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One-dimensional nuclear design analyses of the SST-2

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Abstract. Steady State Tokamak-2 (SST-2) will be an intermediate fusion machine before Indian DEMOnstration power reactor (DEMO) development to realise the reactor technologies. It is designed for fusion gain $Q = 5$ and fusion power in the range of 100–300 MW. Nuclear design analyses of SST-2 machine have been carried out to support the conceptual design work. Analyses have been carried out for two breeding blanket concepts: Indian lead–lithium ceramic breeder (LLCB) and helium-cooled ceramic breeder (HCCB). The analyses assess the tritium production and radiation shielding capability of the machine referring to the engineering design parameters. In this study, one-dimensional radiation transport calculations have been performed to assess the SST-2 nuclear responses for 1 full power year (FPY) operation. Nuclear responses such as tritium breeding ratio (TBR), various radiation loads to toroidal field (TF) coil have been calculated to obtain the radial build-up of SST-2 capable of breeding tritium and satisfying the shielding requirements. The assessment has been made using the ANISEN code and FENDL 2.1 cross-section library. It is observed that the TBRs with LLCB and HCCB blankets are 0.85 and 0.94, respectively. Shielding calculations confirm that the radial build is sufficient to protect the superconducting TF coils for 1 FPY.

Keywords. Fusion reactor; breeding blanket; neutronics; tritium breeding ratio.

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1. Introduction

India's energy demands are rising rapidly [1] and to meet the future requirements, DEMOnstration power reactor (DEMO) development strategy [2] is planned. As per Indian Roadmap of Fusion Energy, an intermediate fusion machine is planned before the DEMO development which is the Steady State Tokamak-2 (SST-2). It will be a new D–T machine with an aim to test and qualify the proposed technologies of a reactor. The development and operation of the SST-2 machine will provide experiences similar to International Thermonuclear Experimental Reactor (ITER) with other major advantages. Technological components such as breeding blanket, helium-cooled divertor, etc. will be indigenously developed and the integrated test will be carried out in the SST-2. It is planned to have a breeding blanket at the outboard (OB) side and shielding blanket at the inboard (IB) side. In this way, the blanket operation will be simulated and it will provide the feedback to modify the DEMO design if needed. It will also strengthen the Indian industry for building the DEMO and prepare a pool of well-trained man power for Indian Fusion Program. The SST-2 design and performance analyses are under progress [3]. Nuclear analyses play a vital role in the design of fusion reactors [4–13]. The physics parameters have been obtained from the SPECTER code [14]. A radial build has been prepared and its nuclear analyses have been carried out. The nuclear analyses of this radial build have been carried out to assess the tritium breeding performance and shield capability for 5 full power year (FPY). The breeding capability of the two blanket concepts, lead–lithium cooled ceramic breeder (LLCB) and helium-cooled ceramic breeder (HCCB), has been assessed and tritium breeding ratio (TBR) is obtained. As the SST-2 has a breeding blanket at the OB side, only tritium self-sufficiency is not expected from it. The neutronics and shielding calculations reported herein were performed using the one-dimensional (1D) discrete-ordinates code, ANISN [15] with the P5-S8 approximation and the FENDL-2.1 cross-section library [16] in the 46n-21g group structure. Main results of these analyses are presented in this paper.

2. Description of blanket concepts

Two breeder blanket concepts have been considered as options for the SST-2 reactor. The primary blanket concept is the LLCB [17–19] blanket and the other is the conventional HCCB [20,21] concept with variance in geometrical design. The nuclear performance of these two concepts has been evaluated by placing them in the OB breeder blanket region of the SST-2 reactor.

2.1 *LLCB blanket*

The LLCB blanket concept consists of lithium titanate (Li_2TiO_3) and lead–lithium (Pb–Li) eutectic alloy. Li_2TiO_3 acts as a tritium breeder whereas Pb–Li acts as tritium breeder, neutron multiplier and coolant. The structural material of LLCB blanket is Indian reduced activation ferritic martensitic steel (IN-RAFMS). There are two coolants in the LLCB concept: one is helium which cools the first wall of the blanket and the other is the Pb–Li eutectic which cools the breeding zone. The Pb–Li flow velocity is moderate enough such that its self-generated heat and the heat transferred from ceramic breeder (CB) bed is extracted effectively. Helium extracts the surface heat loads and neutronic heat faced by first wall (FW) and external box structure. Helium will be circulated on 80 bar pressure and 300°C to extract high-grade heat. The schematic view of the LLCB blanket is shown in figure 1. Tritium is extracted by helium purge gas which flows on 1.2 bar pressure. It also has 0.1% hydrogen to enhance the catalytic exchange of H and T. The extraction of tritium produced in Pb–Li is done externally. In order to overcome the magnetohydrodynamic (MHD) pressure drop in Pb–Li channels, appropriate coating will be used.

