF/beam ON; sudden beam ON/beam OFF; fast beam OFF to beam ON transition (beam trip) with switching times of 1, 5, 15, 30 µs. As it can be seen, for the beam trips, the peak pressure value increases monotonically with the switching times, approaching that of the sudden beam OFF/ON transient which indeed corresponds to a beam trip with infinite switching time. Therefore, this latter case represents the worst one from the fatigue point of view as it presents the greatest pressure excursion during the transient. The sudden beam ON/OFF switch gives rise to much lower pressures and thus it is not relevant to thermomechanical aspects (it is however important for the study of potential cavitation issues, see [5]). The propagation of the pressure along the backplate in case of sudden switch OFF/ON of the beam is illustrated in Fig. 4 where it can be observed that the peak intensity decreases as the pressure wave moves away from the center. It is also noted that the phenomenon is completely extinguished in less than 10 µs.

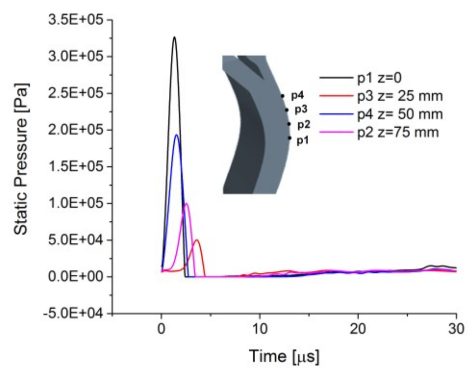

Fig. 4. Pressure propagation along the BP in case of sudden switch ON of the beam

The whole pressure distribution on the BP at the time in which the maximum peak pressure occurs is reported in Fig. 5 for the case of sudden beam OFF/ON scenario. A maximum pressure of 0.32 MPa is developed after a few microseconds since the beam ON switch. This pressure field is used in input to the thermomechanical model to calculate the stresses arising in the BP for both static and fatigue evaluations (see Sect. IV-B).

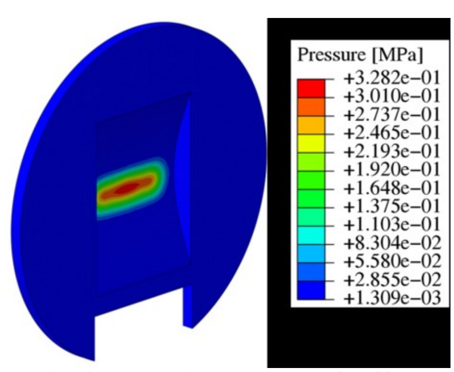

Fig. 5. Pressure distribution on the BP in case of sudden switch-on of the beam.

B. Fatigue calculation method

In order to assess the fatigue life of the BP subject to an accumulation of repeated beam trips, the fatigue usage fraction approach established in the RCC-MRx nuclear code [6] was followed. In this approach, a linear elastic calculation is carried out to determine the maximum strain range generated by the thermally-induced pressure wave during the beam transient. From this elastic strange range, an estimate of the plastic contributions to the total strange range ($\Delta\varepsilon_{t,}$) is obtained by applying a series of coefficients tabulated in the RCC-MRx material database for the material of interest (EUROFER in our case). The procedure is then repeated for all those selected paths which are deemed to be the most critical from the structural point of view (see Fig. 7) in order to evaluate the highest $\Delta\varepsilon_t$ arising in the component. With this value, it is possible to enter into the fatigue diagram $\Delta\varepsilon_t$ - N_f (which is also provided in the RCC-MRx material properties database) to obtain the number of cycles to failure, N_f.

