Proposal of a new type of electrostatic confinement reactor able to produce nuclear fusions with a yield superior to 1

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Revision B

CONTENTS

Page

Revision B:

- Replacement of the term « efficiency » by « yield » to avoid an ambiguity (everywhere).
- Precision about the final reactor diagram (§11.1).
- Heat source and fusion products (§12.5).
- Precisions (§3.1)
- About the aneutronic fusions (§12.3)

1. Goal, presentation and notations used

The goal of this presentation is to progressively introduce the description of an electrostatic confinement reactor able to produce nuclear fusions with a yield (kinetic fusion products energy / electric energy consumed) superior to 1.

This presentation relies on the Multiplasma program (in French and English) developed by the author. Multiplasma permits the simulation of such reactor. It is proposed to download it in "freeware": http://f6cte.free.fr/MULTIPLASMA_setup.exe. Possibly, see the article aimed to users: http://f6cte.free.fr/Simulation_of_an_electrostatic_confinement_fusion_nuclear_reactor.pdf

The first reactor studied, under the name « LKR1 », is a simple reactor which confinement is done with only one electrostatic lens. It will permit to present the different types of fusion managed by Multiplasma.

In what follows, it is presented the description of this reactor followed by an abstract of different simulations done on this reactor, which permits to establish a hierarchy between the different types of fusions and to see the problems of that type of reactor.

It is afterwards presented a reactor a bit improved, under the name « LKR1m ». It will permit to present several improvements useful for the following, several calculations and a beginning of design.

It is finally presented a solution to the problems described in the anterior chapters and, finally, a proposal of reactor with its working cycle.

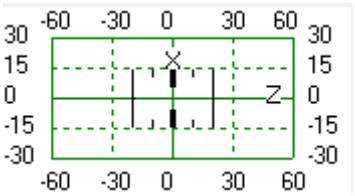
Two final tests permit to highlight the interest of this solution.

It is set aside the fact that the presented project be, at the moment, physically achievable or not.

Notations

- the simple product is indicated with « * » or « x » or « . » or is not indicated if there is no ambiguity,
- the powers of ten are indicated with Ex or 10^x (for example 10^{-7} or E-7),
- the other powers are noted ^ (for example x^2 for x^2),
- "§" for chapter.

2. Description of the LKR1 reactor



Thereafter, it is supposed that « a pixel = 1 mm » (default value, but can be modified between 0.1 and 10 mm). So, it will be spoken of mm instead of pixel.

The reactor LKR1 (inspired from references [15] and [38]) is composed of 5 electrodes and an ions source:

- A central washer of 3 mm thickness with respective interior and exterior diameters of 10 and 28 mm. This electrode is called further « central electrode ».

- 2 symmetrically disposed, one mm thickness washers with respective interior and exterior diameters of 20 and 28 mm, located at a distance of 10 mm from the central washer. These electrodes are called further « intermediate electrodes ».

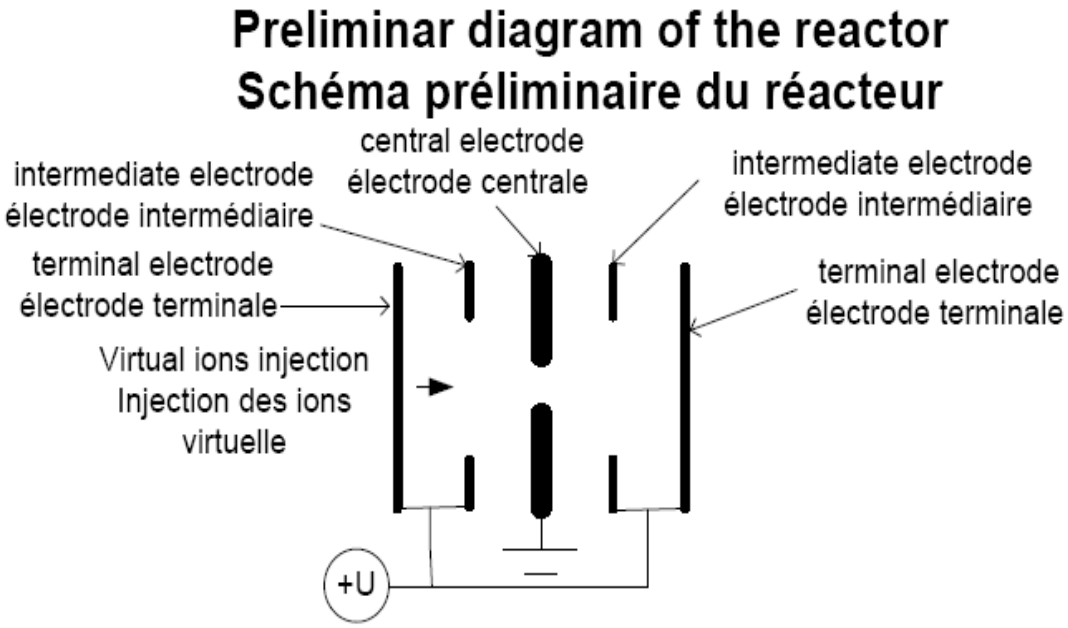
  Note: the central electrode and these two intermediate electrodes form an electrostatic lens said “Einzel”, aimed to focus the ions beam.

- 2 symmetrically disposed, one mm thickness disks with a diameter of 28 mm, located at a distance of 20 mm from the central washer. These electrodes are called further « terminal electrodes ».

  Note about the working: these electrodes of positive potential compared to the central electrode push ions (of positive charge) towards the central electrode. Ions get to circulate for endless between the 2 terminal electrodes with a precise frequency, a bit as a mass-spring system. Each time ions pass through the electrostatic lens, they are focused (which is necessary due to the tendency of the ions beam to scatter).

- An ions source located at a distance of 15 mm from the central washer. Its area is equal to 1 pixel^2 relatively to the current density in A/cm^2 (so the intensity in A is equal here to 1/100th of the current density). It can be considered that the emission is randomly done from a circular surface of 0.5 pixel radius, according to the laws applicable to hot cathodes. I.e., the speed distribution follows a Maxwell-Boltzmann distribution and the electrons leave the cathode in any direction (but at Z increasing), with:
  - the colatitude calculated according to the Lambert's cosine law, cosine measured by comparison with the direction perpendicular to the surface,
  - the longitude calculated according to a uniform distribution.

The ions source is supposed « virtual » (without any electrostatic influence and without any possibility of collision with ions). It is a theoretical hypothesis, practical but not realizable in the reality.
For this model (“LKR1”), the ions injection must be done at 15 mm from the central electrode.



3. Simulation of D+ <-> D+ fusions

Objectives in term of yield:

- the minimum objective is that the kinetic energy of the fusion products supplied by the reactor be superior to the consumed electrical energy (yield>1),

- a more ambitious objective is to generate more than 3.333 times more kinetic energy than the consumed electrical energy (yield>3.333), so that to permit an hypothetical exploitation of the produced energy, supposing that the thermodynamic efficiency permitting to transform this kinetic energy in electricity be equal to 0.3 (standard pessimistic value).

In addition, the power fusion must be the largest possible.

Generalities

All simulations have been done on 10000 time steps for two reasons:

- to limit the calculation duration,

- to be able to maintain the confinement during this small period of time.

All these simulations have been done with an old version of the program (which is optimist about yield). Even if it is not the last version of the program (and so not the more accurate), it permits to show the hierarchy of the behaviors.

The injection duration is defined by Nos x Tsp, with:

- the number of time steps (Nos) during which ions are injected. It corresponds here to the number of ions packets injected. The duration NosxTsp must correspond to the necessary time for an ion to cover an integer number of round trips,
- the time step (Tsp) in ps is defined to have more or less the same “maximum displacement” for each test (to have about the same accuracy).

The test duration is equal to 10000 times steps x Tsp. It is not equal for all tests because Tsp varies from a test to another. This makes tests results on voltages from 1 to 10 MV slightly pessimistic due to the bigger time step selected.

The current density (Cd) is the maximum possible value:

- for the voltage (U),
- for the injection duration (Nos x Tsp).

It can be said that these tests give for a set of voltages, the maximum electric charge (Q) that the reactor can confine during a limited time. For the charge Q, see further.

3.1 Results of the simulation for D+ <-> D+ fusions at the gas pressure of 10 pPa

On the next page, it will be found the results panel and then the curve giving the yield E (without dimension) and the fusion power P (in W) versus the voltage U on electrodes (in MV).

It can be seen that E increases up to 3.845 then decreases.

For about limits on E and P when U tends either towards 0 or towards a very big value :

- when U tends towards 0, the fusion cross section tends towards 0 and so E and P tends towards 0,
- when U tends towards a very big value, the yield tends towards 1, since the lost electric energy and the gain of energy connected to fusion tend towards the same value (i.e. the kinetic energy of particles “fusing”). P tends towards a maximum value during a short moment before decreasing with time.

The ideal value for the voltage U is the one for which the exploitable power EP is maximum. For the minimum yield Emin=3.333, the exploitable power is equal to 0 W. For E>3.333, the supplied electric power is equal to P/3.333, the consumed electric power is equal to P/E and so the exploitable power is equal to P/3,333 –P/E
=P x (0.3-1/E)
From the found values, the ideal value for U (at the maximum exploitable power) is equal to 20 MV.

It must be noted that the power P depends on the ions number in the reactor and so to the charge of these ions. This charge Q is equal to I (the current in A) x the injection duration.
The current is equal to the product of the current density Cd (A/cm^2) by the emitting surface (Se in cm^2).
This injection duration is equal to the product of the time step duration (« Tsp ») by the number of time steps during which ions emission occurs (« Nos »).
So Q = K’ x Se x Cd x Tsp x Nos (K’ being a constant)
Moreover, we know that the number of fusions depends on the ions kinetic energy in their path in the reactor according of the fusion cross section D+ <-> D+. These two parameters (kinetic energy and cross section) depend on the voltage U on electrodes (on average). So it can be supposed that $P=K'' \times Q \times U^n$ (K’’ is a constant). Between 5 and 20 MV (E approximately constant), it will be found that n is worth about 1.361.
It is finally found **$P= 3.24\ E\text{-}20 \times Se \times Cd \times Tsp \times Nos \times U^{1,361}$** (with « Ex » for « 10^x »)
It is an approximate formula for the D+ <-> D+ interaction, in the maximum yield zone.