2.2 *HCCB blanket*

Indian solid breeder blanket concept is a conventional helium-cooled solid breeder concept with variance in geometrical design. Indian HCCB blanket has IN-RAFMS as the structural material, lithium titanate as the breeder and beryllium (Be) as the neutron multiplier in an 'edge-on' configuration with the tapering width of the breeder in the radial direction. Figure 2 shows the two-dimensional representation of radial–poloidal cross-section of one breeder unit of HCCB module with the dimension of each zone marked inside. Each breeder unit has four CB zones surrounded by the cooling plates (CP) and five Be zones. All these CB and Be zones are alternately stacked in the canister. There are two coolant circuits for the FW and CBs. The FW is cooled by helium gas whereas helium gas flowing in the 5-mm-thick CP extracts heat from the CBs. The low-pressure helium gas is used as the purge gas for tritium extraction.

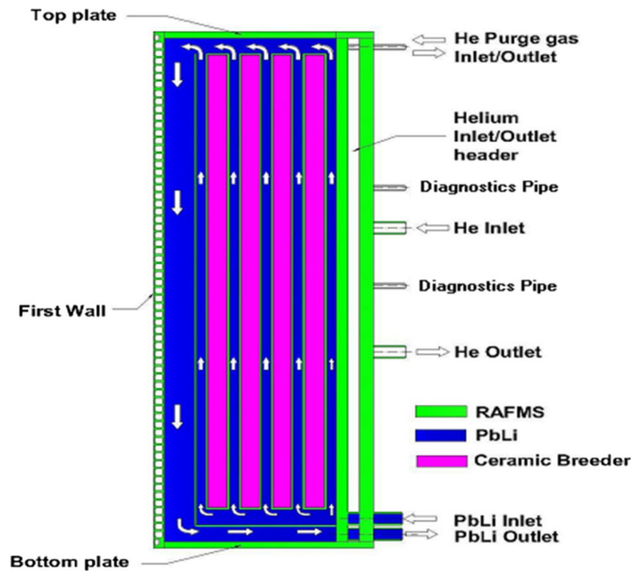

Figure 1. Schematic of the LLCB blanket concept.

3. Neutronic modelling and calculation procedure

Neutronics analysis has been performed on the proposed SST-2 medium-size reactor. The radial build-up of the machine is shown in figure 3. The total radial build from the scrap-off layer (SOL) to the vacuum vessel (VV) that includes the blanket and the shield is 50 cm in IB and 100 cm in OB. The VV thickness used in the calculation is 35 cm in IB and 64 cm in OB. Thick water-cooled steel shield of 50 and 45 cm in IB and OB, respectively, is used in the calculation. A 50-cm-thick breeder blanket is placed only in the OB for tritium breeding. The component-wise details of the materials are described in table 1 and the composition of steels is given in table 2. A 1D discrete ordinate code ANISN has been used in the neutronics calculations. A specially prepared group-independent cross-section library based on Fendl-2.1 data has been generated in the 46n-21g energy groups to

