Effect of Nuclear Side Reactions on Magnetic Fusion Reactors in Space

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A generalized burn criterion for thermonuclear fusion reactors in space is extended with respect to side reactions among all reactant and product species contained in a magnetically confined fusion plasma. The obtained criterion is verified against two simpler forms and a D-T mixture with a 1:1 fuel ratio. The power balance based on a newly developed flux scheme model is solved in conjunction with particle balances. Side reactions are observed to broaden the ignition temperature curve and keep or increase the temperature optimum under the given conditions. This is hinting at options to enhance the ingitability of aneutronic reactions. A brief fusion propulsion modelling was performed with D-T plasma volumes of 10 and $30m^3$ both with 1:1 and 4:1 mixture ratios. It is found that this fueling entails huge space craft masses and thus small accelerations confirming older conclusions on the limited suitability of D-T plasmas for fusion space propulsion.

Nomenclature

Latin letters

B	Magnetic fielt, T
c_0	Speed of Light, ms^{-1}
c_e	Exhaust velocity, ms^{-1}
c	Concentration,-
D	Distance, m
E	Energy, J
F	Thrust, N
f	Reflected/rebound power fraction, -
g	Power fraction absorbed by working medium, -
h	Mass specific enthalpy, Jkg^{-1}
k	Powerflux fraction, -
k_B	Boltzmann constant, -
$\dot{m}$	Mass flow rate, kgs^{-1}
n	Volume specific particle density, m^{-3}

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$\tilde{n}$	Temperature weighted particle density, m^{-3}
P	Volume specific power, Wm^{-3}
p	Pressure, pa
q	Elementary charge, C
S_BrS	Bremsstrahlung constant, 1.628 10^{-38} $m^4C^{0.5}kg^{0.5}s^{-2}$
S_Syn	Synchrotron radiation constant, 6.212 10^{-23} $Cs^{-1}T^{-2}$
s	Particle feeding source, m^{-3}
T	Temperature, keV
t	Time, s
V	Volume, m^{-3}
Z	Number of protons per core or number of charges, -

Greek letters

δ	Kronecker's Delta, 1 or 0
ε_0	Vacuum permittivity, $A^2s^4kg^{-1}m^{-3}$
ζ	Product ions' multiple, -
μ_0	Vacuum permeability, $VsA^{-1}m^{-1}$
Ξ	Factor, -
ξ	Fraction of power distributed to charged particles, -
η	Efficiency of thermal to electric conversion, -
η_T	Thrust efficiency, -
ϕ	Hot ion mode, -
Ψ	Particle number relating factor, -
ψ	Mixture factor, -
τ	Confinement time, s
$\tilde{\tau}$	Confinement time factor, -
$\langle\sigma v\rangle$	Reaction rate coefficient, m^3s^{-1}

Superscript

i	Ions
ip	Product ions
ir	Reactant ions
e	Electrons
T	Transposed

Subscript

$back$	With respect to recycling
$Blanket$	With respect to the blanket
BrS	Bremsstrahlung
dir	Direct heating
e	Electron
G	Net gain
g, h	Other species g, h among the reactants
H_2	Hydrogen
ind	Indirect heating
j	Species j among reactants and products in the plasma
k	Reaction partner k of species j if applicable
L	Net loss
n_0	Neutrons
q	Species among the products of a reaction
Rad	Radiators
rtv	Radiative
Syn	Synchrotronradiation
T	Thrust
$Therm$	Thermal

tot	Total
wg	Working gas (working medium)
Z	Charges

Isotopes

^{11}B	Boron-11
D	Deuterium (Hydrogen-2)
^{3}He	Helium-3
^{4}He	Helium-4
T	Tritium (Hydrogen-3)
p	Protium (Hydrogen-1)

I. Introduction

Currently, the sustainable development of the solar system is impeded by limited capacities in space power and propulsion. The limitations in the domain of propulsion are rather obvious. Present day's thrusters are either energy or power limited.[1,2] They force specific profiles upon the mission architectures, like Hohmann's transfer which is suitable for the first type since it is a minimum energy maneuver, albeit a time consuming one.[3] Power limited propulsion systems – the second type – succumb to the trade off which separates high impulse concepts from high thrust concepts.[4] However, considering basic rocketry equations it can be argued that enhancing both parameters can considerably augment a propulsion system's capacities and allow for optimum transfer duration or optimum payload fraction transfers[5] with respective system benefits. The prerequisite for such a disruptive accomplishment consists in an *indefinite* raise in mass specific power as already predicted by aerospace pioneer Robert Esnault-Pelterie in 1912.[6] In the respective communication, nuclear power sources were identified to be an interesting key technology for this purpose in astronautics. This also extends to the second domain: Many interesting destinations in the solar systems are so far away from the sun that sun independent power provision systems become vital since the available solar power decreases proportionally to the inverse square of the distance. This will be an even more severe issue if a mission aims at implementing processes demanding higher power or an increased longevity – which is the most likely characteristic of voyages to farther destinations. Both the requirement of sun independence and of an important power yield make another case for nuclear power sources in space.

Among these, nuclear fusion[7] seems to be particularly promising.[8,9] Its power output is more important than the one of fission and only excelled by the one of matter-anti matter annihilation. Fusion is yet more advantageous than this process since it can be fed with isotopes found in the solar system[10] while anti matter needs to be costly produced in particle accelerators.[9] Further, fusion entails less radiologic issues than fission, especially if aneutronic reactions are implemented.[11,12] These and many more features make nuclear fusion in space an interesting topic of research.

In fusion propulsion, several concepts have already been proposed as summarized in Ref. 13 and – in greater detail – in Ref. 8. The latter reference covers many systemic, physical and technical aspects, including an introduction to gas dynamic mirrors[14,15] which are a special type of magnetically confined fusion reactors distinct from typical designs by a significantly increased particle density. Further research focuses on advanced fusion fueling aiming at reducing radiation and life time issues.[10,11] A preliminary design study of a fusion propelled space craft for interplanetary transport is presented in Ref. 16. It has also been suggested to use fusion – here inertially confined – for so called interstellar precursor probes like Daedalus.[17] Recently, a focus was put on systematically identifying necessary key technologies[18] to make fusion propulsion viable, assessing methodically the suitability of fusion reactions,[19,20] and well founded elimination of potential system architectures.[21]

A notable effort was put on extending the classical Lawson criterion as a simple and efficient engineering instrument for the evaluation of fusion space systems.[20] The resulting, more general criterion is based upon a model considering the most pertinent subsystems of a Magnetic Confinement Fusion (MCF) reactor in space with a special focus on aspects related to fusion powered thermal propulsion. It allows studying the effect of various parameters: The plasma related reactant mixture ratio, the so called hot ion mode, the confinement time of energy and educts, the retention time of fusion products and the plasma stability parameter β are regarded as well as power flux fractions related to the architecture and scalable subsystems

yielding a preliminary sizing and first estimations of – if applicable – the propulsion performance.

