# On the feasibility of self-sustainable deuterium production in fusion reactors using an ionization chamber

Francisco J. Arias* and Geoffrey T. Parks
*Department of Engineering, University of Cambridge*
*Trumpington Street, Cambridge, CB2 1PZ, United Kingdom*

In this technical note we examine a method for self-sustainable (*in-situ*) deuterium production in a fusion reactor, using a very different approach to those considered in previous studies. Here, instead of pursuing the production of deuterium via neutron capture ($H + n \rightarrow D$) inside and/or outside the fusion chamber, the deuterium is obtained by ionization induced by the neutronic flux in an ionization chamber and then electromagnetically separated. Using conservative modelling assumptions, an estimate of the amount of deuterium obtainable per day is made. The results show the feasibility of this approach, encouraging further research. Using the proposed method in combination with the use of lithium blankets for tritium breeding opens a new possibility for integral *in-situ* production of all the nuclear fuel required for fusion.

***Keywords.*** *In-situ integral fuel production, Deuterium production, Tritium production.*

## I. INTRODUCTION

While tritium can be produced within a fusion reactor (*in-situ production*) when neutrons escaping the plasma interact with a specific element (lithium) contained in the surrounding blanket [1], there is no similar mechanism for *in-situ* deuterium production, and, as a result, deuterium must be sourced externally. In-situ self-sustainable production of deuterium in the fusion reactor, in combination with the use of lithium blankets for tritium production, could lead to an integral closed cycle in which all the nuclear fuel needed is produced in the reactor itself, with obvious advantages.

By simple inspection of the neutron capture reaction

$$H + n \rightarrow D \tag{1}$$

in which a hydrogen atom turns into a deuterium atom, it is straightforward to show that the maximum amount of deuterium obtainable has an upper limit given by

$$M_D < N_H \sigma_a \Phi \frac{P_D}{N_a} V t \tag{2}$$

where: $M_D$ is the mass of deuterium (in grammes); $N_H$ is the concentration of hydrogen (atoms $\mathrm{b}^{-1}\,\mathrm{cm}^{-1}$); $\sigma_a$ is the neutron absorption cross-section of hydrogen (barns); $\Phi$ is the neutronic flux (neutrons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$); $t$ is the time of irradiation (s); $V$ is the volume of the chamber ($\mathrm{cm}^3$); $P_D$ is the atomic mass of deuterium (g/mol); and $N_a$ is Avogadro's number.

To obtain an estimate of the amount of deuterium obtainable in this way, we assume some typical, realizable values of these parameters: using a pressurized chamber with a practical volume of 1 $\mathrm{m}^3$ working at, say, 100 atmospheres, the hydrogen density $N_H \approx 10^{-3}$ atoms $\mathrm{b}^{-1}\,\mathrm{cm}^{-1}$, with $\sigma_a = 0.33$ b for thermal neutrons [2], and a typical neutronic flux from the nuclear core of $\Phi = 10^{14}$ n $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, with $P_D = 2$ g $\mathrm{mol}^{-1}$ and $N_a = 6.02 \times 10^{23}$ atoms/mol, we get a value for $M_D$ of only $\sim$3 g/year. We also note that Eq. (2) neglects the simultaneous destruction of deuterium by neutron capture. In any case, even in the most optimistic scenario this rate of production comes nowhere near the anticipated rate of consumption of deuterium in a 1.5 GWe fusion reactor of 400 g/day [3].

By this reasoning, it seems clear that the breeding of sufficient quantities of deuterium via neutron capture is not remotely feasible, and at first glance it appears that in-situ, self-sustainable production of deuterium, at least from neutron capture reactions, is unpractical. However, it is possible to approach the problem from a different angle, as we will discuss.

In the present study, instead of pursuing the production of deuterium via neutron capture, deuterium is obtained by ionization and electromagnetic separation using the process shown schematically in Fig. 1. In this process, the mixture of hydrogen + deuterium is partially ionized using an ionization chamber exposed to the neutronic flux coming directly from the fusion reactor core, the same neutronic flux that is used to breed tritium in lithium blankets (see Fig. 2). Then, the deuterium and hydrogen ions are electromagnetically separated.

