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# Proposal of a Deuterium-Deuterium Fusion Reactor Intended for a Large Power Plant

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## Abstract

This article looks for the necessary conditions to use Deuterium-Deuterium (D-D) fusion for a large power plant. At the moment, for nearly all the projects (JET, ITER…) only the Deuterium-Tritium (D-T) fuel is considered for a power plant. However, as shown in this article, even if a D-D reactor would be necessarily much bigger than a D-T reactor due to the much weaker fusion reactivity of the D-D fusion compared to the D-T fusion, a D-D reactor size would remain under an acceptable size. Indeed, a D-D power plant would be necessarily large and powerful, *i.e.* the net electric power would be equal to a minimum of 1.2 GWe and preferably above 10 GWe. A D-D reactor would be less complex than a D-T reactor as it is not necessary to obtain Tritium from the reactor itself. It is proposed the same type of reactor yet proposed by the author in a previous article, *i.e.* a Stellarator "racetrack" magnetic loop. The working of this reactor is continuous. It is reminded that the Deuterium is relatively abundant on the sea water, and so it constitutes an almost inexhaustible source of energy. Thanks to secondary fusions (D-T and D-He3) which both occur at an appreciable level above 100 keV, plasma can stabilize around such high equilibrium energy (*i.e.* between 100 and 150 keV). The mechanical gain ($Q$) of such reactor increases with the internal pipe radius, up to 4.5 m. A radius of 4.5 m permits a mechanical gain ($Q$) of about 17 which thanks to a modern thermo-dynamical conversion would lead to convert about 21% of the thermal power issued from the D-D reactor in a net electric power of 20 GWe. The goal of the article is to create a physical model of the D-D reactor so as to estimate this one without the need of a simulator and finally to estimate the dimensions, power and yield of such D-D reactor for different net electrical powers. The difficulties of the modeling of such reactor are listed in this article and would certainly be applicable to a future D-He3 reactor, if any.

## Keywords

Fusion Reactor, Deuterium-Deuterium Reactor, Catalyzed D-D, Colliding

Beams, Stellarator Reactor, Power Plant

# 1. Introduction

## 1.1. Goal, Presentation and Notations Used

The goal of this article is to describe a power plant using Deuterium-Deuterium (D-D) fusion rather than Deuterium-Tritium (D-T) fusion and to determine if the size of such machine would be compatible with an industrial power plant, let's say, less than 500 m.

It is reminded that Deuterium (D) and Tritium (T) are hydrogen isotopes comprising, besides one proton, either one neutron (Deuterium) or 2 neutrons (Tritium).

The interest of such reactor is that the source of energy is almost inexhaustible. Below is explained why.

A $m^3$ of sea water contains 32.4 g of Deuterium (D2). The volume of the sea water is equal to about 1.338E18 $m^3$. So the oceans contain 4.335E16 kg of D2.

Without taking into account the secondary fusions (D-T and D-He3), which is a pessimistic hypothesis, the sole D-D fusion supplies 3.655 MeV. The weight of the D+ ion is equal to 3.3445E-27 kg, which means that 2 × 3.3445E-27 kg of D2 supply 3.655 MeV (=5.856E-13 J), in form of thermal power. So 1 kg of D2 supplies 8.755E13 J of thermal power.

The world's primary energy consumption in 2021 is equal to 595.15 EJ according to [1] page 9.

Let's suppose that the net electrical yield (Ye) between the net electrical power delivered to the electrical grid and the thermal power from the reactor is equal to 0.2. To supply this quantity of energy (595.15 EJ) in the sole form of electricity, it would be necessary to consume 595.15E18/(8.754E13 × 0.2) = 3.40E7 kg of D2 per year. With half of the available quantity of D2 (2.167E16 kg), it would be possible to consume energy, at this rhythm, for 2.167E16/3.40E7 = 6.37E8 years (*i.e.* 637 millions of years).

The reactor is a colliding beam fusion one using magnetic confinement and hosting two opposite beams of fast D+ ions injected by powerful ions beam guns. The charge neutrality is obtained thanks to two opposite beams of fast electrons injected by electrons beam guns. All these beams, initially directed axially, circulate inside a figure of "0" configuration, also called "racetrack". The global injected current is nil. This reactor has been described in [2] §2 and especially in the §2.2.3 of [2]. Note that the thermalization of particles in the D-D reactor is also progressive but at least 3 times slower, this due to the higher plasma energy (about 150 keV versus 70 keV) and the correlative lower collision frequency (See Appendix D).

This reactor would produce nuclear fusions with a mechanical gain ($Q$), *i.e.* fusion power/mechanical injection power, depending on the pipe radius ($Rp$). For example $Q = 2.5$ at $Rp = 1$ m, $Q = 6$ at $Rp = 1.5$ m and $Q = 17$ at $Rp = 3$ and

4.5 m (see §3.2).

The problems of heat extraction, cryogenic systems, ultra high vacuum, particles diversion in the "Divertor" (to "clear" plasma) and plasma/first wall interface are not addressed. Other problems as radiation hygiene, possible instabilities, way to realize toroidal and poloidal fields are not addressed either.

This article is only concerned by the fusion aspect, at the level of principles, the physics used being relatively simple. However, it is briefly discussed of the surface energy flow on the inner wall and the neutrons management relatively to materials in §2.2.10.

The novelty brought by this article is to propose a physical model of this D-D reactor integrated in a power plant and based on the present technology, the objective for this reactor being to supply the necessary thermal energy for a power plant delivering from 1.2 GWe (power delivered by a standard fission reactor) to 22 GWe of net electrical power.

A simple program called "D_D_reactor_model" (§1.4) based on the model developed in this article is proposed (with the Delphi 6 source). Thanks to this model, any D-D reactor of the type proposed can be roughly designed.

Note that the Multiplasma simulator program version 1.19 (§1.4) developed by the author has been used to determine certain parameters.

However, due to the necessary extrapolations made in this article, the working of such reactor is not certain. This especially, if the real loss of energy is as enormous for high energy plasma as predicted by certain scalings as the "$1/\gamma$ regime" one, for example.

In this paper, to simplify, the relativity is not considered.

**Notations**

• In a formula, the × and / operations take precedence over the + and − operations, as for example: $A\times B + C\times D = (A\times B) + (C\times D)$.

• "$\ll$" for "very inferior" and "$\gg$" for "very superior".

• $|x|$, absolute value of $x$.

• "≈" for "about".

• ~ for "proportional"

• Vectors are in bold and scalar in standard font.

• $<x>$ for "mean value" of $x$.

SI units, multiples (km for example) and sub-multiples (mm for example) are only used, with the exception of the "eV" ("Electronvolt"), which is a unit of energy quantity used in the particles domain.

1 eV is equivalent to 1.60219E-19 J. It is the potential energy of a single charge submitted to a potential of 1 V. Note that "We" means "W" (watt) for electrical power.

## 1.2. Method of the Work

Step 1: the proposed D-D fusion reactor is first described, at the level of principle, in §2.1.

Step 2: in §2.2, the reactor working is modeled using classical formulas of physics and several results of the Multiplasma simulator 1.19. The global working of the reactor is shown in **Figure B1** (Appendix B). Note that the list of the main variables used for this estimation in given in §1.3. Local variables are not listed.

Step 3: once the physical model achieved, it will be used, in §3, to estimate this reactor in several configurations. In §4, conclusions will be drawn.

### 1.3. List of the Variables and Acronyms Used in This Article

Below are the main variables used all along the article:

*λm*: Plasma concentration factor, without dimension;

*B*: Toroidal magnetic field (T);

*E_equi*: Equilibrium energy of plasma in eV;

*Ecom*: Center-of-mass energy in eV (*i.e.* available energy for a collision);

*E_inj*: Energy of the injected Deuterium ions and electrons in eV;

*nD*: Deuterium ions density (number of Deuterium ions per $m^3$);

*ne*: Electrons density (number of electrons per $m^3$);

*nHe*3: Helium He3+ ions density (number of He3+ ions per $m^3$);

*nHe*4: Helium He4+ ions density (number of He4+ ions per $m^3$);

*nT*: Tritium ions density (number of Tritium ions per $m^3$);

*Pr*: Gas pressure (Pa);

*q*: Elementary electric charge, positive or negative, $|q|$ = 1.60219E-19 C;

*Q*: Mechanical gain (*i.e.* the ratio "fusion power/mechanical injection power"), without dimension;

*Rp*: Pipe radius (m);

*Tdc*: Equivalent time of deceleration of fusion ions, for about the same radial transport as the D+ ions;

*TDexp*: Mean lifetime of a D+ ion issued from the center of the pipe and lost on the wall;

*VD*: Deuterium ions speed (Velocity) (m/s);

*Ye*: Net electrical yield, without dimension;

*Gpa*: Power amplifier gain (*i.e.* the ratio "electrical energy supplied by the alternator/electric energy consumed (auxiliary equipment included)"), without dimension;

*Z*: Atomic number (number of protons by atom);

The other variables are explained locally, but their mantissa (first letter) is, in general, generic:

Δ or *δ*: (Delta) for a difference or an interval;

*γ*: for a frequency (occurrences/s);

*σ*: for a cross section ($m^2$). It refers to the collecting surface of the interaction. The larger it is and the more interactions are produced. It can also be seen as an interaction probability.

*E*: for an energy (J) but can be expressed in eV (1 eV is equivalent to 1.60219E-19 J);

*m*: for a mass (kg);

*n*: for a density (number of particles per $m^3$);

*P*: for a power (W) or a surface power ($W/m^2$) or a volume density of power ($W/m^3$);

*Q*: for a rate (*i.e.* per ($s \times m^3$));

*r* or *R*: for a radius (m);

*S*: for a surface area ($m^2$);

*t*: for time (s);

*T*: for a temperature (˚K) but can be expressed in eV (T(eV) = 2/3 × E(eV));

*V*: for a speed (Velocity) (m/s);

*V*: for a volume ($m^3$);

*w*: for a relative speed between 2 particles (m/s);

<u>Several suffixes are used in the variables naming</u>:

ADec: for "After Deceleration";

ce: for "charge exchanges";

cy: for "cyclotronic";

D: for "Deuterium ions";

DD: for "D-D fusion";

DDec: for "During Deceleration";

DT: for "D-T fusion";

DHe3: for "D-He3 fusion";

e: for "electrons";

f: for "fusion";

Fi: for "Fusion ions", *i.e.* T+, p, He3+ and He4+;

He3: for "He3+ ions";

l: for "loss of ions on the wall";

m3: for "by $m^3$";

p: for "proton";

T: for "Tritium ions";

w: for "wall" (*i.e.* the inner wall of the reactor);

<u>Below are the three acronyms used:</u>

"IM": for "Isotropic Monokinetic" (distribution);

"COM" for "Center-Of-Mass" (see "Ecom" above);

"MB": for "Maxwell-Boltzmann" (distribution);

### 1.4. "D_D_Reactor_Model" Program Based on the Physical Model

It is proposed the program called "D_D_reactor_model" V1.0 implementing the physical model described in this article. The executable program with its Delphi 6 source can be downloaded from this direct link: http://f6cte.free.fr/D_D_reactor_model.zip. It is enough to paste this address in your Internet browser. Download the file. Create a folder (C:\D_D_reactor for example), unzip the D_D_reactor_model.zip file in it, then start C:\D_D_reactor\D_D_reactor_model.exe.

<u>Note</u>: the simulator, developed by the author and called Multiplasma V.1.19, is a 3D particle-in-cell one under Windows, written in Delphi 6 (*i.e.* Pascal object). It is able to simulate particles trajectories and the main interactions be-

tween particles. The version 1.18 has been yet described in §3.1 of [2]. The main difference between both versions is that it has been integrated secondary fusions (D-T and D-He3). However, the D-T and D-He3 fusions are not simulated by particles but their behavior is calculated in a simplified incremental way (*i.e.* each 0.1 s), from the current results of the D-D simulation. This simulator is limited to D+ ions circulating through straight pipes in an isotropic monokinetic (IM) distribution. It has been used for punctual needs. For information, the Multiplasma version 1.19 is proposed to download in "freeware", from this direct link http://f6cte.free.fr/MULTIPLASMA_V_1_19_reactor_D_D_setup.exe.

First read the "**Quick start-up of the Multiplasma V.1.19 program in its limited version for a D-D fusion reactor**" document in the "Quick_start_up_of_the_Multiplasma_V_1_19_program_in_its_limited_version_for_a_D_D_fusion_reactor.pdf" file, before using this program. For both programs, in case of failure of these two above WEB addresses, these programs will be available on the Zenodo WEB open repository, by searching with the title of this article."

## 2. Description and Physical Model of the D-D Fusion Reactor

### 2.1. Description of the D-D Fusion Reactor

This type of reactor is described in [2], except that here there are no T+ ions. Below is an abstract. So for details, refer to [2].

The proposed reactor pertains to the "Colliding Beam Fusion Reactors" (CBFR) category of reactors.

D+ ions and electrons are injected, at the same energy, with elevated currents, up to the moment when the currents circulating in the figure of "0" reach their nominal values (the global current being nil). In permanent working, the electrons and the D+ ions are injected (at $E\_inj$) at a rate permitting to cover losses and fusions, so as to keep the beam neutral. The working of such D-D reactor is continuous.

Below, on **Figure 1**, is displayed the principle diagram of this figure of "0" reactor. On this figure, the reactor appears stocky for representation necessity, but it is rather long and narrow: the length of this reactor ($L$ in **Figure 2**) being, in fact, more than 10 times larger than the width ($W$ in **Figure 2**).

The geometry of the reactor is detailed in **Figure 2**.

- $H = L + 2 \times r$, $H$ being the overall height of the reactor;
- $W = 2 \times r$, $W$ being the reactor width.

From an initial rectilinear movement, the particles behavior quickly become isotropic, in about 17 ms for electrons and 1.0 s for D+ ions. See Appendix C.

Afterwards, the thermalization of both electrons and ions progressively occurs in about 0.8 s at $E\_equi$ = 150 keV. See Appendix D part 1.

Moreover, the Coulomb collisions between D+ ions and electrons permit a permanent exchange of energy which leads to a permanent equilibrium of energy between all these particles. However this exchange is relatively slow, about 4.0 s at $E\_equi$ = 150 keV. See the Appendix D part 2.

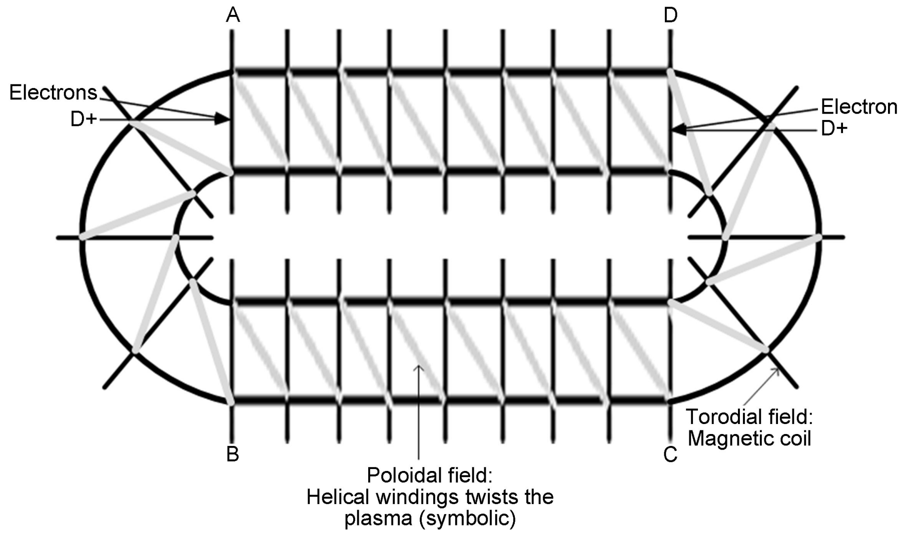


**Figure 1.** D-D fusion reactor principle diagram.

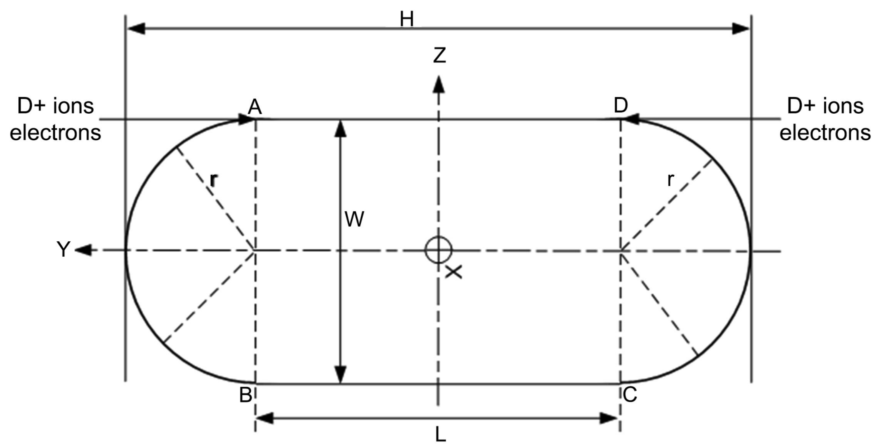


**Figure 2.** Geometry of the D-D reactor on the YZ plane, along the axis of the reactor

D+ ions are injected in opposition at the same speed and form a neutral beam with the injected electrons. The beam turns in a magnetic closed loop in form of figure of "0" (see **Figure 1**).

After isotropization (1.0 s), the particles will turn on the loop in one direction or the other, randomly. Meanwhile, the particles (electrons and D+ ions) are progressively thermalized.

The plasma is heated by fusion products: T+, p, He3+ and He4+ ions (see §2.2.5) and maintained at an equilibrium energy *E_equi* between 100 and 150 keV, where the primary and secondary fusions (§2.2.5) are numerous. This heating is sufficient to compensate the losses by radiations (mainly by Bremsstrahlung), the plasma cooling in the two half-toruses, and the particles losses.

The replacement particles are injected at a relatively low energy (*E_inj* about 45 keV) to replace lost particles.

It is targeted a power plant generating 20 GW (20,000 MW) of net electric power to the grid. The global conversion will be such that at least 20% of the thermal power issued from the D-D reactor will be converted in net electric power. So around 100 GW of thermal energy might be produced by the D-D reactor.

The toroidal magnetic field ($B$) must be axial relatively to the pipe, and maximum to confine particles (electrons + ions). The present industrial maximum $B$ limit for superconducting coils is 5 T (Tesla). So this 5 T field will be supposed all along this paper, as the default value. It is reminded that the cryogenic electric power for superconductive coils depends on the pipe radius ($Rp$) and the power supplied by the reactor depends approximately on $Rp^2$. So it is advantageous to make big units. However, the power to supply is also proportional to the reactor length and this reactor is long. Therefore the surface to thermally isolate is very large, which is a challenge for a reasonable cryogenic energy cost (see §2.2.11.3).

A poloidal field is indispensable to limit the particles shift inside loops particularly for the half-torus at each end of the reactor (see §2.2.3 of [2] and Appendix C of [2]).

The charge exchange interaction with gas neutrals can't be avoided, which is an important cause of loss of ions (see §2.2.4).

The diamagnetism is the main cause of D+ ions losses at the wall of the straight pipes (see Appendix A part 2). The loss of electrons is not taken into account for straight pipes because this loss is much smaller than the ions loss (see Appendix A part 2).

The half-torus at each end of the reactor will only be considered in term of energy loss, loss which is much more important than on straight pipes. For details about these parts, refer to §2.2.8 of this document and on the Appendix C of [2].

## 2.2. Physical Model of the D-D Fusion Reactor

### 2.2.1. Generalities about the Physical Model

There are two ways to design this reactor:

- The ideal would be a simulator for the whole reactor. The author's simulator Multiplasma can simulate the sole D+ ions circulating in straight pipes, under an isotropic monokinetic (IM) distribution, so without thermalization. Therefore, this simulator can only give punctual pieces of information.
- Calculating the D-D reactor, thanks to a physical model.

Note: of course, this model is not precise in regards of the complexity of such reactor. However, orders of magnitude and difficulties encountered (§3.4) are sufficient, at this stage, to assess the interest of such machine.

The straight parts ("$L$" on **Figure 2**) will be calculated and partly simulated for a small radius (0.8 m), whereas the two halves of torus will be estimated from Tokamak and Stellarator literature and integrated in the model (§2.2.8).