In the same paper, first results concerning the fuelling were published. The use of the criterion indicates that D-^{3}He is the fuelling which appears to pose the least challenges in space MCF under the given constraints and parameter settings in Ref. 20. The two other commonly studied low to aneutronic fusion reactant couplings for space, ^{11}B-p and ^{3}He-^{3}He, might pose challenges in thermonuclear fusion burning. Especially in the case of the latter, the retention of fusion products risks to quench the reaction process. It would be necessary to eject the ashes after a shorter period than the energy confinement time. Simple considerations made in the preparation of this contribution hint however that controlled side reactions may offer a response to this issue. This makes a case to develop a tool for an investigation of their influence.

In the present contribution, a first attempt to consider side reactions in an extended generalized Lawson criterion is shared. The philosophy of providing such an engineering tool is not to replace physical experimentation or more sophisticated numerical simulations but to enable preliminary estimations of the expected plasma properties, prediction of experimental trends and to offer a simple approach to the configuration of space MFC systems. It is also desired to gain an occasion for obtaining a general, let it be called academic, understanding of side reactions in a fusion plasma.

In the next section, the criterion is derived from a particle and a power balance. For the latter, the power flux in the system architecture is established and respective fractions derived before nominal and non-nominal side reactions are introduced for the particle balance. Then both balances are written down. The models of considered phenomena are detailed. After identifying useful abbreviations, the balances yield the criterion. In the subsequent section, the new results are briefly discussed. A verification of the criterion is made through simplification with respect to Lawson's classical criterion before the first results of the extended criterion are presented for typical D-T plasma fueling at a 1:1 ratio of both reactants and at a 4:1 ratio. This encompasses the triple products and other plasma parameters but also the effect on the neutronics is considered. Results concerning fusion propulsion are briefly concentrated in the last section before concluding the contribution.

II. Modelling

A. System overview and power flux model

A space borne MCF device can be used for either power provision or for propulsion.[20] The model underlying the present contribution stipulates a space fusion MCF propulsion system (MCFP) with an additional working medium.[21] This design which can be called a "Working Gas Fusion Drive" (WGD) is more general than a space borne fusion power plant since it contains propulsive subsystems in addition to power plant specific ones. A WGD consists of a reactor core which is the plasma emitting its power losses, and a reactor periphery. The plasma is composed of the nominal fuel mixture and a certain amount of fusion products, called ashes, and potential impurities. The periphery maintains and contains the plasma and realizes the propulsion. It is made up of a first wall with adjoining blanket, Direct Electrical Conversion (DEC), a set of magnets, a nozzle, and radiators. A generic one dimensional layering is depicted in figure 1. Note that supra conducting electro magnets with a respective cryo plant are considered with preference.

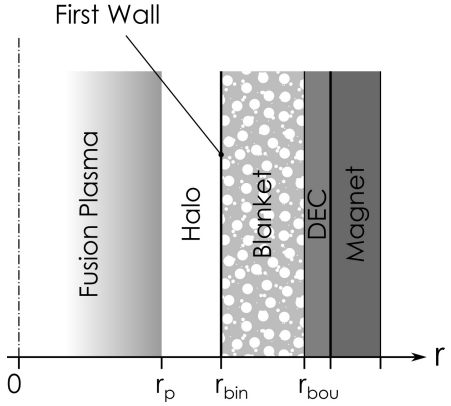

Figure 1. Layering of reactor core and periphery. Radiators and nozzles are not shown.[20]

The studied system architecture relies on porous materials for blanket and first wall to enable an injection of the eventual working medium mass flow into the fusion reactors scrap off layer (SOL) assuming perfect separation of the SOL and the plasma.[20] For the sake of simplicity, the geometry of the plasma and its containment are disregarded. It is assumed that a fraction f of each loss of the plasma will be reflected or rebounded back into the plasma by the first wall. Another fraction g of the remainder $(1-f)$ will be absorbed by the working medium either indirectly via the blanked or directly in the SOL. This fraction

$$k_T = (1-f)\ g \tag{1}$$

is relevant for thrust generation in working medium approaches of fusion propulsion. The fraction

$$k_{Blank} = (1-f)\ (1-g) \tag{2}$$

reaching the DEC will be converted with an efficiency η into electrical power which can be recycled into the plasma. Thus the fraction of totally recycled power is

$$k_{back} = f + (1-f)\ (1-g)\ \eta. \tag{3}$$

The remainder fraction of this stage,

$$k_{Rad} = (1-f)\ (1-g)\ (1-\eta), \tag{4}$$

is considered as waste heat and needs to be radiated into space. These definitions are identical with the ones introduced in the prior work. The resulting power flux schematic is shown in figure 2. Note that the proportions of this flux are differen for each phenomenon and that the fractions' numbers depend heavily on the phenomenon's physics. For example, long-wave emissions like synchrotron radiation are more likely to reflect at the first wall than short-wave bremsstrahlung. Hence, the fraction f will be larger for synchrotron radiation than for bremsstrahlung. Neutron radiation is not a loss phenomenon since the neutrons are not heated by the plasma but yielded by fusion reactions. Thus, the neutrons constitute a background radiation and are treated respectively.

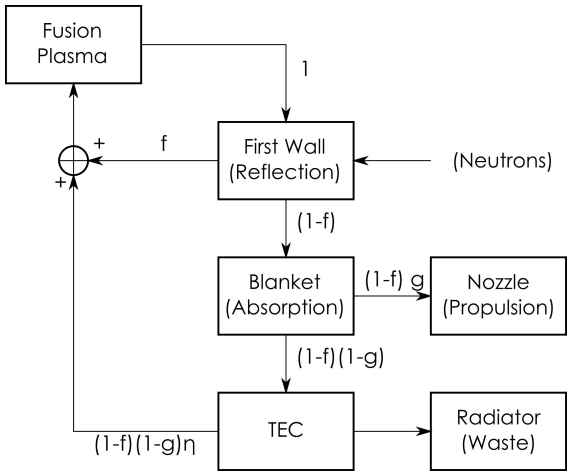

Figure 2. Power flux schematic of a generic WGD.[20]

B. Side or secondary reactions

Traditionally, analytic estimations of thermal fusion regard solely the main or primary reaction of the nominal fuel mixture defined by reactant species and a relative number among the primary or majority species and the secondary or minority species.[7,22] In the case of the conventional D-T coupling the nominal fueling consists in a majority of deuterons and in a minority of tritons. According to Ref. 7, a maximum fusion power is yielded with a 1:1 fueling ratio, but a lean mixture like a 4:1 ratio can reduce neutronic issues. The main reaction consumes a deuterium and a tritium ion and produces a helium nucleus, a neutron, and

Table 1. Overview on reactions in a D-T plasma. Reactions based on ^{4}He and neutron breeding are disregarded, same as reactions with three participants, and p-p, T-p and ^{3}He-p.[7, 23, 24]