Note 1 : the fusion power P is optimist because the calculation was done in « Good » and not « Very good » accuracy,

Note 2 : this is only applicable for the very small duration corresponding to 10000 time steps (<<1 µs). Beyond, the confinement is lost (and so a part of the energy

spent to accelerate the ions).

Note 3: also to limit the time calculation, the time step has been kept to 6 ps for 30, 35 and 40 MV voltages, which degrades accuracy for these voltages.

Note 4 : in the reality, it would necessary to take into account the static pressure which exercises between electrodes. Indeed, charges on both exterior washers and on disks are at very important voltage. They are attracted by the central electrode which is at 0 V. It can be roughly estimated the squeezing force by considering that one disk and the central electrode form a plane capacitor. It is applied a static pressure Ps that can be estimated by $Ps=U^2/2 \times \epsilon / d^2$ (U : voltage between electrodes, ϵ : permittivity of the electric insulator and d the distance between disk and central electrode).
For a voltage of 20 MV the squeezing pressure is in the order of 4.4 E6 Pa or 44 bars…

Note 5: in this document and in the program Multiplasma, it is not taken into account the braking radiation (‘Bremsstrahlung”), because a simple numerical application with the Larmor formula applied to ions in constant acceleration and deceleration shows that the radiative power remains negligible in the voltage range (U<=125 MV) used, compared to the fusion power.

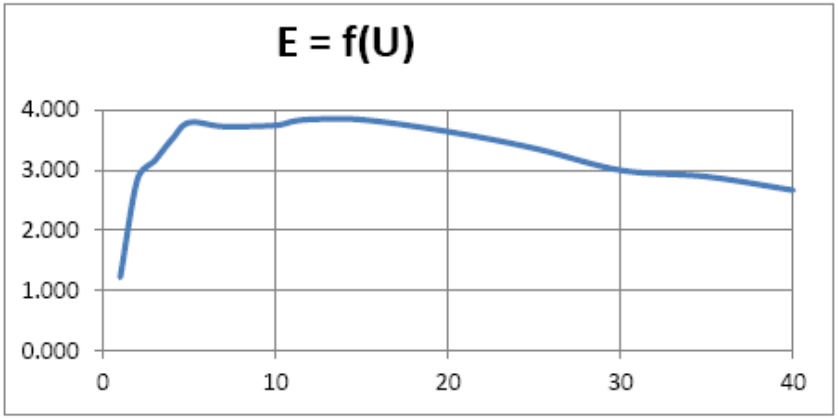
Note 6: it must be noted that Multiplasma includes the kinetic energy Ek of ions fusing in :

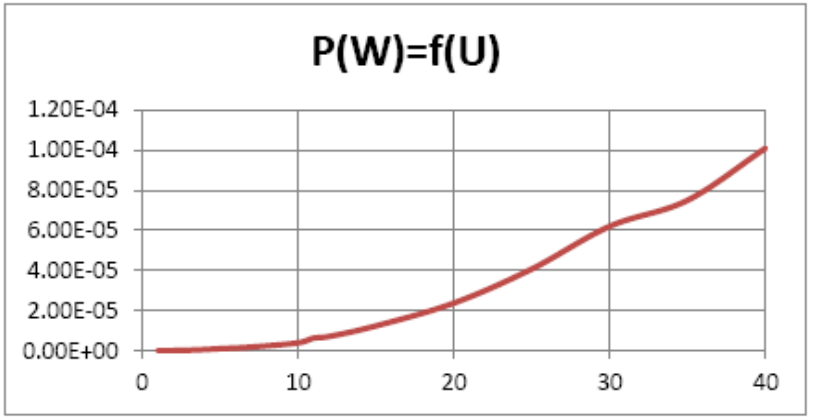
- the global fusion energy, for example:
  D+ + T+ (+Ek) ->He4+ + n (+17.6 MeV + Ek)

- the consumed electric energy.

Study of E and P = f(U) for D+ <-> D+ at Pgas=10pPa / Etude de E et P = f(U) pour D+ <-> D+ à Pgaz=10 pPa

Voltage on electrodes / Tensions sur les électrodes U (MV)	Current density / Densité de courant Cd (A/cm2)	Time step / Pas de temps Tsp (ps)	Number of injection time steps / Nombre de pas de temps en injection Nos	Charge Q (C)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)	Exploitable power / Puissance exploitable EP (W)
1	10	20	791	1.582E-09	1.216	6.31E-09	-3.30E-09
2	20	20	562	2.248E-09	2.848	2.37E-08	-1.21E-09
3	50	20	925	9.250E-09	3.159	2.05E-07	-3.39E-09
4	95	10	1587	1.508E-08	3.515	5.25E-07	8.14E-09
5	150	10	1427	2.141E-08	3.793	9.68E-07	3.52E-08
7	205	10	1214	2.489E-08	3.728	1.77E-06	5.62E-08
10	230	10	1535	3.531E-08	3.747	3.85E-06	1.28E-07
11	310	6	2424	4.509E-08	3.812	6.21E-06	2.34E-07
12	320	6	2327	4.468E-08	3.845	7.05E-06	2.81E-07
15	470	6	2099	5.919E-08	3.841	1.23E-05	4.88E-07
20	540	6	2457	7.961E-08	3.642	2.37E-05	6.03E-07
25	620	6	2798	1.041E-07	3.364	4.07E-05	1.11E-07
30	750	6	2609	1.174E-07	3.000	6.20E-05	-2.07E-06
35	770	6	2466	1.139E-07	2.892	7.50E-05	-3.43E-06
40	870	6	2354	1.229E-07	2.667	1.01E-04	-7.57E-06





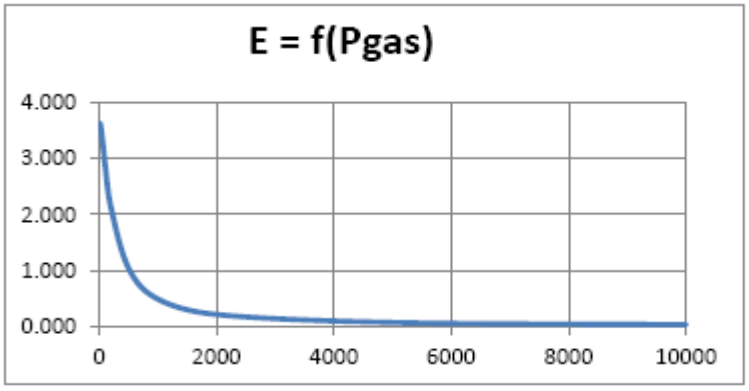
3.2 Results of the simulation for D+ <-> D+ fusions at different gas pressures

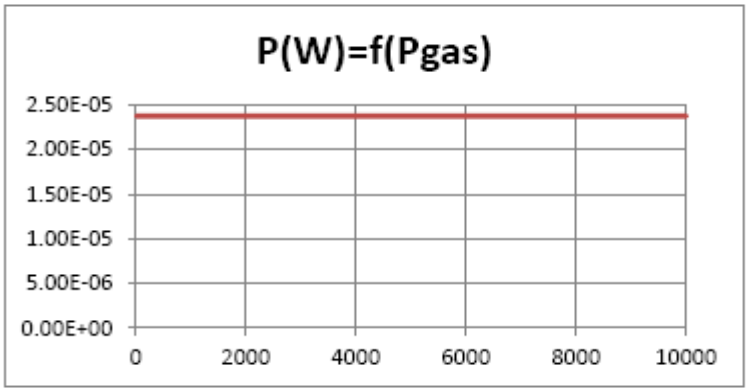
It will be considered the “best” solution determined previously so a voltage of 20 MV, a current density of 540 A/cm^2 under a pressure of 10 pPa and we will see the evolution of E and P according to the gas pressure. It is expected a degradation of the reactor performances due mainly to the Ions-Neutrals charge exchanges but also to Ions-Neutrals elastic collisions.

The following panel gives an abstract of the results obtained. It can be seen that less than 50 pPa of gas permits to pass the minimum yield of 3.333. The fusion power is stable because it only depends on the Ion-Neutrals fusions in a tiny way.

Study of E and P = f(Pgas), for D+<->D+ / Etude de E et P = f(Pgaz), pour D+<->D+
All tests done at 20MV Cd=540 A/cm2
Tous les tests faits à 20 MV Cd=540 A/cm2

Gas pressure / Pression du gaz Pgas (pPa)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)
10	3.642	2.37E-05
20	3.589	2.37E-05
50	3.341	2.37E-05
100	2.850	2.37E-05
200	2.108	2.37E-05
500	1.033	2.37E-05
1000	0.486	2.37E-05
2000	0.211	2.37E-05
5000	0.068	2.37E-05
10000	0.030	2.37E-05





3.3 Results of the simulation for D+ <-> D+ fusions in the long term

The goal is to have a configuration which is stable over time, without loss of the confinement. Previous simulations have been realized on a rather short period (10000 time steps) because calculation durations are large.
Starting from the “best” solution previously determined , i.e. a voltage of 20 MV and a current density of 540 A/cm^2, the simulation will be left until the confinement loss. Moreover the simulation will be done in “Very good” accuracy, which is going to much more take into account the space charge.

The test has been realized without speed correction. It is reached 14770 steps (0.0886 µs), the confinement being lost due to the collision of an ions packet with an electrode.
So this reactor in this form does not permit to reach the necessary long confinement time.