The 3 successive behaviors of new injected ions are the following:

- When D+ ions are injected in opposite direction, their movements are rectilinear. They are submitted to almost opposite collinear collisions which are very favorable for fusion because the COM energy is ideally the sum of the energies of both ions and the relative speed is equal to the double of the ion speed. So, the reactivity of monokinetic opposite collinear collisions is about the double of the reactivity of monokinetic central collisions (for the same particle energy). However, this behavior is really favorable if the injection energy (*E_inj*) is superior or equal to the equilibrium energy (*E_equi*). This behavior lasts less than about 1.0 s. It is not taken into account in the calculation.

- In 1.0 s, the movement of these new D+ ions becomes isotropic (Appendix C). Meanwhile, the speed is supposed fixed. So after 1.0 s, it can be considered that they are submitted to an IM distribution. Note that the D+ ions are, in fact, in the mean time, submitted to a beginning of thermalization with electrons (Appendix D).
- Finally the new D+ ions will progressively thermalize (Appendix D). At about 1.8 s, the very big majority of the D+ ions in plasma will be thermalized and so submitted to a Maxwell-Boltzmann (MB) distribution. The calculation of the whole reactor will be made supposing that all the D+ ions are thermalized (slightly optimistic hypothesis).

Consequently, the way to work will be the following:

- The IM distribution on the straight parts is the behavior that ions cross at the beginning. So the way to calculate the reactor limited to straight pipes will be presented in this article, for information. Moreover, as the simulator (Multiplasma) works in this configuration, punctual results from this simulator will be used and adapted to the MB distribution.

Note that the very first behavior (rectilinear trajectories) presented above will be ignored.

- To remain simple, the calculation of the whole reactor will be made with the sole MB distribution, without taking into account the two first behaviors presented above. The goal of this calculation is to estimate, in the best way possible, the different configurations and to select the best one.

The calculation will be based on the general energy balance explained in Appendix B and detailed in the chapters below. The reactor is supposed stabilized, so having worked for, at least, one hour.

#### 2.2.2. Isotropization and Thermalization of Plasma

Initially the electrons beams and D+ ions beams are straight, monokinetic and slightly divergent.

Note that for the default values of Multiplasma V.1.19, the beam diameter is equal to 100 mm (0.1 m) and the maximum divergence angle is equal to 0.08 rad.

According to the Appendix C, due to collisions between ions, the ions isotropization (*i.e.* a random direction of the movement) will take place in about 1.0 s. It can be estimated to 17 ms for electrons.

Note that between the same particles there is no thermalization, but only an isotropization (cf. Appendix D part 1). Ions thermalization will be obtained thanks to collisions with electrons. According to the Appendix D part 1, the thermalization occurs for ions and electrons in about 0.8 s.

Note: as shown in §2.2.6.1, relatively to the D+ ions fusion frequency, an MB distribution is much more favorable than an IM distribution.

### 2.2.3. Loss of Ions on the Pipe Wall

**1) Loss of D+ ions on the pipe wall**

a) Time to collide with the wall

The mean time *TDexp* for a D+ ion to collide the wall has been estimated:

• In Appendix A Part 2 as *TDexpsp*, for the straight pipes only. So *TDexp* = *TDexpsp*.

• In Appendix A Part 3, for the whole reactor.

b) Frequency for a D+ ion to collide with the wall and loss rate of D+ ions

The frequency for a D+ ion to collide with the wall is equal to the inverse of TDexp, so $\gamma lD = \frac{1}{TDexp}$.

For 1 $m^3$ of plasma, there are nD D+ ions, so the loss rate of D+ ions is equal to:

$$QlwDm3 = nD \times \gamma lD = \frac{nD}{TDexp} \tag{3.1}$$

**2) Loss of T+, He3+, He4+ ions and protons on the pipe wall during the deceleration**

Before reaching the equilibrium energy of plasma (*E_equi*), the fusion ions (He4+, p, T+ and He3+) must be decelerated as explained in Appendix E. In this appendix, it has been determined the equivalent time of deceleration of fusion ions on D+ ions (*Tdc*), for the same radial transport as the D+ ions, based on *TDexp*.

Once the T+, He3+, He4+ ions and the protons have reached *E_equi*, it is considered that they have delivered all their fusion energy to the plasma as heat. Once *E_equi* reached:

• For about the T+ and He3+ ions at *E_equi*, the D-T and the D-He3 fusions are considered as possible (cf.§2.2.6.3).

• The He4+ ions and the protons are considered as ashes. They are harmful because they make indirectly increase the Bremsstrahlung radiation (cf. §2.2.7).

It is neglected the exchanges of charge during the deceleration, because the reactivity $\langle \sigma ce \times V \rangle$ depends on $1/Ei$ (cf. §2.2.4), which is negligible for the high energy of fusion ions. Note that a direct loss of fusion ions due to the large initial Larmor radius is taken into account by the simulator, but it is neglected for the calculation due to the large pipe radius necessary for such reactor.

Let's call "$\delta N0$" the number of fusion ions created between $t = -\delta t$ and $t = 0$. The 3 terms of $\delta N0$ are (see §2.2.6 for the fusion rates "*QfD…*"):

• $\frac{QfDDm3}{2} \times \delta t$ for protons at 3.03 MeV, T+ ions and He3+ ions.

- $QfDTm3 \times \delta t$ for He4+ ions at 3.52 MeV.
- $QfDHe3m3 \times \delta t$ for He4+ ions at 3.67 MeV and protons at 14.67 MeV.

Among these $\delta N0$ fusion ions, a certain number of ions are going to collide with the wall before the complete deceleration. Let's suppose that $\delta N(t)$ is the number of surviving ions at $t$ (>0). It can be written: $\frac{d\delta N(t)}{\delta N(t)} = \frac{-dt}{TDexp}$ or $d\delta N(t) = \frac{-\delta N(t) \times dt}{TDexp}$ which solution is: $\delta N(t) = \delta N0 \times \exp\left(\frac{-t}{TDexp}\right)$ The number of ions surviving at $Tdc$ is $\delta N(Tdc) = \delta N0 \times \exp\left(\frac{-Tdc}{TDexp}\right)$. Let's call

$$\lambda lw = \exp\left(\frac{-Tdc}{TDexp}\right) \text{ the proportion of survivors} \quad (3.2)$$

So the number of survivors is $\delta N(Tdc) = \delta N0 \times \lambda lw$ and the number of non- survivors (*i.e.* having collided with the wall) is $\delta N0 \times (1 - \lambda lw)$.

A survivor gives all its kinetic energy to plasma, whereas a non-surviving fusion ion is supposed to give all its kinetic energy in the collision with the wall, which is transformed in heat.

This way to estimate the survivors and the non-survivors applies to the 6 fusion ions.

$TDexp$ and $Tdc$ depend on $E\_equi$ which is only considered after stabilization (calculation hypothesis). So $TDexp$, $Tdc$, $\lambda lw$ are also fixed. This means that the proportions of survivors and non-survivors are fixed.

Let's calculate, according to the Equation (3.2), the proportion of surviving fusion ions, respectively:

- $\lambda lwT$ for T+ ions,
- $\lambda lwHe3$ for He3+ ions,
- $\lambda lwpDD$ for protons issued from the D-D fusion,
- $\lambda lwpDHe3$ for protons issued from the D-He3 fusion,
- $\lambda lwHe4DT$ for He4+ ions issued from the D-T fusion and
- $\lambda lwHe4DHe3$ for He4+ ions issued from the D-He3 fusion.

**3) Loss of surviving T+, He3+, He4+ ions and protons on the pipe wall after the deceleration**

The radial transport of p and T+ ions is similar to D+ ions (cf. Appendix A) because p and T+ ions have only one charge as D+ ions. The He3+ and He4+ ions radial transport will be 4 times higher than radial transport of D+ ions due to their double charges.

For 1 m$^3$ of plasma, the loss rates of p, T+, He3+ and He4+ ions (in ions/(s × m$^3$)) due to collisions on the inner wall are respectively equal to

$$Qlwpm3 = \frac{np}{TDexp} \quad (3.3)$$

$$QlwTm3 = \frac{nT}{TDexp} \quad (3.4)$$

$$QlwHe3m3 = \frac{4 \times nHe3}{TDexp} \tag{3.5}$$

and

$$QlwHe4m3 = \frac{4 \times nHe4}{TDexp} \tag{3.6}$$

#### 2.2.4. Loss of D+, p, T+, He3+ and He4+ Ions by Collisions with Neutrals

**1) Loss of D+ ions by collisions with neutrals**

The description and main results about the interactions between ions and neutrals are detailed in §2.2.6 of [2].

The gas pressure (in D2 neutrals) must be the weakest possible, due to charge exchanges. It is supposed neutrals in the form of D2 molecules, not D atoms (no dissociation).

The fusions between D+, T+, He3+ ions and D2 molecules will be neglected.

No electrons energy losses on gas are considered, because the cross-sections of the electrons interactions with neutrals are weak. Ionization of the D2 molecules by electrons is neglected.

The degradation of the reactor performance due to neutrals is mainly caused by the ions-neutrals charge exchanges.

Note: there are at several orders lower, other interactions as ions-neutrals elastic collisions, ionizations, dissociations etc. They will be neglected and only charge-exchanges will be taken into account in the energies balance.

The charge exchange interaction is given here by: D+ + D2 → D2+ + D

Note that a symbol underlined means "with energy", and if not underlined it means "almost without any energy (almost stopped)". Finally, a fast D+ is "transformed" in a very slow D2+, after an exchange of charge.

Charge-exchange interactions are problematic, because:

- the charge exchange cross section is very large compared to the Coulomb collisions one,

- all the ion kinetic energy is lost for the benefit of an atom which will collide with the wall.

So for such interaction, it is considered that the ion and the neutral are lost. The initial kinetic energy of the ion at E_equi is transformed in heat by collision of the neutral on the wall.

The initial gas pressure of D2 (supposed at 20˚C, *i.e.* 293.15˚K), just before filling of the vacuum vessel, is supposed equal to 10 nPa (Ultra High Vacuum domain). Even if the volume to empty is large, it is a feasible target of pressure, as it is obtained in particles accelerators. Afterwards, after the filling, the quantity of D2 molecules (and so the density $nD2$) is supposed to remain stable due to the vacuum chamber wall release of absorbed Deuterium.

Charge exchange frequency $\gamma ceD$ for an IM distribution

The charge exchange frequency $\gamma ce$ for a D+ ion circulating at the speed $VD$ in a D2 gas having a density $nD2$, the interaction cross section $\sigma ce$ being depending on $E\_equi$, is equal to:

$$\gamma ceD = nD2 \times \sigma ce(E\_equi) \times VD(E\_equi) \quad (4.1)$$

With $VD$ the D+ ions speed equal to:

$$VD = \sqrt{\frac{2 \times q \times E\_equi(eV)}{mD}} \quad (4.2)$$

the neutrals being considered as immobile.

The density of D2 molecules at 293.15 ˚K (20˚C) can be summarized by the following formula:

$$nD2 = 2.471\text{E}20 \times Pr \quad (4.3)$$

$Pr$ being the gas pressure in Pa (Pascal).

The charge exchange cross section σce, which depends on $E\_equi$, is extracted from the Figure 19 of [3]. This reference concerns charge exchanges of H2+ with Hydrogen H2. It will be supposed that it applies to the D+ ions with Deuterium D2, for high energies (*i.e.* ≥ 100 keV).

Note that a formula to estimate the cross section for exchange of charge between H+ and H atoms is given in [4] page 368. Above 120 keV, it gives a cross-section more than 10 times weaker than the above cross-section (from [3]), so this last one must, a priori, be considered as pessimistic.

<u>Charge exchange frequency $\gamma ceD$ for a MB distribution</u>

In this case, the charge exchange frequency $\gamma ce$ is equal to

$\gamma ceD = nD2 \times \langle \sigma ce \times VD \rangle (E\_equi)$

The reactivity $\langle \sigma ce \times VD \rangle$ has been calculated numerically with $VD = \sqrt{\frac{2 \times q \times ED(\text{eV})}{mD}}$ and σce extracted from the Figure 19 of [3]. The final results have been interpolated with the formula:

$$\langle \sigma ce \times VD \rangle (E\_equi) = \frac{2.92\text{E}-9}{E\_equi(\text{eV})}$$

so

$$\gamma ceD = nD2 \times \frac{2.92\text{E}-9}{E\_equi(\text{eV})} \quad (4.4)$$

For the same reason as explained above, this formula is probably pessimistic.

Note that, at stabilization, $E\_equi$ is fixed so $\gamma ceD$ is fixed for both distributions.

<u>Charge exchange rate $QlceDm3$</u>

For 1 m$^3$ of plasma, there are $nD$ D+ ions, so the charge exchange rate of D+ ions ($QlceDm3$) per (s × m$^3$) is equal to

$$QlceDm3 = nD \times \gamma ceD \quad (4.5)$$

$QlceDm3$ is also the number of D+ ions lost by charge exchanges per (s × m$^3$).

**2) Loss of p, T+, He3+ and He4+ ions by collisions with neutrals**

It will be supposed that the charge exchanges frequencies for p, T+, He3+ and He4+ ions will be the same as for D+ ions, either for an IM distribution or for a MB distribution (§2.2.4.1). So

$$\gamma cep = \gamma ceT = \gamma ceHe3 = \gamma ceHe4 = \gamma ceD \quad (4.6)$$

The respective charge exchange rates of the p, T+, He3+ and He4+ ions per (s × $m^3$) are equal to

$$Qlcepm3 = np \times \gamma cep \quad (4.7)$$

$$QlceTm3 = nT \times \gamma ceT \quad (4.8)$$

$$QlceHe3m3 = nHe3 \times \gamma ceHe3 \quad (4.9)$$

and

$$QlceHe4m3 = nHe4 \times \gamma ceHe4 \quad (4.10)$$

Note that the He3+ and He4+ ions have two charges missing, so after a charge exchange with a D2, the He3+ and He4+ will remain as ions with one ion charge missing. However, they will be supposed lost as the neutrals T or D.

#### 2.2.5. Fusion Interactions Considered

A fusion is a specific interaction where two particles (as D+) collide with sufficiently energy to be transformed in other particles with production of a certain quantity of kinetic energy (besides the initial kinetic energy of the particles colliding with each other).

The fusion reactions considered are given below. The two first D-D interactions are the primary ones, the D-T and D-He3 ones are the secondary fusions generated with the Tritium issued from the fusion 1) and with the Helium 3 issued from the fusion 2).

Primary D-D fusion reactions from [4] page 13

1) D+ + D+ → T+ (+1.01 MeV) + p (+3.03 MeV) (at 50%);

2) D+ + D+ → He3+ (+0.82 MeV) + n (+2.45 MeV) (at 50%).

These two fusion reactions can be abstracted in a sole equivalent fusion reaction:

D+ + D+ → T+ (+0.505 MeV) + p (+1.515 MeV) + He3+ (+0.41 MeV) + n (+1.225 MeV)

So the neutrons energy is equal to 1.225 MeV and the ions energy is equal to 2.43 MeV.

Secondary D-T fusion reaction from [4] page 12

D+ + T+ → He4+ (+3.52 MeV) + n (+14.06 MeV)

This reaction uses the Tritium ions (T+) generated by the primary D-D fusion 1) given above.

Secondary D-He3 fusion reaction from [4] page 13

D+ + He3+ → He4+ (+ 3.67 MeV) + p (+ 14.67 MeV) (aneutronic fusion)

This reaction uses the Helium 3 ions (He3+) generated by the primary D-D fusion 2) given above.

The neutrons energy is nil and the ions energy is equal to 18.34 MeV.

In **Figure 3**, it will be found the cross-sections of:

- the global D-D fusion reaction from [5] and [6],
- the D-T fusion from [7],
- the D-He3 fusion from [8].

Note: the cross section is useful as long as the particles of plasma are not thermalized (so at the beginning of the life of a new injected ion).

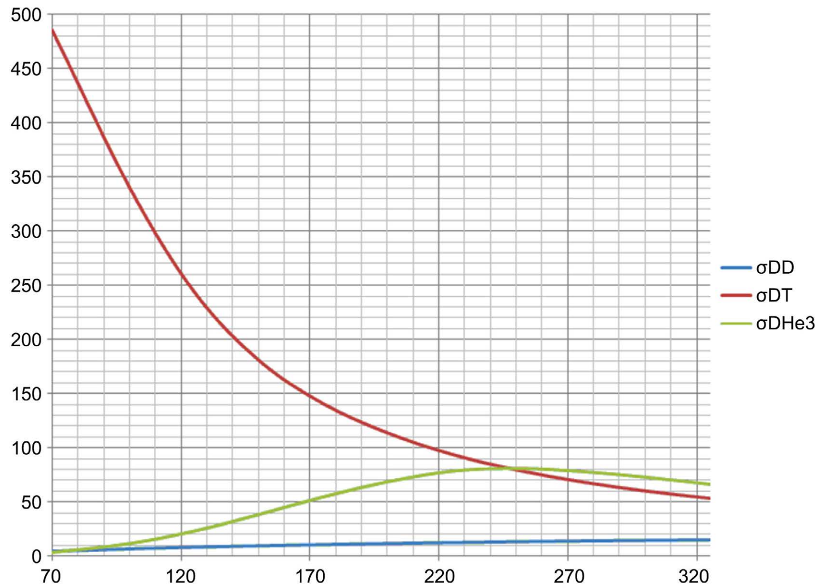


**Figure 3.** Cross-sections of the D-D/D-T/D-He3 fusions (The abscissa is the COM energy in keV and the ordinate is the cross-section in m2 × 1E-30).

It is clear that it is advantageous to work at an equilibrium energy (*E_equi*) around 250 keV (let's say 200 to 300 keV) because the cross-sections of the three fusions reactions are relatively high. It is particularly interesting for the D-He3 fusion reaction which cross-section is maximum at 250 keV, this fusion participating strongly and entirely to the plasma heating, without emitting neutrons. The D-T fusion interaction participates thanks to its powerful neutron. Indeed, this one has its kinetic energy transformed in heat by slowing down in the wall but mainly in the blanket. However, this high energy neutron causes problem with materials (cf. §2.2.10).

In **Figure 4**, it will be found the reactivities of:

- The global D-D fusion reaction from [9],
- The D-T fusion reaction from [9],
- The D-He3 fusion reaction from [10].

Note: the reactivity, written "$<\sigma \times w>$", is the integration of the product of the fusion cross-section $\sigma$ by the relative speed $w$ between particles over all the energies distributed according to the MB distribution. The reactivity must be used once plasma is thermalized.

The reactivity of the D-He3 fusion reaction is relatively stable within the domain 110 to 300 keV, whereas the D-D reactivity grows regularly. The D-T reactivity is always very superior to the D-D reactivity. The a priori assumption is that it is advantageous to work at an equilibrium energy (*E_equi*) inside the domain 100 to 300 keV, where the reactivities of the three fusions reactions are relatively high.

### 2.2.6. Fusion Frequencies and Energies

The general form of the interaction frequency is
$\langle \gamma\alpha\beta \rangle = n\beta \times \langle \sigma\alpha\beta(w\alpha\beta) \times w\alpha\beta \rangle$ (cf. [11] page 66).

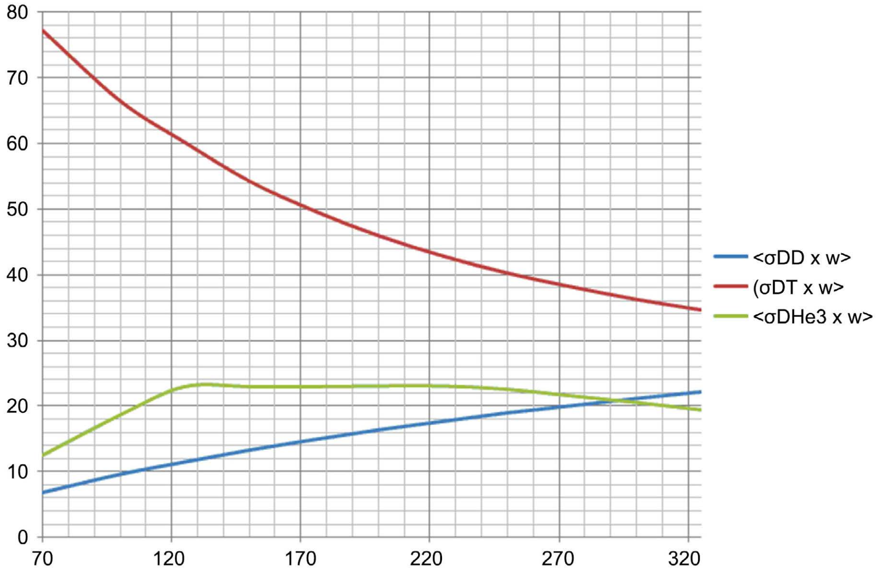


**Figure 4.** Reactivities of the D-D/D-T/D-He3 fusions (The abscissa is the COM energy in keV and the ordinate is the reactivity in m3/s × 1E-23).