N$^{o.}$	Reaction		Products & energies (MeV)
1	D + T	→	^{4}He(3.5) + n(14.1)
2,3	D + D	→	^{3}He(0.82) + n(2.45) T(1.01) + p(3.02)
4	T + T	→	^{4}He + 2n + (11.33)
5	D +^{3} He	→	^{4}He(3.6) + p(14.7)
6,7,8	T +^{3} He	→	^{4}He + p + n(2.45) + (9.65) ^{4}He(4.8) + D(9.5) ^{3}He(2.4) + p(11.9)
9	^{3}He +^{3} He	→	^{4}He + 2p + (12.86)
10	D + p	→	^{3}He + γ + (5.49)

some energy. But in fact, the nominal fueling entails side or secondary reactions, too.[7] In the case touched above, there may also appear some D-D or even T-T reactions. Because these reactions utilize the nominal fuel species, they are called "nominal side reactions" in the present contribution. Products of the main reaction and the nominal side reaction are named "primary" products. Further, the retention of ashes in a real plasma can enable reactions among reactants and products, which are consequently called "non-nominal side reactions". For example the nominal D-D side reaction creates a helium-3 core which can be consumed in a D-^{3}He reaction. Considering couplings among all reactants and the primary products and neglecting neutron breeding, there would be fifteen possible couples in a D-T plasma. Table 1 recapitulates those which have been considered in the current evaluation, indicating their products and the energy released per reaction. Note that some reactions branch, i.e. they can have two or more different outcomes like the D-D coupling.

C. Particle dynamics and balance

All of these reactions run with a certain probability which is reflected in their reaction rate coefficient $\langle\sigma v\rangle$. Figure 3 allows to compare this parameter for the reactions based on the seven couplings from table 1. While it would seem possible to decide from this information which side reaction to discard from consideration, one has to be aware that the relative probabilities will also depend on the actual population within the plasma. Ions with a relatively short retention time will less likely react than those with a long one. This is taken into account using the particle dynamics equations[7, 25] for all the species and where the respective reaction rates are a weighting parameter. In the plasma, an ion of a species j can act as a reactant or as a product. The dynamics equation of a reactant is with respect to the volume specific particle density n_j

$$\frac{dn_j^{ir}}{dt} = s_j - \sum_k \frac{n_j^{ir} n_k^{ir}}{1+\delta_{jk}} \langle\sigma v\rangle_{jk} - \frac{n_j^{ir}}{\tau_j^{ir}}, \tag{5}$$

where the superscript ir is indicating the consideration as a reactant ion. The first term of the right hand side of this equation is the fuel source s_j which determines the plasma's replenishment with the volume specific particle density of the species j per unit of time. The second term quantifies the consumption of reactants in the reaction with the species k. Since this term is a loss, it is negative. In this reaction term the respective reaction rate coefficient $\langle\sigma v\rangle_{jk}$ is taken in account. The Kronecker delta avoids double counting of like couplings and the summation over k concentrates all the reactions consuming species j. The leaking of particles is modeled in the last term – which is also negative – stating a constant loss rate as an average during the fixed ion confinement time τ_j^i.[25] For a species j as a product marked with the superscript ip, the dynamics is analogously given by

$$\frac{dn_j^{ip}}{dt} = \sum_{g,h\geq h} \frac{n_g^{ir} n_h^{ir}}{1+\delta_{gh}} \langle\sigma v\rangle_{gh} \zeta_{gh,j} - \frac{n_j^{ip}}{\tau_j^{ip}}. \tag{6}$$

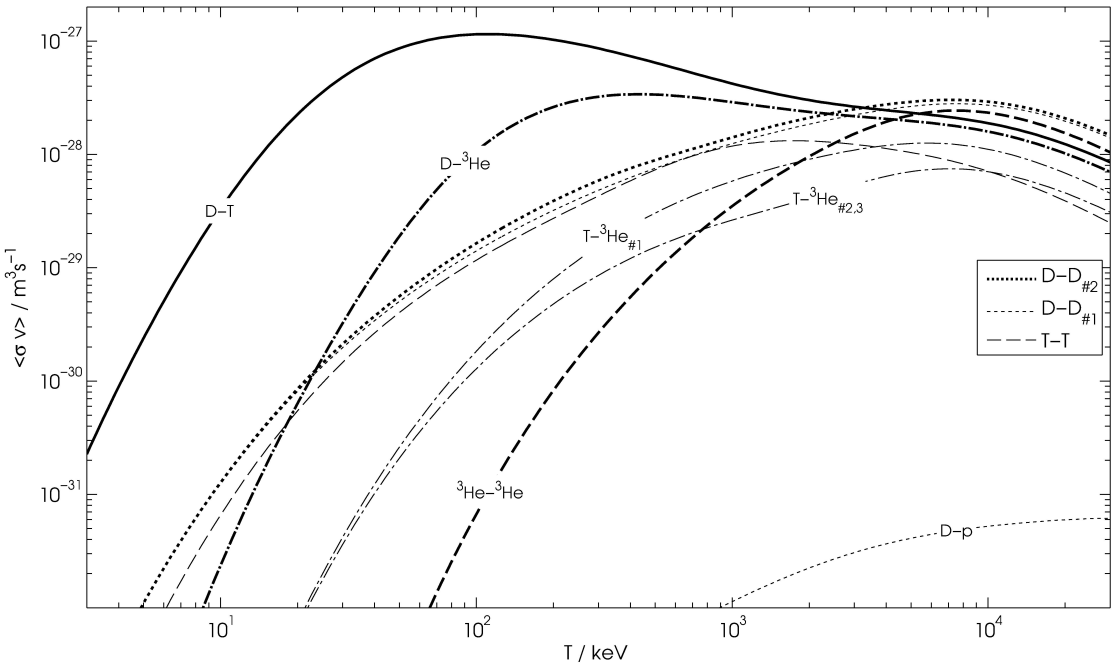

Figure 3. Reaction rate coefficients of the seven considered couplings in a nominal D-T plasma.[24]

Reactions of the species g and h yield new particles of various species which is described in a manner similar to the one introduced in equation (5). Here, the product ions' multiple $\zeta_{gh,j}$ is a factor indicating how many individuals of j are yielded in one reaction among all products. For example, the ^{3}He-^{3}He reaction releases two protons and one ^{4}He ion. This would be noted $\zeta_{^3\mathrm{He}^3\mathrm{He},p} = 2$ and $\zeta_{^3\mathrm{He}^3\mathrm{He},^4\mathrm{He}} = 1$ respectively. While this term designates a gain in particles of species j and is consequently positive, the other term is negative, stating the particle leakage analogously to equation (5). Since an ion of species j can be fed into the plasma both as a reactant and as a product, its total dynamics

$$\frac{dn_j^i}{dt} = \frac{dn_j^{ir}}{dt} + \frac{dn_j^{ip}}{dt} = s_j - \sum_k \frac{n_j^{ir} n_k^{ir}}{1+\delta_{jk}} \langle\sigma v\rangle_{jk} - \frac{n_j^i}{\tau_j^i} + \sum_{q,g,h\geq g} \frac{n_g^{ir} n_h^{ir}}{1+\delta_{gh}} \langle\sigma v\rangle_{gh} \zeta_{gh,q} \tag{7}$$

is the sum of both models in which

$$\frac{n_j^i}{\tau_j^i} = \frac{n_j^{ir}}{\tau_j^{ir}} + \frac{n_j^{ip}}{\tau_j^{ip}} \tag{8}$$

is the leakage of the total population of species j. Note that $\tau_j^{ir} = \tau_j^{ip} = \tau_j^i = \text{const.}$ due to assuming instant thermalisation of the released particle and thus a corresponding kinetics. The last term of equation (7) contains a summation for all products q; to avoid the for- and backwards consideration of reactions since a T-D reaction is the same as a D-T reaction, the second species index h may not be less than the first species g, i.e. $h \geq g$. This implies that the set of species needs to be ordered.

