Nuclear Engineering and Technology 54 (2022) 2334–2337

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Technical Note

Estimation of the neutron production of KSTAR based on empirical scaling law of the fast ion stored energy and ion density under NBI power and machine size upgrade

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A R T I C L E I N F O

Article history:
Received 2 November 2021
Received in revised form
22 December 2021
Accepted 2 January 2022
Available online 5 January 2022

Keywords:
KSTAR
Neutron
Fusion
14 MeV

A B S T R A C T

Deuterium-tritium reaction is the most promising one in term of the highest nuclear fusion cross-section for the reactor. So it is one of urgent issues to develop materials and components that are simultaneously resistant to high heat flux and high energy neutron flux in realization of the fusion energy. 2.45 MeV neutron production was reported in D-D reaction in KSTAR and regarded as beam-target is the dominant process. The feasibility study of KSTAR to wide area neutron source facility is done in term of D-D and D-T reactions from the empirical scaling law from the mixed fast and thermal stored energy and its projection to cases of heating power upgrade and DT reaction is done.

Fusion reaction converts the binding energy difference between the reactants and the products to kinetic energy of products. Deuterium-tritium reaction is the most promising one in near future in term of the highest nuclear fusion cross-section for the reactor. But the resulting reaction product, 14 MeV neutron is not an easy element to handle in fusion reactor. So it is one of urgent issues to develop materials and components that are simultaneously resistant to high heat flux and high energy neutron flux in realization of the fusion energy. The bombardment of high energy 14 MeV neutrons leads to combined material displacement damage and helium bubble formation in the bulk structure material and results in shortage of structure lifetime. It is well known that neutron flux of about 1018–1019/m2.s is required to accommodate DEMO reactor condition of 100 dpa [1]. To solve this, IFMIF/EVEDA was pursued as one of world-wide efforts and IFMIF-Dones and Japanese program has been progressed based on the accelerator driven neutron production facility using nuclear stripping process of energetic deuterium nucleus by target [1–3]. In addition to the narrow area beam facilities, wide area neutron source is also required to demonstrate the function of blanket module and TBM(Test Blanket Module) is one of the critical research items in ITER to realize the fusion reactor. Since NBI(Neutral beam injector) has been used in heating KSTAR plasmas, 2.45 MeV neutron production was reported in D-D reaction and regarded as beam-target is the dominant process. Accumulated neutron dose and energy spectrum are measured [4,5]. Recently, it was reported that the highest ion temperature up to 10 keV has been sustained in superconducting tokamak, KSTAR, which aims to sustain the fusion reaction continuously. In this study, feasibility study of KSTAR to wide area neutron source facility is done in term of D-D reactions from the empirical scaling law from the mixed fast and thermal stored energy using profile data and its projection to cases of heating power upgrade and DT reaction is done. Compared with the conventional scaling law of neutron production, suggested method considers the plasma parameter with profile data so that more accurate results are expected. The comparison between the measured and calculated by empirical scaling is done and the calculation is also compared by NUBEAM code [6]. The difficulty of the fast ion density in fusion reaction calculation is solved by fast ion pressure approximation in the calculation of velocity averaged reaction cross-section in neutron emission. The fusion power projection in D-T plasmas of KSTAR does not include alpha particle power and isotope effect on confinement.

Fusion reaction neutrons in beam driven plasma consists of beam-thermal (Y_{bt}), thermal (Y_{th}), beam-beam (Y_{bb}) interactions as shown in eqs (1)–(3). It is well known that neutrons are mainly

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https://doi.org/10.1016/j.net.2022.01.004
1738-5733/

from beam-target interactions in KSTAR level medium size tokamak with NBI driven plasmas.

$$Y_{bt} = \int n_b n_i (\sigma v_{bi}) \mathrm{dV} \tag{1}$$

$$Y_{th} = \int n_i n_i (\sigma v_{ii}) \mathrm{dV} \tag{2}$$

$$Y_{bb} = \int n_b n_b (\sigma v_{bb}) \mathrm{dV} \tag{3}$$

Where $n_b, n_i\ \sigma v_{bi}, \sigma v_{ii.}, \sigma v_{bb}$ is fast ion (beam) density, plasma ion density, velocity averaged fusion cross-section of beam-thermal ion, thermal/thermal ion and beam-beam respectively.