Here the $\alpha$ projectile is always a D+ ion. The target $\beta$ can be a D+ ion, a T+ ion or a He3+ ion. $w\alpha\beta$ is the relative speed between ions. The Center Of Mass (COM) energy $Ecom$ is calculated as: $Ecom = \frac{\mu\alpha\beta \times w\alpha\beta^2}{2}$ (cf. [11] page 48).

The reduced mass $\mu\alpha\beta$ is equal to $\mu\alpha\beta = \frac{m\alpha \times m\beta}{m\alpha + m\beta}$ (cf. [11] page 48) with $m\alpha = mD$, $m\beta = mD$ for a D-D fusion and $m\beta \approx \frac{3}{2} \times mD$ for a D-T or a D-He3 fusion.

The fusion frequency $\gamma fD\beta$ for a D+ ion fusing with another ion (D+, T+ or He3+) is equal to:

$$\langle \gamma fD\beta \rangle = n\beta \times \langle \sigma D\beta(Ecom) \times wD\beta(Ecom) \rangle = n\beta \times \langle \sigma D\beta \times wD\beta \rangle (Ecom)$$

The total kinetic energy following a fusion can be split between two kinds of energy (see Appendix B for the energy balance):

- The neutrons energy: these particles cross the pipe wall and are moderated down to thermal energy and then absorbed by the blanket, where they transform their kinetic energy in thermal energy.
- The fusion ions energy: the ions issued from the reaction products have a kinetic energy which will be transformed in heat. This heat can be produced by collisions on electrons and ions in plasma. These ions can also collide the wall where their kinetic energy is also transformed in heat (cf. §2.2.3).

For each type of fusion, the sharing among both types of energy is given in §2.2.5. The energy terms are prefixed by "*Efn*" for neutrons energy and "*Efi*" for ions energy:

- $EfnDD$ = 1.225E6 eV and $EfiDD$ = 2.43E6 eV for the D-D fusion;
- $EfnDT$ = 14.06E6 eV and $EfiDT$ = 3.52E6 eV for the D-T fusion;
- $EfnDHe3$ = 0 eV and $EfiDHe3$ = 18.34E6 eV for the D-He3 fusion;

**1) D-D fusion rate and powers**

Here the $\beta$ particle is the D+ ion. The D-D fusion rate per (s × m$^3$) of plasma is equal to: $QfDDm3=\frac{nD}{2}\times\langle\gamma fDD\rangle(Ecom)=\frac{nD^2}{2}\times\langle\sigma DD\times wDD\rangle(Ecom)$.

Note that the factor 1/2 in "$nD/2$" comes from the need not to count twice the same collision between 2 D+ ions (A/B and B/A).

Now the reactivity $\langle\sigma DD\times wDD\rangle(Ecom)$ depends on the type of distribution. Both IM and MB distributions will be considered.

Plasma concentration factor $\lambda m$

It must be noted that in the $QfDDm3$ formula, it is supposed a flat ions density $nD$ in any section, so $nD$ represents a mean $nD$ for the whole reactor. In fact, plasma is rather concentrated in the center, so the plasma density decreases, more or less rapidly, from the center to the pipe wall.

As $QfDDm3$ depends on $nD^2$ and not on $nD$, it is necessary to correct $nD^2$ with a factor $\lambda m$ to take into account this concentration, so as to replace $nD^2$ by $nD^2\times\lambda m$.

$\lambda m$ could be expressed by: $\lambda m=\frac{\int_0^{Rp}nD(r)^2\times2\times\pi\times r\times dr}{\pi\times Rp^2}$.

With $r$ the radius considered, $Rp$ the interior pipe radius and $nD(r)$ the D+ ions density at $r$. Of course, there is no simple way to estimate $nD(r)$.

However, simulations show that, at equilibrium, the mean $\lambda m$ factor (displayed on the Multiplasma simulator) is equal to about 1.2 (with an uncertainty of about ±0.15). Note that the factor $\lambda m$ also applies to the Bremsstrahlung (+ impurities) cooling because it also depends on $nD^2$ (see §2.2.7).

So $QfDDm3=\lambda m\times\frac{nD^2}{2}\times\langle\sigma DD\times wDD\rangle(Ecom)$.

MB distribution

After isotropization and thermalization of D+ ions (§2.2.2), the distribution is a MB one.

It can be shown that, in that case, $Ecom = E\_equi$.

For the reactivity $\langle\sigma DD\times wDD\rangle(E\_equi)$, refer to §2.2.5.

So the D-D fusion rate is equal to:

$$QfDDm3=\lambda m\times\frac{nD^2}{2}\times\langle\sigma DD\times wDD\rangle(E\_equi) \tag{6.1}$$

IM distribution

The simulator does not simulate electrons so it only occurs an isotropization of D+ ions (Appendix C) and no thermalization (Appendix D).

It can be shown, in that case, that $Ecom = E\_equi$ and $<wDD> = 1.3326\ VD$, with $VD$ the D+ ions speed $VD=\sqrt{\frac{2\times q\times E\_equi(\text{eV})}{mD}}$ so

$\langle\sigma DD\times wDD\rangle(E\_equi)=\sigma DD(E\_equi)\times1.3326\times VD(E\_equi)$

Note: this way to estimate the fusion reactivity is simple, *i.e.* based on mean values, but the reality is more complex because the collisions are almost central and each collision is submitted to a particular *E_com*, from 0 to 2 × *E_equi*. The simulation is more precise and gives a slight superior fusion reactivity value.

For the cross-section *σDD*(*E_equi*), refer to §2.2.5. So the D-D fusion rate is equal to:

$$QfDDm3 = \lambda m \times \frac{nD^2}{2} \times \sigma DD\left(E\_equi\right) \times 1.3326 \times VD\left(E\_equi\right) \tag{6.2}$$

Note that at stabilization *E_equi* is fixed so *QfDDm*3 is fixed for both distributions.

<u>Comparison between the IM distribution and the MB one relatively to the D+ ions fusion frequency</u>

Using the reactivities and the cross sections for the D-D fusion reactions (see above), it can be estimated the ratio *K* between both frequencies:

$$K = \frac{\gamma\, fDD\left(MB\_distribution\right)}{\gamma\, fDD\left(IM\_disribution\right)}.$$

For the interval of energies *E_equi* between 100 and 300 keV, it is found:

- 3.32 for *E_equi* = 100 keV;
- 2.70 for *E_equi* = 150 keV;
- 2.38 for *E_equi* = 200 keV;
- 2.18 for *E_equi* = 250 keV;
- 2.05 for *E_equi* = 300 keV.

It is clear that the MB distribution is very favorable. However, these values of *K* are optimistic due to physical limits on D+ ions speeds (*i.e.* real lowest and highest speeds). The real MB distribution is rather a "truncated MB distribution". However, it will be considered this distribution as perfect in this document.

<u>D-D fusion power and neutrons power (in W/m$^3$)</u>

The fusion power *PfDDm*3 is equal to

$$PfDDm3 = q \times QfDDm3 \times \left(EfiDD + EfnDD\right) \tag{6.3}$$

The neutrons fusion power *PfnDDm*3 is equal to

$$PfnDDm3 = q \times QfDDm3 \times EfnDD \tag{6.4}$$

**2) Loss rate of D+ ions by D-D fusions**

As two ions are lost for each D-D fusion, the loss rate of D+ ions by fusion is equal to:

$$QlfDDm3 = 2 \times QfDDm3 \tag{6.5}$$

**3) D-T and D-He3 fusion rates and powers**

Here the *β* particle is either the T+ ion or the He3+ one.

*nT* and *nHe*3 are the respective densities of the T+ and the He3+ fusion ions in plasma (calculated in §2.2.6.4).

It is supposed, to simplify, that:

- Secondary fusions only occur once the T+ and the He3+ fusion ions are slowed down to the *E_equi* energy, not during the deceleration (cf. §2.2.3.2).
- The distribution of fusion ions when they reach *E_equi* is considered to be a MB one. So it can be shown that, in that case, *Ecom* = *E_equi*.

• T/T and He3/He3 fusions are neglected.

The respective D-T fusion frequency $<\gamma fDT>$ and fusion rate $QfDTm3$ per (s × m$^3$) are equal to:

$$\langle \gamma\, fDT \rangle (E\_equi) = nD \times \langle \sigma DT \times wDT \rangle (E\_equi) \tag{6.6}$$

and

$$QfDTm3 = nT \times \langle \gamma\, fDT \rangle (E\_equi) \tag{6.7}$$

For the reactivity $\langle \sigma DT \times wDT \rangle (E\_equi)$, refer to §2.2.5.

The respective D-He3 fusion frequency $<\gamma fDHe3>$ and fusion rate $QfDHe3m3$ per (s × m$^3$) are equal to:

$$\langle \gamma\, fDHe3 \rangle (E\_equi) = nD \times \langle \sigma DHe3 \times wDHe3 \rangle (E\_equi) \tag{6.8}$$

$$QfDHe3m3 = nHe3 \times \langle \gamma\, fDHe3 \rangle (E\_equi) \tag{6.9}$$

For the reactivity $\langle \sigma DHe3 \times wDHe3 \rangle (E\_equi)$, refer to §2.2.5.

D-T fusion power and neutrons power (in W/m$^3$)

The fusion power $PfDTm3$ is equal to

$$PfDTm3 = q \times QfDTm3 \times (EfiDT + EfnDT) \tag{6.10}$$

The neutrons fusion power $PfnDTm3$ is equal to

$$PfnDTm3 = q \times QfDTm3 \times EfnDT \tag{6.11}$$

D-He3 fusion power (in W/m$^3$)

The fusion power $PfDHe3m3$ is equal to

$$PfDHe3m3 = q \times QfDHe3m3 \times EfiDHe3 \tag{6.12}$$

The neutrons fusion power is nil for the D-He3 fusion.

**4) Determination of $nT$ and $nHe3$**

At this level the current $nT$ and $nHe3$ are unknown.

Just after the filling of the reactor with plasma, $nT = nHe3 = 0$. At an arbitrary time $t$, if there is no loss of T+ and He3+ ions after D-D fusions and during the deceleration of fusion ions, the rate of increase of $nT$ ($QiTm3$) and $nHe3$ ($QiHe3m3$), in ions/(s × m$^3$), would be equal to: $\frac{QfDDm3}{2}$ with $QfDDm3$ in §2.2.6.1.

Now according to §2.2.3.2, the proportions of T+ and He3+ ions having survived to the deceleration without collision with the inner wall are fixed and respectively equal to $\lambda lwT$ and $\lambda lwHe3$.

So

$$QiTm3 = \frac{QfDDm3}{2} \times \lambda lwT \tag{6.13}$$

and

$$QiHe3m3 = \frac{QfDDm3}{2} \times \lambda lwHe3 \tag{6.14}$$

Note that, at stabilization, $QfDD$ is fixed and therefore $QiTm3$ and $QiHe3m3$ are fixed.

About the T+ ions, it is created $QiTm3$ ions/(s × m$^3$), whereas is it lost $QlwTm3$ (§2.2.3.3, Equation (3.4)) due to collisions on the wall after the deceleration, $QlceTm3$ (§2.2.4.2, Equation (4.8)) due to exchanges of charge and $QfDTm3$ due to D-T fusions (§2.2.6.3, Equation (6.7)). At stabilization (at $E\_equi$), one has gain = losses, so:

$$QiTm3 = QlwTm3 + QlceTm3 + QfDtm3 = \frac{nT}{TDexp} + (nT \times \gamma ceT) + (nT \times \gamma\, fDT)$$

So

$$nT = \frac{QiTm3}{(1/TDexp) + \gamma ceT + \gamma\, fDT} \tag{6.15}$$

For the He3+ ions, with similar Equations (3.5), (4.9) and (6.9), it is found:

$$\begin{aligned} QiHe3m3 &= QlwHe3m3 + QlceHe3m3 + QfDtm3 \\ &= \frac{4 \times nHe3}{TDexp} + (nHe3 \times \gamma ceHe3) + (nHe3 \times \gamma\, fDHe3) \end{aligned}$$

So

$$nHe3 = \frac{QiHe3m3}{(4/TDexp) + \gamma ceHe3 + \gamma\, fDHe3} \tag{6.16}$$

**5) Determination of $np$ and $nHe4$**

At this level the current $nT$ and $nHe3$ are known (§2.2.6.4), so $QfDTm3$ and $QfDHe3m3$ can be calculated according to Equations (6.7) and (6.9) of §2.2.6.3, but np and nHe4 are unknown.

It is reminded that p (protons) and He4+ ions are fusion "ashes". Their presence after having left their energies is harmful as they indirectly increase the Bremsstrahlung (see §2.2.7).

According to §2.2.3.2, the proportions of p and He4+ ions having survived to the deceleration without collision with the inner wall are fixed and respectively equal to $\lambda lwpDD$ for protons issued from D-D fusion, $\lambda lwpDHe3$ for protons issued from D-He3 fusion, $\lambda lwHe4DT$ for He4+ ions issued from D-T fusion and $\lambda lwHe4DHe3$ for He4+ ions issued from D-He3 fusion. So the rates of increase of $np$ and $nHe4$, in ions/(s × m$^3$), are respectively equal to:

For protons issued from the D-D fusions:

$$QipDDm3 = \frac{QfDDm3}{2} \times \lambda lwpDD \tag{6.17}$$

For protons issued from the D-He3 fusions:

$$QipDHe3m3 = QfDHe3m3 \times \lambda lwpDHe3 \tag{6.18}$$

So for protons:

$$Qipm3 = QipDDm3 + QipDHe3m3 \tag{6.19}$$

For He4+ ions issued from the D-T fusions:

$$QiHe4DTm3 = QfDTm3 \times \lambda lwHe4DT \tag{6.20}$$

For He4+ ions issued from the D-He3 fusions:

$$QiHe4DHe3m3 = QfDHe3m3 \times \lambda lwHe4DHe3 \tag{6.21}$$

So for He4+ ions:

$$QiHe4m3 = QiHe4DTm3 + QiHe4DHe3m3 \tag{6.22}$$

About the protons, it is created $Qipm3$ protons/(s × m$^3$), whereas is it lost $Qlwpm3$ (§2.2.3.3) due to collisions on the wall after the deceleration, $Qlcepm3$ (§2.2.4.2) due to exchanges of charge. At stabilization, we have gain = losses, so:

$$Qipm3 = Qlwpm3 + Qlcepm3 = \frac{np}{TDexp} + (np \times \gamma cep)$$

so

$$np = \frac{Qipm3}{(1/TDexp) + \gamma cep} \tag{6.23}$$

About the He4+ ions, it is created $QiHe4m3$ ions/(s × m$^3$), whereas is it lost $QlwHe4m3$ (§2.2.3.3) due to collisions on the wall after the deceleration, $QlceHe4m3$ (§2.2.4.2) due to exchanges of charge. At stabilization, we have gain = losses, so:

$$QiHe4m3 = QlwHe4m3 + QlceHe4m3 = \frac{4 \times nHe4}{TDexp} + (nHe4 \times \gamma ceHe4)$$

so

$$nHe4 = \frac{QiHe4m3}{(4/TDexp) + \gamma ceHe4} \tag{6.24}$$

**6) Loss rate of D+, T+ ions by D-T fusions and D+, He3+ ions by D-He3 fusions**

$QfDTm3$ (§2.2.6.3) is also the number of D+ ions and T+ lost by the D-T fusion per (s × m$^3$):

$$QlfDTm3 = QfDTm3 \tag{6.25}$$

$QfDHe3m3$ (§2.2.6.3) is also the number of D+ ions and He3+ lost by the D-He3 fusion per (s × m$^3$):

$$QlfDHe3m3 = QfDHe3m3 \tag{6.26}$$

### 2.2.7. Radiation Losses

The description and main results about the radiation losses are detailed in §2.2.4.3 of [2] and 2.2.7.3 of [2].

The radiations losses cool plasma. They are listed below:

• Synchrotron radiated power due to electrons turning in the two half-toruses. The radiated power is very weak and is neglected.

• Cyclotronic radiated power due to electrons turning on their orbits around axial magnetic lines.

In §2.2.4.3.2 of [2], it has been made the hypothesis that 1% of the cyclotronic radiation is lost, the rest being absorbed by other electrons of the plasma.

• Bremsstrahlung due to braking radiation when electrons collide with ions or matter.

• Impurities with high *Z*, due to sputtering of the inner wall by ions of the plasma.

The cooling power *Pcym*3 in W/m$^3$ due to Cyclotronic radiation is given by the formula from §2.2.4.3.2 of [2]:

$$Pcym3 = 4E-22 \times ne \times B^2 \times E\_equi(\text{eV}) \tag{7.1}$$

*ne* is equal to

$$ne = nD + nT + np + 2 \times nHe3 + 2 \times nHe4 \tag{7.2}$$

The cooling power *Pbrm*3 in W/m$^3$ due to Bremsstrahlung is given by the formula (2.25) of the reference [12] (page 23), with $Te(\text{eV}) = 2/3 \times Ee(\text{eV}) = 2/3 \times E\_equi(\text{eV})$ and

$$Zeff = \frac{nD + nT + np + 4 \times nHe3 + 4 \times nHe4}{ne} \tag{7.3}$$

for a mixture of D+, T+, p, He3+ and He4+ ions.

$$\begin{aligned} Pbrm3 = \lambda m \times 1.69\text{E}-26 \times \left(\frac{ne}{1\text{E}6}\right)^2 \times \sqrt{Te} \times \Bigg\{ Zeff \times \Bigg[ 1 + \left(0.7936 \times \frac{Te}{me \times c^2}\right) \\ + \left(1.874 \times \left(\frac{Te}{me \times c^2}\right)^2\right) \Bigg] + \left(\frac{3}{\sqrt{2}} \times \frac{Te}{me \times c^2}\right) \Bigg\} \end{aligned} \tag{7.4}$$

Note that *Pbrm*3 is multiplied by the concentration factor (*λm*) as described in §2.2.6.1.

The cooling power *Pimm*3 in W/m$^3$ due to radiation losses on impurities, called *Pimm*3, is taken equal to the cooling power due to Bremsstrahlung, by hypothesis:

$$Pimm3 = Pbrm3 \tag{7.5}$$

### 2.2.8. Integration of the Half-Torus at Each End of the Fusion Reactor

**1) Generalities about these two half-toruses**

Up to now, it has only been considered the straight pipes of the reactor, but not the half-torus at each end of the reactor (cf. **Figure 1** and **Figure 2**). So, it has been calculated the reactor limited to the straight pipes. In this chapter it will be included the two half-toruses at the ends of the reactor. These two half-toruses form a torus. This torus can be considered either as a Tokamak or a Stellarator. Both will be considered even if this pseudo-torus is closer to the Stellarator, but there are much more results on Tokamaks at more elevated plasma temperature.

For the straight pipes, the radial transport has been considered as a classical one (see Appendix A), which is not the case for a torus where the magnetic field is not uniform. Indeed, it is the seat of turbulences and complex behaviors, out of the scope of this paper. So it will be estimated, in a simple way, the loss of power, the other powers being the same as the straight part.

**2) About the *Pfusion* and *Pra* powers**

To simplify the model, the powers *Pfusion* (so *PlostFi*, *Pah*, *Pneu*) and *Pra* (W/m³) (Appendix B) in the two half-toruses are considered as equal as *Pfusion* and *Pra* in the straight pipes. In fact, due to the larger fusion ions loss *PlostFi* in the half-toruses, *Pah* and *Pneu* will be inferior to the one in the straight pipes and *Pfusion* will be probably a bit inferior. However the total volume of the two half-toruses being at least ten times weaker than the straight pipes volume, the error is weak and will be neglected.

**3) Loss of power (*PlostHT*) from the half-toruses**

The impact of these half-toruses will be a large increase of the loss of power from the reactor. Even if this reactor is close to a Stellarator, it will be studied the tokamaks and stellarators data necessary to extrapolate the expected energy confinement time *Tct* at the required plasma energy (*E_equi*). For the D-D reactor, *E_equi* will be supposed equal to a maximum of 225 keV as target (or *Tplasma* = 150 keV).

a) About tokamaks (ITER reactor)

The mean confinement time of ITER *Tct* is expected to be between 1.8 and 5 s, for *Rp* = 2 m and *B* = 5.3 T ([13] pages 87 and 97), with an expected plasma temperature at the center of about 150E6˚K (12.9 keV or *E_equi* = 19.35 keV) and <*ne*> ≈ 1E20.