A first condition of a criterion for a stationary fusion plasma consists in particle stationarity.[7,25] This means that the number of particles per species including reactants and products does not vary over time. Thus, we establish

$$\frac{dn_j^i}{dt} = 0 \tag{9}$$

for each species j in the plasma. There is an exchange of particles though, particles are fed in through sources s or as products and lost through leaking and consumption. This allows to obtain the steady state number density of ions of a species j in the plasma according to

$$n_j^i = \left(s_j + \sum_{q,g,h\geq h} \frac{n_g^{ir} n_h^{ir}}{1+\delta_{gh}} \langle\sigma v\rangle_{gh} \zeta_{gh,q} \right) \left(\frac{1}{\tau_j^i} + \sum_k \frac{n_k^{ir}}{1+\delta_{jk}} \langle\sigma v\rangle_{jk} \right)^{-1}. \tag{10}$$

In this contribution, the sources are $s = 0$ except for the nominal fuel species for which the term assures stationarity. The particle balance of the whole plasma which indicates the net dynamic is following equation (9), i.e.

$$\frac{dn^i}{dt} = \sum \frac{dn^i_j}{dt} = 0. \tag{11}$$

Writing out this sum,

$$\sum_j \frac{dn^i_j}{dt} = \sum_j \left(S_j - \sum_{k \geq j} \frac{n^{ir}_j n^{ir}_k}{1+\delta_{jk}} \langle \sigma v \rangle_{jk} + \sum_{j,g,h \geq g} \frac{n^{ir}_g n^{ir}_h}{1+\delta_{gh}} \langle \sigma v \rangle_{gh} \zeta_{gh,j} - \frac{n^i_j}{\tau^i_j} \right) \tag{12}$$

one has to keep in mind to avoid backward consideration which is assured by the selection restrictions for the second species already introduced in equation (7). The whole plasma contains a stationary volume specific ion density of

$$n^i = \sum_j n^i_j. \tag{13}$$

In the quasi neutral plasma, particle stationarity applied to ions also brings about a stationarity of electrons. Their number is calculated from

$$n^e = \sum_j \left(Z_j n^i_j \right), \tag{14}$$

in which Z_j is the number of charges proper to ions of the species j. The electron number is assumed to be tied firmly to the number of ions[26] and thus it's dynamics is discarded for the sake of simplicity.

D. Power balance and summary of considered phenomena

Another condition for a stationary fusion reaction is the invariance of the plasma's energy E over time.[7,25] This is written

$$\frac{dE}{dt} = P = 0, \tag{15}$$

where the plasma's power P is introduced. This equation may seem unexpected at first since the purpose of fusion as an energy source is to provide a considerable amount of power. However, this is not the technical power of the plasma but the power balance

$$P = P_G - P_L = 0. \tag{16}$$

In MCF, the net power losses P_L cool the plasma which is compensated by the net gains P_G – which in turn preserves fusion relevant ion energies in the plasma.[20] Technically, a part of the losses can be tapped in accordance to figure 2 at different stages.[21]

The net gains

$$P_G = \xi P_{Fus} + k_{back,n_0}(1-\xi) P_{Fus} + P_{ext} \tag{17}$$

are composed of a fraction ξ of the fusion power P_{Fus} distributed to charged products, a part k_{back,n_0} of the remainder which is distributed to neutral products i.e. neutrons, and of an external heating P_{ext} which can be linked to P_{Fus} employing the power multiplication factor

$$Q = \frac{P_{Fus}}{P_{ext}}. \tag{18}$$

The fusion power equals

$$P_{Fus} = \sum_{j,k \geq j} \left(\frac{n^{ir}_j n^{ir}_k}{1+\delta_{jk}} \langle \sigma v \rangle_{jk} E_{jk} \right) \tag{19}$$

with the energy E_{jk} yielded in each fusion of ions of species j with those of species k.[7]

The considered losses consist in thermal losses P_{Therm}, losses by bremsstrahlung P_{Brs}, losses by synchrotron radiation P_{Syn}. If impurities were considered, line radiation losses should be considered, too. These

are however omitted here, because a thorough investigation of impurities has not yet been completed in the frame of this research. Thus, the net losses with respect to the total power flux depicted in figure 2 are

$$P_L = \begin{pmatrix} 1 - k_{back,Therm} \\ 1 - k_{back,BrS} \\ 1 - k_{back,Syn} \end{pmatrix}^T \cdot \begin{pmatrix} P_{Therm} \\ P_{BrS} \\ P_{Syn} \end{pmatrix}, \tag{20}$$

an equation which describes a scalar product as the superscript T marks a transposition.[20] The model for thermal losses is classically

$$P_{Therm} = \frac{3}{2}\frac{k_B}{\tau_E}\left(n^e T_e + n^i T_i\right) \tag{21}$$

with the Boltzmann constant k_B and the energy confinement time τ_E.[7] The temperature of ions is noted T_i which is assumed to be the same for all species. The one of electrons is T_e without regard of the electrons' original atom. It is also possible to factor out T_i introducing the hot ion mode

$$\phi = \frac{T_i}{T_e}. \tag{22}$$

In the prior work[20] temperature weighted particle densities

$$\tilde{n} = n\frac{T}{T_i} \tag{23}$$

have been introduced for electrons with a subscript and each ion species. This has been discarded from the current scope as differences among ion temperatures were estimated to be negligible and as the hot ion mode did not play a role as important as the respective confinement times. It may however be interesting to consider a significantly colder impurity ion temperature at a later stage of investigation.