Indeed, according to the ions loss rate by fusion (5.79 ions for the confinement period of 0.0886 µs), at this rate, it would be necessary, to consume all the 5E11 ions present in the reactor, about 7600 sec of confinement…

3.4 Evolution of the supplied fusion power according to the reactor size

As an example, it will be supposed, thereafter, that the user expands his configuration by multiplying each dimension (x, y and z) by a factor R which will be supposed equal to 10. So a pixel will be equal to 10 mm

First, it can be noted that the limit to the confinement is mainly due to the space charge.

Now the space charge influence on the induced potential depends linearly on the charges impacted and on the inverse of the distance between charges. So to keep the same space charge effect, each charge must be multiplied by R, to compensate the factor 1/R due to the distance between charges.
Because the time step Tsp must be multiplied by R (to have the same speed evolution), it follows that the current density Cd must be divided by a factor R^2 to compensate the multiplication of Se by a factor R^2 (the intensity is hence kept at the same value). The charge will be R larger (it is reminded that Q = K’ x Se x Cd x Tsp x Nos). In this case, the effect will be similar.
However, it can be shown that the collision and fusion probability as well as the fusion power P will be divided by R.

Consequently the more the reactor expands and the more the supplied fusion power decreases (which is paradoxical). Reversely, the more the reactor is reduced and more the supplied fusion power increases (in other words P~1/R, all other things remaining equal).

This can be shown on a simulation. By reducing the size by a factor 10, it is found on one of the cases seen previously (at 10 MV), on 10000 steps:

- initially with 1 pixel=1 mm, U=10 MV, Cd=230 A/cm^2 (so I=2.3 A), Tsp=10 ps, Nos=1535 pas : R=3.747 and P=3.85E-6 W

- Now with 1 pixel=0,1 mm, U=10 MV, Cd=23000 A/cm^2 (so I=2,3 A), Tsp=1 ps, Nos=1535 steps, it is found : R=4,285 and P=5,661E-5 W

It can be seen that the ratio between powers is 15 instead of 10 (surely due to the limited number of steps). It confirms, anyhow, that smaller is the reactor, more powerful it is.

3.5 Tests of accelerated collision for fusions D+ <-> D+ in a gas at 10 pPa

We want to know how the confinement reacts if the collision probability increases. The test is done on 6000 steps. It will be considered the “best” solution determined previously so a voltage of 20 MV and a current density of 540 A/cm$^{2.}$. The probability of collision is going to be multiplied by a factor increasing from 1 to 1E9.

It is found that the confinement deteriorates but is never lost for included the factor of 1E9. This means that the probable duration “t” without confinement loss due to collisions, in a gas at a pressure of 10 pPa, would be t=6x6000x1E9=3.6 E13 ps or 36 s.

Even if it is not precise, this test gives an idea of the confinement time, in the hypothesis whereby one considers only collisions problem, so in ignoring space charge effect.

4. Simulation of D2+ <-> D2+ fusions

4.1 Results of the simulation for D2+ <-> D2+ fusions at the gas pressure of 10 pPa

On the next page, it will be found the results panel and then the curve giving the yield E (without dimension) and the fusion power P (in W) versus the voltage U on electrodes (in MV).

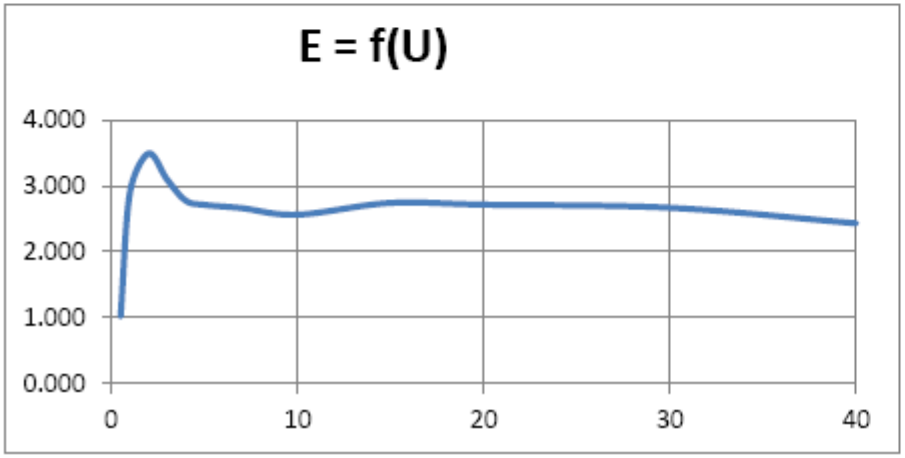
With respect to D+ <-> D+ fusions, it can be noted that :

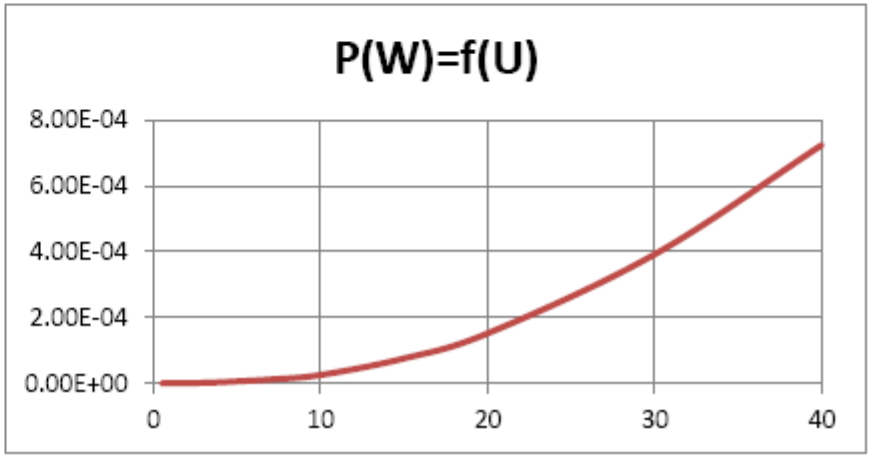
- the maximum of yield is located at 2 MV and not 15 MV,
- however, for the same voltage the fusion power is about 6 times more important,
- the only voltage for which the exploitable power is positive is 2 MV.

For a yield E superior to 3.333, it is evident that the D+ <-> D+ fusions are more favorable. But if the minimum yield was of 2 (instead of 3.333), for example, all the analysis would be different.

Study of E and P = f(U) for D2+ <-> D2+ at Pgas=10pPa / Etude de E et P = f(U) pour D2+ <-> D2+ à Pgaz=10 pPa

Voltage on electrodes / Tensions sur les électrodes U (MV)	Current density / Densité de courant Cd (A/cm2)	Time step / Pas de temps Tsp (ps)	Number of injection time steps / Nombre de pas de temps en injection Nos	Charge Q (C)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)	Exploitable power / Puissance exploitable EP (W)
0.5	3	30	1053	9.477E-10	1.016	1.88E-09	-1.29E-09
1	8	20	1119	1.790E-09	2.899	1.98E-08	-8.89E-10
2	25	20	794	3.970E-09	3.499	1.57E-07	2.23E-09
3	40	20	1308	1.046E-08	3.102	1.01E-06	-2.27E-08
4	70	10	2244	1.571E-08	2.781	2.76E-06	-1.65E-07
5	110	10	2019	2.221E-08	2.717	5.48E-06	-3.73E-07
7	160	10	1718	2.749E-08	2.667	1.13E-05	-8.44E-07
10	185	10	2171	4.016E-08	2.567	2.49E-05	-2.23E-06
15	350	6	2968	6.233E-08	2.746	7.52E-05	-4.83E-06
20	440	6	3474	9.171E-08	2.720	1.52E-04	-1.02E-05
30	640	6	3690	1.417E-07	2.672	3.92E-04	-2.91E-05
40	840	6	3330	1.678E-07	2.435	7.25E-04	-8.02E-05



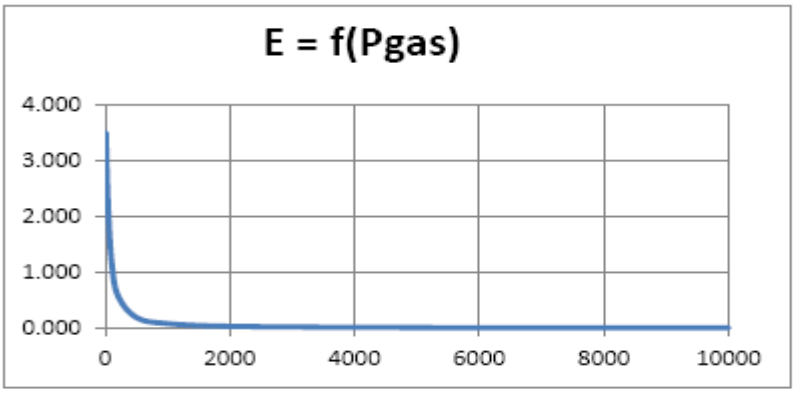


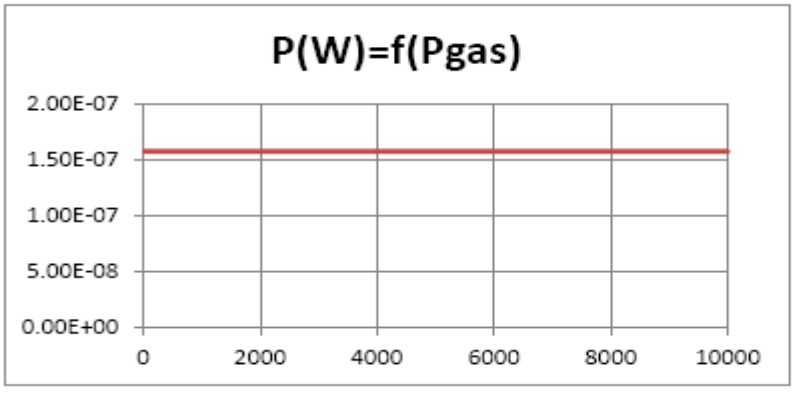
4.2 Results of the simulation for D2+ <-> D2+ fusions at different gas pressures
It will be considered the “best” solution determined previously so a voltage of 2 MV, a current density of 25 A/cm^2 under a pressure of 10 pPa and we will see the evolution of E and P according to the gas pressure. It is expected a degradation of the reactor performances due mainly to the Ions-Neutrals charge exchanges but also to Ions-Neutrals elastic collisions.

