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Fusion reactor start-up without an external tritium source

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HIGHLIGHTS

- Investigated the feasibility (including plasma physics, neutronics and economics) of starting a fusion reactor from running pure D–D fusion reactor to gradually move towards the D–T operation.
- Proposed building up tritium from making use of neutrons generated by D–D fusion reactions.
- Studied plasma physics feasibility for pure D–D operation and provided consistent fusion power and neutron yield in the plasma with different mixture of deuterium and tritium.
- Discussed the economics aspect for operating a pure D–D fusion reactor towards a full-power D–T fusion reactor.

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ABSTRACT

It has long been recognised that the shortage of external tritium sources for fusion reactors using D–T, the most promising fusion fuel, requires all such fusion power plants (FPP) to breed their own tritium. It is also recognised that the initial start-up of a fusion reactor will require several kilograms of tritium within a scenario in which radioactive decay, ITER and subsequent demonstrator reactors are expected to have consumed most of the known tritium stockpile. To circumvent this tritium fuel shortage and ultimately achieve steady-state operation for a FPP, it is essential to first accumulate sufficient tritium to compensate for loss due to decay and significant retention in the materials in order to start a new FPP. In this work, we propose to accumulate tritium starting from D–D fusion reactions, since D exists naturally in water, and to gradually build up the D–T plasma targeted in fusion reactor designs. There are two likely D–D fusion reaction channels, (1) $D + D \rightarrow T + p$, and (2) $D + D \rightarrow He3 + n$. The tritium can be generated via the reaction channel '(1)' and the 2.45 MeV neutrons from '(2)' react with lithium-6 in the breeding blanket to produce more tritium to be fed back into plasma fuel. Quantitative evaluations are conducted for two blanket concepts to assess the feasibility and suitability of this approach to FPP reactors. The preliminary results suggest that initial operation in D–D with continual feedback into the plasma of the tritium produced enables a fusion reactor designed solely for D–T operation to start-up in an acceptably short time-scale without the need for any external tritium source.

1. Introduction

Due to the high reaction cross-section of the D–T fusion reaction, so far, the vast majority of fusion power plant studies have employed the D–T fuel cycle–the easiest way to reach ignition. Deuterium exists naturally and can be extracted from water; tritium is unstable because of its radioactive decay ($T_{1/2} \sim 12.3$year) and occurs naturally only in trace amounts, formed principally by the interaction of cosmic radiation with oxygen and nitrogen atoms in the upper atmosphere. Tritium may be produced in civil nuclear fission reactors by the following five mechanisms: (a) fissioning of uranium, (b) neutron capture reactions with boron and lithium added to the reactor coolant, (c) neutron capture reactions with boron in control rods, (d) activation of deuterium in water and (e) high energy neutron capture reactions with structural materials [1]. In the civil tritium market, the principle source of tritium is fission reactors with heavy water cooling and moderation, which in total, world-wide, produce only a few kg per year from neutron capture by the deuterium in the heavy water. However this is a very small quantity of tritium generated as a by-product compared to the actual need of a fusion power plant (FPP). The annual tritium consumption of a fusion power plant operating at 1 GW fusion power is ~55.6 kg per full power year (FPY) or ~152 g per full power day (FPD). As there is generally a lack of external tritium sources,

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all FPPs must breed their own tritium needed for fuelling the D–T fusion plasma unless a purpose built facility supplies the tritium, meeting the fusion need. This does not address the issue of reactor start-up however, where the required inventory is estimated to be of order 10 kg against an expected world inventory of order 7–32 kg in 2050 [2] when there will be likely multiple DEMO fusion reactors and/or FPPs built in different nations. Thus, it would be essential to accumulate sufficient tritium to start a new FPP operating at the targeted fusion power, to compensate the loss due to the decay and any inventory retention in the plant. It is generally assumed that regulatory authorities would not sanction the stockpiling of any excess tritium that may be produced by precursor demonstration plants [3]. Thus, even though we expect a FPP will maintain a self-sufficient supply of tritium, the issue remains where to obtain sufficient tritium for the initial fuel to start a D–T fusion reactor under the condition that there is no external tritium supply.

There have been some previous studies addressing this issue. Ref. [4] proposed increasing the percentage of deuterium into the D–T mixture to enhance the D–D reactions so as to reduce the need for tritium. The consequent plasma performance was studied for its consistency although a simple plasma energy balance was used for the study. There were some discussions [5–7] on commissioning of a D–T fusion reactor without external supply of tritium, based on a Japanese conceptual FPP design—CREST (Compact Reversed Shear Tokamak). In Refs. [8–10], the investigations have focused on applying a small amount of tritium as a catalyst for other fusion reactions using natural fuels in order to avoid demanding a large quantity of external tritium. Ref. [11] discussed the plasma physics feasibility of using D-He3 and D–D fusion fuels in appreciation of the significantly more demanding plasma conditions, including energy confinement time, density, temperature and beta, than those required by D–T fusion reactions and in preference of minimising neutron generation in fusion reactions. In this paper we investigate alternative ways to meet the tritium requirements for D–T fusion reactors by accumulating tritium from the D–D fusion operation and exploiting the capabilities and functions of the blanket in the fusion reactor. In Section 2, the mechanism is described and two different blanket concepts are introduced to extend this study in later sections; Section 3 discusses the results of preliminary simulations demonstrating the neutronics and plasma physics feasibility of the method; the economics is discussed in Section 4; the conclusion is given in Section 5.