It is necessary to extrapolate the *Tct* time from *Tplasma* = 12.9 keV to 150 keV, for a fixed magnetic field *B* equal to 5 T.

There are two main types of particles radial transport for the torus (*Drt*):

- The neoclassical one. In that case the scaling is the same as the classical transport: $Drt \sim \frac{n}{B^2 \times \sqrt{E\_equi(\text{eV})}}$ with n the particles density (electrons or ions)

*Drt* can be extrapolated to: (*Drt* at 150 keV) = 0.29 × (*Drt* at 12.9 keV) which is favorable.

- The Bohm one. In that case the scaling is equal to $Drt \sim \frac{E\_equi}{B}$

*Drt* can be extrapolated to: (*Drt* at 150 keV) = 11.6 × (*Drt* at 12.9 keV) which is unfavorable.

Based on the pessimistic value of the confinement time of ITER (1.8 s), a Bohm scaling would give the following expected confinement time:

$$Tct(\text{s}) = 1.8 \times \frac{B(\text{T})}{5.3} \times \left(\frac{Rp(\text{m})}{2}\right)^2 \times \frac{19350}{E\_equi(\text{eV})} \quad (8.1)$$

b) About stellarators (Wendelstein 7-X and Helias reactors)

The mean confinement time *Tct* of the future reactor Helias (HSR5/22) is 1.65 s (LGS scaling) for *Rp* = 1.8 m, <*ne*> = 2.12E20 and *B* = 5 T, with an expected plasma temperature at the center of 15 keV (see [14]).

According to the ISS04 equation of [15] page 4, the energy confinement time *Tct* is proportional to $ne^{0.54}$, to $a^{2.28}$ (and to $B^{0.84}$). Based on this data and on the Helias confinement time, it could be written:

$$Tct = 1.65 \times \left(\frac{ne}{2.12\text{E}20}\right)^{0.54} \times \left(\frac{Rp}{1.8}\right)^{2.28}$$

According to [16], the diffusion could be a gyro-Bohm one with a scaling of $Tct$ proportional to $Tplasma^{1.5}$, which is often worse than the Bohm diffusion.

In this case, it could be extrapolated: ($Drt$ at 150 keV) = 31.6 × ($Drt$ at 15 keV) which is very unfavorable.

Moreover according to [17], after an experience done at $Tplasma$ about 2.5 keV, 2.5 T for $Rp \approx 0.5$m and $ni = ne \approx$ 1E20 and giving a confinement time of 0.23 s, it appears that the transport is neoclassical for the ions. But, due to an helical ripple, the main transport of electrons is particular and called "$1/\gamma$ regime". In this energy transport, the power lost $Pl$ evolves according to $Pl \sim Tplasma^{4.5}$ instead $Pl \sim Tplasma^{0.5}$ for a classical transport. In other words, $Tct \sim Tplasma^{-3.5}$. The power lost by the electrons, in the standard configuration, is equal to about 0.375 MW (for a heat power of 4.5 MW). An extrapolation of the power lost by electrons from 2.5 keV to 150 keV would give 1E8 MW, which has no physical sense. It is the worse scaling.

c) Conclusion about the loss of power ($PlostHT$) from the half-toruses

For about tokamaks and stellarators, extrapolations to $Tplasma$ = 150 keV, respectively through a Bohm transport and through a "gyro-Bohm" or a "$1/\gamma$ regime", are very unfavorable but not certain, as no test has been done at 150 keV.

It will be taken into account the Kovrizhnikh scaling formula from [18] pages 559/560: $Tct \sim \dfrac{Rp^2 \times B}{\sqrt{Tplasma}}$

The particles transport will not depend on the plasma density, this scaling being intermediate between the neoclassical transport and the Bohm and gyro-Bohm ones. It will be based on the experience done on [17], so:

$$Tct(\text{s}) = 0.23 \times \frac{B(\text{T})}{2.5} \times \left(\frac{Rp(\text{m})}{0.5}\right)^2 \times \left(\frac{3750}{E\_equi(\text{eV})}\right)^{0.5} \quad (8.2)$$

Notes:

• This time ($Tct$) is used to determine the mean $TDexp$ for the whole reactor in Appendix A part 3.

• This formula does not take into account the larger diamagnetism of plasma at 200 keV compared to plasma at 20 keV (D-T reactor) for which the Beta is about 5% (See Appendix A part 2).

So the power lost in the half-toruses (in W/m$^3$) is equal to

$$PlostHT = \frac{q \times E\_equi(\text{eV}) \times npar}{Tct} \quad (8.3).$$

With

$$npar = ne + nD + nT + nHe3 + nHe4 \quad (8.4)$$

as $Tct$ applies to all the particles, with ne calculated in Equation (7.2).

Note that the loss of energy only depends on the loss of ions for the straight lines (according to Appendix A), but it depends on the loss of electrons and ions for the two half-toruses, for which, it must be added a heat flow from the center of the reactor to the wall mainly due to ions.

**4) Calculations of PlostReactor and PlostReactorPar—Limit on *Rp***

From **Figure 2**, it can be seen that the straight length $Sl$ is equal to $Sl = 2 \times L$ and the total half-toruses length $HTl$ is equal to $HTl = 2 \times \pi \times r$. So the ratio of both lengths is equal to $RatioL = \frac{Sl}{HTl} = \frac{L}{\pi \times r}$

Moreover the volume of the torus ($VT$) formed by the two half-toruses is equal to $VT = 2 \times \pi^2 \times Rp^2 \times r$

It is reminded that $Rp$ is the small radius and r the large radius of the torus. In general, for tokamaks, $r \approx 3 \times Rp$ ([13] page 87) and rather around $10 \times Rp$ for Stellarators (cf. [14]).

Of course, as energy loss in the half-toruses is several orders of magnitude larger than the energy loss in the straight parts, $RatioL$ must be the largest possible (let's say $RatioL \geq 10$), and so r the shortest possible. For this reason, from now on, it will be chosen:

- $r = 3 \times Rp$, so

$$VT = 6 \times \pi^2 \times Rp^3 \tag{8.5}$$

- $RatioL = 10$. Of course, $RatioL$ could be larger than 10 but at the price of an increase of the length of the reactor.

These conditions on $r$ and $RatioL$ will set $L$ to

$$L = RatioL \times \pi \times r = 30 \times \pi \times Rp \tag{8.6}$$

The overall length $H$ (**Figure 2**) is equal to

$$H = L + 2 \times r = (30 \times \pi \times Rp) + (6 \times Rp) = Rp \times [(30 \times \pi) + 6].$$

H must be limited to 500 m (§1.1). This leads to $Rp(\text{m}) \leq \frac{500}{(30 \times \pi) + 6} \approx 5$.

So 5 m is the maximum limit on $Rp$.

Moreover, the volume of the straight pipes ($VSP$) is equal to

$$VSP = 2 \times \pi \times Rp^2 \times L = 2 \times \pi \times Rp^2 \times (30 \times \pi \times Rp) = 60 \times \pi^2 \times Rp^3 \tag{8.7}$$

So

$$Vreactor = VT + VSP = (6 \times \pi^2 \times Rp^3) + (60 \times \pi^2 \times Rp^3) = 66 \times \pi^2 \times Rp^3 \tag{8.8}$$

Note that $VT$, $VSP$ and $VT$+ $VSP$ are multiples of $6 \times \pi^2 \times Rp^3$

With $VT$, $VSP$, $VT$+ $VSP$ and $PlostHT$ (§2.2.8.3.c), from the Equations (B5) and (B6) of the Appendix B, it can be calculated *PlostReactor* and *PlostReactorPar*.

### 2.2.9. Calculation of the Fusion Reactor

It is reminded that two calculations will be done:

- One, for information, using an IM distribution and limited to the straight pipes. It is called Configuration "SP" (for "Straight Pipes").
- The other for the whole reactor (straight pipes and the two half-toruses) us-

ing the MB distribution. It is called Configuration "WR" (for "Whole Reactor").

All the parameters of the fusion reactor will be calculated up to the mechanical gain $Q$ (Appendix B), in these 2 configurations. First of all consider the Appendix B, which briefly explains how all the calculation is made.

The input parameters of the calculations are $nD$ the D+ ions density, $E\_inj$ the electrons and D+ ions injection energy in eV, $Rp$ the pipe radius in m and $B$ the magnetic field in T. $ne$ is implicitly supposed to make the plasma neutral.

Note that in the "D_D_reactor_model" program (§1.4), the initial energy $E\_equi = E\_inj$ is taken as hypothesis. Then $E\_equi$ will be progressively adjusted so as to reach the equilibrium (§2.2.9.6). In the same way, ne is initially equal to $nD$ and then evolves to make the plasma neutral, up to the stabilization.

For a radius $Rp$ given and for a constant $B$ = 5 T, a set of tests will be made with different $nD$ and $E\_inj$. The best configuration will be selected.

**1) Preliminary calculations**

Before calculating the main parameters, it is necessary to calculate the basic parameters of the reactor (displayed in italic), based on the fixed parameters $nD$, $E\_inj$, $Rp$ and $B$ (with $E\_equi = E\_inj$ and $ne = nD$ initially), as described below.

a) D+ ions confinement time $TDexp$

Beta, the diamagnetism factor, is calculated with the Equation (A1) (Appendix A part 2) then $TDexpsp$, the lifetime of a D+ ion to travel from the center of the pipe to the inner wall, for the straight pipes, is calculated with the Equation (A2) (Appendix A, part 2).

According to the configuration:

- for the "SP" one, $TDexp = TDexpsp$.
- for the "WR" one, from the Equation (8.2 (§2.2.8.3.c), it is calculated the confinement time for the half-toruses $Tct$, then $TDexp$, the mean lifetime of a D+ ion calculated with the Equation (A3). (Appendix A, part 3).

b) Proportions of fusion ions survivors

These 6 proportions are calculated according to the description below.

- Thanks to the Appendix E, using the Equation (E1), it is determined $Tdi$ the time during which the deceleration is mainly done by D+ ions.
- $Tdc$ the equivalent time of deceleration of fusion ions on D+ ions, for about the same radial transport as the D+ ions, is calculated with the Equation (E2) for the proton and the T+ ion, and with the Equation (E3) for the He3+ and He4+ ions.
- Thanks to §2.2.3.2 and according to the Equation (3.2), it is calculated the 6 proportions of surviving fusion ions after deceleration, *i.e.* $\lambda lwT$, $\lambda lwHe3$, $\lambda lwpDD$, $\lambda lwpDHe3$, $\lambda lwHe4DT$ and $\lambda lwHe4DHe3$.

c) Charge exchanges frequencies

The gas pressure of D2 ($Pr$) is supposed equal to $Pr$ = 10 nPa at 293.15˚K (§2.2.4.1).

- Thanks to §2.2.4.1 and according to the Equations (4.1) to (4.3) for the IM distribution (Configuration "SP") and according to the Equations (4.3) and (4.4) for the MB distribution (Configuration "WR"), let's calculate the charge exchanges frequency $\gamma ceD$.

• Thanks to §2.2.4.2 and according to the Equation (4.6), let's calculate the charge exchanges frequencies $\gamma cep$, $\gamma ceT$, $\gamma ceHe3$ and $\gamma ceHe4$.

d) <u>Fusion frequencies and rates</u>

• From $nD$ and $E\_equi$, it is calculated the D-D fusion rate $QfDDm3$ (§2.2.6.1) from Equations (6.1) (Configuration "WR") or 6.2 (Configuration "SP") according to the chosen configuration.

• Thanks to §2.2.6.3 and according to the Equations (6.6) and (6.8), let's calculate the D-T and D-He3 fusion frequencies $<\gamma fDT>$ and $<\gamma fDHe3>$.

e) <u>nT, nHe3, np and nHe4</u>

• Thanks to §2.2.6.4 and according to the Equations (6.13) and (6.14), let's calculate the respective rates of increase of $nT$ and nH3: $QiTm3$ and $QiHe3m3$. Afterwards, according to the Equations (6.15) and (6.16), it can be calculated $nT$ and $nHe3$. Then $QfDTm3$ and $QfDHe3$ can be calculated according to Equations (6.7) and (6.9).

• Thanks to §2.2.6.5 and according to the Equations (6.17) to (6.22), let's calculate the respective rates of increase of np and nHe4:

o $QipDDm3$, $QipDHe3m3$ and $Qipm3$ for protons,

o $QiHe4DTm3$, $QiHe4DHe3m3$ and $QiHe4m3$ for He4+ ions.

Afterwards, according to the Equations (6.23) and (6.24), it can be calculated np and nHe4.

**2) Fusion power (*Pfusion*)**

As indicated in Appendix B (Equation (B1)), the fusion power (W/m$^3$) is equal to: $Pfusion = PlostFi + Pah + Pneu$

Each term is calculated below.

<u>a) Calculation of the power lost by fusion ions (*Plostfi*)</u>

The power lost by fusion ions (T+, He3+, p, He4+) can have 3 origins:

• collisions on the inner wall during the deceleration ($PlostFiDDecm3$),

• collisions on the inner wall after the deceleration ($PlostFiADecm3$),

• charge exchanges with neutrals (PlostFicem3).

So

$$PlostFi = PlostFiDDecm3 + PlostFiADecm3 + PlostFicem3 \tag{9.1}$$

The 3 elements of $PlostFi$ are calculated below.

<u>Kinetic power of fusions ions lost by collisions on the inner wall ($PlostFiDDecm3$) during the deceleration</u>

From §2.2.3.2, §2.2.6.4 and §2.2.6.5, it can be deduced that the rates of T+, He3+, p and He4+ fusion ions having collided the inner wall during the deceleration ("non-survivors") are respectively equal to:

For T+ ions

$$QlTm3 = \frac{QfDDm3}{2} \times (1 - \lambda lwT) \tag{9.2}$$

For He3+ ions

$$QlHe3m3 = \frac{QfDDm3}{2} \times (1 - \lambda lwHe3) \quad (9.3)$$

For protons produced by the D-D fusions

$$QlpDDm3 = \frac{QfDDm3}{2} \times (1 - \lambda lwpDD) \quad (9.4)$$

For protons produced by the D-He3 fusions

$$QlpDHe3m3 = QfDHe3m3 \times (1 - \lambda lwpDHe3) \quad (9.5)$$

For He4+ ions produced by the D-T fusions

$$QlHe4DTm3 = QfDTm3 \times (1 - \lambda lwHe4DT) \quad (9.6)$$

For He4+ ions issued from the D-He3 fusions

$$QlHe4DHe3m3 = QfDHe3m3 \times (1 - \lambda lwHe4DHe3) \quad (9.7)$$

The power lost by a fusion ion is equal to the rate of loss times the initial energy of the fusion ion. Consequently the total power of fusion ions lost on the inner wall during deceleration ($PlostFiDDecm3$) is equal to:

$$\begin{aligned} PlostFiDDecm3 = q \times \big[ &(QlTm3 \times 1.01\text{E}6) + (QlHe3m3 \times 0.82\text{E}6) \\ &+ (QlpDDm3 \times 3.03\text{E}6) + (QlpDHe3m3 \times 14.67\text{E}6) \\ &+ (QlHe4DTm3 \times 3.52\text{E}6) + (QlHe4DHe3m3 \times 3.67\text{E}6) \big] \end{aligned} \quad (9.8)$$

<u>Kinetic power of fusions ions lost by collisions on the inner wall (*PlostFiA-Decm3*) after the deceleration.</u>

The loss rate of p ($Qlwpm3$), T+ ($QlwTm3$), He3+ ($QlwHe3m3$) and He4+ ($QlwHe4m3$) ions due to collisions on the inner wall are respectively calculated in Equations (3.3) to (3.6) (§2.2.3.3).

The power lost by a fusion ion is equal to the rate of loss times the equilibrium energy.

Consequently the total power of fusion ions lost on the inner wall after deceleration ($PlostFiDDecm3$) is equal to:

$$\begin{aligned} &PlostFiADecm3 = \\ &q \times E\_equi(\text{eV}) \times (Qlwpm3 + QlwTm3 + QlwHe3m3 + QlwHe4m3) \end{aligned} \quad (9.9)$$

<u>Kinetic power of fusions ions lost by charge exchanges with neutrals (*PlostFi-cem3*)</u>

The respective charge exchange rates of the p, T+, He3+ and He4+ ions in ions/(s × m$^3$) $Qlcepm3$, $QlceTm3$, $QlceHe3m3$, $QlceHe4m3$ are respectively calculated in Equations (4.7) to (4.10) (§2.2.4.2).

Consequently, the total power of fusion ions lost by charge exchanges is equal to:

$$\begin{aligned} &PlostFicem3 = \\ &q \times E\_equi(eV) \times (Qlcepm3 + QlceTm3 + QlceHe3m3 + QlceHe4m3) \end{aligned} \quad (9.10)$$

<u>b) Calculation of the power used to heat the plasma *Pah*</u>

The power lost by a fusion ion is equal to the rate of loss times the initial energy of the fusion ion. With the §2.2.9.1.e results, the total power of fusion ions lost to heat the plasma (*Pah* in W/m$^3$) is equal to:

$$\begin{aligned} Pah = q \times \big[ & (QiTm3 \times 1.01\text{E}6) + (QiHe3m3 \times 0.82\text{E}6) \\ & + (QipDDm3 \times 3.03\text{E}6) + (QipDHe3m3 \times 14.67\text{E}6) \\ & + (QiHe4DTm3 \times 3.52\text{E}6) + (QiHe4DHe3m3 \times 3.67\text{E}6) \big] \end{aligned} \quad (9.11)$$

c) Calculation of the neutron power (*Pneu* in W/m$^3$)

As described in Appendix B (Equation (B2)): $Pneu = PfnDDm3 + PfnDTm3$

With:

- $PfnDDm3$ calculated with the Equation (6.4) (§2.2.6.1),
- $PfnDTm3$ calculated with the Equation (6.11) (§2.2.6.3).

d) Calculation of the fusion power (*Pfusion*)

Pfusion (in W/m$^3$) is calculated as $Pfusion = PlostFi + Pah + Pneu$ (Equation (B1)).

However, it could also be calculated as the sum of the fusion powers issued from the D-D, the D-T and the D-He3 fusions.

$$Pfusion\_bis = PfDDm3 + PfDTm3 + PfDHe3m3 \quad (9.12)$$

With:

- the D-D fusion power $PfDDm3$ calculated with the Equation (6.3) (§2.2.6.1),
- the D-T fusion power $PfDTm3$ calculated with the Equation (6.10) (§2.2.6.3),
- the D-He3 fusion power $PfDHe3m3$ calculated with the Equation (6.12) (§2.2.6.3).

The second way to calculate *Pfusion_bis* must give almost the same result as the first way (*Pfusion*). "Almost" because the fusion ions lost on the wall or by charge exchanges after deceleration from *E_equi* are not taken into account in *Pfusion_bis*. So *Pfusion_bis* is slightly inferior to *Pfusion* by several %. Rigorously,

$$Pfusion\_bis = Pfusion + PlostFiADecm3 + PlostFicem3 \quad (9.13)$$

This last formula can be used as a checking.

**3) Power lost by D+ ions (*PlostD*) on the straight pipes**

As described in Appendix B (Equation (B3)):

$$PlostD = q \times E\_equi(\text{eV}) \times [QlwDm3 + QlceDm3 + QlfDDm3 + QlfDTm3 + QlfDHe3m3]$$

The rate of loss on the inner wall $QlwDm3$ is calculated with the Equation (3.1) (§2.2.3).

The rate of loss by charge exchanges $QlceDm3$ is calculated with the Equation (4.5) (§2.2.4.1).

The rate of loss by D-D fusions $QlfDDm3$ is calculated with the Equation (6.5) (§2.2.6.2).

The rate of loss by D-T fusions $QlfDTm3$ is calculated with the Equation (6.25) (§2.2.6.6).

The rate of loss by D-He3 fusions $QlfDHe3m3$ is calculated with the Equation (6.26) (§2.2.6.6).

**4) Power lost by radiations ($Pra$)**

According to the Appendix B (Equation (B8)), the total radiations power is equal to: $Pra = Pcym3 + Pbrm3 + Pimm3$

The cyclotronic power $Pcym3$ is calculated with the Equations (7.1) and (7.2) (§2.2.7).