The following panel gives an abstract of the results obtained. It can be seen that only 10 pPa of gas permits to pass the minimum yield of 3.333. The fusion power is stable because it only depends on the Ion-Neutrals fusions in a tiny way.

Study of E and P = f(Pgas), for D2+<->D2+ / Etude de E et P = f(Pgaz), pour D2+<->D2+
All tests done at 2 MV Cd=25 A/cm2
Tous les tests faits à 2 MV Cd=25 A/cm2

Gas pressure / Pression du gaz Pgas (pPa)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)
10	3.499	1.57E-07
20	2.943	1.57E-07
50	2.011	1.57E-07
100	1.178	1.57E-07
200	0.583	1.57E-07
500	0.189	1.57E-07
1000	0.080	1.57E-07
2000	0.032	1.57E-07
5000	0.010	1.57E-07
10000	0.004	1.57E-07





5. Simulation of D+ <-> T+ fusions

5.1 Results of the simulation for D+ <-> T+ fusions at the gas pressure of 10 pPa

On the next page, it will be found the results panel and then the curve giving the yield E (without dimension) and the fusion power P (in W) versus the voltage U on electrodes (in MV).

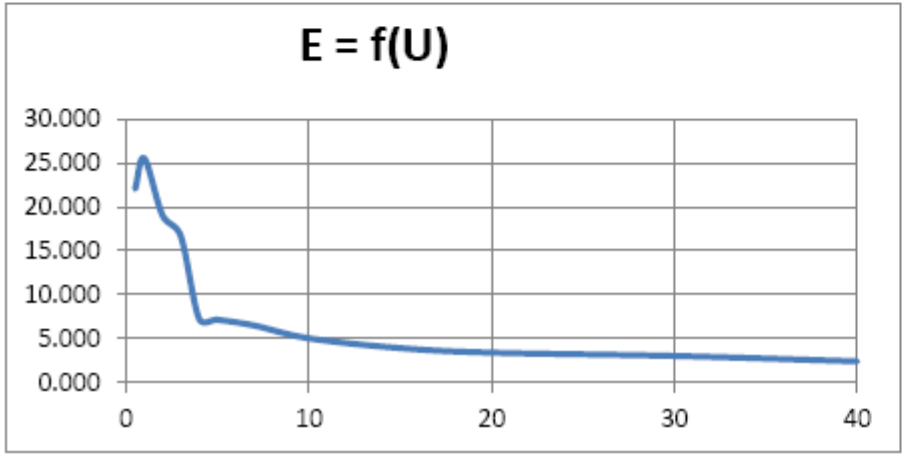
With respect to D+ <-> D+ fusions, it can be noted that :

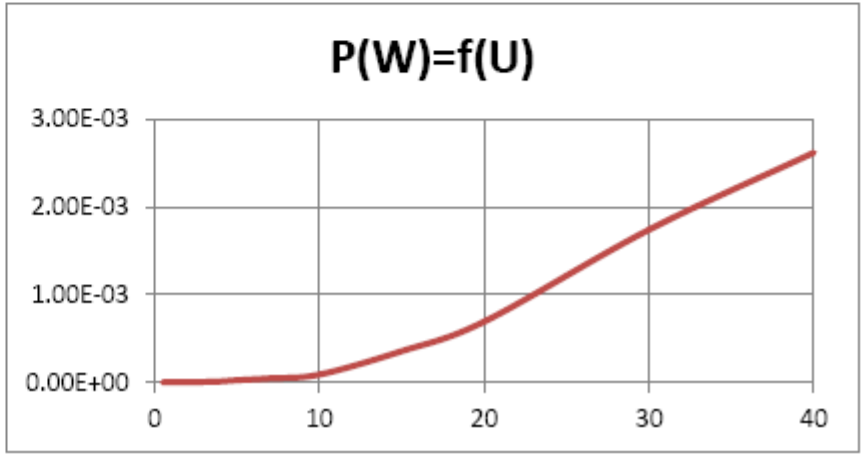
- the maximum of yield is more than 6 times larger,
- for the same voltage the fusion power is about 25 much more important,
- the voltage for which the exploitable power is maximum is 15 MV.

It is evident that the D+ <-> T+ fusions are much “easier” to obtain and hence the yield is very good. It is reminded that the main problem is the extreme rarity of Tritium and secondly the emission of the double of neutrons compared with the D+ <-> D+ interaction (beyond the well known effects on health, the neutrons flow weakens steel).

Study of E and P = f(U) for D+ <-> T+ at Pgas=10pPa / Etude de E et P = f(U) pour D+ <-> T+ à Pgaz=10 pPa

Voltage on electrodes / Tensions sur les électrodes U (MV)	Current density / Densité de courant Cd (A/cm2)	Time step / Pas de temps Tsp (ps)	Number of injection time steps / Nombre de pas de temps en injection Nos	Charge Q (C)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)	Exploitable power / Puissance exploitable EP (W)
0.5	4	30	820	9.840E-10	22.070	6.32E-08	1.61E-08
1	11	20	871	1.916E-09	25.570	1.66E-07	4.33E-08
2	32	20	618	3.955E-09	19.060	4.38E-07	1.08E-07
3	40	20	1018	8.144E-09	16.670	2.77E-06	6.65E-07
4	80	10	1747	1.398E-08	7.280	8.58E-06	1.40E-06
5	120	10	1572	1.886E-08	7.145	2.24E-05	3.58E-06
7	190	10	1337	2.540E-08	6.492	4.41E-05	6.44E-06
10	200	10	1690	3.380E-08	5.031	8.68E-05	8.79E-06
15	430	6	2311	5.962E-08	3.911	3.54E-04	1.57E-05
20	520	6	2705	8.440E-08	3.390	6.91E-04	3.47E-06
30	750	6	2873	1.293E-07	3.016	1.74E-03	-5.49E-05
40	840	6	2592	1.306E-07	2.398	2.62E-03	-3.07E-04



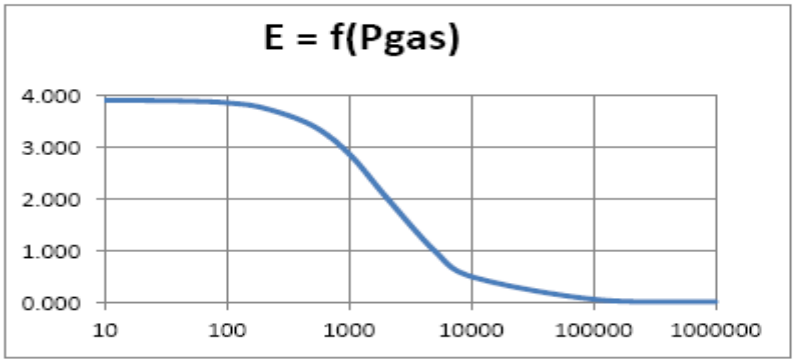


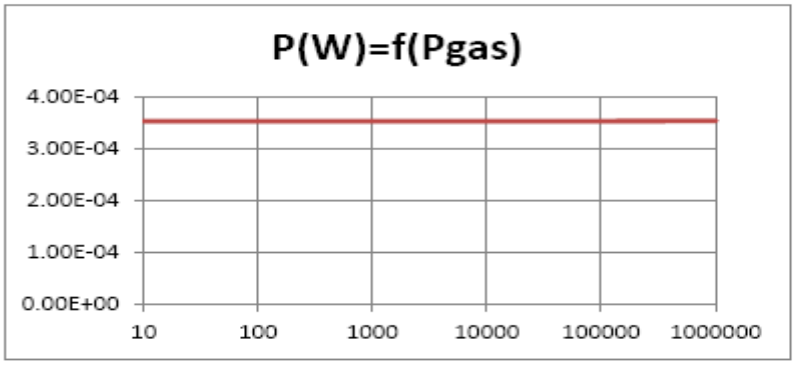
5.2 Results of the simulation for D+ <-> T+ fusions at different gas pressures
It will be considered the “best” solution determined previously so a voltage of 15 MV, a current density of 430 A/cm^2 under a pressure of 10 pPa and we will see the evolution of E and P according to the gas pressure. It is expected a degradation of the reactor performances due mainly to the Ions-Neutrals charge exchanges but also to Ions-Neutrals elastic collisions.

The following panel gives an abstract of the results obtained. It can be seen that the loss of yield is much slower than for D+<->D+ or D2+<->D2+ fusions. Until 500 pPa and a bit beyond, the minimum yield of 3.333 is passed. The fusion power is stable because it only depends on the Ion-Neutrals fusions in a tiny way.

Study of E and P = f(Pgas), for D+<->T+ / Etude de E et P = f(Pgaz), pour D+<->T+
All tests done at 15 MV Cd=430 A/cm2
Tous les tests faits à 15 MV Cd=430 A/cm2

Gas pressure / Pression du gaz Pgas (pPa)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)
10	3.911	3.54E-04
20	3.908	3.54E-04
50	3.894	3.54E-04
100	3.862	3.54E-04
200	3.760	3.54E-04
500	3.421	3.54E-04
1000	2.873	3.54E-04
2000	2.045	3.54E-04
5000	1.004	3.54E-04
10000	0.509	3.54E-04
100000	0.072	3.54E-04
1000000	0.024	3.54E-04





6. Simulation of D2+ <-> T2+ fusions

6.1 Results of the simulation for D2+ <-> T2+ fusions at the gas pressure of 10 pPa

On the next page, it will be found the results panel and then the curve giving the yield E (without dimension) and the fusion power P (in W) versus the voltage U on electrodes (in MV).