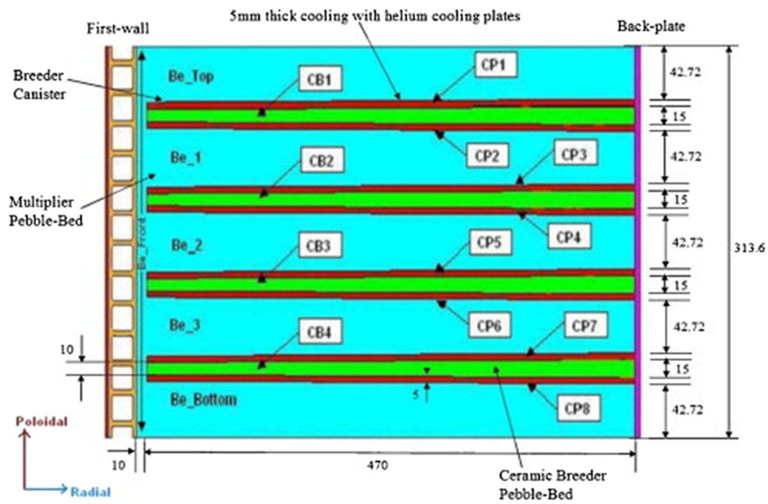

Figure 2. Radial–poloidal cut view of the one breeder unit of HCCB module showing different zones and their thicknesses (in mm).

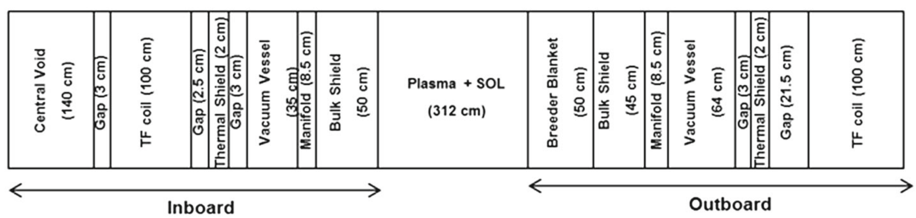

Figure 3. 1D radial build-up model of the SST-2.

be used in the ANISN calculation. The whole geometry is divided into 32 zones and 504 intervals. The Pn and Sn orders applied are 5 and 8, respectively. The SST-2 reactor geometry was modelled by using a toroidal cylindrical model with a height of 1 cm.

IB and OB components are modelled as concentric cylindrical rings with the plasma chamber in between, and the torus axis as the model symmetry axis. The 14 MeV source neutrons are uniformly distributed in the cylindrical plasma ring with the scrape-off zones of 9 cm each on IB and OB. Reflective boundary condition has been applied at the torus axis as one half of the geometry has been used in the calculation. In this way, the 1D geometry of the SST-2 model is simulated in the ANISN calculation. In each zone, the materials are homogeneously mixed for the neutronics calculations. Coupled radiation transport calculation for neutron and gamma fluxes has been carried out to find the energy and spatial distribution of neutron and gamma fluxes, TBR and radiation loads to TF coil. The nuclear responses of TF coils are calculated at the first layers of the different parts of TF coil to obtain the peaking values. All nuclear responses are normalised with an average neutron wall loading (NWL) of 0.54 $\mathrm{MW/m^2}$. Also, nuclear responses for the peak neutron wall load of 0.58 $\mathrm{MW/m^2}$ at the IB side have also been evaluated and reported. Expected machine availability is $\sim$7%.

4. Results

4.1 *Neutron and gamma fluxes*

The D–T reaction in the SST-2 plasma will continuously generate 14 MeV neutrons. They will undergo multiple scattering and finally, the neutrons entering into the IB and OB components of the reactor will have a complete spectrum of neutron energies rather than only 14 MeV. The radial profiles of neutron and gamma fluxes have been obtained both in the IB and OB of the SST-2 reactor. Figure 4 shows the neutron and gamma-ray fluxes in IB and OB regions during the D–T operation.

The highest values of fluxes are in the components of IB and OB near the plasma of the SST-2 and they reduce along the radial direction as we move from the plasma. The component of high energy (> 0.1 MeV) is also shown in figure 4 along with the specific 14 MeV neutron flux. The neutron attenuation of four orders took place inside the shield and VV of an IB. The total high-energy flux at the inner surface of the TF coil is 8.3×10^9 $\mathrm{n/cm^2}$ s by considering the average wall load.

Table 1. Radial structure of the SST-2 with material composition (% volume fractions).