The Bremsstrahlung power $Pbrm3$ is calculated with the Equations (7.2) to (7.4) (§2.2.7).

The impurities power $Pimm3$ is calculated with the Equation (7.5) (§2.2.7).

**5) Consumed power ($Pinput$)**

As described in Appendix B (Equation (B7)):

$$Pinput = \frac{PlostReactorPar \times E\_inj}{E\_equi}$$

With $PlostreactorPar$ calculated from the Equations (B4) and (B6) of the Appendix B. Note that for the "SP" configuration, $Pinput = \frac{PlostD \times E\_inj}{E\_equi}$ (Equation (B7bis)).

**6) Equilibrium state of plasma**

As described in the Equation (B9) (Appendix B), the equilibrium state is reached when the energy is stable at $E\_equi$, if the following equality is checked: $PlostReactor + Pra = Pinput + Pah$ with $PlostReactor$ calculated with the Equation (B5) (Appendix B) for the "WR" configuration and the Equation (B5bis) for the "SP" configuration.

The first side of the equation corresponds to losses of energy whereas the second side corresponds to gains of energy.

If $PlostReactor + Pra > Pinput + Pah$ it means that losses of energy are superior to gains, so $E\_equi$ is too high and it must be decreased, and reversely.

Let's call

$$DeltaP = \left(PlostReactor + Pra\right) - \left(Pinput + Pah\right) \tag{9.14}$$

If $|DeltaP| \le 100\ \text{W/m}^3$, it is considered that the equilibrium state of plasma is reached and the calculation stops. Reversely,

$$E\_equi\left(n+1\right) = E\_equi\left(n\right) - \left(DeltaP/100\right) \tag{9.15}$$

and the calculation is remade. This way to do is repeated until reaching the stopping criterion $|DeltaP| \le 100\ \text{W/m}^3$.

Once the equilibrium state of plasma is reached, it is calculated the surface heat power ($SHP$) and the surface neutrons power ($SNP$) (in $\text{W/m}^2$) according to the Equations (10.1) and (10.2) of §2.2.10.

**7) Mechanical gain ($Q$) and global output power ($Poutput$)**

The equilibrium state of plasma being reached, it can be calculated the mechanical gain $Q$ according to the Appendix B (Equation (B10)), *i.e.* the ratio "Fusion power/mechanical input power": $Q = \frac{Pfusion}{Pinput}$.

The global output power collected at the exterior of the reactor, according to the Appendix B (Equation (B12)), is equal to $Poutput = Pfusion + Pinput$.

However, for the "WR" configuration only, *Q*, *Poutput* and the other results will be taken into account if the following conditions are met:

- $Beta \le 0.5$ (cf. Appendix A part 2),
- $SHP \le 2$ MW/m$^2$ (§2.2.10),
- $SNP \le 2$ MW/m$^2$ (§2.2.10).

### 2.2.10. Determination of the Limits on the Surface Heat Power and on Surface Neutrons Power

It will be considered limits on the surface heat power (*SHP* in W/m$^2$) and on the surface neutrons power (*SNP* in W/m$^2$) through the inner wall. These limits concern the whole reactor without differentiations between the straight pipes and the half-toruses. Now, it is obvious that the straight pipes will have to support less heat power that the half-toruses, due to the high losses on these ones (cf. §2.2.8.3). This point will be considered "to deepen" (§3.4).

SHP takes into account the radiations and losses powers, *i.e.* *PlostFi* + *PlostD* + *Pra*

Note that this heat will finally be mainly absorbed by the refrigerant circulating through the blanket (Appendix B), but the inner wall will rise in temperature. The vacuum vessel shield will protect magnets against radiations, thermal energy and neutrons.

SNP will take into account the term *Pneu*.

*SNP* must be determined because neutrons affect the mechanical properties of materials. Solutions exist for the fission reactors but for 2 to 3 MeV neutrons. However, materials able to withstand the impact of the high-energy neutrons (14.1 MeV) for D-T reactors will be tested under the IFMIF program.

It will be supposed that both limits on *SHP* and *SNP* are equal to 2 MW/m$^2$. These values are high but are susceptible to be borne by actual or close future material.

Note that the necessary Divertor aimed to recover ashes and impurities is out of the scope, as its surface heat flux is much larger and constitutes a specific problem.

In a general way, if *P* is the density of power in W/m$^3$, *V* the volume of the pipe of length *L* equal to $V = \pi \times Rp^2 \times L$ whereas its inner wall surface *S* is equal to $S = 2 \times \pi \times Rp \times L$, it can be deducted that the surface power *SP* (*SHP* or *SNP*) is equal to:

$$SP = \frac{P \times V}{S} = \frac{P \times \pi \times Rp^2 \times L}{2 \times \pi \times Rp \times L} = \frac{P \times Rp}{2}$$

so

$$SHP = \frac{\left(PlostFi + PlostD + Pra\right) \times Rp}{2} \qquad (10.1)$$

and

$$SNP = \frac{Pneu \times Rp}{2} \quad (10.2)$$

It must be noted that the neutrons power (*Pneu*) represents around 50% of the fusion power (*Pfusion*) for a D-D reactor, versus 80% for a D-T reactor. Moreover around one-quarter of this neutrons power is issued from neutrons at 2.45 MeV, similar to the fission neutrons which are well mastered in fission reactors.

#### 2.2.11. Determination of the Net Electrical Yield (*Ye*) of the Water/Steam Circuit, the Power Amplification Gain (*Gpa*) and the Net Electrical Power Supplied by the Plant (*Pe_plant*)

1) Generalities

The thermal power supplied by the D-D reactor is *Poutput* (§2.2.9.7). However, this power can't be totally recovered due to the different openings for measuring devices, pipes, Divertor, etc. Moreover, the conversion of the neutrons kinetic energy and the radiations energy in heat can't be perfect. So it will be supposed that only $\alpha e$ = 90% of this output power is really used for the thermodynamic cycle. So, the available output heat power (*Psg* in W/m$^3$ of plasma) crossing the steam generators (see Appendix B) will be equal to: $Psg = \alpha e \times Poutput$

The rest of *Poutput* (10%) cannot be used and is evacuated by the heat sink.

The word "yield" refers, here, to:

- either an "electrical energy to primary (thermal) energy" ratio of any form,
- or the "mechanical to electrical energy ratio" for the particles injectors.

A "yield" value is comprised between 0 and 1. Reversely, a gain value can take any positive value.

In this paragraph, it will be determined the expected net electrical yield *Ye*, *i.e.* the ratio "net electrical energy supplied to the electricity grid (*Pe_net*)/output heat power (*Poutput*)".

2) Thermodynamic conversion to electricity

In what follows, it is considered a thermodynamic conversion of the output power in form of heat (*Psg*) supplied by the fusion reactor, in electricity (see Appendix B). The chosen gross yield $Yg = 0.39$ of this conversion corresponds to the gross yield of a modern fission reactor (as the EPR one).

So the gross power delivered by the alternator will be equal to

$$Pe\_gross = Yg \times Psg = Yg \times \alpha e \times Poutput \quad (11.1)$$

3) Electrical consumers and net electrical yield *Ye*

Relatively to the fusion reactor itself (auxiliary equipment being apart), the sole source of energy consumption is the particle injectors. The yield of these injectors, *i.e.* kinetic energy of the particles injected (*Pinput*)/electric power consumed (*Pe_input*) to inject them, is supposed equal to 0.8, which is possible for powerful injectors. So 20% of the energy of these injectors is lost in the form of heat at low temperature. This heat cannot be used and is evacuated by the heat sink.

So for a mechanical injection power Pinput in W/m$^3$ (see §2.2.9.5), the consumed electrical power is equal to *Pe_input*:

$$Pe\_input = \frac{Pinput}{0.8} = 1.25 \times Pinput \quad (11.2)$$

Now to make work the reactor, a certain number of auxiliary pieces of equipment are necessary.

It will be supposed that 20% of the gross electric power delivered by the alternator will be used:

• 14% for the cryogenic equipment aimed to cool the magnetic coils.

• 2% for the ultra high vacuum (included the cryogenic equipment for the cryogenic pumps),

• 4% for the other auxiliary equipment.

The global auxiliary electrical power (*Pe_aux*) will be equal to

$$Pe\_aux = \left(Pe\_gross \times 0.2\right) + Pe\_input \quad (11.3)$$

And the net power delivered by the alternator to the grid will be equal to:

$$Pe\_net = Pe\_gross - Pe\_aux = \left(Pe\_gross \times 0.8\right) - Pe\_input$$

The overall net electrical yield *Ye* is the ratio between the net electric power to the grid and the thermal output power (*Poutput*) so:

$$Ye = \frac{Pe\_net}{Poutput} = \frac{\left(Pe\_gross \times 0.8\right) - Pe\_input}{Poutput} \quad (11.4)$$

The maximum *Ye*, for *Pe_input* = 0, is equal to 0.28.

4) Power amplification gain (*Gpa*)

This plant can be considered as a power amplifier. The input electrical power is equal to *Pe_aux* whereas the output electrical power is equal to *Pe_gross*. So

$$Gpa = \frac{Pe\_gross}{Pe\_aux} = \frac{Pe\_gross}{\left(Pe\_gross \times 0.2\right) + Pe\_input} \quad (11.5)$$

Gpa must be superior to 1, because for *Gpa* < 1, the plant consumes more electricity than it is supplied by the alternator. A reasonable goal would be *Gpa* ≥ 2, the maximum being equal to 5 for *Pe_input* = 0.

5) Net electrical power supplied by the plant (*Pe_plant*)

From the total volume of the reactor *Vreactor* (§2.2.8.4) calculated by the Equation (8.8), it can be determined the total thermal power supplied and therefore *Pe_plant* (in W)

$$Pe\_plant = Vreactor \times Poutput \times Ye \quad (11.6)$$

## 3. Results and Discussion

### 3.1. Comparison of the Physical Model with the Simulator in IM Distribution—Straight Parts Only

With the program based on the calculation developed in §2.2.9 for an IM distribution ("*SP*" configuration), it has been calculated a typical configuration, *i.e.* $nD$ = 12E19, $E\_inj$ = 300 keV and $Rp$ = 0.8 m, as this pipe radius $Rp$ needs a reasonable simulated time (1 minute). $B$ is fixed to 5 T.

The calculated mechanical gain $Q$ and the energy $E\_equi$ found are:

- By calculation: $Q$ = 0.94 and $E\_equi$ = 142 keV;
- By simulation: $Q$ = 1.00 and $E\_equi$ = 187 keV.

The results are coherent. The difference on $E\_equi$ is mainly due to the simulator fusion power which is 33% larger than the one calculated. This difference of fusion power is explained in §2.2.6.1. It is also due, for a small part, to the fact that the collisions are not strictly central, the final isotropy not being equal to 100% (cf. §2.2.1 and Appendix C). Now both $Q$ are similar because, in the same time, the loss considered by the simulator is larger, this due to a 44% smaller confinement time.

The calculation is considered validated by the simulation, which permits to make calculations for larger $Rp$. Results are presented in the **Table 1** below.

For each radius, there are 2 parameters to test:

- $nD$ between 10E19 and 20E19;
- $E\_inj$ between 250 keV and 300 keV.

The best configuration is the one which gives the best mechanical yield $Q$. The equilibrium plasma energy $E\_equi$ is determined by the program. It is added the global output power $Poutput$ (§2.2.9.7), the surface heat power $SHP$ (§2.2.10) and the surface neutrons power (§2.2.10).

The conclusion is that such configuration gives a very low mechanical gain ($Q$) even with large radius (5 m). A D-D reactor cannot work on such conditions.

### 3.2. Calculation Made with a MB Distribution—Whole Reactor Considered

With the program based on the calculation developed in §2.2.9 for a MB distribution ("WR" configuration), it has been determined the best configurations (in terms of $nD$ and $E\_inj$) for several pipe radii $Rp$.

Results are presented in **Table 2**.

$B$ is still fixed to 5 T. Both half-toruses at the ends of the reactor have been considered as described in §2.2.8, so all the reactor is considered. It has been added the Beta factor (Appendix A part 2), the net electrical yield $Ye$ (§2.2.11.3) and the power amplification gain ($Gpa$) (§2.2.11.4).

The configurations with $Gpa \leq 1$ generate less electricity than they consume electricity. So only the configurations with $Rp$ equal or superior to 1.5 m must be considered. The best configuration is the one which gives the highest $Q$. It is found the best one for $Rp$ = 4.5 m. Note that the configuration with $Rp$ = 5 m is not very interesting due to a $Q$ inferior to the one at 4.5 m. The configuration with $Rp$ = 3 m is almost as well as the one with $Rp$ = 4.5m, but inferior for about Beta, SHP and SNP.

The conclusion is that such configuration (*i.e.* $Rp$ = 4.5 m) permits a relatively high mechanical gain ($Q$).

A D-D reactor can work on such conditions.

**Table 1.** Results for a physical model based on an IM distribution, the straight parts being only considered.

| *Rp* (m) | *nD* | *E_inj* (keV) | *Q* | *E_equi* (keV) | *Poutput* ($MW/m^3$) | *SHP* ($MW/m^2$) | *SNP* ($MW/m^2$) |
|---|---|---|---|---|---|---|---|
| 1 | 16E19 | 295 | 1.43 | 137 | 1.71 | 0.60 | 0.25 |
| 2 | 17E19 | 277 | 2.66 | 122 | 1.75 | 1.15 | 0.61 |
| 3 | 17E19 | 272 | 3.14 | 119 | 1.75 | 1.72 | 0.92 |
| 4 | 15E19 | 300 | 3.11 | 124 | 1.49 | 1.98 | 1.00 |
| 5 | 13E19 | 300 | 2.74 | 123 | 1.12 | 1.90 | 0.91 |

**Table 2.** Results for a physical model based on an MB distribution, the whole reactor being considered.

| *Rp* (m) | *nD* × 1E19 | *E_inj* (keV) | *Q* | *E_equi* (keV) | *Poutput* ($MW/m^3$) | *SHP* ($MW/m^2$) | *SNP* ($MW/m^2$) | *Beta* | *Ye* | *Gpa* |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 45 | 46 | 2.53 | 42 | 7.855 | 1.97 | 1.52 | 0.419 | −0.073 | 0.828 |
| 1.5 | 34 | 37 | 6.15 | 52 | 5.330 | 1.80 | 1.90 | 0.396 | 0.106 | 1.433 |
| 2 | 25 | 38 | 9.91 | 72 | 4.017 | 1.79 | 1.95 | 0.419 | 0.166 | 1.900 |
| 2.5 | 20 | 38 | 13.36 | 89 | 3.192 | 1.82 | 1.92 | 0.425 | 0.194 | 2.233 |
| 3 | 17 | 37 | 17.07 | 104 | 2.704 | 1.92 | 1.92 | 0.431 | 0.212 | 2.518 |
| 3.5 | 14 | 43 | 13.65 | 102 | 1.800 | 1.55 | 1.46 | 0.347 | 0.195 | 2.257 |
| 4 | 13 | 43 | 15.80 | 116 | 1.780 | 1.80 | 1.62 | 0.378 | 0.211 | 2.499 |
| 4.5 | 12 | 45 | 17.27 | 122 | 1.599 | 1.87 | 1.61 | 0.371 | 0.212 | 2.532 |
| 5 | 11 | 49 | 15.72 | 123 | 1.352 | 1.79 | 1.49 | 0.342 | 0.206 | 2.421 |

### 3.3. Determination of the Different Acceptable D-D Reactors

It will be determined the dimensions *r*, *W*, *L* and *H* (Figure 2 in §2.1), the reactor volume (§2.2.8.4) and the net electrical power supplied by the plant (*Pe_plant*) (§2.2.11.5), for all the acceptable configurations defined in §3.2. Results are presented in Table 3 below.

With:

$r = 3 \times Rp$ by hypothesis made in the §2.2.8.4.

$W = 2 \times r$ (see Figure 2 in §2.1).

$L = 30 \times \pi \times Rp$ (Equation (8.6)).

$H = L + 2 \times r = L + W$ (see Figure 2).

$Vreactor = 66 \times \pi^2 \times Rp^3$ (Equation (8.8)).

$Pe\_plant = Vreactor \times Poutput \times Ye$ (Equation (11.6)), in MW as *Poutput* is here in $MW/m^3$.

It can be seen that the net power supplied by the plant can be between 1243 and 22,684 MW. However the best choice is, a priori, the reactor with *Rp* = 4.5 m which has the best *Q*, *Ye* and *Gpa* with a high net power *Pe_plant* (about 20 GW). Note that a smaller reactor with *Rp* = 3 m (instead 4.5 m) would give 10 GWe.

Note about a Bohm scaling

For the best configuration (*Rp* = 4.5 m), it has been supposed a Bohm scaling for the *Tct* calculation made previously by the Equation (8.2). For this, it has been used the Equation (8.1).

**Table 3.** Dimensions, powers and yield of the reactor according to different radiuses.

| *Rp* (m) | *r* (m) | *W* (m) | *L* (m) | *H* (m) | *Vreactor* ($m^3$) | *Poutput* ($MW/m^3$) | *Ye* | *Pe_plant* (MW) |
|---|---|---|---|---|---|---|---|---|
| 1.5 | 4.5 | 9 | 141.4 | 150.4 | 2198 | 5.330 | 0.106 | 1243 |
| 2 | 6 | 12 | 188.5 | 200.5 | 5211 | 4.017 | 0.166 | 3480 |
| 2.5 | 7.5 | 15 | 235.6 | 250.6 | 10178 | 3.192 | 0.194 | 6295 |
| 3 | 9 | 18 | 282.7 | 300.7 | 17588 | 2.704 | 0.212 | 10063 |
| 3.5 | 10.5 | 21 | 329.9 | 350.9 | 27928 | 1.800 | 0.195 | 9828 |
| 4 | 12 | 24 | 377.0 | 401.0 | 41689 | 1.780 | 0.211 | 15623 |
| 4.5 | 13.5 | 27 | 424.1 | 451.1 | 59358 | 1.599 | 0.212 | 20156 |
| 5 | 15 | 30 | 471.2 | 501.2 | 81424 | 1.352 | 0.206 | 22684 |

After calculation, it is found *nD* = 14E19, *E_inj* = 49 keV, *E_equi* = 100 keV, *Beta* = 0.338, *Q* = 11.17 (instead 17.27), *Poutput* = 1.775 $MW/m^3$ (instead 1.599 $MW/m^3$), *Ye* = 0.178 (instead 0.212) and *Pe_plant* = 18768 MW (instead 20156 MW). The results are degraded, as expected (cf. §2.2.8.3).

### 3.4. Discussion and Points to Deepen

In the §3.3, it has be shown that a plant supplying between 1.2 and 22 GWe, based on a D-D reactor, is possible. The best choice is the configuration with *Rp* = 4.5 m which would deliver 20 GWe.

However, it has been shown that a Bohm scaling would degrade the performance of such reactor.

It must be noticed that for the *Rp* = 4.5 m configuration, for about the power produced by the neutrons (*i.e.* 47.4% of *Pfusion*), 73.3% of this power is in the form of 14.06 MeV neutrons issued from D-T fusion, the rest being 2.45 MeV neutrons issued from the D-D fusion and comparable to fission neutrons. So from the total SNP equal to 1.61 $MW/m^2$, the *SNP* relative to the 14.06 MeV neutrons is only equal to 1.18 $MW/m^2$.

Now the calculation is a rough estimation of the possibility of such D-D reactor and, above all, this design is based on many hypotheses. Regarding a more detailed study, all the hypotheses of this article would have to be deepen, included the points of [2] §3.2.2.5.

Below is a list of the main points to deepen.

- The most problematic point is the real magnitude of energy loss in both half-toruses for plasma at high energy (*E_equi*), as explained in §2.2.8.3. The worst case is the "$1/\gamma$ regime" as described in 2.2.8.3.2 which leads to $Tct \sim Tplasma^{-3.5}$. Such extrapolation will prevent any working of such reactor except if the effective helical ripple expressed by the coefficient $\varepsilon_{eff}$ in [17] page 222 would be drastically reduced, thanks to a strong optimization of the magnetic field.
- The non-turbulent radial diffusion of the particles inside the straight pipes might be confirmed. Indeed, in Appendix A, the radial diffusion has been

considered as classical. Diamagnetism has been considered, but without any turbulences, because implicitly the toroidal magnetic field is supposed perfect. However, modulation of this field by the discrete toroidal coils is possible.