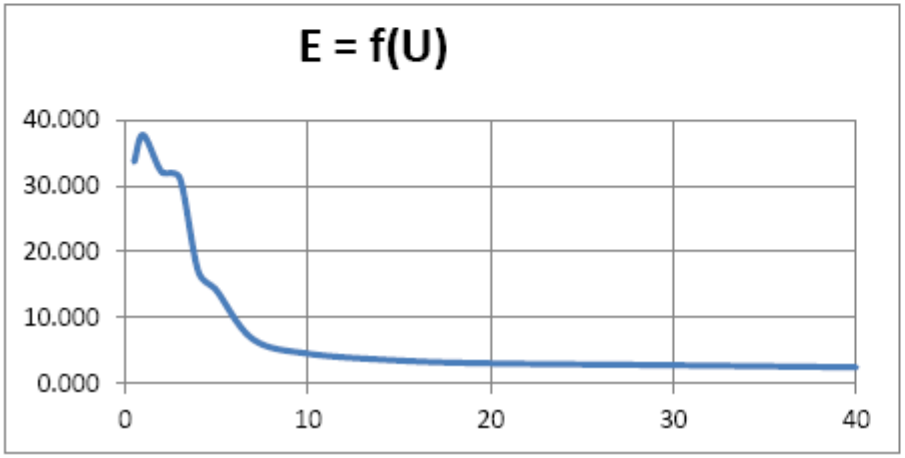
With respect to D+ <-> T+ fusions, it can be noted that :

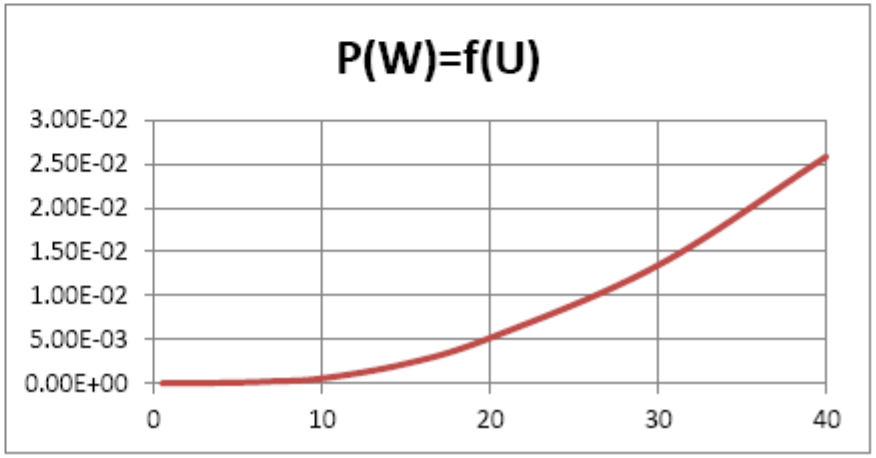
- the maximum of yield is larger until to 7 MV and smaller from 10 MV,
- for the same voltage the fusion power is much more important, between 3 and 10 more power.
- the voltage for which the exploitable power is maximum is 10 MV.

This fusion is the one which produces the maximum of exploitable power. The problem of this fusion is the same as the one of the D+ <-> T+ fusion (see above).

Study of E and P = f(U) for D2+ <-> T2+ at Pgas=10pPa / Etude de E et P = f(U) pour D2+ <-> T2+ à Pgaz=10 pPa

Voltage on electrodes / Tensions sur les électrodes U (MV)	Current density / Densité de courant Cd (A/cm2)	Time step / Pas de temps Tsp (ps)	Number of injection time steps / Nombre de pas de temps en injection Nos	Charge Q (C)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)	Exploitable power / Puissance exploitable EP (W)
0.5	4	30	1160	1.392E-09	33.710	1.86E-07	5.03E-08
1	10	20	1232	2.464E-09	37.780	6.76E-07	1.85E-07
2	25	20	874	4.370E-09	32.190	3.32E-06	8.93E-07
3	40	20	1440	1.152E-08	31.210	1.56E-05	4.18E-06
4	60	10	2471	1.483E-08	17.130	3.45E-05	8.33E-06
5	80	10	2223	1.778E-08	14.140	6.23E-05	1.43E-05
7	155	10	1891	2.931E-08	6.711	2.01E-04	3.03E-05
10	170	10	2390	4.063E-08	4.510	5.30E-04	4.14E-05
15	350	6	3267	6.861E-08	3.463	2.21E-03	2.48E-05
20	480	6	3825	1.102E-07	3.029	5.15E-03	-1.55E-04
30	690	6	4063	1.682E-07	2.747	1.35E-02	-8.61E-04
40	880	6	3666	1.936E-07	2.431	2.59E-02	-2.88E-03





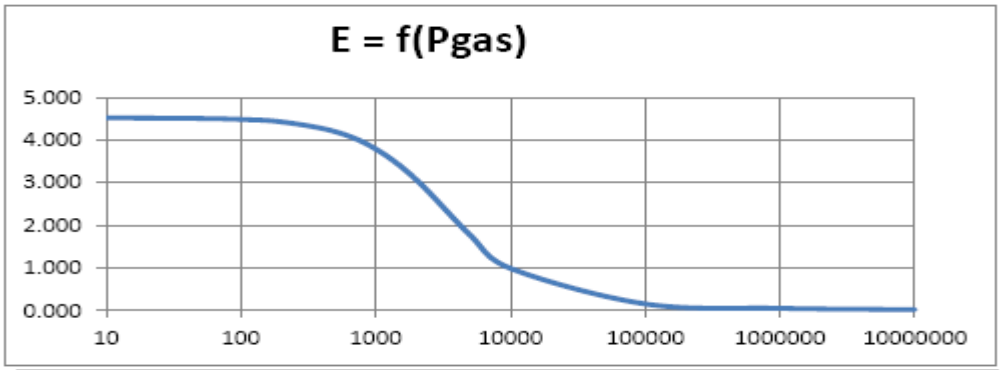
6.2 Results of the simulation for D2+ <-> T2+ fusions at different gas pressures

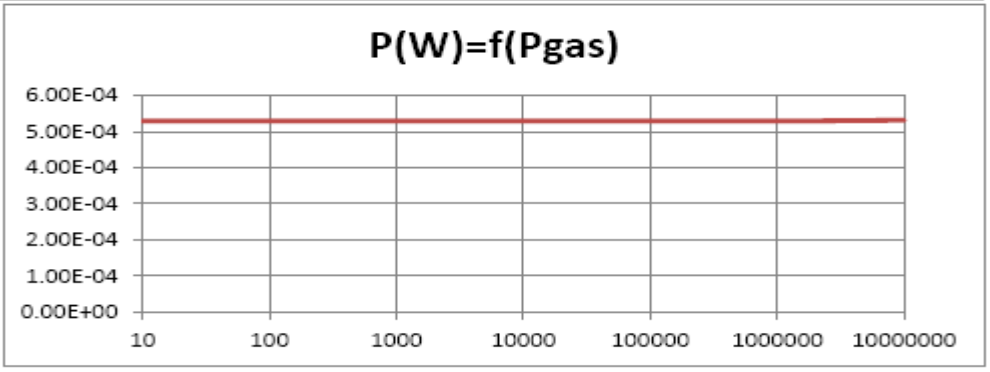
It will be considered the “best” solution determined previously so a voltage of 10 MV, a current density of 170 A/cm^2 under a pressure of 10 pPa and we will see the evolution of E and P according to the gas pressure. It is expected a degradation of the reactor performances due mainly to the Ions-Neutrals charge exchanges but also to Ions-Neutrals elastic collisions..

The following panel gives an abstract of the results obtained. It can be seen that until 1000 pPa, the minimum yield of 3.333 is passed. The fusion power is stable because it only depends on the Ion-Neutrals fusions in a tiny way.

Study of E and P = f(Pgas), for D2+<->T2+ / Etude de E et P = f(Pgaz), pour D2+<->T2+
All tests done at 10 MV Cd=170 A/cm2
Tous les tests faits à 10 MV Cd=170 A/cm2

Gas pressure / Pression du gaz Pgas (pPa)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)
10	4.510	5.30E-04
20	4.508	5.30E-04
50	4.498	5.30E-04
100	4.476	5.30E-04
200	4.418	5.30E-04
500	4.189	5.30E-04
1000	3.782	5.30E-04
2000	3.061	5.30E-04
5000	1.770	5.30E-04
10000	0.986	5.30E-04
100000	0.153	5.30E-04
1000000	0.051	5.30E-04
10000000	0.019	5.32E-04





7. Problem of the confinement

The problem of this type of reactor is the big difficulty (not to say the impossibility) to confine for a long time.

This is mainly due to the space charge effect, which periodically attracts and then pushes back each ion, in a non-totally symmetrical way. The ions energy is hence « thermalized » (scattered). That means that instead of having all ions at the same total energy (potential + kinetic), due to energy exchanges between ions, one finishes to get a total energies distribution around the initial total energy. The energy "thermalization" does not stabilize. It increases with time and depends, of course, of the total electrical charge. As this one depends on the ions density in the ions beam, so it depends on the electric field set by the device: the stronger is the field, the more the beam is concentrated and the more the space charge is intense (ions being closer and closer).

The effect of this behavior is to slow down certain ions and to accelerate some others. The ones which slow down are going to strike the central electrode and the others are going to strike the terminal electrodes (« disks ») or to escape. It can be seen this phenomena thanks to the indications displayed each 2000 steps, on the editor :

- « Var » (energy Variability),
- « dmax » (maximum distance from the center)

« Var » and « dmax » regularly increase.