Electromagnetic bremsstrahlung yielded by the deviation of a moving electron around another charge is described with the equation

$$P_{Brs} = S_{Brs} n^e \sqrt{\frac{T_e k_B}{\|q\|}} \sum_j \left(n_j^i (Z_j^i)^2\right) \tag{24}$$

in which q is the elementary charge.[7,23] The number

$$S_{Brs} = \frac{q^6}{24\pi\varepsilon_0^3 c_0^3 m_e h}\sqrt{\frac{12q}{\pi m_e}} = 1.628 \cdot 10^{-38}\left(m^4\frac{\sqrt{Ckg}}{s^2}\right) \tag{25}$$

is the bremsstrahlungs constant calculated from the vacuum permittivity ε_0, the speed of light c_0, the Planck constant h, and the mass of an electron m_e. Synchrotron radiation

$$P_{Syn} = S_{Syn} B^2 n^e \frac{T_e k_B}{\|q\|}\left(1 + \frac{5T_e k_B}{2m_e c_0^2} + \mathcal{O}_2\right) \tag{26}$$

is the electromagnetic radiation released in the deviation of an electron in a magnetic field B.[7] This model is based on a series which is cut before its term $\mathcal{O}_2$ of second order. The respective constant is

$$S_{Syn} = \frac{q^4}{3\pi\varepsilon_0 m_e^2 c_0} \cdot \frac{q}{m_e c_0^2} = 6.212 \cdot 10^{-23}\left(\frac{C}{sT^2}\right). \tag{27}$$

The magnetic field introduced in equation (26) can be replaced using the definition of the magnetic stability parameter

$$\beta = \frac{p_{th}}{p_{mag}} = 2k_B\frac{\mu_0}{B^2}\left(n^e T_e + \sum_i \left(n^i T_i\right)\right). \tag{28}$$

E. Solving the balances for the criterion

The criterion describes the plasma properties necessary for a sustained thermonuclear fusion burning and is obtained through solving the power balance with respect to the particle balance. It is possible to rewrite equation (16) with respect to the equations (20) and (17) yielding

$$1 = \frac{(1 - k_{back,therm})P_{Therm}}{\Xi P_{Fus} - (1 - k_{back,BrS})P_{BrS} - (1 - k_{back,Syn})P_{Syn}} \tag{29}$$

in which a factor

$$\Xi = \left(\frac{1}{Q} + \xi\right) + k_{back,n_0}\,(1 - \xi) \tag{30}$$

is introduced. Solving this equation for the triple product can be simplified using additional abbreviations.[20] The ion concentration

$$c_j = \frac{n_j^i}{n^i} \tag{31}$$

of a species allows to quantify the relative particle number density in the entire plasma as a number from 0 to 1. It also allows to determine the mutual mixture number

$$\psi_{jk} = c_j c_k \tag{32}$$

which can be introduced in the respective fusion reaction terms. Further, the electron multiple

$$\Psi_e = \frac{n^e}{n^i} \tag{33}$$

can be obtained in a similar manner, however, this is not a concentration since the electrons are not participating to n^i. The number can therefore be superior to unity as $n^e > n^i$ is true in relevant cases. If the electron multiple is multiplied with the effective proton number of the plasma Z_{eff}, the sum of the weighted squares of the present charges

$$\Psi_Z = Z_{eff}\Psi_e = \sum_j \left(c_j Z_j^2\right) \tag{34}$$

is obtained. Finally, the effective particle number of the plasma

$$\Psi_{tot} = \Psi_e + \sum_j c_j = \Psi_e + 1 \tag{35}$$

joins the sum of the concentrations – which per definition equals unity – with the electron multiple.

The various confinement times can be related to the energy confinement time τ_E using the factors

$$\tilde{\tau}_{Ej} = \frac{\tau_j^i}{\tau_E} \tag{36}$$

for all ion species present in the plasma.

Using all available abbreviations, the equations of the volume specific powers are expressed as follows:

$$P_{Fus} = (n^i)^2 \sum_{j,k\geq j} \frac{\psi_{jk}}{1 + \delta_{jk}} \langle\sigma v\rangle_{jk} E_{jk}, \tag{37}$$

$$P_{Therm} = \frac{3k_B T_i n^i}{2\tau_E}\Psi_{tot}, \tag{38}$$

$$P_{Syn} = (n^i)^2 T_i^2 S_{Syn} \frac{2\mu_0 k_B}{\beta \left\|q\right\| \phi}\Psi_{tot}\Psi_e \left(1 + \frac{5T_i k_B}{2m_e c_0^2 \phi}\right) \text{ and} \tag{39}$$

$$P_{Brs} = (n^i)^2 S_{Brs}\sqrt{\frac{k_B T_i}{\left\|q\right\| \phi}}\Psi_e \Psi_Z. \tag{40}$$

Filling these in yields the criterion

$$n^i \tau_E T_i = \frac{\frac{3}{2}k_B T_i^2 \Omega_{Therm}}{(\Xi\Omega_{Fus} - \Omega_{Syn} - \Omega_{Brs})} \tag{41}$$

in which

$$\Omega_{Fus} = \sum_{j,k\geq j} \frac{\psi_{jk}}{1+\delta_{jk}} \langle\sigma v\rangle_{jk} E_{jk}, \tag{42}$$

$$\Omega_{Therm} = (1-k_{back,therm})\Psi_{tot}, \tag{43}$$

$$\Omega_{Syn} = (1-k_{back,Syn}) S_{Syn} \frac{2\mu_0 k_B) T_i}{\beta \|q\| \phi} \Psi_{tot} \Psi_e \left(1 + \frac{5 T_i k_B}{2 m_e c_0^2 \phi}\right) \text{and} \tag{44}$$

$$\Omega_{Brs} = (1-k_{back,Brs}) S_{Brs} \sqrt{\frac{k_B T_i}{\|q\| \phi}} \Psi_e \Psi_Z. \tag{45}$$

Note that the criterion (41) is implicit since the volume specific ion density appears not only on the left hand side of the equation, but also on the right hand side through various particle related abbreviations Ψ. Therefore, the evaluation of the criterion is executed with a *Matlab*® script implementing an iterative solution process.

Also note that there has been a shift of the focus of the criterion from formerly n_i to n^i. In the former case (n_i), only the particle density of the first species is considered while in the new case an information about all the ion species in the plasma (n^i) is offered since the concept of a prime reactant does not appear useful any more. To obtain the original triple product it would suffice to apply the concentration of a seemingly dominant reactant to the evaluated criterion.

III. Verification - methods and results

A. Obtaining Lawson's criterion

The criterion (41) can be verified with a set of parameters listed in table 2 describing the system assumed by Lawson for his original criterion and underlying in Ref. 7. This yields the classical double product

$$n_i \tau_E = \frac{12 k_B T_i}{\frac{1}{5}\langle\sigma v\rangle E_F - 4 S_{BrS} \sqrt{\frac{k_B T_i}{\|q\|}}}. \tag{46}$$

Table 2. Parameters for the classic Lawson criterion.[20]

Parameter	Value	Comment
$k_{back,Syn}$	1	negligible P_{Syn} loss
$k_{back,BrS}$	0	entirely lost
$k_{back,th}$	0	entirely lost
k_{back,n^0}	0	entirely lost
ϕ	1	no hot ion mode
$c_D = c_T$	-	1:1 mixing ratio
$\langle\sigma v\rangle_{DD} = \langle\sigma v\rangle_{TT}$	0	side reactions negligible vs.
$\langle\sigma v\rangle_{DT}$	$\neq 0$	main reaction
Q	$\longrightarrow \infty$	ignition
ξ	1/5	80% of E_F carried by neutrons
$\tilde{\tau}^{ip}$	0	no product retention

B. Exemplary evaluation for D-T fueled plasmas

The next step consisted in successfully reproducing the data obtained with the criterion from Ref. 20 for a D-T fusion reactor with a set of underlying parameters summarized in table 3.