• Another tricky point is the real permanent consumption of the cryogenic equipment aimed to cool the magnetic coils, this because the D-D reactor is very long. Therefore the surface to thermally insulate is very large, which is a challenge for a reasonable cryogenic energy cost (see §2.2.11.3).

• The Beta factor (Appendix A part 2) is much superior to the classical Beta used on Tokamaks and Stellarators, *i.e.* in general $Beta \leq 5\%$. Here the sole limit is $Beta \leq 50\%$, taken into account for the whole reactor calculation. It could be necessary to see the consequence on the energy loss rate in both half-toruses of such high Beta factor. However, note that for the best configuration ($Rp = 4.5$ m in §3.2), the Beta factor is only equal to 37%.

• The hypotheses made about the deceleration of fusion ions in Appendix E might be refined. In particular, the time of deceleration of fusion ions by electrons (*Tde*) is relatively long for the protons (see Appendix E). For this deceleration by the electrons, the radial transport has been neglected. However, inside both half-toruses the behavior is more uncertain due to turbulence, so it is possible that this hypothesis does not apply on both semi-torus, which would decrease the plasma heating.

• About the cyclotronic radiated power due to electrons turning on their orbits around axial magnetic lines, it has been made, in §2.2.7, the hypothesis that 1% of the cyclotronic radiation is lost, the rest being absorbed by other electrons of the plasma. This hypothesis, realistic for tokamaks, might be checked for high energies plasma, *i.e.* about 120 keV, as for the best configuration ($Rp = 4.5$ m in §3.2).

• It has been taken the hypothesis, in §2.2.10, that the mean *SHP* and *SNP* must not pass 2 MW/m$^2$. However it is clear that all along the reactor the *SNP* (surface neutrons power) will be more or less constant. However, due to the high losses on the half-toruses wall, the local *SHP* (surface heat power) will be much more important in the half-toruses than in the straight pipes. This point is also related to the first point to deepen (real loss of energy in half-toruses). One solution is, perhaps, to have a less elevated *RatioL* (§2.2.8.4), supposed initially equal to 10.

Other points:

• The filling of the reactor will need very big ions and electrons sources (see §2.2.4.6 of [2]), due to the very big volumes to fill (see §3.3). The filling will have to take into account the losses during this filling, the goal being to fill the reactor more rapidly than the losses empties the reactor. A filling of 0.3 s as expected in the §2.2.4.6.2 of [2] is, in any case, much too short for such reactor.

• Due to the very large volume to empty down to 10 nPa, the UHV equipment to expect must be very important and surely not common.

• It would be interesting to more precisely estimate the real proportion of thermalized ions in plasma (§2.2.1 and §2.2.2), as it is supposed 100% for the whole reactor calculation, based on a MB distribution. It would also be interesting to estimate the real MB distribution (see §2.2.6.1) and to take into account the opposite collinear collisions in the calculation (see §2.2.1) and the non-total isotropy (Appendix C) relatively to Coulomb collisions and fusions.

• A more precise estimation of the losses by charge exchanges (§2.2.4), for all the ions, would be welcome.

• In this document, it has not been taken into account that part of the kinetic energy of ions fusing normally adds to the kinetic energy of neutrons (see Appendix B). Such consideration would have been possible, supposing that the exact allocation of this energy between fusion products had been known which was not the case. Such consideration would be interesting in a more detailed analysis

### 3.5. Improvement of the Reactor with a Small Addition of Helium 3, Fetched from the Tritium and the Helium3 Lost by This D-D Reactor

Even if this reactor is able to work, an improvement would be to inject some He3+ to the reactor. The advantages of such small addition injection (let's say 1% of He3+) would be:

• An improvement of the plasma heating which would lead to an injection of D+ ions at a lower energy ($E\_inj$) and so to an increase of the mechanical gain $Q$, the yield $Ye$ and the gain $Gpa$.

• The proportion of energy produced by neutrons will decrease, and correlatively the problem with materials.

The produced T+ and He3+ ions are lost by fusions, loss on the wall and charge exchanges, as described in §2.2.6.4. A large part of the He3 produced by the reactor is lost in the form of He3+ ions colliding with the wall and after charge exchanges. About half of the tritium produced by this D-D reactor is also lost by collisions on the wall and by charge exchanges.

For example, for the $Rp$ = 4.5 m configuration, the percentages of losses by collisions and charge exchanges, compared to the total losses, are equal to:

• 82% for He3+, whereas $nHe3/nD = 2.633\%$;

• 52% for T+, whereas $nT/nD = 2.650\%$.

Moreover, in both cases, about 38.5% of the T+ and He3+ ions produced in the reactor are lost due to charge exchanges.

Let's suppose that the sole neutral Tritium atoms issued from charge exchanges could be fetched. The Tritium decays in Helium 3 with a period of 12.32 years. So it can be considered that all the tritium will be transformed in Helium 3.

This He3, *i.e.* Tritium decayed in He3, could be re-injected in this D-D reactor. These 38.5% of He3 corresponds to a He3 partial pressure of about 1% of $nD$ ($\approx 2.633\% \times 0.385$).

A calculation has been made with an addition of 1% of He3. The results are compared with the standard configuration:

- *nD* = 11E19 and *E_inj* = 41 keV (instead 12E19 and 45 keV);
- *Q* = 19.01 (instead 17.27);
- *SNP* = 1.35E6 W/m$^2$ (instead 1.61E6 W/m$^2$);
- However *Pe_plant* = 18.5 GW (instead 20.2 GW), due to a lower *Poutput* (1.429E6 MW/m$^3$ instead 1.599E6 MW/m$^3$).

The mechanical gain is a bit superior and the *SNP* a bit inferior to the standard configuration (§3.2), as expected.

Of course a bigger addition than 1% of Helium 3 will be better, but there is no solution on Earth as He3 does not exist in nature.

Note that if all the lost T+ and He3+ ions could be recovered in form of neutrals, in addition to the Tritium atoms and, possibly, to the Helium 3 atoms lost by charge exchanges, and if the tritium will be decayed in Helium 3, the maximum additional He3 partial pressure would be equal to about 3.5% of the *nD* pressure (for the *Rp* = 4.5 m configuration).

Note that, according to [19] pages 6 and 7, another possibility is to partly remove the generated Tritium. This removed Tritium will be decayed in He3 and then re-injected in this reactor. So the 14.1 MV neutron flow will be decreased and the first wall lifetime increased. The He3 injected will partly compensate the loss of power due to the removal of Tritium.

### 3.6. Improvement of the Reactor Using an Almost-MB Distribution to Inject Particles

The progressive thermalization of D+ ions and electrons will take place after 0.8 s (§2.2.2), depending on the plasma energy, the time to thermalize decreasing when the plasma energy (*E_equi*) decreases, because the Coulomb collisions frequency increases.

Now, the chapters §3.1 and §3.2 shows that plasma following a MB distribution is a necessary condition for a functional D-D reactor.

If the time to thermalize becomes critical, it would be possible to inject particles (electrons and D+ ions) in an almost-MB distribution (referred to speeds, the direction being still rectilinear along the pipe), so as to accelerate the thermalization. Of course, it is not possible to inject particles following a strict MB distribution, but probably in a reasonable range of values (let's say 1/3 to 3 times the average squared speed).

## 4. Conclusions

After a description of the reactor in §2.1 at the level of principle, the D-D reactor has been modeled in §2.2, in two configurations:

- The "SP" one, for the straight pipes, using an IM distribution, is more simple but not realistic because a progressive thermalization takes place in the reactor.
- The "WR" one, for the whole reactor, uses an MB distribution.

In §3.1, for the sole straight parts and considering an IM distribution, this model has been checked by comparison with the simulator results. Afterwards, it has been calculated the fusion reactor for different radii. The results show a very low mechanical gain (*Q*), which prevents any D–D reactor to work in such conditions.

In §3.2, the whole reactor has been analyzed for different radii. The results show that the MB distribution permits a relatively high mechanical gain (*Q*). A D-D reactor can work on such conditions.

The dimensions of a 20 GWe plant based on this type of reactor have been estimated. It is compatible with an industrial plant (*i.e.* ≤ 500 m). Indeed, §3.3 shows that a reactor of a radius $Rp = 4.5$ m, a width of 27 m and a length of 451 m would be able to supply 20 GWe of net electrical power, with a reasonable mechanical gain, *i.e.* $Q = 17$ and an amplification power gain (*Gpa*) superior or equal to 2, using a thermodynamic conversion.

Due to the diverse hypotheses taken in this document, the §3.4 lists a certain number of points to deepen.

The §3.5 shows how this D-D reactor can be boosted by a small addition of He3. This one could be fetched from the Tritium and the Helium 3 produced and lost in the reactor, given that the Tritium decays in Helium 3 with time.

The §3.6 shows how to accelerate the thermalization of the injected particles, given that a MB distribution of the ions speeds is the key for a functional D-D reactor.

These results are orders of magnitude but sufficient to consider the possibility of a functional D-D fusion reactor, necessarily very powerful. Even if many points relative to this type of reactor would have to be detailed (§3.4), it must be taken into account that Deuterium is an almost inexhaustible source of energy (§1.1).

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

## References


[1] (2022) bp Statistical Review of World Energy. 71st Edition. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

[2] Lindecker, P. (2022) Progressive Thermalization Fusion Reactor Able to Produce Nuclear Fusions at Higher Mechanical Gain. *Energy and Power Engineering*, **14**, 35-100. https://doi.org/10.4236/epe.2022.141003

[3] Guidini, J. (1962) Mesure des sections efficaces d’échange de charge et de dissociation des ions $H_2^+$ dans une large gamme d’énergie (25 - 250 keV). Rapport CEA n˚2135-1962.

[4] Rax, J.-M. (2011) Physique des tokamaks. Editions de l’Ecole Polytechnique.

[5] IAEA Library. ENDF/B-VIII.0 Sub-Library:[D], Incident-Deuteron Data, Mate-

rials:5 1-H-2 LANL EVAL-SEP01 G.M.HALE MT50 Table.
https://www-nds.iaea.org/exfor/servlet/E4sGetSect?SectID=8937861&req=14246

[6] IAEA Library. ENDF/B-VIII.0 Sub-Library:[D], Incident-Deuteron Data, Materials:5 1-H-2 LANL EVAL-SEP01 G.M.HALE MT600 Table.
https://www-nds.iaea.org/exfor/servlet/E4sGetSect?SectID=8937860&req=15881

[7] IAEA Library. ENDF/B-VIII.0 Sub-Library:[D], Incident-Deuteron Data, Materials:5 1-H-3 LANL EVAL-JAN95 G.M.HALE AND M.DROSG MT50 Table.
https://www-nds.iaea.org/exfor/servlet/E4sGetSect?SectID=8937867&req=14247

[8] IAEA Library. ENDF/B-VIII.0 Sub-Library:[D], Incident-Deuteron Data, Materials:5 2-He-3 LANL EVAL-FEB01 G.M.HALE MT600 Table.
https://www-nds.iaea.org/exfor/servlet/E4sGetSect?SectID=8937874&req=14248

[9] McNally Jr., J.R. (1979) Fusion Reactivity Graphs and Tables for Charged Particle Reactions. Oak Ridge National Laboratory. https://doi.org/10.2172/5992170

[10] Majeed, R.H. and Oudah, O.N. (2018) Achieving an Optimum Slowing-Down Energy Distribution Functions and Corresponding Reaction Rates for the (D+$^3$He and T+$^3$He) Fusion Reactions. *AIP Conference Proceedings*, Beirut, 1-3 February 2018, Article 030048. https://doi.org/10.1063/1.5039235

[11] Moisan, M. and Pelletier, J. (2014) Plasmas Collisionnels. EDP Sciences.

[12] Rider, T.H. (1995) A General Critique of Inertial-Electrostatic Confinement Fusion Systems. *Physics of Plasmas*, **2**, 1853-1872.
https://doi.org/10.1063/1.871273

[13] Bobin, J.-L. (2011) La fusion thermonucléaire controlee. EDP Sciences.

[14] Beidler, C.D., *et al.* (2001) The Helias Reactor. *Nuclear Fusion*, **41**, 1759.
https://doi.org/10.1088/0029-5515/41/12/303

[15] Murari, A., Peluso, E., Spolladore, L., Vega, J. and Gelfusa, M. (2022) Considerations on Stellarator's Optimization from the Perspective of the Energy Confinement Time Scaling Laws. *Applied Sciences*, **12**, Article 2862.
https://doi.org/10.3390/app12062862

[16] Fuchert, G., Beurskens, M.N.A., Bozhenkov, S., Warmer, F., Brunner, K.J., Dinklage, A., Hacker, P., Hirsch, M., Knauer, J., Langenberg, A., Pasch, E., Rahbarnia, K., Zhang, D. and Wolf, R.C. (2020) Energy Confinement in W7-X, More Than just a Scaling Law. Preprint 1334 (IAEA-EX/P6-16).

[17] Beidler, C., *et al.* (2021) Demonstration of Reduced Neoclassical Energy Transport in Wendelstein 7-X. *Nature*, **596**, 221-226.
https://doi.org/10.1038/s41586-021-03687-w

[18] Miyamoto, K. (1980) Plasma Physics for Nuclear Fusion. MIT Press, Cambridge, MA. https://doi.org/10.1063/1.2914166

[19] Sheffield, J. and Spong, D.A. (2016) Catalyzed D-D Stellarator Reactor. *Fusion Science and Technology*, **70**, 36-53.
https://www.osti.gov/servlets/purl/1261560

[20] Chéron, B. (2001) Théorie cinétique—Gaz et plasmas. Ellipses.

## Appendix A

**Determination of the time for D+ ions and electrons to collide the pipe wall**

**Generalities about this appendix**

The parts 1 and 2 of this appendix only apply to the straight pipes of the reactor. These pipes form a cylindrical configuration where the magnetic field can be considered as uniform. Consequently, the radial transport can be considered as a "classical" one, *i.e.* only determined by collisions between particles in a uniform magnetic field, as described below.

The part 3 of this appendix takes into account the confinement time estimated for D+ ions (and electrons) in both half-toruses of the reactor, so as to determine a mean value of the confinement time for D+ ions *TDexp*, applicable to the reactor.

**Part 1: Theoretical values of the classical transport of electrons and ions in straight pipes**

To calculate the radial diffusion coefficient, it is implicitly supposed that plasma fills a volume having inside variations of density, without plasma frontier. Under this condition, collisions between particles of the same kind, *i.e.* either D+ ions or electrons, cannot lead to a diffusion because the variations of speed after collisions are symmetrical so the sum of the exchanges of impulse between the same particles is nil (*i.e.* there is no force of viscosity) and there is no variation of the overall speed. Only collisions between different kinds of particles can lead to this type of diffusion. In our case, the two main kinds are D+ ions and electrons.

$\alpha$ being the projectile and $\beta$ being the target, from the Langevin equation (cf. [11] page 161 (3.129)), at stability, without electric field and neglecting the viscosity with neutrals, it can be written:

$$0=\left(q\times \boldsymbol{V\alpha}\wedge \boldsymbol{B}\right)-\left(Kb\times T\alpha\times\frac{\nabla n\alpha}{n\alpha}\right)-\left(\mu\alpha\beta\times\gamma\alpha\beta\times \boldsymbol{w\alpha\beta}\right)$$

"$\wedge$" is the vector product operation. The reduced mass $\mu\alpha\beta$ is equal to $\mu\alpha\beta=\dfrac{m\alpha\times m\beta}{m\alpha+m\beta}$.

The relative speed $\boldsymbol{w\alpha\beta}$ is equal to $\boldsymbol{w\alpha\beta}=\boldsymbol{V\alpha}-\boldsymbol{V\beta}$.

For about the transport of electrons, the speed of ions is negligible compared with the speed of electrons so

$$\boldsymbol{w\alpha\beta}\approx\boldsymbol{V\alpha}.$$

Moreover, for both transports (electrons and ions), the vector $\boldsymbol{V\beta}$ is supposed isotropic relatively to the direction of the vector $\boldsymbol{V\alpha}$. Consequently, the mean value of $\boldsymbol{w\alpha\beta}$ is $\boldsymbol{V\alpha}$, which permits to satisfy the hypothesis $V\beta = 0$ (so the term of viscosity by collisions on the ions $\beta$ $\mu\alpha\beta\times\gamma\alpha\beta\times\boldsymbol{w\alpha\beta}$ is equal to $\mu\alpha\beta\times\gamma\alpha\beta\times\boldsymbol{V\alpha}$).

**Transport of electrons**

$\alpha$ particles are electrons ("e") and $\beta$ particles are D+ ions ("D"). Taking into account that the mass of electrons is much lighter than the mass of D+ ions, then $\mu eD=\dfrac{me\times mD}{me+mD}\approx me$ $\quad 0=\left(q\times\boldsymbol{Ve}\wedge\boldsymbol{B}\right)-\left(Kb\times Te\times\dfrac{\nabla ne}{ne}\right)-\left(me\times\gamma eD\times\boldsymbol{Ve}\right)$ so

$$\boldsymbol{Ve} = \frac{1}{me \times \gamma eD}\left[\left(q \times \boldsymbol{Ve} \wedge \boldsymbol{B}\right) - \left(Kb \times Te \times \frac{\nabla ne}{ne}\right)\right].$$

This equation is similar to the one shown in [11] page 172 (3.172), so its resolution is the one described in [11] pages 173 to 176.

It will be calculated the radial diffusion coefficient for electrons, which is associated to the flow of electrons.

Taking into account that the cyclotronic pulsation $\omega c$ ( $wc = \frac{q \times B}{m}$ ) is very superior to the collision frequency $\gamma eD$ in a fusion plasma, the radial diffusion coefficient of electrons can be written ([11] page 176 and [4] page 87):

$$DreD = \frac{kb \times Te \times \gamma eD \times me}{\left(q \times B\right)^2}.$$

Now $kb \times Te = \frac{E\_equi(\text{eV}) \times q \times 2}{3}$ and for a MB distribution

$\gamma eD = \frac{1.6\text{E}-15 \times ne}{Te(\text{keV})^{1.5}}$ (cf. [4] page 71)

With $Te(\text{keV}) = \frac{E\_equi(\text{eV}) \times 2}{3000}$ it follows $\gamma eD = \frac{9.3\text{E}-11 \times ne}{E\_equi(\text{eV})^{1.5}}$ (Equation (A0))

So $DreD = \frac{3.52\text{E}-22 \times ne}{B^2 \times \sqrt{E\_equi(\text{eV})}}$

**Transport of D+ Ions**

$\alpha$ particles are D+ ions ("D") and $\beta$ particles are electrons ("e").

It can be written $\boldsymbol{VD} = \frac{1}{me \times \gamma De}\left[\left(q \times \boldsymbol{VD} \wedge \boldsymbol{B}\right) - \left(Kb \times TD \times \frac{\nabla nD}{nD}\right)\right]$

For a neutral plasma at equilibrium: $TD = Te$ and $nD \approx ne$. As $\gamma De = \gamma eD$ (cf. [11] pages 454 and 455), it comes:

$$DrDe = \frac{kb \times TD \times \gamma eD \times me}{\left(q \times B\right)^2} = \frac{3.52\text{E}-22 \times ne}{B^2 \times \sqrt{E\_equi(\text{eV})}}.$$

So $DrDe = DreD$, *i.e.* the classical electrons transport by collisions with ions ($DreD$) is equal to the classical ions transport by collisions with electrons ($DrDe$).

**Theoretical time for D+ ions and electrons to collide the pipe wall in straight pipes**

Let's calculate the time $TDDe$ for a D+ ion to come from the center of the pipe to the wall. As the pipe has a cylinder form, it can be written $TDDe = \frac{\Delta^2}{DrDe}$ (cf. [11] page 199) with, for a long cylinder $\Delta = \frac{Rp}{2.405}$ (cf. [11] page 185). With $Rp$, the radius of the inner wall of the pipe. So

$$TDDe = \frac{Rp^2}{5.784 \times DrDe} = 4.9\text{E}20 \times \frac{Rp^2 \times B^2 \times \sqrt{E\_equi(\text{eV})}}{ne}.$$

$TDDe$ is also applicable for electrons ($TDeD$).

Let's estimate $TDDe$. For example, let's suppose a Tokamak as ITER with $Rp$

= 2 m, ne supposed equal to 1E20, *E_equi* = 20,000 eV, *B* = 5.3 T. The formula for *TDDe* gives *TD* = 77,860 s, which can be compared with the average value of 3.4 s for ITER (for all the energy lost not only due to the lost particles).