The main parameter to follow is dmax. For a small intensity (i.e. less that 1/6th of the maximum, for a charge confined at least 100 ns), dmax increases linearly with time and ions don't collide the central electrode but one of the two terminal electrodes. So it is easy to roughly determine the probable time of confinement observing the dmax evolution. For example, if after 10000 steps dmax has increased of 1 mm and if the maximum distance before collision is 5 mm, the probable time of confinement will be about 50000 steps.

One can try to limit the thermalization but it can't be avoided. There is no long term solution to this problem.

Note 1 : the energy exchange between particles when they collide (Coulomb collisions I-I), is the other source of energies « thermalization », overall at low intensity.

Note 2 : the loss of energy linked to elastic collisions between ions and neutrals is not a « thermalization » because it is a loss not an exchange. Globally in a « thermalization » the sum of the ions total energies is constant, which is not the case when an elastic collision ion-neutral occurs.

New goal to reach: thereafter, to avoid a too big difficulty, it will be searched to have only a yield superior to 1, independently to the exploitable power.

8. Elements of solution

8.1 Preliminary notes

In all cases, it is important that the multiplying fusion factor be the smallest possible due to a big bias introduced by a too much large cross section (in that case, the fusion probability depends on the section but also on the sphere volume). The smallest is the one which permits to get at least 100 fusions to be representative and stays below 1000 fusions.

Moreover, the larger is the number of ions packets and the more accurate is the calculation, but the more longer is the simulation time. The limit is, according to the PC, about 10000 packets. Beyond, calculation time is too much long. About 2000 packets are a good compromise for ordinary calculations and about 5000 for the final calculation.

8.2 Limitation of the space charge and Coulomb collisions and increase of the confinement time by reduction of the electric charge stored

If one decreases the electric charge stored in the device (by decreasing the current density or the number of packets injected), the “thermalization” effect due to the space charge and Coulomb collisions is going to effectively decrease but, on the other hand, the supplied fusion power (and so the consumption of ions by fusions) will also decrease, with about the same factor.
But as the goal, here, is not to supply the maximum fusion power, it will be considered very low electric charge, which will permit a very long confinement time. Indeed, experimentally one notes that this time is roughly inversely proportional to the charge stored in the device (all other things remaining equal).

So to increase the confinement time, it is enough to reduce the electric charge stored in the device.

<u>About reducing the electric charge stored until a very weak value</u>
When the electric charge is very weak, it comes a problem of calculation accuracy caused by the “natural” expansion of the ions turnaround point due to digital errors. Indeed, the calculation introduces a very weak digital error which accumulates with time. To be precise, then the speed could be corrected. This correction is not a panacea because it does not really solve the problem, but transfers it (generally speaking, it is better to avoid to use this function which is also an errors source). The sole solution would be to use a very short step time (compensated by an enormous increase of calculation time), see below.

The relative amplitude of the error depends on the distance travelled during one step (cf. « maximum displacement » parameter). The larger is this distance and the more important is this error. This error can be reduced by decreasing the time step and hence the distance by step, but extending the calculation time. However, the error can’t be reduced to 0.

The other solution is to determinate the increase of “dmax” (maximum distance to the center) due to error calculation alone, in a configuration without space charge, collisions, charge exchange and fusions and for a given number of time steps). Then this “dmax” will be substrated from the “dmax” obtained in the real configuration, with the same number of time steps. From this calculated “dmax” expansion, it will be determined the probable confinement time (when “dmax” reaches the terminal electrodes).

In all cases, with a simple PC, it is not possible to completely simulate the cycle from the ions injection to the loss of all injected ions. Rather than a complete simulation, elements of simulation plus several manual calculations (done from experimental laws) will permit to reconstitute all the cycle.

8.3 Concentration of the ions flow

Rather than to send ions in the same way as the one used to send electrons with a heated cathode, it can be taken the hypothesis that all ions are sent at the same speed and longitudinally along the Z axis (so with one direction and one speed) from a very small section. The ions beam will be concentrated (in a cylinder having a diameter of several microns, according to the intensity) and fusions will be much more numerous, at least at the beginning. Afterwards the space charge and the Coulomb collisions will spread the flow of ions and the local density of ions will decrease slowly. Consequently, the rate of fusions will also decrease.
Multiplasma gives this possibility ("Linear injection" button) but only in the case of a cathode in form of dot (injection ions packet after packet).

After experimentation, this solution is adopted (the gain on the number of fusions being very superior to 10).

8.4 Symmetrization of the ions flow

If the flow of ions is concentrated, as this concentration can’t be maintained, it could be interesting to inject ions symmetrically with respect to the center. So, the first fusions will be done rapidly, after a short course. This is only interested in case of linear injection because the probability of fusion is much larger.

After experimentation, it turns out that this solution only brings, in average, a very slight gain. It will be taken into account later (§11).

8.5 Improvement of the LKR1 model (for weak currents)

At this level, one can a doubt about the reactor model LKR1, being very simple, to be the best model on its capacities to:

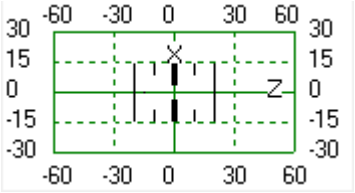
- confine the plasma in the most concentrated way along the device axis,
- confine the plasma for a duration the longest possible.

However, for the following reasons, the author is not going to, exhaustively, look for the best model :

- it would be necessary to have at one's disposal very big calculation capacities (because it is a multi-variables problem), which is not at author's disposal,

- it would be necessary to simulate new forms of electrode more complex than the simple forms proposed by the program, which would be perfectly possible but would require much time, which is not at author's disposal, either.

So, finally, one will remain to the LKR1 model.
However, after several tests about diameters, it has been found a modified LKR1 model (interior diameters of intermediate and central electrodes reduced by 3 mm) giving more fusions for weak currents. It is named "LKR1m" (with "m for "modified").



As the « LKR1 » model, it can be found in the sub-directory « CONFIGURATIONS » of the MULTIPLASMA program.

9. Preliminary working principles of this reactor

It is given, below, the (theoretical) working principles of this reactor, from the ions injection to the loss of all these ions.

Ions injection in the device

The ions source can be supposed virtual in the program. In the reality, the ions source would be struck at the ions return. At this level of the document, there is no solution proposed. A solution of the injection will be given further, at §11.

Reactor working and beginning of the confinement loss

The ions beam is left circulating between the two terminal electrodes, producing fusions in the same time. Progressively, the ions turnaround points are going to approach the terminal electrodes.
When the first ion will strike, in end position, a terminal electrode, the confinement will be lost.

Note that with small electric charge, the loss of confinement is always done on one of the terminal electrodes and never on the central electrode.

Loss of all the ions

After the first ion, progressively, ions are going to strike the terminal electrodes at very low speed.

All these ions losses generate only very weak energy losses because the speed, at the end of the road, is very weak. However, even these very weak losses can be very superior to the energy supplied by products fusion. The lost energy Epc depends on the mean drift speed of the turnaround points and can be determined experimentally.

10. Selection of the best configuration and results

10.1 Preliminaries

Thereafter, it will be chosen the D2+<->T2+ fusion which permits to produce the maximum exploitable power under a good yield.

On the basis of the previous working principles, one wishes to have the best ratio between the energy supplied by the fusion products and the consumed electric energy.
By taking into account the complete cycle and, consequently, the kinetic lost energy Epc (electrically compensated), one can find that the global yield is equal to:

Eg=(Fp*Df)/(((Fp*Df)/E)+Epc) with:

- Eg: global yield of the working cycle
- Fp: fusion power in W
- Df: probable confinement time in s
- E: probable fusion yield
- Epc: lost electric energy by collision of ions on terminal electrodes from the confinement loss (at the end of the cycle)

So we must::

- maximize the ratio between the fused ions during the confinement time and the number of ions present at the end of ions injection,
- have the mean drift speed of the turnaround points the weakest possible.

Note relative to the “resistive cooling”: in this document, we have neglected the “resistive cooling” effect due to charges inducing current on electrodes. Indeed, it is supposed that there are as many charges going from the central electrode as charges going towards the central electrode (and this applies to all electrodes). So the global induced current through each electrode is equal to 0.

Notes relative to the way energy is taken into account in this document
In this document, it is implicitly considered the first principle of thermodynamics. In this case, the active lost electrical power is the one which compensate the losses of kinetic energy, either ions escaping from the reactor (included due to fusions) or collisions with the electrodes.
It is possible, thanks to the confinement, to reduce the lost ions to the sole ions which fuse.
The kinetic energy lost in collisions can be reduced to the minimum by ensuring that ions collide only the terminal electrodes, and at very low speed (ideally at zero speed).

The passive electrical energy necessary to load electrodes (which form a capacitor) is not considered because it is recoverable during discharge of these electrodes.

The resistive losses are neglected. However, this hypothesis obliges to target a

relatively important power, otherwise even very weak, the resistive losses could be superior to the produced power.

The electric energy consumed due to ions circulating without collisions is nil because currents induced on positive electrodes by these ions circulating compensate each other.

10.2 First test

As it is not possible to calculate on long simulation durations and as all possibilities cannot be tested exhaustively, it has been created a model based on a mix of theoretical and experimental laws. It takes only into account the fusions created in a regular way in the “confinement cylinder” along the Z axis, which radius roughly stabilizes once the injection done then grows slowly.
In fact, progressively, due to Coulomb collisions, the mean confinement radius increases which makes decrease the fusions frequency, until a very weak value at the end of the confinement period.
So the author has made the hypothesis that the radius once “stabilized”, it will increase by a mean factor of 1.5 for the confinement time.

This model ignores the fusions created before stabilization, hence during the injection and a bit after.
This model is not described as it would be too long. It is given in Appendix 1 (procedure in Pascal language).

Result:
The maximum global yield Eg found is equal to 1.45 for the configuration: U=124,4 MV and Cd=2152 µA/cm2. But the fusion power Fp is very tiny: 1 E-8 W, which is not very satisfactory.