## II. OBTAINING DEUTERIUM VIA IONIZATION AND SEPARATION

Although neutrons have zero electrical charge and thus often do not directly cause ionization in a single step or interaction with matter, nevertheless fast neutrons will

*Corresponding author: Tel.: +32 14 33 21 94; Electronic address: fja30@cam.ac.uk

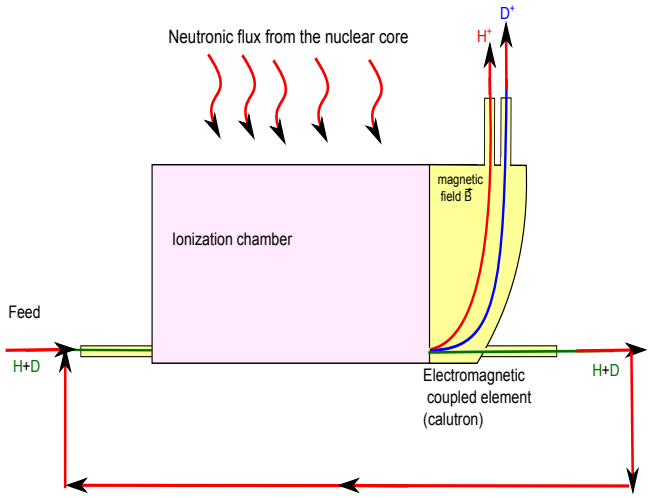


FIG. 1: Schematic representation of the concept of an ionization chamber and in-situ deuterium separation in the fusion reactor.

interact with the protons in hydrogen via elastic scattering, and this mechanism scatters the nuclei of the gas in the target chamber, causing direct ionization of the hydrogen atoms. When neutrons strike the hydrogen nuclei, proton radiation (fast protons) results. These protons are themselves ionizing because they are of high energy, are charged, and interact with the electrons in matter.

In this study, we seek to account for the ionization from the charged protons by fundamental interaction through the Coulomb force, as we believe this will be significant. However, we neglect ionization due to gamma radiation through the photoelectric effect and Compton scattering. We also neglect recombination. Although these effects will need to be accounted for in detailed design studies, they are second-order (and somewhat compensatory) effects.

Many models for elastic scattering are available which allow us to obtain a first, rather conservative, estimate of the extent of ionization, but in view of the uncertainties, the simplest model due to Kinchin and Pease [4] seems sufficient for present purposes. According to this model, the obtainable rate of production of deuterium ions $N_D^+$ (number per unit volume and time) is given by

$$\frac{dN_D^+}{dt} \approx R_D N_H \sigma(\bar{E}_n)\Phi \left\{ \frac{\Lambda \bar{E}_n}{4E_i} \right\} \times I_c \qquad (3)$$

where: $dN_D^+/dt$ is the number of deuterium ions produced per $\mathrm{cm}^3$ per second; $N_H$ is the concentration of hydrogen atoms (in $\mathrm{b}^{-1}\,\mathrm{cm}^{-1}$) in the chamber (as target atoms); $R_D$ is the deuterium enrichment; $\sigma(\bar{E}_n)$ is the elastic scattering cross-section (b); $\bar{E}_n$ is the weighted average neutron energy (eV); $\Phi$ the neutronic flux ($\mathrm{n\,cm^{-2}\,s^{-1}}$); $E_i$ is the ionization energy for hydrogen (eV); and

$$\Lambda = \frac{4A}{(1+A)^2} \qquad (4)$$

where $A$ is the atomic mass number. $A = 2$ for deuterium and thus $\Lambda = \frac{8}{9}$.

In Eq. (3), the factor $I_c$ accounts for the increase in the production of deuterium ions due to specific secondary ionization by protons. According to Feather [5] this factor can be as high as 2320 for the ionization of air and given hydrogen's lower ionization energy (13.6 eV cf. 30 eV for air) it could be higher still for hydrogen; however, in view of the uncertainties, in the present calculations we assign $I_c$ a more conservative value of 464 (i.e. 20% of 2320). It is evident that because of the similar mass of neutrons and deuterium a significant rate production of $D^+$ ions can be obtained. The value of the factor $\Lambda$ in Eq. (4) is also the reason behind of the widespread use of hydrogen and deuterium as moderators in thermal nuclear fission reactors, reflecting to their propensity for elastic scattering. In our proposed approach we are also taking advantage of the high propensity of hydrogen for neutronic scattering.

The ions of deuterium $N_D^+$ and hydrogen $N_H^+$ produced can readily be separated by conventional electromagnetic methods, for example, by using a simple calutron.

