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The need to minimize the T inventory of a fusion reactor is a strong constraint on the design of the fuel cycle and favors a high burn-up fraction of the fuel. In this note, we describe the fuel cycle by a simple model that points out the free/unknown parameters of the system that can be used for optimization, pointing out directions of future research.

We start with the definition of the total particle fluxes (i.e. unit: *1/s*). All fluxes relate to D-T 50:50 mixture and are in stationary state. The He flux can then be determined from the pumped flux by inserting the He concentration $c_{He} = n_{He}/n_e$. The flux into the vessel by gas puff or pellets is needed to restore the fuel that is either burned or pumped:

$$\Gamma_{in} = \Gamma_{pump} + \Gamma_{burn}$$

Where the burned flux is given by

$$\Gamma_{burn} = \int n_D n_T \langle \sigma v \rangle dV = \frac{n_e^2}{4} R(T) V$$

Where V is the plasma volume and we have neglected the dilution due to He, assumed a flat density profile and defined the reactivity by

$$R(T) = \frac{1}{V} \int \langle \sigma v \rangle dV$$

For the pumped flux, we use the definition of the effective particle confinement time

$$\tau_p^* = N/\Gamma_{pump}$$

where $\Gamma_{pump}$is the flux of particles pumped out of the vessel[1] and N the number of particles in the plasma. We relate the effective particle confinement time to the 'true' particle confinement time $\tau_p = N/\Gamma_{plasma}$ where Γ_{plasma} is the flux of particles crossing the separatrix due to diffusion and convection by

$$\tau_p^* = \beta \tau_p$$

where the parameter β can in principle take any non-negative value since it includes the effect of recycling ($\beta \to \infty$ for strong recycling, i.e. negligible pumping) as well as the 'bypass' in the SOL when approaching the fuelling limit ($\beta \to 0$ for vanishing fuelling efficiency, i.e. large bypass, which formally also implies $\tau_p \to \infty$ to keep N finite). Finally, the particle confinement time is linked to the energy confinement time by a parameter α that is essentially determined by the ratio of heat conductivity to diffusion, $\alpha \approx \chi/D$, at least for He that is generated by fusion reactions and hence can be represented by a central source:

$$\tau_p = \alpha \tau_E$$

[1] Wall pumping is neglected, corresponding to a situation where the wall is in saturated equilibrium.

So that the pumped flux becomes

$$\Gamma_{pump} = \frac{N}{\tau_p^*} = \frac{nV}{\alpha\beta\tau_E}$$

The burn-up fraction can be written as

$$f_b = \frac{\Gamma_{burn}}{\Gamma_{in}} = \frac{\Gamma_{burn}/\Gamma_{pump}}{1 + \Gamma_{burn}/\Gamma_{pump}}$$

which, as expected, varies between 0 (negligible burn) and 1 (negligible pumping). Inserting the definitions from above, we get

$$\Gamma_{burn}/\Gamma_{pump} = \frac{1}{4} n_e \tau_E R(T) \alpha\beta$$

For a fusion reactor, the quantitiy $n_e \tau_E$ is essentially fixed by the Lawson criterion and, assuming the optimum temperature of roughly 13 keV, also *R(T)* is given and the dimensionless product $\frac{1}{4}\, n_e \tau_E R(T)$ is roughly 0.25 x $3\text{x}10^{20}\text{m}^{-3}\text{s}$ x $2\text{x}10^{-22}\text{m}^3\text{s}^{-1}$ = 0.015 (more general, for finite $Q=P_{fus}/P_{AUX}$, the relation $nT\tau_E = (nT\tau_E)_{ignition}\, Q/(Q+5)$ holds, so that for ITER (*Q=10*) the value is 0.01 instead of 0.015). The burn-up fraction becomes

$$f_b = \frac{0.015\alpha\beta}{1 + 0.015\alpha\beta}$$

which is shown below (setting $x=\alpha\beta$):

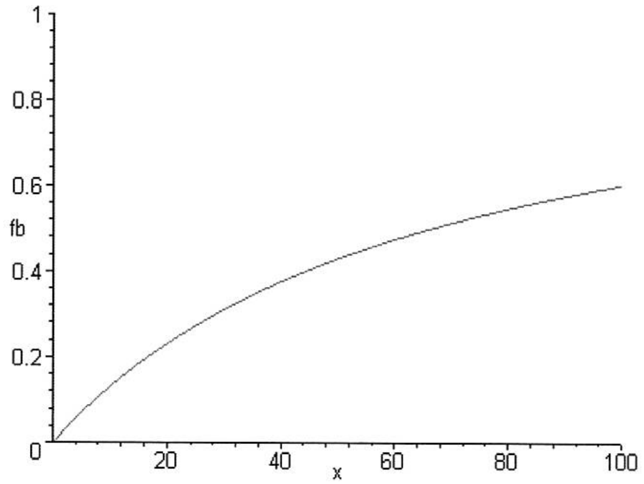

Fig. 1: The burnup fraction f_b as function of the parameter $x=\alpha\beta=\tau_p^*/\tau_E$.