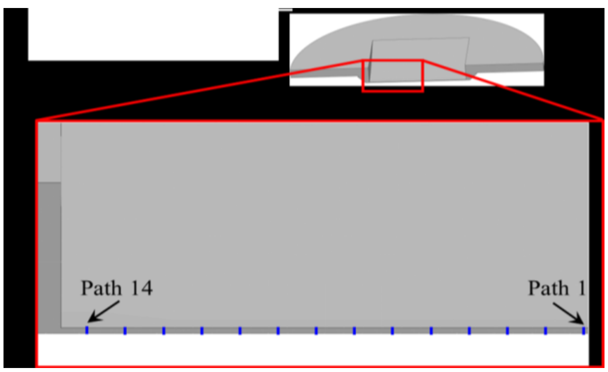

Fig. 7. Selected paths on the BP for stress linearization

In detail, the whole procedure is as follows:

i. For each selected path and for each time instant corresponding to the maximum and the minimum pressures achieved on the BP during the beam transient, a stress linearization is performed to calculate the membrane (P_m) and the bending (P_b) stress components of the total *primary* stress $P=P_m+P_b$, i.e., the part of the stress caused by mechanical loadings (mainly, the wave pressure distribution). P_m and P_b represents the averaged (uniform) and linearized components, respectively, of the primary stress tensor over the given path (more precisely, P_m and P_b refer to the Von Mises equivalent stress intensities of such tensors). The total *secondary* stress intensity $Q = Q_m+Q_b$, i.e., that part of the stress induced by thermal loadings, is calculated as well over the various paths.

ii. The maximum variation of the total stress $\Delta[P+Q+F]$ (being F the complementary, non-linear part to the calculated total stress S_{tot}, i.e., $F = S_{tot} - P - Q$) and of the stress combination $\Delta[P_m+0.67P_b]$ are calculated for each selected path by taking the difference of the corresponding tensors at the two time instants considered above and then calculating the respective Von Mises stress intensities.

iii. The elastic strain range, $\Delta\varepsilon_1$, is obtained as the value corresponding to the total stress range $\Delta[P+Q+F]$ on the linearized EUROFER cyclic stress-strain curve reported in the RCC-MRx Code. This curve is that associated to the maximum (over time) value of the average temperatures, $\max[T_{avg}]$, in the considered path;

iv. The estimated plastic increase in strain, $\Delta\varepsilon_2$, due to the primary stress range is obtained from the abovementioned cyclic stress-strain curve in correspondence to the previously calculated $\Delta[Pm+0.67Pb]$ value

v. The estimated plastic increase in strain, $\Delta\varepsilon_3$, due to stress redistribution, is calculated, in our case, as $\Delta\varepsilon_3 = (K_\varepsilon-1)\Delta\varepsilon_1$where K_ε is a coeffiecient tabulated in RCC-MRx as a function of $\Delta[P+Q+F]$ and $\max[T_{avg}]$

vi. The estimated plastic increase in strain, $\Delta\varepsilon_4$, due to triaxiality effects, is calculated as $\Delta\varepsilon_4 = (K_v-1)\Delta\varepsilon_1$ where K_v is a coeffiecient tabulated in RCC-MRx as a function of $\Delta[P+Q+F]$ and $\max[T_{avg}]$

vii. The total strain range $\Delta\varepsilon_t = \Delta\varepsilon_1 + \Delta\varepsilon_2 + \Delta\varepsilon_3 + \Delta\varepsilon_4$ is calculated in all the selected paths

viii. For the path with the highest value of $\Delta\varepsilon_t$, the number of cycles to failure N_f corresponding to $\Delta\varepsilon_t$ is obtained from the EUROFER fatigue diagram $\Delta\varepsilon_t$ - N_f reported on the RCC-MRx.

V. RESULTS

The transient associated to the sudden beam-ON case has been considered for fatigue assessment as it represents the worst case in terms of peak pressure achieved in the BP (see Fig. 3). A thermomechanical calculation was performed first for the normal steady-state condition (i.e., with D+ beam running smoothly at 5 MW). Then, a second calculation run was carried out for the case of sudden beam-ON transient assuming a pressure distribution on the BP (Fig. 5) corresponding to the time in which the pressure field reaches its maximum (around 0.3 MPa). For this latter analysis, the temperature and the Von Mises stress distributions in the BP are shown in Figs. 8 and 9 respectively.