The total neutron yield is consists of beam target reaction (Y_{bt}), thermal reaction (Y_{th}) , and beam-beam reaction (Y_{bb})

As the fast ion fraction or fast ion density is very difficult measurement parameter for extraction, the calculation of neutron yield could be simple if we can use the fast ion pressure or fast ion stored energy rather than the fast ion density. Reaction cross-section is also a function of particle velocity and we assume that velocity distribution is Gaussian form and we can extrapolate velocity average cross-section term as constant value times square of the electron temperature. When we approximate the reactivity as proportional to square of ion temperature, which is valid approximation in DD and DT reaction under the ion temperature is less than 100 keV. In addition, the plasma density is constant across the plasma volume which is also valid for H-mode plasmas. The reaction neutrons are expressed in simple as follows,

$$Y_{bt} = \alpha_1 n_i T_b W_b = \sim \alpha_1 n_i / n_b W_b W_b \tag{4}$$

$$Y_{th} = \alpha_1 \int n_i n_i T_i T_i \mathrm{dV} = \alpha_1 W_i W_i \tag{5}$$

$$Y_{bb} = \alpha_1 \int n_b n_b T_b T_b \mathrm{dV} = \alpha_1 W_b W_b \tag{6}$$

Where,
$\alpha_1, T_i, T_b, W_i, W_b$ *is the reactivity constant, ion temperature, the average fast ion energy, the thermal ion stored energy, and fast ion stored energy respectively*. From (4) and (6), depending on the ratio of fast ion and thermal ion, where under nominal H-mode condition, fast ion is about ten percent of thermal ion density, so Y_{bb} is negligible to Y_{bt}. Compared with (4) and (5), depending on the ratio of fast ion ratio and fast ion energy ratio to thermal ion and thermal ion energy, the dominant part is determined. It can be conjected that neutron production from thermal reaction process is dominant only when fast ion density is smallest compared with plasma density and thermal nuclear fusion reaction is dominant at high ion temperature and high ion density. So when the beam density is very small compared with plasma density, beam-beam interaction is negligible. For beam-target reaction dominant cases, total neutron yield is proportional to the ion density times fast ion stored energy for constant incident beam energy as shown in equation (4). Recently, it is reported that KSTRA produce the highest ion temperature in 20 s. The neutron measurement and fast ion energy estimation is shown in Table 1 for hybrid, H-mode, and high li mode that KSTAR produced the highest neutron yield. Neutron yield is also calculated using Nubeam code for high performance shots as well as L-mode discharge. The fast ion pressure is deduced from the total stored energy minus the thermal plasma energy. The total stored energy is EFIT calculated MHD energy and thermal plasma energy is calculated from measured profile data of ion and electron temperature and electron density.

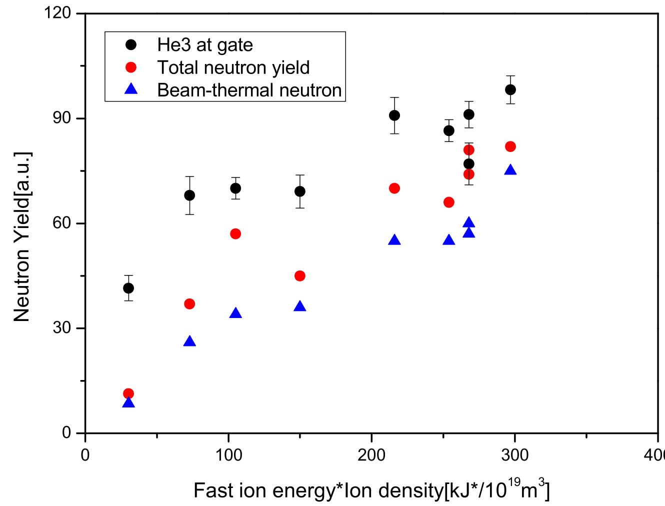

Fig. 1. Neutron yield vs. fast ion stored energy times ion density, where the total and beam thermal neutron yield calculated by Nubeam and profile data. He^3 neutron counter is located at main entrance gate.