The triple product of this set with respect to side reactions (i.e. $\langle\sigma v\rangle_{DD} \neq 0, \langle\sigma v\rangle_{TT} \neq 0$) is depicted in the left hand side of figure 4.In addition to that, respective graphs for a 4:1 D-T mixture are shown in

Table 3. Parameters for the verification with data from Ref. 20.

Parameter	Value	Comment
$k_{back,Syn}$	0.95	highly reflectable
$k_{back,BrS}$	0.103	poorly reflectable
$k_{back,th}$	0.06	only DEC recuperation
k_{back,n^0}	0.03	barely recuperable
ϕ	1,2	study of influence of hot ion mode
$c_D = c = T$	-	1:1 mixing ratio
$\langle\sigma v\rangle_{DD} = \langle\sigma v\rangle_{TT}$	0	side reactions negligible vs.
$\langle\sigma v\rangle_{DT}$	$\neq 0$	main reaction
Z_D	1	one proton
Z_T	1	one proton
Q	$\longrightarrow \infty$	ignition
$\tilde{\tau}^{ip}$	$1, 5, 10$	product retention
τ_E	5	conservative assumption

the left half of figure 4. The comparison confirms that the fueling lean in Tritium requires higher pitched conditions to ignite.

On the right hand side of figure 4 the effect of the consideration of side reactions is depicted for a 1:1 D-T mixture. It appears that the optima are pushed to higher temperatures as a general trend. However, side reactions decrease the minimum at a short ash retention of $\tilde{\tau}_{Ea} = 1$ while it increases it significantly at $\tilde{\tau}_{Ea} = 5$. In the same time, the criterion becomes less severe at temperatures higher than those of the optima. This is expectable since D-T has the best cross section among the relevant fusion reactions which is in addition culminating at the lowest temperatures. At these temperatures, the side reactions have a detrimental effect on the triple product since they consume reactants for less ignitable processes. Some side reactions' cross sections may however reach the same order of magnitude of the D-T reaction at higher temperatures which then has a beneficial effect. In this situation, they support the overall thermo nuclear

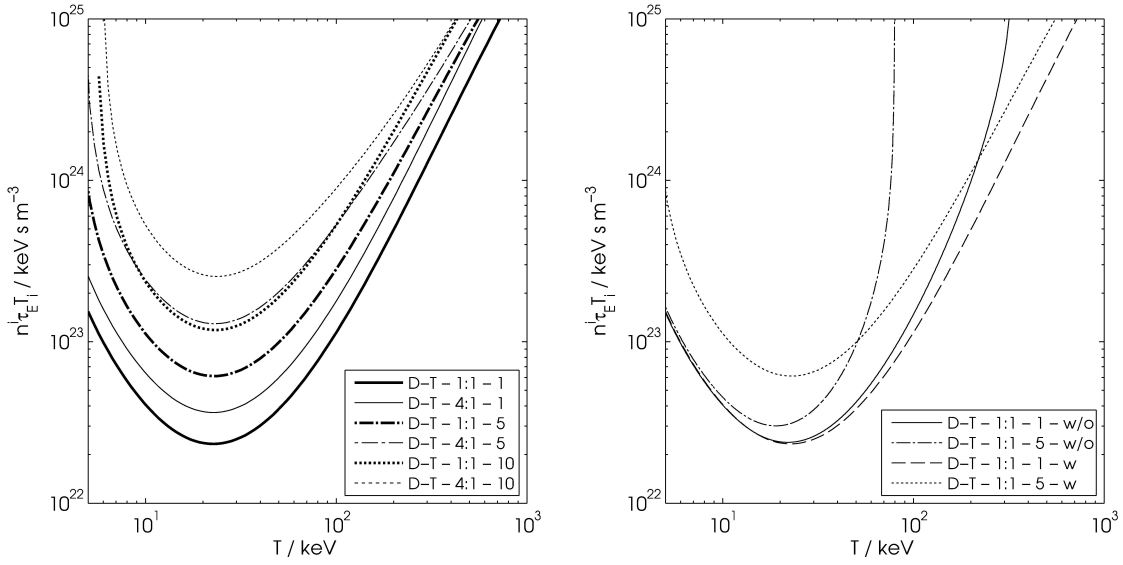

Figure 4. Left hand side: Triple products for D-T plasmas with 1:1 fueling mixture and with 4:1 fueling for $\tilde{\tau}_{Ea} = 1, 5, 10$ and with side reactions. Right hand side: Triple products for a D-T plasma with a 1:1 mixture with (w) and without (w/o) consideration of side reactions.

ignition. This is pushing the triple product to lower values as in the case without side reactions. For more detailed data enabling an understanding of that and a more reliable comparison further evaluation is planned as soon as relevant cross section data is available for each side reaction for all the interesting fueling options, i.e. D-T, D-^{3}He, ^{11}B-p, and ^{3}He-^{3}He.

Neutronic effects predicted by Ref. 7 are also observable with the new criterion. It allows to estimate the concentration of fusion reactions releasing neutrons for a set energy confinement time and therefore a volume specific particle density n_{n_0} of newly generated neutrons in the plasma shown in figure 5. It appears from the magnification around the optimum on the right of the figure that the lean 4:1 D-T mixture has lower radiation than the 1:1 D-T mixture at longer ash retention. This could be beneficial both for the system masses, as it could enable smaller shielding, and for the longevity of the first wall and blankets. The graphs on the left of figure 5 also hint that longer ash retention may damp neutron radiation at temperatures above the optimum.