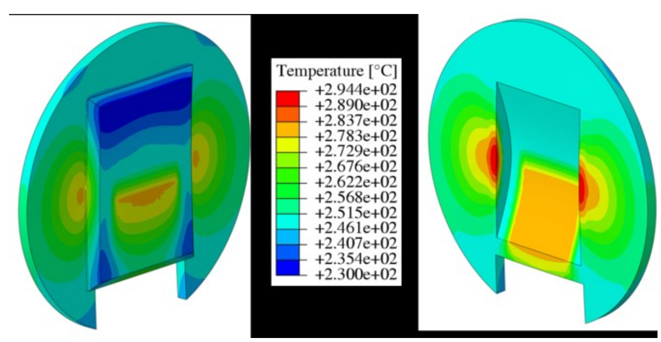

Fig. 8. Temperature distribution in the BP at the instant of maximum pressure for the beam-ON transient case

As it can be noted, a maximum Von Mises stress of about 170 MPa is achieved at the mid plane of the BP, in the lateral zones of the beam footprint close to the Li channel walls. This has suggested to identify the points lying on this plane as the most critical ones. Therefore, a number of 14 equally-spaced paths as shown in Fig. 7 have been selected for stress linearization purposes. Before proceeding to the fatigue analysis, a check of the RCC-MRx design criteria for static loading conditions and ratcheting effect has been done. From this check, a confirmation was obtained that the related allowable limits are not exceeded in any of the selected paths, so demonstrating the safe design of the BP against such type of damages even under off-normal conditions like beam trips transients.

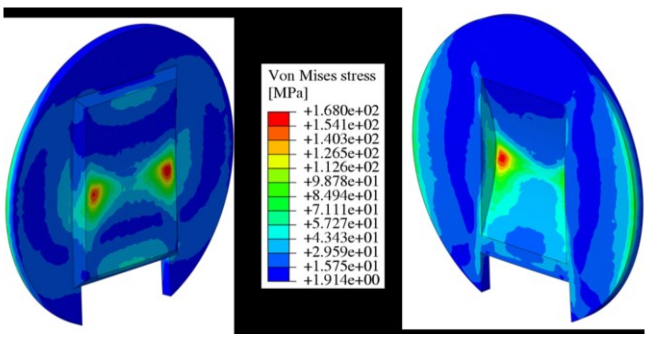

Fig. 9. Von Mises stress distribution in the BP at the instant of maximum pressure for the beam-ON transient case

After this preliminary check, the procedure for fatigue analysis outlined in Sect. IV-B has been applied. It turned out that the highest total strain range is achieved in Path 2. The calculation parameters for this path, whose meaning is described in detail in Sect. IV-B, are shown in Tab. I.

TABLE I
Fatigue calculation parameters for Path 2 (beam-on transient)

Parameter	value
$\max(T_{avg})$	265 °C
$\Delta(P+Q+F)$	21 MPa
$\Delta(P_m+0.67P_b)$	20 MPa
k_ε	1.000
k_v	1.001
$\Delta\varepsilon_1$	0.0139%
$\Delta\varepsilon_2$	0%
$\Delta\varepsilon_3$	0%
$\Delta\varepsilon_4$	0.000014%
$\Delta\varepsilon_t$	0.014%

It is interesting to note that the path with the highest strain range (Path 2) is not coincident with that having the highest stress (Path 14). This is probably due to the stronger local stiffness of the regions near the channel walls compared to those in the center which are more free to deform thus allowing higher strain ranges.

Another aspect to be noted is that all the plastic contributions to the total strain range ($\Delta\varepsilon_2$, $\Delta\varepsilon_3$, $\Delta\varepsilon_4$) are practically zero which means that the behavior of the material is essentially elastic. For this reason, the fatigue phenomenon is actually occurring in the high-cycle regime.

This explains why a rather small total strain range of 0.014% is obtained. From the EUROFER RCC-MRx fatigue curve it is seen that this value is even below the minimum strain range considered in the diagram (which is 0.1%) which corresponds to 10^6 cycles to failure. As a conclusion, since a replacement of the BP is foreseen every year during the IFMIF-DONES scheduled maintenance, it turns out that the fatigue phenomena induced by fast beam trips does not pose any concern as the fatigue life of the BP is surely longer than its operating time before it is replaced.

VI. Conclusions

It is demonstrated that the maximum strain range generated in the BP by thermally induced shock waves due to fast beam transients lies below the limit corresponding to 10^6 cycles. Therefore, fatigue effects are proven not to be a concern for the BP over its foreseen irradiation period.

Acknowledgment

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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission, Fusion for Energy, or of the authors' home institutions or research funders.

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