In fact, for a tore as used by tokamaks, the transport is closer to the Bohm transport and is surely much more turbulent than on a straight pipe. However, this "classical" transport of electrons and D+ ions, even for a straight pipe is extremely weak.

**Part 2: Consideration of the other types of transport**

When the beam is injected in the reactor, there is a plasma frontier around the beam. Ions and electrons turn in a cyclotronic movement around their guiding center, at a radius called "Larmor radius". For each collision, there is a certain displacement of both guiding centers. After a collision between two particles located at the plasma frontier, one particle can cross the frontier, so the frontier will be gradually displaced. Once the inner wall is reached, the frontier is this wall. If a particle crosses the frontier after a collision, it is lost on the wall. Consequently, it must also be considered:

- The transport of D+ ions by collisions on D+ ions.
- The transport of electrons by collisions on electrons.

This diffusion seems to a Brownian diffusion, except that it concern ions of the same specie instead neutrals of the same specie and Coulomb collisions instead collisions between neutrals. As Coulomb collisions are also elastic, a pseudo-Brownian diffusion could be considered.

For a Brownian diffusion: $R(t)=\sqrt{Dr\times t}$ ([20] page 54) with *R* the radius of the volume of the particles at the time *t* and *Dr* the radial diffusion coefficient equal normally to $Dr=\frac{\langle V\rangle\times\langle\lambda\rangle}{3}$ ([20] page 53).

It will be supposed that the radial diffusion is a pseudo-Braginsky coefficient, so equal to $Dr=\frac{kb\times T\times\gamma\times m}{(q\times B)^2}$ ([4] page 87). This formula will be applied to electrons and ions below.

Let's calculate the diffusion time *TD* for an ion or an electron, to come from the center of the pipe to the wall (at the radius *Rp*). $Rp=\sqrt{Dr\times TD}$ so $TD=\frac{Rp^2}{Dr}$

**Transport of electrons by collisions with other electrons**

The diffusion coefficient is equal to: $Dree=\frac{kb\times Te\times\gamma ee\times me}{(q\times B)^2}$

With $\gamma ee=\gamma eD\times\sqrt{2}$ (cf. [11] page 455), so $Dree=\frac{4.99\text{E}-22\times ne}{B^2\times\sqrt{E\_equi(\text{eV})}}$.

And $TDee=\frac{Rp^2}{Dree}=2.01\text{E}21\times\frac{Rp^2\times B^2\times\sqrt{E\_equi(\text{eV})}}{ne}$.

**Transport of D+ Ions by collisions with other D+ ions**

The diffusion coefficient is equal to: $DrDD=\frac{kb\times TD\times\gamma DD\times mD}{(q\times B)^2}$.

With $\gamma DD = \gamma ee \times \sqrt{\frac{me}{mD}}$ for $Te = TD$ (from [11] page 455), so $DrDD = \frac{3.02\text{E}-20 \times nD}{B^2 \times \sqrt{E\_equi(\text{eV})}}$.

And $TDDD = \frac{Rp^2}{DrDD} = 3.31\text{E}19 \times \frac{Rp^2 \times B^2 \times \sqrt{E\_equi(\text{eV})}}{nD}$.

Note: the ratio between *DrDD* and *Dree* ( $= \sqrt{\frac{mD}{me}} = 60.6$ ) is equal to the ratio between their respective Larmor radius.

**Comparison between the different types of transports of particles**

It can be noted that *TDDD* for ions is very inferior to *TDee*, *TDeD* and *TDDe*: by a factor 60.6 for *TDee* and by a factor 14.8 for *TDed* and *TDDe*. So the radial diffusion coefficients *Dree*, *DreD* and *DrDe* will be neglected. Therefore, on the straight pipes, the diffusion of electrons will be neglected. Consequently, as no electrons will be supposed lost, the replacement particles to inject will only be D+ ions.

To abstract the behavior of each particle:

- D+ ions diffuse towards the wall due to collisions with the other ions.
- Electrons catch up ions through the ambipolar potential.

**Taking into account the diamagnetism**

The losses are in fact multiplied by a certain factor due to the diamagnetism. The diamagnetism, which opposes a magnetic field to the main toroidal field *B*, is taken into account by Multiplasma in a simplified way. Indeed, the high density of replacements D+ ions within the beam injected at the center of the pipe introduces some diamagnetism which makes locally decrease the magnetic field. So the confinement at the center of the pipe is not so good. The confinement came back to the normal when the distance of the center of the pipe increases. This loss of confinement can strongly make increase the particles loss on the wall.

The Beta factor for a local density of D+ ions called "*nD_local*" would be a way to measure the diamagnetism for the simulator

$$Beta = \frac{5.369\text{E}-25 \times nD\_local \times E\_equi(\text{eV})}{B^2}$$

Now for about the calculation, the *nD_local* is not known and it must also be considered the fusion ions. So it will be considered the electrons density ne (from the Equation (7.2) of §2.2.7) rather than *nD* and a mean *Beta*:

$$Beta = \frac{5.369\text{E}-25 \times ne \times E\_equi(\text{eV})}{B^2} \quad \text{(A1)}$$

For *Beta* = 0 there is no diamagnetism which is the best case. At *Beta* = 0.5, the local magnetic field *B* is reduced to 50% of the initial magnetic field. For the "WR" configuration only, beyond *Beta* = 0.5, the results of the calculation are considered as not pertinent.

Stellarators and tokamaks respect, in general, a maximum *Beta* of about 5%. It is not possible to respect such limit for this D-D reactor because the plasma energy (*E_equi*) is at least 5 times higher than in a D-T reactor (100 keV minimum versus 20 keV).

**Formula to determine the particles loss on the wall taking into account the diamagnetism**

After experimentation, it has been determined the number of ions lost by the simulator according to the different parameters. From these data, it has been determined the experimental TDexpsp, *i.e.* the ratio between the number of packets of ions permanently inside the reactor to the flow of packet of ions lost on the wall by second. It corresponds to the lifetime of a D+ ion issued from the center of the pipe, regarding loss on the wall, for the straight pipes. Note that the uncertainty of this formula (Equation (A2)) is rather important (about—60%/+120%), above all when the Beta is superior to 0.5.

The number of Coulomb central collisions taken into account by the simulator is in fact much more numerous than the one given by *γeD* in Equation (A0), this because the Coulomb collisions occur inside the Debye sphere, with effects which become very small with the distance between ions. For this reason, the simulator gives a confinement time TDexpsp about 109 times less that the theoretical TDDD. Moreover, the necessary very high simulator amplification of the Coulomb cross-section leads to a scaling on $B$ rather than on $B^2$.

The diamagnetism makes slowly increase the losses on the wall up to *Beta* = 0.5 (with a mean multiplicative factor ≈ 2) and rapidly above *Beta* = 0.5. The formula below (Equation (A2)) supposes that the effect of the diamagnetism really begins at *Beta* = 0.5 (through the "Max" term). However, for the whole reactor ("WR") calculation, if the final stabilized configuration is such that *Beta* > 0.5, this configuration is not taken into account for the final choice of the best configuration.

$$TDexpsp = \frac{1.81\text{E}18 \times Rp^2 \times B \times \sqrt{E\_equi(\text{eV})}}{ne \times Max\left[1, 125 \times (Beta - 0.3)^3\right]} \quad \text{(A2)}$$

To simplify, *ne* (§2.2.7) is considered rather than *nD* to take into account the fusion ions.

This lifetime must be the most elevated possible, which is the case:

- if the confinement is very good thanks to a high magnetic field,
- and if the pipe radius is very large so to have a long time radial travel inside the pipe.

This formula will apply to the IM distribution. It will also be supposed applicable to the MB distribution. The magnitude of the real confinement time is probably superior and so better than *TDexpsp*, except if turbulences, due to a loss of uniformity of the magnetic field, occur in the straight pipes. It is, a priori, not supposed. No heat transfer is considered for straight pipes.

For the same example as the one used in part 1, *TDexpsp* = 54 s which is still very high, compared to the 3.4 s of ITER.

**Part 3: Consideration of the loss of energy in both half-toruses of the**

**reactor to calculate the mean confinement time *TDexp* for D+ ions, for the whole reactor**

The confinement time *Tct* associated to the loss on the half-torus at each end of the reactor is estimated by the Equation (8.2) in §2.2.8.3.c. It is the equivalent of *TDexp* (but applicable to all particles).

After several developments, for a D+ ion circulating through the straight pipes of volume *VSP* and through both half-toruses of volume *VT*, the mean value of the confinement time (*TDexp*) is equal to: $TDexp = \frac{(VSP + VT) \times (TDexpsp \times Tct)}{(VSP \times Tct) + (VT \times TDexpsp)}$.

*VSP*, *VT* and *VSP* + *VP* are defined in §2.2.8.4 as multiples of $6 \times \pi^2 \times Rp^3$ (Equations (8.5) and (8.7)). So, it can be deduced:

$$TDexp = \frac{TDexpsp \times Tct \times 11}{(10 \times Tct) + TDexpsp} \tag{A3}$$

## Appendix B

### D-D reactor energy balance

This Appendix shows, in a general way, how the D-D reactor energy balance is taken into account in this paper. The main goal is to determine the mechanical gain (*Q*) of the D-D reactor. The following **Figure B1** summarizes the reactor energy balance relatively to the power plant.

As an introduction, in **Table B1** above are summarized the behavior of each particle (from the birth to the loss). Note that strictly speaking, photons are also lost by the diverse radiations (see *Pra* below).

Note that powers, in this appendix, are implicitly referred as densities of power in W/m$^3$. There are all positive.

**Table B1.** Summarized behaviors of all the particles used in this article.

| Characteristic | Electron | D+ ion | T+ ion | Proton | He3+ ion | He4+ ion | Neutron |
|---|---|---|---|---|---|---|---|
| Issued from fusion or injection | Injection | Injection | D-D | D-D and D-He3 | D-D | D-T and D-He3 | D-D and D-T 2.45 and 14.06 MeV |
| Loss on wall during deceleration (fusion ions) | No | No | Yes from 1.01 MeV | Yes from 3.03 and 14.67 MeV | Yes from 0.82 MeV | Yes from 3.52 and 3.67 MeV | No |
| Plasma heating | Only replacement electrons, from *E_inj* | Only replacement ions, from *E_inj* | Yes from 1.01 MeV | Yes from 3.03 and 14.67 MeV | Yes from 0.82 MeV | Yes from 3.52 and 3.67 MeV | No |
| Fusions induced | No | D-D/D-T/D-He3 | D-T | No | D-He3 | No | No |
| Loss on wall from *E_equi* (after deceleration for fusion ions) | Only for half-toruses | Yes | Yes | Yes | Yes | Yes | No |
| Charge exchanges from *E_equi* | No | Yes | Yes | Yes | Yes | Yes | No |
| Loss by fusion from *E_equi* | No | Yes and to consider | Yes but not to consider | No | Yes but not to consider | No | No |

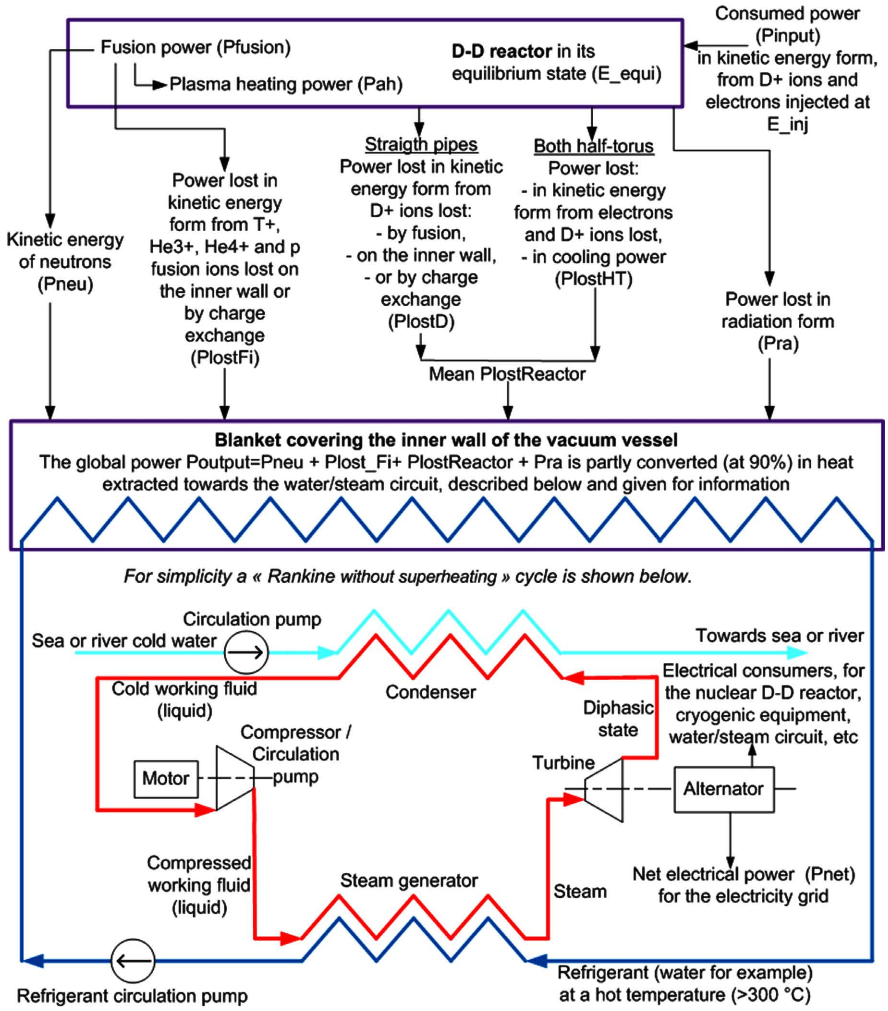


**Figure B1**. D-D reactor energy balance.

**Fusion power (*Pfusion*)**

The fusion power represents the total kinetic energy of the reaction products: neutrons and fusion ions, according to the primary and secondary fusion reactions (see §2.2.5) and to their frequencies. The fusion power (calculated in §2.2.9.2.d) can be shared in three parts:

$$Pfusion = PlostFi + Pah + Pneu \quad \text{(B1)}$$

About the kinetic energy of the fusion ions:

• A part is lost (*PlostFi* calculated in §2.2.9.2.a) on the pipe wall (including the Divertor) or by charge exchanges with neutrals.

• The rest heats the plasma (*Pah*) (§2.2.9.2.b).

The neutrons leave their kinetic energy mainly inside the blanket. The power *Pneu* is equal to:

$$Pneu = PfnDDm3 + PfnDTm3 \quad \text{(B2),}$$

with:

• $PfnDDm3$ the neutrons power from the D-D fusion (§2.2.6.1).

• $PfnDTm3$ the neutrons power from the D-T fusion (§2.2.6.3).

**Power lost by D+ ions (*PlostD*), only applicable to the straight pipes**

$$PlostD = q \times E\_equi(\mathrm{eV}) \times [QlwDm3 + QlceDm3 + QlfDDm3 + QlfDTm3 + QlfDHe3m3] \quad \text{(B3)}$$

The lost D+ ions leave their kinetic energy:

• By loss on the inner wall of the pipe. The loss rate is equal to $QlwDm3$ (§2.2.3.1),

• By charge exchanges with neutrals. The loss rate is equal to $QlceDm3$ (§2.2.4.1),

• By D-D fusions (a couple of D+ ions are involved for each D-D fusion). The loss rate is equal to $QlfDDm3$ (§2.2.6.2),

• By D-T fusions. The loss rate is equal to $QlfDTm3$ (§2.2.6.6),

• By D-He3 fusions. The loss rate is equal to $QlfDHe3m3$ (§2.2.6.6).

Note 1: the loss rates are in particles/(s × $m^3$).

Note 2: the kinetic energy of the D+ ions lost by D-D fusions is normally added to the neutrons energy and to the fusion ions energy. For about the neutrons, this additional energy is not taken into account (slightly pessimistic). For about the fusion ions, this additional energy is recovered on fusion ions after deceleration from $E\_equi$ by loss on the wall or by charge exchanges.

$E\_equi$ is the mean energy of the plasma (mainly D+ ions and electrons), at equilibrium, *i.e.* in the stabilized state of the reactor.

The electrons losses on the wall are neglected (see Appendix A part 2).

**Power lost on both half-toruses (PlostHT)**

For both half-toruses, an estimation based on Tokamaks and Stellarators has been done by the Equation (8.2) in §2.2.8.3 to determine the confinement time of energy ($Tct$), from which it has been determined $PlostHT$ in W/$m^3$ calculated by the Equation (8.3). This power covers the plasma loss of energy, due to both sources:

• loss of particles (ions and electrons),

• plasma cooling.

It will be considered that the loss of particles power ($PlossHTpar$) is equal to the plasma cooling power ($PlossHTcoo$), as the respective transports have about the same value (see [4] page 292).

So

$$PlostHTpar = PlossHTcoo = \frac{PlostHT}{2} \quad \text{(B4)}$$

**Mean power lost by the reactor (*PlostReactor*)**

The goal is to determine the mean density of power $PlostReactor$ (W/$m^3$) lost for the whole reactor.

According to §2.2.8.4, $VSP$ is the volume of the straight pipes and $VT$ is the total volume of both half-toruses (so the volume of a torus). It can be deduced that the mean power lost per $m^3$ is equal to:

$$PlostReactor = \frac{(PlostD \times VSP) + (PlostHT \times VT)}{VSP + VT}.$$

$VSP$, $VT$ and $VSP+VP$ are defined in §2.2.8.4 as multiples of $6\times\pi^2\times Rp^3$ (Equations (8.5) and (8.7)). So, it can be deduced:

$$PlostReactor = \frac{(PlostD\times 10)+PlostHT}{11} \quad \text{(B5)}$$

Note that when straight pipes are only considered, $PlostReactor = PlostD$ (Equation (B5bis)).

**Mean power lost by the reactor due to the sole loss of particles (*PlostReactorPar*)**

The goal is to determine the mean density of power in W/m$^3$ only due to the loss of particles, for the whole reactor:

$$PlostReactorPar = \frac{(PlostD\times 10)+PlostHTpar}{11} \quad \text{(B6)}$$

**Consumed power (*Pinput*)**

All the particles (D+ ions and electrons) lost at *E_equi* are replaced by the same particles but injected at *E_inj*, so the consumed power (W/m$^3$) is equal to:

$$Pinput = \frac{PlostReactorPar\times E\_inj}{E\_equi} \quad \text{(B7)}$$

Note that when straight pipes are only considered, *PlostD* must be used instead *PlostReactorPar*:

$$Pinput = \frac{PlostD\times E\_inj}{E\_equi} \quad \text{(B7bis).}$$

**Power lost by radiations (*Pra*)**

Pra is the radiation power lost due to Cyclotronic effects, Bremsstrahlung and impurities (§2.2.7), so equal to:

$$Pra = Pcym3 + Pbrm3 + Pimm3 \quad \text{(B8)}$$

**Equilibrium state of plasma**

The plasma inside the D-D reactor receives energy from particles injected to replace lost particles (*Pinput*) and from the plasma heating (*Pah*). It is cooled by radiations (*Pra*) and losses (*PlostReactor*).

At the equilibrium state of plasma inside the D-D reactor, the energy is stable at *E_equi*, if the following equality is checked:

$$PlostReactor + Pra = Pinput + Pah \quad \text{(B9)}$$

The *Pneu* and *PLostFI* powers are exterior to this equality because:

• They are issued from the fusion power which is taken from the ions density of mass *dm_ions* $Pfusion = \frac{d(dm\_ions)\times c^2}{dt}$ and not from the plasma itself.

• And they have no interaction with plasma.

A more general equation involving the mass of plasma and its variation would be possible, but it would be useless here.

Now, by running the Multiplasma simulator, it can be observed that:

• The final stability can be long to occur. Indeed, successive periods of pseudo-stability followed by a period of slow variation can occur. One minute of simulated time to reach the final stability for a pipe radius (*Rp*) of 0.8 m is the minimum. For a larger radius, a minimum time for stability equal to about $(Rp/0.8)^2$ minutes seems adequate.

• Even at the final stability, there is a slow oscillation around *E_equi* of several keV of magnitude.