Zone name	Material composition
Central solenoid	Void
Gap	Void
TF coil	
TF case	SS316 L(N) (100%)
TF insulation	Ce ground insulation
TF winding pack	SS316 L(N) (54.31%), He liquid (14.95%), Nb_3Sn (14.82%), Cu (8.59%), glass (7.33%)
TF insulation	CE ground insulation
TF case	SS316 L(N)-(100%)
Gap	Void
Thermal shield	SS316 L(N)-IG (100%)
Gap	Void
Vacuum vessel	
VV wall	SS316 L(N)-IG (100%)
VV filler	Water (41%), SS304B7 (36.9%), SS316 L(N)-IG (15.9%), Ti–6Al–4 V (1.9%), Inconel 718 (0.5%), void (3.4%)
VV Wall	SS316 L(N)-IG (100%)
Manifold and maintenance region	Void
Bulk shield	SS316 L(N)-IG (60%) and water (40%)
SOL	Void
Plasma	Void
SOL	Void
Breeding blanket	LLCB/HCCB blanket
Bulk shield	SS316 L(N)-IG (60%) and water (40%)
Manifold and maintenance region	Void
Vacuum vessel	
VV wall	SS316 L(N)-IG (100%)
VV filler	Water (41%), SS304B7 (36.9%), SS316 L(N)-IG (15.9%), Ti–6Al–4V (1.9%), Inconel 718 (0.5%), void (3.4%)
VV wall	SS316 L(N)-IG (100%)
Gap	Void
Thermal shield	SS316 L(N)-IG (100%)
Gap	Void
TF coil	
TF case	SS316 L(N) (100%)
TF insulation	Ce ground insulation
TF winding pack	SS316 L(N) (57.14%), He liquid (13.98%), Nb_3Sn (13.86%), Cu (8.04%), glass (6.99%)
TF insulation	CE ground insulation
TF case	SS316 L(N) (100%)

4.2 *Tritium production*

The TBR of the machine provides a measure of the tritium breeding capability of the reactor. TBR should be >1 and should have the margin for fuel cycle losses, tritium decay losses, start-up inventory for other plants, reserve inventory and account for uncertainties in estimation due to nuclear data. In the SST-2 reactor, the breeding blanket is planned only in the OB area which limits the tritium production in the machine. The tritium breeding performance of the two Indian breeder blanket concepts, viz. LLCB and HCCB, are investigated by placing them in the OB in two separate calculations. The homogeneous mixtures of the breeder blanket materials were assumed in the 1D calculations. The materials used in the neutronics calculations for LLCB and HCCB are listed in table 3.

The TBR values predicted for LLCB and HCCB blanket configurations considered are 0.85 and 0.94, respectively. The HCCB blanket configuration provides

Table 2. Elemental composition of steel used in the SST-2.

Element	SS316 L(N)-IG (wt%)	SS316LN (wt%)	SS-304B7 (wt%)
C	0.0225	0.03	0.08
Mn	1.8	2	2
Ni	12.25	12	13.5
Cr	17.5	17	19
Mo	2.5	2.5	–
N	0.07	0.14	0.1
P	0.025	0.045	0.045
S	0.0075	0.03	0.03
Si	0.5	0.75	0.75
Nb	0.01	0.01	0.01
Ta	0.01	0.01	0.01
Ti	0.15	0.15	0.15
Cu	0.3	0.3	0.1
Co	0.05	0.05	0.05
B	0.001	0.001	1.5
Al	0.05	0.05	0.05
O	0.002	0.002	0.002
K	0.0005	0.0005	0.0005
Bi	0.0008	0.0008	0.0008
V	0.004	0.004	0.004
Zr	0.002	0.002	0.002
Sn	0.002	0.002	0.002
W	0.001	0.001	0.001
Pb	0.0008	0.0008	0.0008
Fe	64.7409	64.9209	62.6119

TBR greater than that of the LLCB blanket configuration due to the presence of Be neutron multiplier and higher Li-6 atom density. However, it is not reaching the tritium self-sufficiency criteria as per present breeding blanket configuration which can be enhanced by increasing the coverage area of the blanket and further optimisation.

4.3 *Radiation damage and radiation loads to vacuum vessel and super-conducting TF coils*

In order to protect the reactor component, certain radiation shielding requirements for the fusion reactor must be fulfilled. These requirements put limits on helium production, atomic displacement in the steel structure and TF coils. Re-weldability of the reactor is possible if the helium content in steel is below 1 appm [22]. Neutron induces degradation in material strength which is an issue as far as the structural integrity of the machine is concerned. The displacement per atom (dpa) level accumulated over the lifetime of the machine should be lower than 2.75 dpa [22] to limit the reduction in the fracture toughness of the austenitic stainless steel up to 30%. The dpa and helium production in the steel structure of the VV of the SST-2 are shown in table 4 with an operational time of 1 FPY. The helium production and dpa in VV are well below the limits.