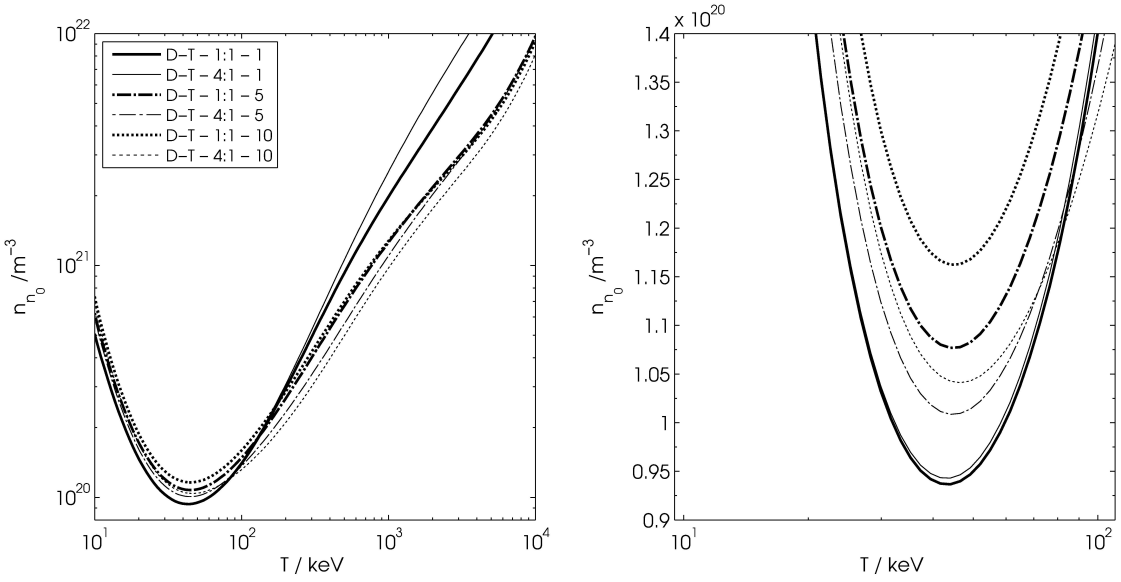

Figure 5. Left hand side: Volume specific particle density of neutrons in D-T plasmas with 1:1 fueling and with 4:1 fueling for $\tilde{\tau}_{Ea} = 1, 5, 10$. Right hand side: Magnification around the minimum.

IV. Fusion Propulsion Modelling

In section II.A a magnetically confined fusion propulsion concept with an additional coolant – typically hydrogen for its extraordinary cooling and propulsive properties – was introduced. In the present section, its thrust and exhaust velocity models are presented and evaluated for the two exemplary cases of a 1:1 and a 4:1 D-T fueling. The mass model necessary for subsequent preliminary mission estimation is adopted identically from Ref. 20 and therefore not further detailed here.

The coolant mass flow needs to assure the cooling of the blanket and the first wall which are exposed to the power of radiative losses composed of bremsstrahlung, synchrotron radiation and the neutron flux $(1-\xi)P_{Fus}$. A part

$$P_{T,ind} = k_{T,BrS}P_{BrS} + k_{T,Syn}P_{Syn} + k_{T,n_0}(1-\xi)P_{Fus} \tag{47}$$

of this power is transfered from the blanket to the coolant as described in figure 2. From this *indirect* heating, the mass flow rate with respect to the plasma volume V is calculated as follows:

$$\frac{\dot{m}_{wg}}{V} = \frac{P_{T,ind}}{(h_{H_2}(T_{Blanket,in}) - h_{H_2}(T_{Blanket,out}))}. \tag{48}$$

Here, $h_{H_2}(T)$ is the mass specific enthalpy of hydrogen at a given temperature T; $T_{Blt,in}$ is the temperature at the inner limitation of the blanket, $T_{Blt,out}$ at the outer one. While the latter is assumed to be determined

by the thermoelectric converters' temperature constraints, the first one must obey the materials thermal limit. Note that the part $k_{T,Therm} = (1 - f_{Therm})g_{Therm}$ of the thermal losses is assumed to be *directly* absorbed by the coolant in the scrap off layer. This power $P_{T,dir}$ will energize the hydrogen additionally. It can further be shown that $P_{T,ing}$ is significant in D-T plasmas due to the neutron flux while in aneutronic fuel combinations the thermal losses are the dominating loss mechanism. This is exemplarily depicted in figure 6 for a 1:1 D-T plasma. Thus, neutron damping requirements and assumptions on g_{Therm} greatly influence the thrust efficiency. The total volumetric thrust power is

$$P_T = P_{T,ind} + P_{T,dir}. \tag{49}$$

The exhaust velocity is estimated with respect to relativistic effects:

$$c_e = \left(1 - \left(\frac{P_T V}{c_0^2 \dot{m}_{wg}} + 1\right)^{-2}\right)^{\frac{1}{2}} c_0 \tag{50}$$

with c_0 as the speed of light. The relativistic correction was introduced since prior investigation[19] indicated that certain configurations and fusion reactant couplings can implicate extremely high power densities at relatively small propellant mass flow rates and thus exhaust velocities reaching up to one third of the speed of light. The thrust is calculated classically

$$F = \dot{m}_{wg} c_e \tag{51}$$

and the mass model is identical to the one in Ref.[20]

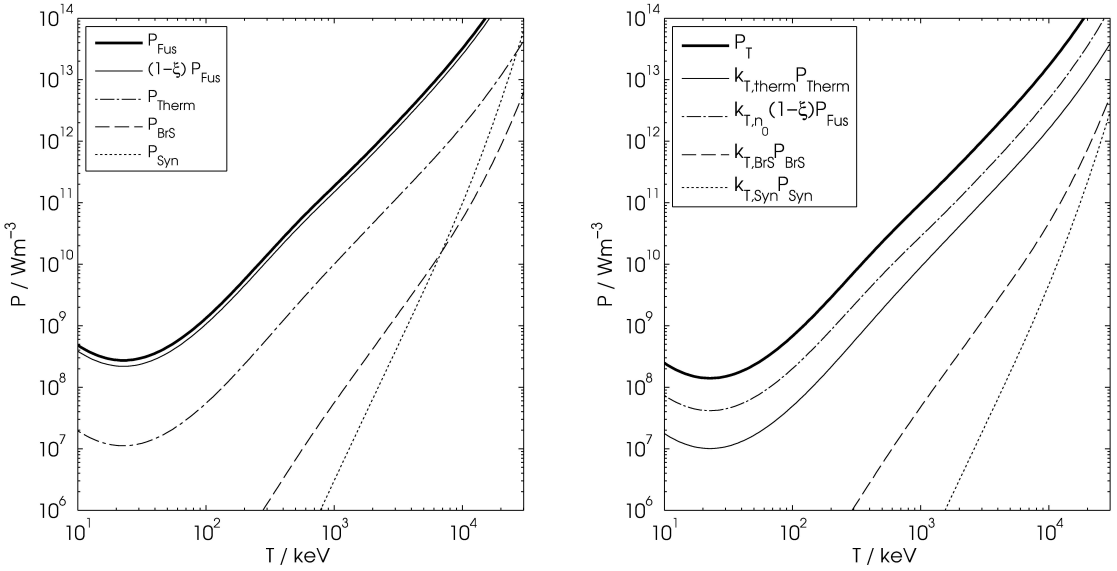

Figure 6. Exemplary distribution of volume specific power densities in D-T plasmas with 1:1 fueling for $\tilde{\tau}_{Ea} = 1$.

It is possible to use the results of these estimations in a preliminary trajectory analysis for high thrust systems. Williams[27] proposed an advanced interplanetary transfer consisting of two continuous burns along a "straight trajectory, extending a field free fly-by estimation proposed by Shepherd.[1] He obtained

$$D_{voy} = \frac{c_e^2}{F} m_d \left(\frac{1}{\sqrt{\mu_M}} - 1\right)^2 \tag{52}$$

for the voyage distance and

$$\Delta t_{voy} = \frac{c_e}{F} m_d \left(\frac{1}{\mu_M} - 1\right). \tag{53}$$

for the voyage duration. The spacecraft's dry mass is m_d and $\mu_M = m_d/m_0$ is the dry mass fraction with respect to the initial mass m_0. The spacecraft's dry mass is set to be five times the thruster's mass m_T as an exemplary value of discussion.