Conclusion of this test
Even if the global yield is superior to 1, the power delivered is too much weak.

10.3 Second test

It will be ignored the fusions regularly created in the “confinement cylinder” . It will be only taken into account the fusions created during the injection and a bit after. This means that the confinement time Df has not to be the biggest possible. Rather the opposite, it will be the shortest possible to reduce the cycle time. Here it will be searched to maximize the number of fusions created at the beginning.

Note: one would think that to reduce the ions emission area size in linear injection. For example, the radius of this area could be switched from 1 micron (default value) to 0.01 micron, even less, so as to concentrate the ions flow to the maximum. However, the accuracy of the software is not sufficient to manage such tiny dimensions: results become chaotic and are not reliable at all.

As one does not search to fuse over time, it is now possible to test a certain number of possibilities, then to apply part of the procedure in Appendix 1 to determine the maximum global yield Eg.

Here Eg is defined in the following way:

Eg=Ef/((Ef/E)+Epc) and Ef=Ns*Epf, with:

- Eg: global yield of the working cycle
- Ef: produced fusion energy (J). Note that Ef includes the mean kinetic energy of fusion products.
- Ns: number of fusions at start
- Epf: mean energy per fusion in J
- E: probable fusion yield
- Epc: lost electric energy (J) by collision of ions on terminal electrodes from the confinement loss (at the end of the cycle)

Result:
The maximum global yield Eg found is equal to 0.069 (<<1…) for the configuration U=25 MV and Cd=18000 µA/cm2 (producing one fusion at the beginning).
The fusion power Fp is equal to: 3.8 E-8 W.

Conclusion of this test
The global yield is very inferior to 1 and the power delivered is also very weak.

11. New solution of reactor and working cycle

11.1 Proposed solution and reactor principle

As indicated in §10 (second test), Eg=(Ns*Epf)/(((Ns*Epf)/E)+Epc) with, particularly, Epc the lost electric energy by collision of ions on terminal electrodes at the end of the cycle.
Epc depends on the speed of ions when the collision occurs. The slower the collision speed it is, the weaker Epc is and the bigger Eg is. In addition, in Appendix 1, one sees that Epc depends on the voltage and on the current density and, consequently, it is a piece of data which must be minimized by adjusting these parameters at the best. However, we are rapidly limited in this adjustment by Ns which also depends on the same parameters.

Now if the collision speed could be controlled, Epc could be made negligible. In this case, Eg would be equal to E, which would give the best yield possible.

This control can be done simply by increasing or by decreasing slowly the voltage, following a ramp. This has been checked on simulation and can be explained in the following way:

Suppose that the electric field be constant along the Z axis, which would mean that the potential is proportional to the distance from the central electrode. Let's call "dmax" the distance along Z between the central electrode and the most distant turnaround point (Tp) among all ions, and ""L" the distance between the central electrode and the terminal electrodes.

Just before to modify the voltage U, the total energy Et of the ion located at the turnaround point Tp is equal to Et=q * U * dmax / L.

Suppose that this ion is just at the center of the device (so with its maximum speed) when the voltage is switched directly from U to U+ ΔU. This ion will keep its total energy and will reach a new turnaround point located at d'max, such that Et=q * (U+ΔU) *d'max / L. So d'max=dmax * U/(U+ΔU) and d'max<dmax.

However, this case is the worst case. For a voltage ramp, it is obtained d'max=dmax * U/(U+ΔU) * 0.5, with a dispersion around this value. So we have a contraction of the ions beam on a ramp-up voltage.

Experimentally, by simulation, it is found that for a ramp-up voltage there is a contraction along Z of the confinement cylinder and reversely for a ramp-down voltage. These evolutions depend on the chosen model.

For example, with L=19,5 mm, dmax=14,5 mm and the "LKR1m" model :

- for a relative increase of voltage of 1 % (ramp-up on 12000 ps), dmax reduces by about 0.058 mm,

- for a relative decrease of voltage of 1 % (ramp-down on 12000 ps), dmax increases by about 0.091 mm,

For a given model, the relation between relative variation of voltage and variation of dmax does not depend neither on the voltage nor on the current density.
Moreover, the confinement radius slightly increases with the voltage increase.

Now that the control of ions turnaround positions is possible, we can by voltage control (via a program fixed in advance) do so that ions collide with the terminal electrodes at a very weak speed.
We are no more limited on current density. The only limitation is to have a confinement volume in form of cylinder, (i.e. a “red dash” on the reactor sectional view) of mean radius less that 0.05 mm, this to avoid collisions with the central electrode. So the current intensity must be limited to about 1/6th of the maximum current density, for a charge confined at least 100 ns.

Moreover, this variation of voltage can be used for the introduction of ions in the reactor

Indeed, suppose that:

- the terminal electrodes are pierced at their center with a small circular orifice of, for example, 0.2 mm of diameter.
- the voltage on electrodes is reversed, i.e. all the electrodes are at 0 V except the central electrode which is at a negative voltage –U. Note that for the ions circulation, this voltages configuration is strictly equivalent as the previous one.

Once the central electrode under voltage (slightly below its nominal value), it will be enough to inject the ions charge, symmetrically through the two orifices of the terminal electrodes and in the same time to increase slowly (following a ramp-up) the voltage on the central electrode up to its nominal value.
Due to the voltage increase, the confinement volume is going to contract and leave a certain space between the ions turnaround positions and the terminal electrodes. The charge introduction is finished and fusions begin.

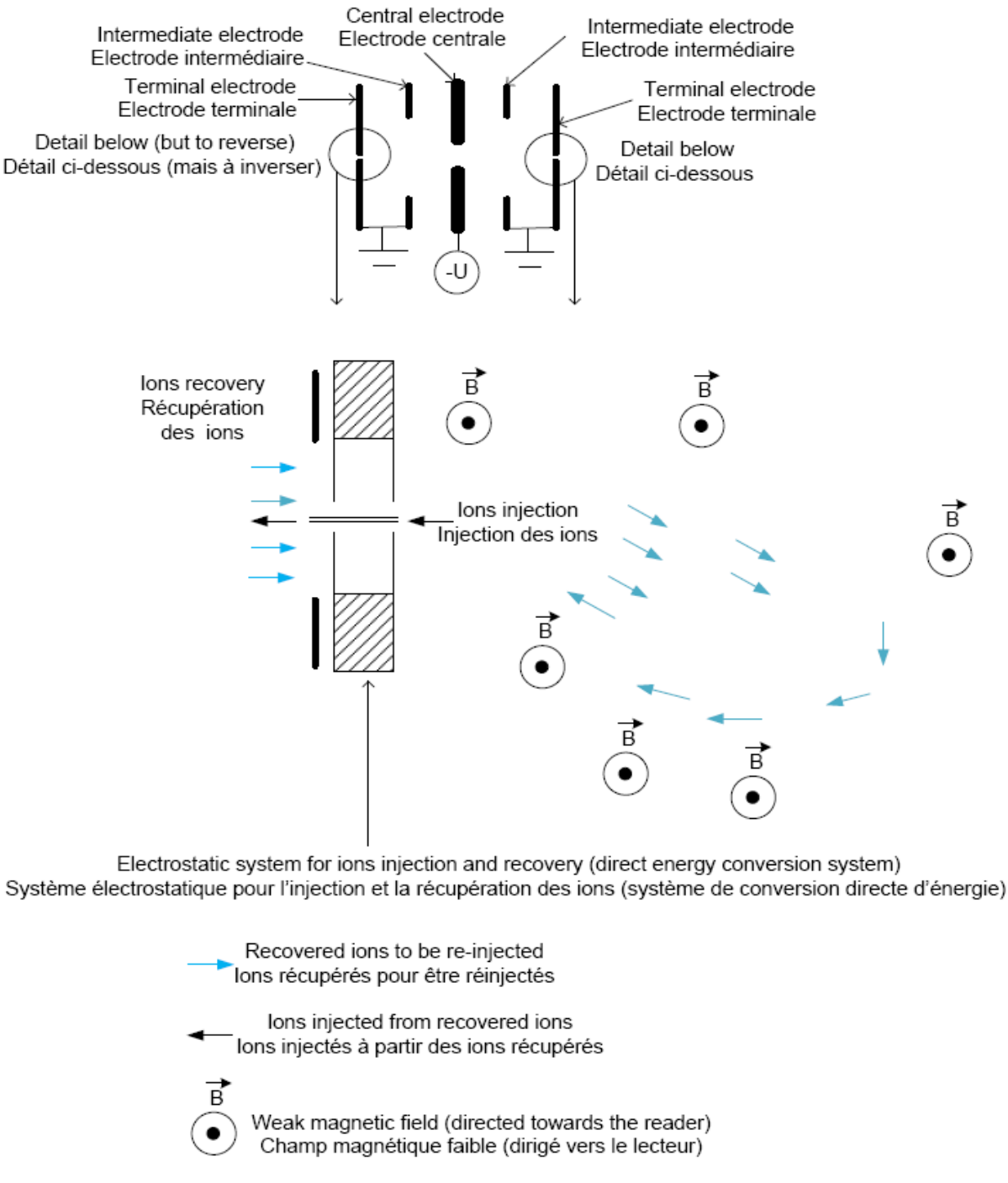
Note that orifices on terminal electrodes will permit to recover ions not fused at the end of cycle, rather than let them collide on terminal electrodes. This does not remove the need that the ions be recovered through the orifices at the weakest speed possible because, in all cases, the loss of residual energy of ions will be done through a non recoverable heat production.

It is given below the principle diagram of this reactor. Note that the parts “management of the recovered ions” and “ions injection” are not described (outside the scope of this document).

However, on each exterior side of the reactor, the recovered ions could be braked with an electrostatic system, which would transform part of the remaining ions kinetic energy in electricity with a efficiency close to 0.9 (direct energy conversion). Reversely, this system could be used to inject ions.