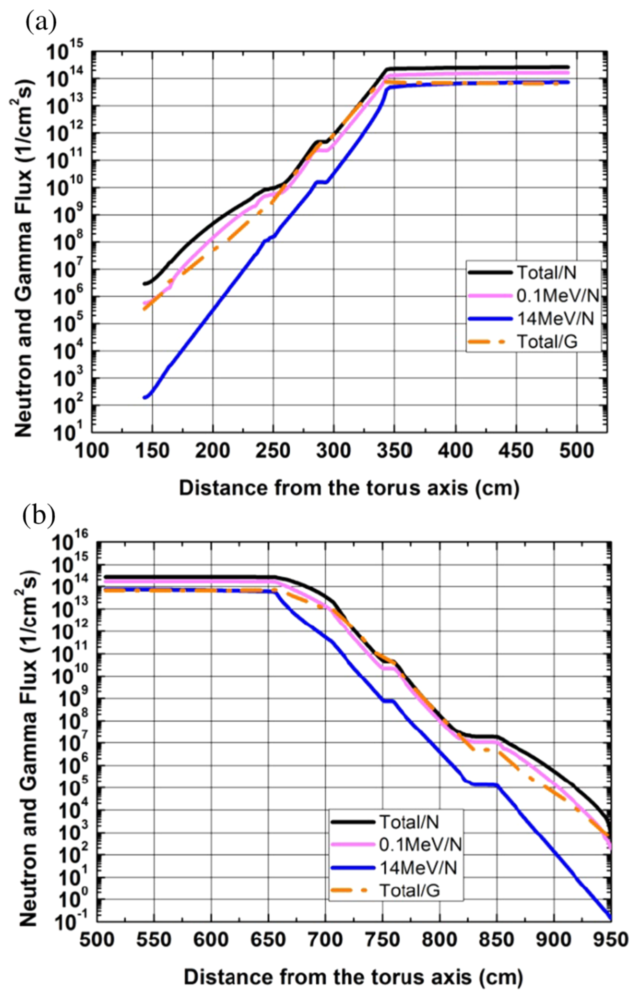

Figure 4. Radial profiles of neutron and γ-ray fluxes in (**a**) IB side and (**b**) OB side of the SST-2.

One of the key functions of the VV and the in-vessel components is that together they shall provide sufficient nuclear shielding to protect the superconducting TF coils. The shielding of the IB superconducting TF coil is most vital due to the space constraint. Table 5 gives the peak magnet radiation loads on the IB TF coil for the SST-2 for 1 FPY operation. This includes the fast neutron fluence ($E > 0.1$ MeV) in the winding pack, total neutron fluence in the insulator, dpa in Cu stabiliser in the winding pack and nuclear heating in the winding pack. The nuclear responses given in tables 4 and 5 suggest that these are well below the limits. However, several factors such as the gap between the shield modules, multidimensional analyses, etc. need to be considered for getting a safety margin. For the operation of 1 FPY, it has significant safety margin (5–6 times) from the design limit which can accommodate various correction factors.

Table 3. Material compositions of Indian LLCB and HCCB blankets.

Breeder blanket	Materials composition
LLCB	PbLi with 90% Li-6 enrichment Li_2TiO_3 with 60% Li-6 enrichment (63% pebble packing fraction with 90% TD) IN-RAFMS, He
HCCB	Be (63% pebble packing fraction with 90% TD) Li_2TiO_3 with 60% Li-6 enrichment (63% pebble packing fraction with 90% TD) IN-RAFMS, He

Table 4. Radiation damage to IB VV.

@Neutron wall load = $0.54\,\mathrm{MW/m^2}$ (@Peak NWL at IB = $0.58\,\mathrm{MW/m^2}$)	Design limits [20]	1 FPY
Peak dpa in VV	2.75	5.04×10^{-3} (5.41×10^{-3})
Peak helium production in VV (appm)	1	5.10×10^{-2} (5.48×10^{-2})

Table 5. Radiation loads on IB TF coil.