Compared with three shots (#27327, 25691, 25460), NB power is nearly constant as 4–5 MW so that the fast ion pressure is higher as the electron temperature is higher and target density is lower due to increase of slowing down time. The beam power is about 4 MW for hybrid shot (#25460) and 5 MW for #27327 and 25691. The neutron calibration factor is about $9.6{*}10^{12}$ for J-port fission chamber detector. It would be over-estimated because solid angle of the calibration source is assumed to be 180° [7].

By using fast ion pressure and thermal plasma profile, neutron yield vs. fast ion pressure times ion density is shown in Fig. 1 for several shots (#25380, 25460, 25691, 26980, 27327,29301,30005). The linear dependency of fast ion stored energy times ion density on neutron yield is clearly seen. Note that during the conversion from the measured electron density, the ion density is deduced from the measured electron density under the assumption that $z_{eff} = 2$ so that the impurity concentration is to be corrected for

Table 1
DD neutron yield for various plasma shots (#30005, 29301, 27327, 26980, 25691, 25460), where $neutron_c$ corresponds to neutron yield of Y_{bt} using Nubeam and value in bracket correspond to the total neutron yield. Measured neutron corresponds to He^3 and fission chamber counter.

Shot#	Time (s)	N_e ($10^{13}/cm^3$)	T_i (keV)	T_e (keV)	W_{mhd} (kJ)	W_{fast} (kJ)	Neutron (arb.unit) (Measured)	$Neutron_c$ (Calculated) ($10^{14}/s$)	Operation Scenario	NBI power (MW)
30005	5.0	1	2	8	227	75	42/18	0.85 (1.05)	L-mode	1.1
29301	4.5	1	9	6	302	147	72/52	2.19 (3.59)	High-Ti	3.1
27327	7	5	4	5	811	108	98.2/147	7.56 (8.28)	H-mode	5
26980	5.5	4	4	6	382	179	80/65	5.71 (7.3)	H-mode	5.3
25691	7.9	4	4	5	421	127	86/87	5.53 (6.79)	High-li	5.1
25460	9.5	4	5	6	522	108	90.8/105	5.55 (7.04)	Hybrid	4

accurate estimation of ion density as a future work.

Application of tokamak plasma to the neutron source has different features compared with fusion energy source, fusion energy required to self-sustaining fusion reaction where fusion product alpha ‘s role is important in addition to the neutron production. Alpha particles are slowed down and reheated plasma to sustain the reaction. On the other hand, neutron source relies on beam-target fusion process as well as thermos-nuclear fusion, when the ion temperature exceeds some value, the process is dominated by thermos-nuclear fusion rather than beam target fusion with the constant beam power condition. Self-sustaining discharge is not a necessary condition for the neutron production. Beam target dependency is clearly seen in single shot (#27327) where the plasma density is varying as the plasma current but the fast ion pressure is nearly constant and electron temperature kept nearly constant. The neutron production is increased as the plasma current and is proportional to ion density.