These propulsion models are exemplarily evaluated for the fusion reactor fuels defined in section III.B and for plasma volumina of 10 and 30 m^3. The k_T fractions are 0.9 for thermal losses, 0.85 for bremsstrahlung, 0.05 for synchrotron radiation and 0.95 for neutrons. The latter is due to the demand to have a blanket thickness able to shield 95 % of the neutron flux which is assumed to be ideally transmitted to the coolant. The temperature profile reaches from 1273 K at the outer blanket to 2000 K at the first wall (SiC). The trajectory analysis solved for a transfer during a nearest approach of Mars and Earth, i.e. $D_{voy} \approx 8 \cdot 10^{10}$ m. The results are concentrated in table 4, but the results of the mission analysis does not appear vindicable. The last two lines of this table contain the initial acceleration of the whole space craft

$$a_{SC,0} = \frac{F\mu_M}{5m_T}. \tag{54}$$

Comparing the respective values with Sun's gravitational acceleration at the distance of Earth, 5.9 10^{-3} ms^{-2}, reveals however that, first, this approach is not viable since a field free approximation relies on the negligibility of the central force field acceleration relative to the propulsion system's acceleration, and second, a fusion propulsion system relying on D-T fueling may face serious challenges due to the c_e which is around the one of classical chemical thrusters i.e. 5 kms^{-1} and consequently high fuel masses. This confirms older results.[5] At this moment, the situation remains open for the more interesting fueling alternative D-^{3}He. Prior studies indicate that this fueling can allow for lighter masses and better c_e implicating that this combination would enable high thrust transfers and entailed system advantages.[5]

Table 4. Propulsion performance of MCFP. (T: MCFP core temperature)

Ratio	1:1			4:1		
$\tilde{\tau}_{Ea}$ / -	1	5	10	1	5	10
T / keV	22.7	22.7	22.7	22.7	22.7	24.0
B / T	2.3	4.0	5.8	2.9	5.6	7.9
c_e / ms^{-1}	5593	5591	5588	5593	5591	5588
F / N (10 m^3)	5.015 10^5	1.552 10^6	3.260 10^6	7.866 10^5	3.029 10^6	6.184 10^6
$\dot{m}$ / kgs^{-1} (10 m^3)	89.7	277.6	583.4	140.7	541.8	1106.6
F / N (30 m^3)	1.505 10^6	4.656 10^6	9.780 10^6	2.360 10^6	9.087 10^6	1.855 10^7
$\dot{m}$ / kgs^{-1} (30 m^3)	269.0	832.7	1750.1	422.0	1625.4	3319.8
M_T / kg (10 m^3)	4.686 10^5	4.952 10^5	5.381 10^5	4.758 10^5	5.324 10^5	6.117 10^5
M_T / kg (30 m^3)	8.028 10^5	8.782 10^5	1.000 10^6	8.233 10^5	9.839 10^5	1.209 10^6
μ_M / - (10 m^3)	1.680 10^{-3}	5.934 10^{-4}	3.109 10^{-4}	1.105 10^{-3}	3.310 10^{-4}	1.878 10^{-4}
μ_M / - (30 m^3)	9.790 10^{-4}	3.548 10^{-4}	1.941 10^{-4}	6.477 10^{-4}	2.055 10^{-4}	1.244 10^{-4}
Δt_{voy} / d (10 m^3)	180	174	172	177	172	170
Δt_{voy} / d (30 m^3)	176	172	170	174	170	169
$a_{SC,0}$ / ms^{-2} (10 m^3)	3.597 10^{-4}	3.720 10^{-4}	3.767 10^{-4}	3.654 10^{-4}	3.766 10^{-4}	3.797 10^{-4}
$a_{SC,0}$ / ms^{-2} (30 m^3)	2.187 10^{-8}	2.243 10^{-8}	2.264 10^{-8}	2.213 10^{-8}	2.263 10^{-8}	2.277 10^{-8}

V. Conclusion and outlook

In this contribution, side reactions have been considered with an analytic approach for the first time as far as observable in literature. Hypothesizing a dimensionless magnetically confined fusion (MCF) plasma, a new generalized criterion was derived using detailed models for the particle dynamics with respect to the side reactions and allowing a species to assume both the role of a reactant and of a product. Setting fueling sources is enabled. Respective particle and power balances have been established. Implementing various parameters depending on the actual system design, the criterion allows for preliminary studies concerning space borne fusion reactions.

The new criterion has been verified by reducing its complexity according to the assumptions underlying the classical Lawson criterion. With another set of simplifications, it was applied to successfully reproduce

results from Ref. 20. The criterion appears therefore qualified to enact preliminary investigation on the effect of side reactions. This activity is however still restricted to the case of the conventional D-T fusion fueling since some necessary data concerning side reactions relevant for the (quasi-) aneutronic D-^{3}He, ^{11}B-p and ^{3}He-^{3}He reactant mixtures are currently not available.

The first results of this investigation confirmed some predictions made in the literature. The new data supports the prediction that a D-T fueling lean in tritium yields less neutrons. It further shows that side reactions in D-T plasmas have a detrimental effect around the nominal couplings minimum triple product while they have a beneficial one at higher temperatures.

This makes an interesting case for studies concerning multiple fuelings – i.e. if not only Deuterium and Tritium are fed into the plasma, but also some species like Helium-3. At this point, such a fueling seems lean in neutronic reactions on one hand. It will also be less ignitable at low temperature than the conventional D-T fuel. But by the same reasoning as outlined in section III.B, it can be hypothesized that it will ignite at better conditions than a nominal D-^{3}He plasma. If the necessary side reaction data was available or at least theoretically modeled the criterion would enable to verify this hypothesis in addition to typical parameter studies. Further, this type of assessment should also be conducted for ^{11}B-p and ^{3}He-^{3}He reactant mixtures. The beneficial effect of large cross section side reactions may countervail the quenching effect of the ash retention reported in Ref. 20. This work is currently under preparation.

An effect which is still not covered is the injection of impurities into the plasma core such as sputtered atoms from the first wall. The models can easily be extended to allow for their consideration. At this time, however, more research on relevant impurity species needs to be accomplished. Also, a final verification consisting in a qualified comparison of the analytically obtained data with realistic fusion experiments needs to be done.

The present contribution also reports about the exemplary evaluation of fusion propulsion models for a 1:1 and a 4:1 D-T mixture. The result was staggering as such a system was identified to be unable to meet the demands of a high thrust space propulsion system. Note however, that this fueling was already assessed to be inviable for propulsion.[5] In contrast, D-^{3}He is still a promising coupling, but this needs to be verified with respect to the side reactions.

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