A common assumption is α=5, which for perfect pumping (β=1), leads to f_b=7 %.

One can see that for achieving a high f_b, one would thus rather minimize the pumped flux, or directly re-inject it. There is however a principal limitation to this Ansatz since He must be pumped to avoid accumulation, which has been analysed to yield the constraint $x < 14$ by Reiter and Wolf [1]. That would limit the burnup fraction to around 10 %. However, if we assume that the pumped flux can be cleaned of He and then injected again, this will still fulfill the constraint of removing the He, but be an 'effective recycling' and hence allow to increase β to very large values, approaching f_b=1. This is the basis for the 'direct re-injection scheme' proposed for the EU DEMO [2].

We note that for a more realistic case, the need to re-inject the pumped fuel is even more pronounced. For example, in the ASDEX Upgrade discharge 28731 [3], which is heavily puffed to flush the seed impurities, running against the fuelling limit, we get roughly nV = 1.5 x 10^{21}, Γ_{in}=Γ_{pump}=5x10^{22}, i.e. τ_p*= 30 ms and τ_E= 1.4 MJ / 23 MW = 60 ms, which means x=0.5 and hence f_b=0.6 % (parameters taken from the plot below) if the pumped flux were not to be re-injected. This also explains the ITER assumption which is very similar to this case. We note that this mode of operation is also in a regime in which the plasma density is relatively independent of the gas puff, indicating a decrease in fuelling efficiency ('fuelling limit'). In ITER and DEMO, this might correspond to a situation where gas puff is used to control SOL flow and divertor (neutral) density while fuelling could be done with pellets.

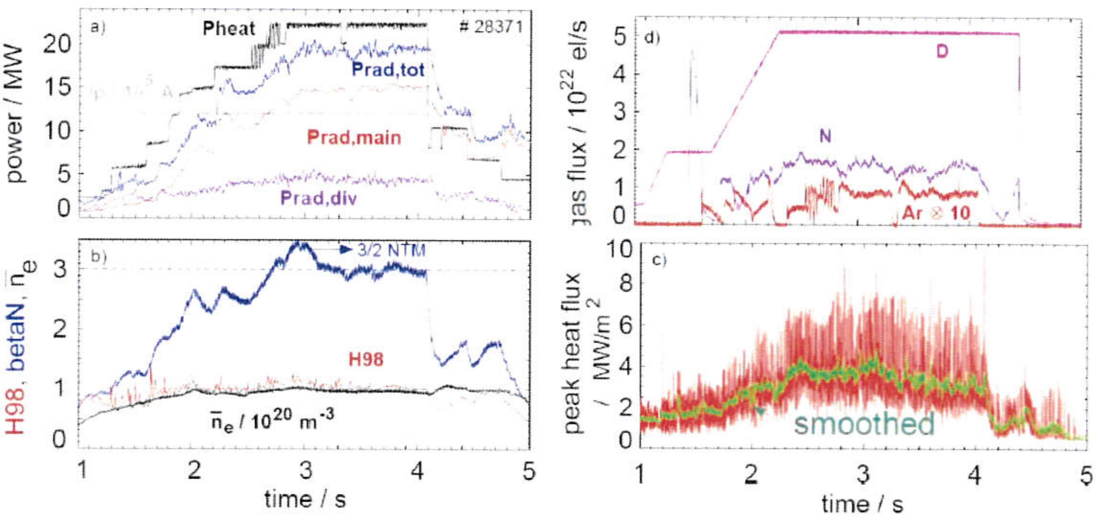

Fig. 2: Parameters for AUG discharge 28371 used to experimentally determine $\alpha\beta$ under exhaust conditions relevant to DEMO.

Following the remarks made above, we now add a system of loops that describes the full fuel cycle. Each of these loops can have the following function:

- Extract a flux Γ^k_{pump} where the index k stands for the particular loop considered. This extracts a flux of He or impurity, labeled by the index ν, of $c^k_\nu \Gamma_{pump}$.
- Clean the flux of He and / or seed impurities by a factor γ^k_ν where ν is the particle species. In the following, we use γ^k_ν to relate all concentrations to the concentration in the vessel pump duct, denoted by c_ν.
- Re-inject a part of the flux $\Gamma^k_{in} = \eta^k_{re}\Gamma^k_{pump}$. In the following, we use η^k_{re} to relate all pumped fluxes to the flux pumped from the vessel, denoted by Γ_{pump}.

Each loop is characterized by a time constant τ^k from which the inventory is calculated as $N^k = \Gamma^k \tau^k$.