When we extrapolate the neutron production to case of neutral beam power upgrade in KSTAR [8], where the beam power is doubled to present NB power with additional NB2, the fast ion pressure would be more than doubled and the electron temperature is also increased as well as ion temperature. Based on the reference scenario, the stored fast ion energy is extrapolated using the incident neutral beam power times slowing down time, whereas the electron temperature is decided using confinement scaling law with the target plasma density is assumed to be constant. .So it is expected that the fast ion pressure is increased due to that both incident beam and beam slowing down time increase, but the thermal energy is increased a little bit regardless of tokamak operation scenarios. According to H-mode confinement scaling, confinement time is inversely proportional to the power factor of 0.63 so that the stored thermal energy is increased to 1.23 times to present value and T_i as well as T_e is to be about 6.1 keV under assumption of constant plasma density. The stored thermal energy could reach to around 1 MJ. Still the neutron from the thermal nuclear reaction is much less than that of beam target reaction. Of course, if the plasma current is increased over 1 MA, the stored thermal energy is increased by $Ip^{0.93}$ under the assumption of no changes in the density and there is another possibility of neutron emission increase. In addition, KSTAR machine upgrade was considered to increase the major and minor radius as 1.95 and 0.65 m and the corresponding plasma confinement is increased as 1.3 times to the present value [9]. Plasma volume is increased 1.8 times to the present value as well. When we follow the confinement scaling, both Te and Ti are decreased and the total stored energy is just increased to 10%. However, most of them is thermal energy and fast ion increase is very small so that neutron production is not big in machine size upgrade without power upgrade as shown in Table 2.

For application to production of 14 MeV neutron, DT discharge can be applicable to KSTAR with the present plasma discharge configuration where the neutral beam power is about 10 MW with 1 MA plasma current. The neutral beam energy is limited in the plasma density by shine through so that cross-section or velocity averaged cross-section dependency on square of ion temperature is

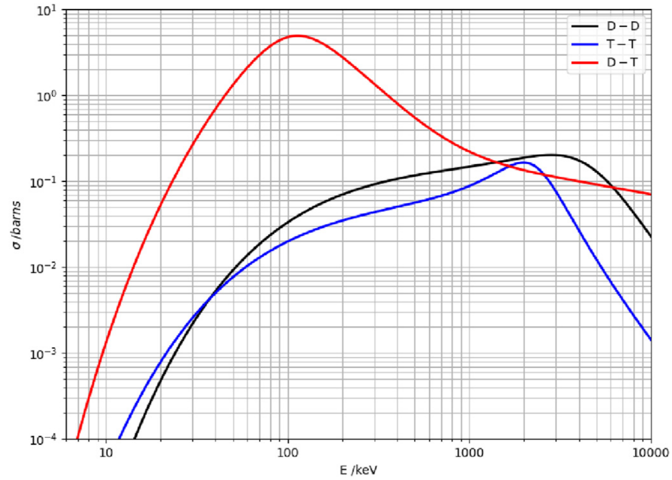

Fig. 2. Reaction cross section of DD, DT and TT (Tritium-tritium) in the energy range up to 10 MeV.

Table 3
Fast ion stored energy, neutron yields vs. various fuel and beam composition in 5 MW NBI power, where T_p is tritium plasma, D_b is deuterium beam, D_p is deuterium plasma and T_b is tritium beam. The neutron yield is calculated by NUBEAM.

Beam/target	T_p (100)/D_b (100)	D_p (100)/T_b (100)	D_p/D_b
W_{fast} (kJ)	132	105	108
Neutron (Y_{bt}, 10^{17}/s)	2.61	0.86	0.0074
Neutron (Y_{bb}, 10^{17}/s)	0.00094	0.00095	0.0006
Neutron (Y_{th}, 10^{17}/s)	0.015	0.015	0.0006