2. Mechanism

In this work, we propose to accumulate tritium starting from D–D fusion reactions, and to gradually build up the D–T fusion plasma towards the targeted design operating point for a fusion reactor. It is assumed that the following two deuterium fusion reaction channels have essentially equal probabilities:

$$(a)\,\mathrm{D}+\mathrm{D}\rightarrow T\,(1.01\,\mathrm{MeV})+p\,(3.03\,\mathrm{MeV})$$

$$(b)\,\mathrm{D}+\mathrm{D}\rightarrow \frac{3}{2}\mathrm{He}\,(0.82\,\mathrm{MeV})+n\,(2.45\,\mathrm{MeV})$$

Although a D–D fusion reactor will possess a much smaller power density in comparison with D–T fusion at equal particle densities and ion temperatures below ~200 keV, the production of tritium from the reaction channel '(a)' can be part of the fuel for D–T fusion reactions and the production of neutrons from the reaction channel '(b)' can induce the lithium compounded in the tritium breeding blanket to generate more tritium (as shown in Fig. 1). The neutron energy is not very high relative to the energy threshold of the ^{7}Li(n,n')T reaction and the neutron multiplication reactions, mainly Pb(n, 2n) and Be(n, 2n), thus, the tritium will be produced mainly via the ^{6}Li(n, T)^{4}He reaction which has a high cross-section for thermal neutrons. The tritium produced in the blanket is directly returned into the plasma, allowing for a suitable transfer period, thus increasing the tritium concentration in the plasma.

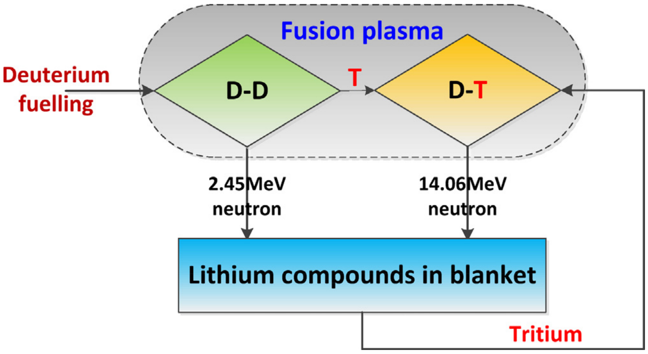

Fig. 1. Mechanism of fusion plasma evolvement from D–D to D–T.

Meanwhile, there is an approximately 50% probability that D–D fusion reactions will produce tritium that will be directly diffused in the plasma mixture and result in D–T fusion reactions due to the higher reaction cross-section. The high energy neutrons from the D–T fusion reactions will further react with ^{6}Li or ^{7}Li in the blanket to produce more tritium with the benefit of more usable neutrons via the multiplication reactions.

The blanket tritium breeding capability is design dependent and evolves with time due to the depletion of the lithium isotopes and the blanket material transmutation, primarily depending on the choice of breeding materials and neutron multipliers. For the purposes of this study we adopted a basis configuration of the EU DEMO plant [12] validated by PROCESS code [13] as part of the EUROfusion Power Plant Physics & Technology (PPPT) working group on DEMO. To assess the practicality of accumulating sufficient tritium from D–D fusion operation to progress towards D–T fusion operation, two different breeding blanket designs, HCLL (Helium Cooled Lithium Lead) and HCPB (Helium Cooled Pebble Bed), which have been adopted as the EU test blanket modules (TBMs) for ITER [14], were employed. The evolution of tritium production through the different operational phases, from the D–D to the D–T phase, was modelled assuming the blanket is the design optimised for the full power D–T operation of the machine throughout.

3. Results and discussions

3.1. Tritium breeding capability

The evaluation of the tritium breeding in the selected reactors is carried out using the neutronics tool MCNP5 [15] and the IAEA fusion nuclear data FENDL2.1 [16]. In the HCLL reactor, the materials composition in the breeding blanket is homogenised with the tritium breeding material being LiPb, where the Lead acts as the neutron multiplier in a high-energy neutron environment and Eurofer as the structural material. In order to achieve a self-sufficient tritium fuel cycle for the D–T operation, the ^{6}Li is enriched to 90%. In the HCPB reactor, Li_4SiO_4 is the tritium breeder and beryllium is employed as the neutron multiplier to enhance the effectiveness of the neutrons; the structural material is again Eurofer. Each D-T fusion reaction consumes one triton and produces one high energy neutron (14.06 MeV) that travels through the breeding blanket to generate both tritium and additional neutrons that also produce tritium. The ratio of generated tritium to consumed tritium is referred to as the tritium breeding ratio (TBR). From D–D fusion reactions, neutrons at 2.45 MeV are generated that react with the lithium in the breeding blanket where additional tritium may be produced. The tritium production rate (TPR), the amount of tritium