We can think of 4 different elements of the fuel cycle:

0. 'Plasma & vacuum vessel': the system as described above consists of 2 reservoirs, the plasma and the vessel, coupled by recycling, but since the injected flux and pump act on the sum of the two, it is possible to treat them as one. The use of two different time scales, τ_p and τ_p^*, which may also be different for different species, allows to calculate c_{He} and c_{imp} in the plasma.
1. 'Short fuel cycle' with no cleaning: this would re-inject the flux Γ^1_{pump} and effectively have the same role as recycling. We note that since no cleaning from impurities is done, this flux may affect the ability to feedback-control radiation if it is too large.
2. 'Intermediate fuel cycle' that cleans to some extent He and impurities and then directly re-injects the cleaned flux [2].
3. 'large fuel cycle' that goes through the full isotopic control. The sum of the He flux separated in 2 and 3 should be $\Gamma_{burn}/2$, i.e. extract all ash. The remaining D-T should be re-injected after cleaning to avoid unnecessary build-up of T-inventory[2].

The T burned in the fusion reaction has to be injected from a separate valve that accesses the breeding circuit. The separated impurities have to be re-injected, but it seems prudent to have some margin for feedback-control here and also, the inventory is not critical.

The fuel cycle can then be represented by the following diagram:

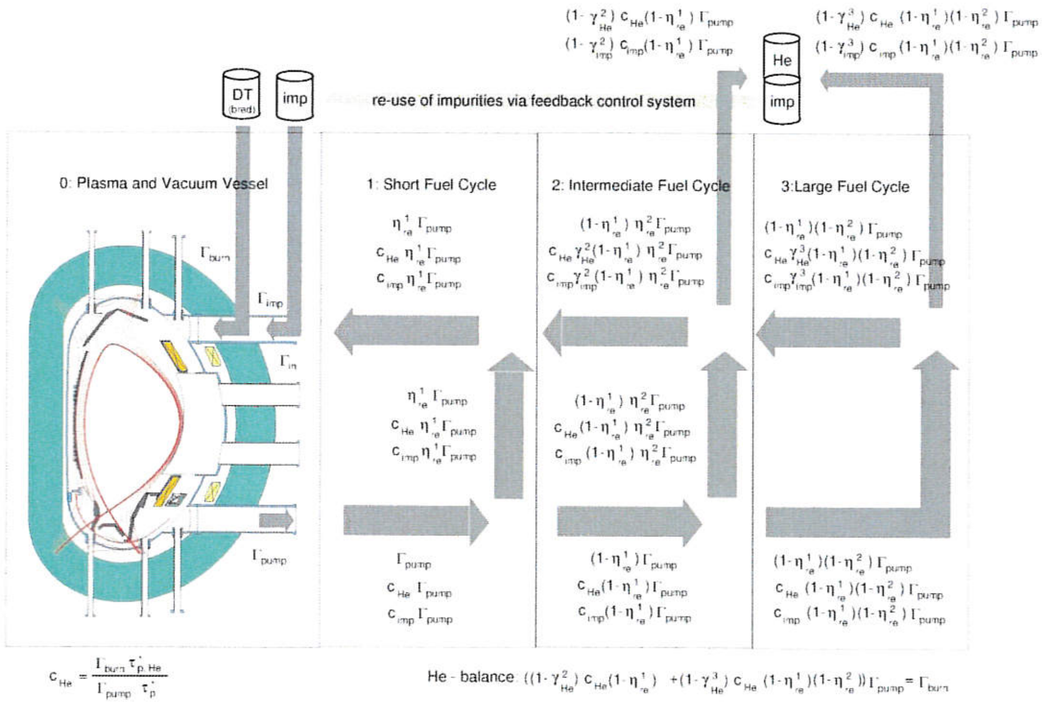

Fig. 3: Schematic representation of the fluxes in the DEMO fuel cycle.

[2] The intentional build-up of a T-inventory to start-up other fusion reactors is not considered here.

Finally, we examine the inventories that are connected with this fuel cycle. One easily shows that the sum of the re-injected flux is equal to the pumped flux, i.e. there is no D-T lost, and hence no build-up of inventory[3]. The inventory can therefore be evaluated in a straightforward manner by applying the above mentioned formula $N=\Gamma\tau$, where τ is the typical turn-around timescale of the individual circuit (e.g. $\tau=\tau_p^*$ for circuit 0). In addition, there will be losses due to leak-rates from the different reservoirs that are not considered here, but should be incorporated in the final balance.

Two immediate conclusions follow:

- The burn-up fraction can be much larger than the ITER value with re-injection (and may become meaningless for the inventory if re-injected flux is dominant).
- There should be an effort to quantify the parameters used in the model to see where we arrive in terms of inventory.

References

[1] D. Reiter et al., Nucl. Fusion **30** (1990), 2141.

[2] C. Day et al., Fus. Eng. Design **88** (2013) 616.

[3] A. Kallenbach et al., Nucl. Fusion **52** (2012) 122003.

[3] This also means that the original definition of the burn-up fraction is of no importance to the inventory due to the re-injection scheme.