still valid as shown in Fig. 2 for DT as well as DD reaction. The fusion DT cross-section is 100 times more than DD reaction within operating plasma temperature and ion temperature dependency on cross-section is still valid. The plasma conditions are nearly the same as DD reaction if we assume no dependency of isotope effect on the confinement. So it is expected that KSTAR can produce above 10^{17} #/s corresponding $10^{16}/m^2$ .s neutron flux at the plasma boundary (LCFS) by optimizing beam-target neutron production process as shown in Table 3. In maximizing the thermal nuclear process, when the target plasma density in DT is shared by deuterium and tritium and density dilution effect can reduce the reaction by 1/4 compared with pure deuterium reaction so that resultant reaction in DT is increased only by 20–30 times than DD reaction in thermal reaction. When we compared the neutron production between deuterium and tritium target plasma, the fast ion energy in target tritium with deuterium beam is higher than that in deuterium target with tritium beam. Therefore the best option for the efficient neutron production is to inject deuterium beam to tritium plasma to maximize the neutron production as shown in Table 3 where the beam target fusion process is still dominant process in DT discharge at KSTAR. As the beam target fusion is dominant process than the thermal fusion and tritium plasma is more efficient that deuterium plasma in 14 MeV neutron

Table 2
DD neutron yield for NBI power upgrade and machine size upgrade of KSTAR.

	Ip (MA)	NB (MW)	Major/minor radius(m)	T_e/T_i (keV)	Density ($10^{13}/cm^3$)	W_{fast} (kJ)	W_{th} (kJ)	Neutron (10^{14}/s)
#27327	1	5	1.8/0.5	5/5	6	108	702	8.2
Size upgrade	1	5	1.95/0.65	3/3	6	~108	912	~8.2
Power upgrade	1	10	1.8/0.5	6.1/6.1	6	283	863	21.4

production, fueling ratio and injection of the tritium gas to the tokamak vacuum chamber would be a critical issue. Recent KSTAR results shows that the additional gas injection is necessary to maintain the longer discharge over 50 s. So the tritium supply issue should be manageable as well as the tritium inventory at graphite PFC. The maximum neutron yield would be around $6.8*10^{17}$/s under the same plasma equilibrium of #27327 with increasing the beam power up to 10 MW. So the best option shows the possibility of maximum neutron yield up to 10^{18}/s in KSTAR with additional plasma performance improvement.

In summary, using the fast ion pressure or fast ion stored energy, an empirical scaling law of the neutron emission is deduced from the ion density times fast ion stored energy and preliminary comparison shows the linear dependence of neutron yield to fast ion stored energy times ion density. KSTAR applicable to wide area 14 MeV neutron source facility is done for DT discharge with present machine size. The maximum neutron yield and flux could reach up to 10^{18}/s and $10^{17}/m^2$.s respectively in DT reaction of KSTAR where the plasma current is about 1 MA and beam power is 10 MW.

Declaration of competing interest

The authors declare no conflicts of interest.

Acknowledgements

This research was supported by R&D Program of "KSTAR Experimental Collaboration and Fusion Plasma Research (EN2101-12)" through the Korea Institute of Fusion Energy (KFE) funded by the government funds

References

[1] J. Knaster, et al., Overview of IFMIF/EVEDA project, NF (57) (2017) 102016.
[2] R. Serber, The production of high energy neutrons by stripping, Phys. Rev. (72) (1947) 1008.
[3] W. Krolas, et al., IFMIF-dones, fusion oriented neutron source, NF (61) (2022) 125002.
[4] Jong-Gu Kwak, et al., Accumulated 2-D neutron flux distribution during KSTAR operation, Fed. Times 136 (2018) 777.
[5] Youngseok Lee, et al., Diamond Fast-Neutron Detector Applied to the KSTAR Tokamak, 2020, https://doi.org/10.1016/j.fusengdes.2019.111452.
[6] A. Pankin, D. McCune, R. Andre, G. Bateman, A. Kritz, Comput. Phys. Commun. 159 (2004) 157.
[7] Private communication with Y.S. Lee at KSTAR.
[8] Jong-Gu Kwak, et al., KSTAR status and upgrade plan toward fusion reactor, IEEE trans. Plasma sciences (48) (2020) 1388.
[9] Jong-Gu Kwak, et al., Long Term Renovation inside KSTAR Vacuum Vessel toward Steady State Operation, IAEA TM SSO at Vienna, 20, March, 2017.