Thus, taking into consideration Eq. (3), the mass of deuterium, $M_D^+$ in grams obtainable is given by

$$M_D \approx R_D N_H \sigma(\bar{E}_n)\Phi \left\{ \frac{\Lambda \bar{E}_n}{4E_i} \right\} \times I_c \times \frac{P_D}{N_a} V t \epsilon_{em} \qquad (5)$$

where $V$ is the volume of ionization chamber, $t$ is the irradiation time and $\epsilon_{em}$ is the efficiency associated with the electromagnetic separation. From the available literature on uranium isotopic separation, classical calutrons operate with efficiencies of ~10% [6]. This rather low efficiency is due mainly to problems associated with the use of uranium tetrachloride, which, of course, will not be present for deuterium-hydrogen separation. The separation efficiency will also be improved by the fact the isotopic mass ratio between deuterium and hydrogen is ~2 which is substantially higher than in the case of isotopic uranium separation where the mass ratio for $^{238}$U and $^{235}$U is 1.012. Thus it is entirely conceivable that the efficiency of electromagnetic separation of deuterium and hydrogen using a calutron will be significantly higher than 10%. However, in view of the uncertainty of the estimation, and in the absence, as far as we are aware, of a more definitive value in the literature, we make the conservative assumption that $\epsilon_{em} = 0.1$ as for uranium isotopic separation.

To obtain an estimate of the amount of deuterium production predicted by Eq. (4), we assume the same typical values as before, and take the deuterium enrichment to be $R_D = \frac{1}{6420}$, as it is for hydrogen-deuterium mixtures coming from the Earth's oceans. With $\sigma = 5$ b [2], with neutrons with energies $E_n = 10$ MeV and taking the ionization potential for hydrogen $E_i = 13.6$ eV, we obtain $M_D \approx 177.3$ g/day which is an encouraging figure in comparison to the daily consumption of 400 g/day mentioned earlier given the conservative assumptions made in calculating this estimate.

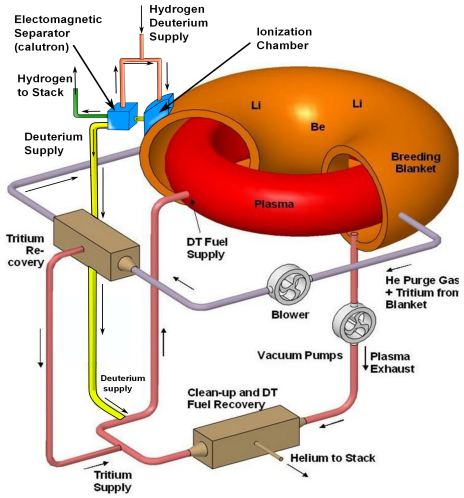


FIG. 2: Schematic implementation of the proposed ionization chamber and electromagnetic separation approach for deuterium production applied to the International Thermonuclear Experimental Reactor (ITER).

Fig. 2 shows a possible schematic implementation of the proposed approach for deuterium production.

## III. CONCLUSIONS

A novel approach for self-sustainable deuterium production in a fusion reactor using an ionization chamber and electromagnetic separation has been proposed and a first estimation of the obtainable amount of deuterium derived. This first preliminary analysis shows that, even when making some deliberately conservative assumptions in calculating the number of ionizations produced in the chamber and for the efficiency of the electromagnetic separation efficiency, the theoretical daily production of deuterium is a substantial fraction of the anticipated daily consumption rate for a 1.5 GWe fusion reactor. The hope is, of course, that further more detailed analysis and optimization of the proposed process will enable the deuterium production rate to match the consumption rate. Certainly this encouraging initial analysis motivates further investigation of the proposed approach, which, in combination with the use of lithium blankets for tritium breeding, offers the tantalising prospect of an integral in-situ process for the production of all the nuclear fuel needed by a fusion reactor.

## REFERENCES

[1] W. Manheimer, Fusion breeding for mid-century sustainable power. J. Fusion Energy **33**, 199–234 (2014)
[2] S. Glasstone, *Principles of Nuclear Reactor Engineering* (1st edition, Van Nostrand, USA, 1955)
[3] Fulham Centre for Fusion Energy, *Fusion Energy Frequently Asked Questions*. http://www.ccfe.ac.uk/FAQ.aspx
[4] D.R. Olander, *Fundamental Aspects of Nuclear Reactor Elements* (Department of Energy, USA, 1976)
[5] N. Feather, Ionization maximum for protons. Nature **147**, 510–511 (1941)
[6] D. Albright, M. Hibbs, Iraq's nuclear hide-and-seek. The Bulletin of the Atomic Scientist **47**, 14–23 (1991)
[7] G.F. Knoll, *Radiation Detection and Measurement* (3rd edition, Wiley, USA, 2000)