Quantity @Neutron wall load = $0.54\,\mathrm{MW/m^2}$ (@Peak NWL at IB = $0.58\,\mathrm{MW/m^2}$)	Design limits [20]	1 FPY
Total neutron fluence to epoxy insulator ($\mathrm{n/cm^2}$)	1.00×10^{18}	1.69×10^{17} (1.82×10^{17})
Peak fast neutron fluence in winding pack ($E > 0.1\,\mathrm{MeV}$) ($\mathrm{n/cm^2}$)	1.00×10^{18}	4.18×10^{16} (4.49×10^{16})
Peak dpa in Cu in winding pack	1.00×10^{-4}	1.66×10^{-5} (1.78×10^{-5})
Peak nuclear heating in winding pack (W/cc)	1.00×10^{-3}	1.38×10^{-5} (1.48×10^{-5})

5. Conclusions

1D neutron and photon radiation transport calculations have been carried out to assess the neutronic performance of the SST-2 using the ANISN code and FENDL-2.1 nuclear data. A reference radial build-up has been obtained, which gives a decent TBR and satisfies the radiation shielding requirements of VV and toroidal field coil for 1 FPY. It was shown that the reference radial build is capable of satisfying these requirements. The TBR obtained from this radial build is 0.85 and 0.94 for LLCB and HCCB concepts, respectively. This is expected because the breeding blanket is kept at the OB side only which can be increased by increasing the coverage area. The radiation damage assessment in terms of helium production in VV indicates that shield blanket thickness is adequate to protect the VV for 1 FPY. Radiation loads to the TF loads have been calculated and it shows that VV and shield blanket together are capable of providing sufficient shielding to TF coils. The helium productions in VV and radiation loads to TF coils are lower than design limits. This provides sufficient margin for accounting several factors such as gape effect, peaking factor, etc. which needs to be taken into account for extrapolating the 1D results to 3D. The results of this analysis provide inputs to the conceptual design of the SST-2.

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References

[1] R B Grover and Subhash Chandra, *Energy Policy* **34**, 2834 (2006)
[2] R Srinivasan *et al*, *Fusion Eng. Des.* **83**, 889 (2008)
[3] R Srinivasan *et al*, *Fusion Eng. Des.* **112**, 240 (2016)
[4] L A El-Guebaly *et al*, *Fusion Eng. Des.* **80**, 99 (2006)
[5] L A El-Guebaly *et al*, *Fusion Eng. Des.* **38**, 139 (1997)
[6] U Fischer *et al*, *Fusion Eng. Des.* **84**, 323 (2009)
[7] U Fischer *et al*, *Fusion Eng. Des.* **85**, 1133 (2010)
[8] M E Sawan *et al*, *Fusion Eng. Des.* **81**, 505 (2006)
[9] M E Sawan *et al*, *Fusion Eng. Des.* **49**, 667 (2000)
[10] T Hayashi *et al*, *Fusion Eng. Des.* **81**, 1285 (2006)
[11] S Liu *et al*, *Fusion Eng. Des.* **88**, 2404 (2013)
[12] X Zhang *et al*, *Plasma Sci. Technol.* **19**, 115602 (2017)
[13] Q J Zhu, J Li and S L Liu, *Plasma Sci. Technol.* **18**, 775 (2016)
[14] V Menon *et al*, Physics design and analysis code SPECTRE for tokamak based fusion reactors, *25th IAEA Fusion Energy Conference (FEC)* (Saint Petersburg, Russia, 2014)
[15] W W Engle Jr, *A user's manual for ANISN, K-1693* (March 1967)
[16] L D Aldama and A Trkov, *FENDL-2 1: Update of an evaluated nuclear data library for fusion applications* (International Atomic Energy Agency, Vienna, 2004)
[17] E Rajendra Kumar *et al*, *Fusion Eng. Des.* **109**, 1522 (2016)
[18] P Chaudhuri *et al*, *Fusion Eng. Des.* **89**, 1362 (2014)
[19] H L Swami *et al*, *Fusion Eng. Des.* **113**, 71 (2016)
[20] P Chaudhuri *et al*, *Fusion Eng. Des.* **88**, 209 (2013)
[21] P Chaudhuri, C Danani and E Rajendrakumar, *Plasma Sci. Technol.* **19**, 125604 (2017)
[22] U Fischer *et al*, *Fusion Eng. Des.* **98–99**, 2134 (2015)