**Mechanical gain (*Q*) and global output power (*Poutput*)**

The conventional mechanical gain (*Q*) is equal to the fusion power which divides the input power, *i.e.* in our case:

$$Q = \frac{Pfusion}{Pinput} \tag{B10}$$

However, from a thermodynamic point of view, the interesting power is the global output power supplied by the reactor (*Poutput*), *i.e.*

$$Poutput = Pneu + PlostFi + PlostReactor + Pra \tag{B11}$$

Once the equilibrium reached, thanks to the Equation B9 and B1, it can be written:

$$Poutput = Pneu + PlostFi + Pinput + Pah = Pfusion + Pinput \tag{B12}$$

Note that in a conservative way, it is not taken into account the energy issued from:

• the material irradiation. Note that this energy must be extracted when the reactor is stopped but this residual energy decreases with time.

• the reactions of the boron as absorber of neutrons (mainly a $\gamma$ of 0.48 MeV, a He4+ of 1.474 MeV and a Li7+ of 0.842 MeV).

Now this power (*Poutput*) is almost totally converted in heat inside the wall and the blanket covering the wall of the pipe, this heat being used by the water/steam circuit, to finally supply electricity thanks to a thermodynamic cycle. The blanket must permit to moderate neutrons down to the thermal energy and then to absorb them. The wall, the blanket and the vacuum vessel shield, must drastically mitigate the radiations energy. The wall (including the Divertor) will transmit to the blanket the heat produced by ions colliding the wall.

Due to the imperfect conversion and to the necessary openings for measuring devices, it will be supposed that the global efficiency *an* to recover the global output power *Poutput* for the water/steam circuit is equal to 90%. So 90% of Poutput is absorbed by the refrigerant crossing the steam generators, the rest being evacuated to the heat sink.

Note: the net electrical yield (*Ye*) of the water/steam circuit and the power amplification gain (*Gpa*) are calculated in §2.2.11

## Appendix C

**Study of the isotropization of electrons and D+ ions**

The goal of this appendix is to determine the time necessary to transform the initial monokinetic straight movement of the beams of electrons and D+ ions in isotropic movements (*i.e.* the direction of the movement is random).

It will be considered a threshold of 80% of isotropy in term of energy, for electrons and for D+ ions. So two isotropic times *Te_iso* (for electrons) and *TD_iso* (for D+ ions) will be estimated.

The isotropization is a consequence of Coulomb collisions between particles, each particle being diffused with a certain scattering angle (called $\theta$).

For D+ ions it will only be considered the collisions with the other D+ ions. The collisions with electrons lead to very weak scattering angles even if there are many. They will be neglected.

For electrons, to simplify, it will only be considered the collisions with the other electrons. Collisions with D+ ions will not be taken into account.

So both isotropic times will have to be considered as a bit greater than the reality, so a bit pessimistic.

Results are different from a configuration to the other. So for D+ ions, it has been simulated the following typical configuration: *Rp* = 3 m, *E_inj* = *E_equi* = 150 keV and *nD* = 12E-19. The D+ ions are injected along a straight pipe (y axis of **Figure 2**).

At each step, the level of isotropization (*Lis*) is calculated as:

$$Lis = \frac{(EDx + EDz) \times 3}{(EDx + EDy + EDz) \times 2}.$$

With *EDx*, *EDy* and *EDz* the mean energy of the D+ ions along x, y and z. (*EDx* + *EDz*) is the radial energy.

Initially *Lis* is close to 0% (*i.e.* *EDx* = *EDy* ≈ 0) but ad infinitum it tends to a value a bit below 100% due to replacement ions. Note that ideally at 100%: *EDx* = *EDy* = *EDz*.

The results for this configuration are the following:

- At 0.3 s, *Lis* = 8%;
- At 0.4 s, *Lis* = 38%;
- At 0.5 s, *Lis* = 56%;
- At 0.7 s: *Lis* = 71%;
- At 1.0 s: *Lis* = 81%;

So *TD_iso* = 1.0 s. Note that for *nD* larger the time *TD_iso* to reach 80% is smaller and reversely.

Now the behavior of electrons and D+ ions regarding the scattering angle is the same (without considering the relativity), either in the center-of-mass frame or in the laboratory frame, because the interactions are done between particles of the same mass. So the isotropization time only depends on the mean frequency of Coulomb collisions for one kind of particle ($\gamma ee$ for electrons and $\gamma DD$ for D+ ions). Therefore *Te_iso* can be calculated from *TD_iso* according to:

$$Te\_iso = \frac{TD\_iso \times \gamma DD}{\gamma ee}.$$

Lets' compare the Coulomb collisions frequencies of D+ ions ($\gamma DD$) and electrons ($\gamma ee$).

The particles being monokinetic at the initial energy *E_inj* = *E_equi*, it can be written, for an isotropic behavior:

- For electrons: $\gamma ee = ne \times \sigma ee(E\_inj) \times 1.333 \times Ve(E\_inj)$;
- For ions: $\gamma DD = nD \times \sigma DD(E\_inj) \times 1.333 \times VD(E\_inj)$.

With $nD$ the D+ ions density, ne the electrons density, $\sigma ee$ and $\sigma DD$ the Coulomb collision cross sections respectively for electrons and D+ ions, $Ve$ and $VD$ the respective speed of electrons and D+ ions.

For neutrality $ne = nD$. $\sigma ee \approx \sigma DD$ because electrons and D+ ions both carry one charge. $Ve$ is about 60 times $VD$ due the very small mass of an electron (9.11E-31 kg) compared to the D+ ion mass (3.34E-27 kg). So

$$\frac{\gamma ee}{\gamma DD} \approx \frac{Ve}{VD} \approx \sqrt{\frac{mD}{me}} \approx 60$$

So $\gamma ee \approx 60 \times \gamma DD$ and $Te\_iso = \frac{TD\_iso}{60} = 17 \text{ ms}$ which is very fast.

## Appendix D

**Thermalization of D+ ions with electrons/Speed of energy exchange**

**Part 1: Thermalization of D+ ions with electrons**

The goal of the first part of this appendix is to determine the number of electron-ion collisions necessary to reach 80% of thermalization and, afterwards, how much time is necessary to reach this threshold.

It is reminded that, at the theoretical 100% of thermalization, the distribution function of speeds is a Maxwell-Boltzmann one (see [11] page 435).

The method used for this task is a small program simulating plasma composed of 10,000 electrons and 10,000 D+ ions. The electrons are supposed to collide the D+ ions in any directions, the electrons behavior being isotropic (*i.e.* their direction of movement is random). There is no isotropic constraint on ions.

Note 1: for a D-T reactor (as the one proposed in [2]), it would also be necessary to take into account the thermalization between the D+ and the T+ ions.

Note 2: between the same particles, there is no thermalization, but only an isotropization.

Note 3: isotropization of electrons is obtained in about 17 ms, so almost instantly (see Appendix C).

According to the reference [11] page 52 formula (1.97), for a collision between two particles (here electrons --> D+), the energy $\Delta Ee$, won by the electron and lost by the D+ ion, is equal to

$$\Delta Ee = -\frac{me \times mD}{(me + mD)^2} \times (1 - \cos\theta) \times \left[2 \times Ee - 2 \times ED + (mD - me) \times (\mathbf{VD} \times \mathbf{Ve})\right]$$

With $me$ and $mD$ the respective masses of the electron and the D+ ion.

With $\mathbf{Ve}$ and $\mathbf{VD}$ the respective speed vectors of the electron and the D+ ion.

The energy of the electron ($Ee$) being equal to $Ee = \frac{me \times Ve^2}{2}$, it can be deduced that $Ve = \sqrt{\frac{2 \times Ee(\text{eV}) \times q}{me}}$.

The initial energy of electrons is called "*Eei*".

Note: to simplify, the relativity is not taken into account

The energy of the D+ ion (ED) being equal to $ED = \frac{mD \times VD^2}{2}$, it can be deduced that $VD = \sqrt{\frac{2 \times ED(\mathrm{eV}) \times q}{mD}}$.

The initial energy of D+ ions is called "*EDi*". Initially, it is supposed that *Ee* = *ED* = *Eei* = *EDi* = 10000 eV. In fact, any value will agree but a value is necessary for the simulation.

For about the scalar product $(\boldsymbol{VD} \times \boldsymbol{Ve})$, ***VD*** is supposed directed in the × direction, whereas ***Ve*** is supposed directed is any direction so the components of ***Ve*** on x, y and z are randomly chosen (with the condition that the module of ***Ve*** be maintained). Consequently, the scalar product is reduced to ***VD*** × ***Ve*** along x.

$\theta$ is the scattering angle in the center-of-mass frame. It is calculated according to the following way.

From the Coulomb collision cross section (see [11] page 453 (A5.46)) $\sigma cc = 4 \times \pi \times s0^2 \times \ln \Lambda$, with *s*0 the critical impact parameter and $\ln \Lambda$ the Coulomb logarithm ranged between 10 and 20 for a Tokamak plasma ([4] page 69) and so chosen equal to the mean value (=15). It is deduced the radius *Rcc* corresponding to this cross section: $Rcc = 7.746 \times s0$

The impact parameter *s* (see [11] page 446) is randomly chosen between 0 and *Rcc*.

The scattering angle $\theta$ is calculated from $\cot(\theta/2) = s/s0$ (see [11] page 450 (A5.32)) which gives $\theta = 2 \times Arctg(s0/s)$. Finally, from $\theta$ it is calculated $(1 - \cos\theta)$, used for the $\Delta Ee$ calculation above.

For each step of calculation, each of the 10,000 ions is submitted to a collision with an electron randomly chosen among the 10,000 electrons. The concerned electron and ion energies are updated after each step: $Ee = Ee + \Delta Ee$ and $ED = ED - \Delta Ee$. Then the *Ve* and *VD* speeds are updated from *Ee* and *ED*.

From the cumulative distribution function of kinetic energy (following the speeds Maxwell-Boltzmann (MB) distribution function) given in [20] page 26, it can be deduced that the probability that the particles energy be comprised between 0.8 and 1.2 times the initial *Eei* and *EDi* energies, is equal to 0.1856. Initially this probability is equal to 1. Then, step after step of calculation, it will gradually evolve from 1 towards 0.1856 as thermalization will take place. The final relative distance between the real probability and the theoretical probability (0.1856) will give the degree of thermalization.

Steps of calculations are repeated until to reach a degree of thermalization equal to 80%. It has been found that 158 electron-ion collisions are necessary to reach this threshold of 80%.

Note: it has also been found that 18 collisions are necessary to reach 25% of thermalization, 43 for 50%, 304 for 90% whereas 100% of thermalization would be obtained ad infinitum.

Now let's calculate the time before thermalization which is considered when the threshold of 80% is reached.

It is known that $\langle \gamma eD \rangle = nD \times \langle \sigma eD(VeD) \times weD \rangle$ (see [11] page 66).

With $nD$ the D+ ions density, $\gamma eD$ the Coulomb collision frequency, $\sigma eD$ the Coulomb collision cross section and $weD$ the relative speed between the electron and the D+ ion. The electron speed being about 60 times greater than the D+ ion speed, it can be written $weD \approx Ve$. The initial particles being monokinetic at the initial energy $EDi$, it could be written $\gamma eDmono \approx nD \times \sigma eD(EDi) \times Ve(EDi)$. But after thermalization, $\gamma eD$ could be written $\gamma eDth = \frac{9.3\text{E}-11 \times ne}{EDi(\text{eV})^{1.5}}$ (Equation ($A0$) of Appendix A).

After several tests, it appears that $\gamma eDth < \gamma eDmono$ so it is conservative to use $\gamma eDth$ rather than $\gamma eDmono$.

So the time $Tth$ necessary to thermalize up to 80% is equal to: $Tth = \frac{158}{\gamma eDth}$.

For an example coherent with the concerned reactor, *i.e.* $nD$ = 12E19 and $EDi$ = 150 keV, it is found $\gamma eDth$ = 192 collisions/s and $Tth$ = 0.8 s. It means that for $Tloss \ll Tth$ = 0.8 s there is no thermalization but for $Tloss > Tth$ = 0.8 s the thermalization is considered as complete, which is widely the case for all the interesting configurations. This time $Tth$ also applies to electrons because the exchange of energy is symmetrical and the collision frequencies are equal.

Note that electrons become isotropic and then thermalized in less than 1 s.

**Part 2: Speed of energy exchange between D+ ions and electrons**

The goal of the second part of this appendix is to estimate, once ions and electrons are thermalized, the necessary number of electron-ion collisions and the time to restore the balance of energy between D+ ions and electrons, in case of variation of the energy of one kind of particles. For example, electrons lose energy through the Bremsstrahlung radiation and ions win energy thanks to the fusions products (T+, He3…) slowdown. Electrons and D+ ions tend to equilibrate at the same mean energy, but it is not instantaneous.

Thanks to the above program, the 20,000 particles (10,000 electrons and 10000 ions) have been thermalized at 99% (1070 steps necessary). Their mean energy is equal (or very close) to their initial energy: $\langle Ee \rangle = \langle ED \rangle = Eei = EDi$ = 10,000 eV.

It is now supposed that for some cause, the energy of each electron is suddenly doubled (without modification of the distribution), so $\langle Ee \rangle \rightarrow \langle 2 \times Eei \rangle$. Normally, thanks to collisions between electrons and D+ ions, the ions energy is going to slowly increase up to the mean equilibrium energy, *i.e.* 1.5 × $Eei$ and the electrons energy is going to slowly decrease down to the mean equilibrium energy. So the same program as described above will be used. The distance between D+ ions and electrons energies and the mean equilibrium energy compared to the initial energies distance will be the criterion.

So steps of calculations are repeated until to reach 80% of the distance to the mean equilibrium energy. In other words, the electrons energy must reach 1.6 × *Eei* (from 2 × *Eei*) and the D+ ions energy must reach 1.4 × *Eei* (from *EDi* = *Eei*). Note that a step of calculation corresponds to one collision of all the 10000 ions, each one with one electron chosen randomly. It has been found that 760 electron-ion collisions are necessary to reach this threshold of 80%.

Note: it has also been found that 141 collisions are necessary to reach 25% of the required distance for equilibrium, 332 for 50%, 1180 for 90% whereas 100% would be obtained ad infinitum.

So the time *Teq* necessary to reach 80% of the required distance for equilibrium is equal to: $Teq \approx \frac{760}{\gamma eDth}$.

With $\gamma eDth$ the collisions frequency at 1.5 × *Eei*. It is approximate as *Ee* and *ED* changes with the time.

For the same example as in the part 1, *i.e.* *nD* = 12E19 and 1.5 × *Eei* = 150 keV, it is found *Teq* = 4.0 s. This duration is relatively long but still controllable. Note that, for the same *nD*, at 1.5 × *Eei* = 20 keV, *Teq* is equal to 0.19 s, which is much more comfortable.

## Appendix E

**Deceleration of ions issued from the fusions**

The deceleration of an ion issued from a fusion, called "fusion ion" below, is given by [4] page 74 (4.93), used for tokamaks:

$$\frac{dV}{dt} = -\frac{nD \times Z^2 \times q^2 \times Q^2 \times \Lambda}{4 \times \pi \times \varepsilon 0^2 \times mD \times M} \times V^{-2} - \frac{ne \times q^2 \times Q^2 \times \Lambda}{3 \times \varepsilon 0^2 \times me \times M} \times \left(\frac{me}{2 \times \pi \times kb \times T\_equi}\right)^{\frac{3}{2}} \times V \tag{E1}$$

The first term corresponds to the D+ ions slowing down whereas the second term corresponds to the electrons slowing down.

*M* is the mass of the fusion ion, *V* is the speed of the fusion ion: $V = \sqrt{\frac{2 \times q \times Ei(\text{eV})}{M}}$ with *Ei* the current energy of the fusion ion. *Z* = 1 for D+ ions. *ne* = *nD* for a neutral plasma (at reactor start-up)

$$kb \times T\_equi = \frac{2 \times q \times E\_equi(\text{eV})}{3}.$$

*Q* = *q* × *Z'* for the fusion ion, with *Z'* = 1 for T+ and p, *Z'* = 2 for He3+ and He4+. Λ is the Coulomb logarithm ranged between 10 and 20 for a Tokamak plasma ([4] page 69) and so chosen equal to 15 (mean value).

Note: this calculation might be, in fact, more complicated because some time after the reactor start-up, the fusion ions at equilibrium will also decelerate new fusion ions. Moreover the density ne will be superior to *nD* for a neutral plasma. The real deceleration would be a bit faster and so more favorable. To remain simple and to be conservative, only electrons and D+ ions will be considered.

The initial energy $Ei = Eii$ of the fusion ion is given in §2.2.5.

It has been realized a small program to calculate the current speed ($V$) and energy ($Ei$) of the fusion ion according to the time. It appears that, for a plasma energy $E\_equi$ around 150 keV and a density $nD$ around 12E19, the fusion ion is in general only decelerated by D+ ions down to $E\_equi$, except for protons for which, they are first mainly decelerated by electrons before being decelerated by D+ ions down to $E\_equi$.

The time during which the deceleration is mainly done by electrons is noted $Tde$, whereas $Tdi$ is the time during which the deceleration is mainly done by D+ ions. The total time of deceleration is called $Td$ with $Td = Tde + Tdi$. The fusion ion energy at the end of the $Tde$ time is called $Eie\_end$.

The collisions between fusion ions and electrons during $Tde$ does not affect much the fusion ion radial trajectory, this due to the weak radial transport by electrons compared to the strong transport by ions, as shown in Appendix A part 2 (for straight pipes).

So during this phase ($Tde$), fusion ions are slowed down without the risk to be lost on the wall, at least for the time when the fusion ions cross the straight pipes. Now, it will be supposed that such behavior also applies for the time when the fusion ions cross the half-toruses. Therefore, after stabilization, the time $Tde$ is transparent and can be ignored.

Reversely, the collisions between fusion ions and D+ ions affect the ion trajectory, because all these particles have similar weight. So for the time $Tdi$, there is a radial diffusion of the fusion ions and a risk of loss on the inner wall.

It can be supposed that the radial diffusion behavior of fusion ions is similar to the D+ ions. When they cross the straight pipes, the current confinement time increases with the ion energy as described by the Equation (A2) in Appendix A. However when they cross the half-toruses, the current confinement time decreases with the fusion ion energy as described by the equation 8.3 in §2.2.8.3.c.

To simplify, it will be supposed that all the fusion ions with one charge (p and T+) diffuse in the same way as D+ ions, so the confinement time will be equal to $TDexp$, as defined in Appendix A part 3.

As the radial transport is correlative with the Coulomb collisions frequency, it will be considered that all the fusion ions with two charges (He3+ and He4+ ions) diffuse 4 times faster than D+ ions, so the confinement time for these particles would be equal to $TDexp/4$.

Let's call $Tdc$ the equivalent time of deceleration of fusion ions on D+ ions, for about the same radial transport as the D+ ions. So $Tdc = Tdi$ (Equation (E2)) for p and T+ ions and $Tdc = Tdi \times 4$ (Equation (E3)) for the He3+ and He4+ ions.

In **Table E1** below, are given results about the 6 concerned fusion ions, for a typical configuration, *i.e.* $E\_equi = 150$ keV and $nD = 12E19$.

It must be noted that the Tdc time for the fusion ions T+ and He3+ is relatively low, which is a good thing relatively to the secondary fusions D-T and D-He3 frequencies.

**Table E1.** Results about the deceleration of different fusion ions, for the different fusions used in this article, supposing *E_equi* = 150 keV and *nD* = 12E19.

| Fusion | Fusion ion | *Eii* (MeV) | *Td* (s) | *Tde* (s) | *Eie_end* (MeV) | *Tdi* (s) | *Tdc* (s) |
|---|---|---|---|---|---|---|---|
| D-T | He4+ | 3.52 | 2.40 | 0 | Irrelevant | 2.40 | 9.60 |
| D_He3 | He4+ | 3.67 | 2.51 | 0 | Irrelevant | 2.51 | 10.04 |
| D-D | Proton (p) | 3.03 | 6.90 | 4.56 | 0.93 | 2.34 | 2.34 |
| D-He3 | Proton (p) | 14.67 | 15.13 | 12.79 | 0.93 | 2.34 | 2.34 |
| D-D | T+ | 1.01 | 2.06 | 0 | Irrelevant | 2.06 | 2.06 |
| D-D | He3+ | 0.82 | 0.39 | 0 | Irrelevant | 0.39 | 1.56 |

Note that the influence of *E_equi* and *nD* is very important. For example, for the first He4 ($\alpha$ particle), of the D-T fusion:

- If *E_equi* = 75 keV and *nD* = 12E19, *Td* = 1.68 s, *Tde* = 0.70 s and *Tdi* = 0.90 s.
- If *E_equi* = 150 keV and *nD* = 24E19, *Td* = 1.21 s, *Tde* = 0 s and *Tdi* = 1.21 s.