For about ions recovery, it is proposed that a weak magnetic field bends the ions beam, once slowed down by the energy conversion system, so as to direct them to the injection part.

Reactor principle diagram
Schéma de principe du réacteur



Electrostatic system for ions injection and recovery (direct energy conversion system)
Système électrostatique pour l'injection et la récupération des ions (système de conversion directe d'énergie)

11.2 Working cycle

It is composed of 3 phases, as described below:

First phase (injection of ions)

At t=0, all the electrodes are at 0 V, except the central electrode at –(U-ΔU):

1) From the internal face of the terminal electrodes left and right (at Z=+/-19.5 mm and X=Y=0), the two ions sources begin to inject into the equipment. It is injected along the Z axis a given number of ions (mixture of D2+ and T2+ ions for example) corresponding to a certain electric charge.

2) Meanwhile, one begins to slowly increase the voltage on the central electrode up the targeted voltage. Under the voltage increasing, ions will have the tendency to move away from the terminal electrodes.

3) Once the injection finished, one continues to increase the voltage, according to the space expected between the ions turnaround position and the terminal electrodes..

4) After the voltage rise and after stabilization, the ions turnaround position will be at the nominal distance from the terminal electrodes.

Second phase (fusions)

Once the ions injection done and the voltage set to its nominal value, ions will begin to circulate regularly in the reactor fusing for a limited number of ions. One will wait a certain time until the fusions frequency be low (less than 100 ns). At this moment, it will be considered that it is useless (relatively to the energy production per unit of time criterion) to wait for more fusions. The beginning of the recovery of ions will begin.

Third phase (ions recovery)

In a first period, the voltage will be slowly increased to reduce the evolution of “dmax” (distance between the turnaround points and the terminal electrodes) down to a very weak value. Ions with a very weak speed will be recovered through the orifices of the terminal electrodes. Once the first ions recovered, it will be necessary to stabilize the voltage to recover most of the ions. Possibly, to accelerate the recovery of the last ions, the voltage will be decreased slowly. It will be necessary to determine the best program of voltage adjustment, so as to recover all not fused ions with the minimum loss of energy. But this is outside the scope of this document.

At a first hypothesis, we could consider a cycle duration (Tc) of 1 µs (1E-6 s) or less. So more than one million of cycles could be realized in one second.
If, during each cycle, it is produced a fusion energy Ef (in J), then the fusion power Pf (in W) will be equal to Ef/Tc for a supplied electrical power equal to Ef/(Eg*Tc) (with Eg the global yield).

11.3 Problem linked to the voltage variation

In reality, the passive power (P in W) necessary to make vary the value of the very high voltage V of a capacity C is simply phenomenal (P=C.V.dV/dt), even if the capacitive energy (E in J) is not so elevated (E=1/2.C.V^2).

The sole solutions are either that the variation of voltage be the weakest possible, or that the variation duration be relatively long:

- In the first case, the injected ions will have to circulate, during the second phase, very closely to the terminal electrodes and the cycle will be shorter. Note that the “LKR1m” model will work very badly in this configuration because it is designed for an injection at 15 mm (14.5 mm in fact) from the central electrode. To adapt the device to an injection at 19.5 mm (at the level of the internal face of the terminal electrodes), both intermediate electrodes must be more separated from the central electrode. For example, if the intermediate electrodes are located at 14 mm from the central electrode and have an interior diameter of 15mm with an injection radius of 50 µm, the result at 200 A/cm2 and an injection at -19.5 mm is not bad (but not as good as the LKR1m model with injection at 14.5 mm). This model, correct until 200 A/cm2, is called “LKR1m3”. It will be used thereafter.

- In the second case, the cycle will be longer and the power delivered weaker.

12. Examples of simulation for the two first phases, results and comments

Although the configuration possibilities for the two first phases be now numerous, it is proposed, below, two examples.

12.1 First example with the fusion D2+ <-> T2+

The targeted voltage is -U=-40 MV on the central electrode, with a ions turnaround position between 19 mm and 19,5 mm (19,5 mm being the position of collision or recovery). The current density is Cd=200 A/cm2 (so the current is equal to 2 A inside the reactor). The model used is the “LKR1m3” one. The time step is equal to 3 ps and the number of ions packets is equal to 1466.
The initial voltage is -U=-36 MV (90 % of the nominal voltage) and the voltage is linearly increased up to -U=-40 MV in 3 ns (1000 time steps). The injection is done in linear mode (radius of injection of 40 microns) and symmetric. One injects during the first 1466x3/2=2199 ps or 2,2 ns. It is noted at 12 ns that ions turnaround position is equal to 19.370 mm (but after having passed through a maximum of 19.398 mm), i.e. the targeted position.

The simulation lasts 4000 time steps so 12 ns. The fusion energy Ef obtained is equal to : 2.076 E-9 J, for a yield E=4.80.

Note 1: this configuration is stored in the LKR1m3_D2_T2.SER file of the sub-directory CONFIGURATIONS of the MULTIPLASMA program.

Note 2: if we suppose that the recovery lasts 8 ns and that Epc=Ef/10=2.076 E-10 J, then the global yield would be equal to Eg=Ef/((Ef/E)+Epc)=3.24.
The cycle will last 12+8=20 ns so the fusion power Pf will be equal to:
Pf = 2.076 E-9 / 20 E-9 = 0.1 W.

Note 3: in the example, 90% of the nominal voltage was taken as initial voltage. However nothing prevents to choose 99% or 99.99 %, the only condition is that no ion collides during the expected period for fusions (here 12 ns). In that case, the reactor will be controlled by slight fluctuations of the voltage which will be easier to implement.

Note 4: for more power, it would be necessary to increase the voltage (for example up to 125 MV) to be able to increase the current. To increase even more the current (remaining with a ions beam in form of cylinder), it must be necessary to change of model (other than LKR1m3) (to determine).

Probably reducing the internal diameter of the intermediate electrodes would be a good option. Indeed, for a working beyond 200 A at 40 MV, a configuration more powerful at radial confinement level must be used. For this, the intermediate electrodes must be closer of the axis. In the case of an injection at 15 mm, the “LKR1m2” configuration is more appropriate (model to determine, in the case of an injection at 19,5 mm). This configuration is stored in the LKR1m2.SER file of the sub-directory « CONFIGURATIONS » of the MULTIPLASMA program.

Note 5: the efficiencies seem, in average, for an injection at -19 mm, more elevated than the ones obtained for an injection at 15 mm (to confirm).

12.2 Second example with the fusion D2+ <-> D2+

The simulation conditions are exactly the same as the ones of the first example except that here the fusion is D2+ <-> D2+ type.

It will be noted at 12 ns that ions turnaround position is equal to 19,390 mm, i.e. the targeted position.

The simulation lasts 4000 time steps so 12 ns. The fusion energy Ef obtained is equal to : 1.95 E-10 J, for a yield E=2.04.

It can be noted that result are clearly less good than with the D2+ <-> T2+ fusion, but we knew this yet (cf. §4 et 6).

Note 1: this configuration is stored in the LKR1m3_D2_D2.SER file of the sub-directory CONFIGURATIONS of MULTIPLASMA.

12.3 About aneutronic fusions

The aneutronic fusion (p + B11) has been integrated to Multiplasma 1.6. It is the object of a specific article available at:
http://f6cte.free.fr/Proposal_of_an_aneutronic_fusion_reactor.pdf
As the cross-section curve of this fusion is roughly located between the D+T curve (the best) and the D+D one (the worst), the results are situated between both ones and are promising.

12.4 Estimation of the calculation accuracy

The calculation accuracy of the simulator Multiplasma is difficult to estimate. Most of the computations are done in simple accuracy (and very few in double accuracy) to avoid prohibitive calculation times. The counterparty is that very fine calculations could be completely wrong.

Roughly, it would be wise to estimate that, in absolute, the “true” values could be between 10 times smaller and 10 times bigger than the results given by the simulator.

However, it is possible to compare configurations, without too much relative error (as done from §3 to 6).

12.5 Heat source and fusion products

It is implicitly considered that fusion products collide electrodes. The kinetic energy of these fusion products is transformed in heat, which constitutes the heat source of the thermodynamic cycle.
Note : charged fusion products which collide the electrodes at 0 V, by rising the electric potential, produce (induced) electricity.

13. Conclusion

The most efficient fusion is the D2+<->T2+ one, in yield and in energy supplied. Moreover, this fusion permits to work up to a relatively high gas pressure.

Despite the confinement problem due to ions thermalization by the space charge and Coulomb collisions, a theoretical solution has been found using the reactor control by the voltage, this one permitting:

- in D2+<->T2+ fusion, to obtain a fusion yield of 4.8,
- in D2+<->D2+ fusion, to obtain a fusion yield of 2.0.

There is a large amount of latitude to improve the last model used (“LKR1m3”), for the purpose to get a better yield and a more important power, because only a very small subset of the possibilities has been tested by the author.

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And many others (thanks to the authors)…

Internet page of the author: http://f6cte.free.fr/multiplasma_english.htm

APPENDIX 1

Calculation of the global yield Eg

```
procedure Eg_Fp_Calculation(U,Cd:DOUBLE;VAR Eg:DOUBLE;VAR Fp:DOUBLE;VAR Df:DOUBLE;VAR Nfs:DOUBLE;VAR
USELESS:BOOLEAN);

{Calculation for the D2-T2 fusion (1 to 125 MV) / Calcul pour la fusion D2-T2 (1 à 125 MV)}


{Input data / Données d'entrée}

{U: Voltage on electrodes in MV / Tension sur les électrodes en MV

 Cd: Current density in A/cm2 (on a section of 1 mm2) / Densité de courant en A/cm2 (sur une surface de 1 mm2)}


 {Output data / Données de sortie}

{Eg: Global yield of the working cycle / Rendement global du cycle de fonctionnement

 Fp: Fusion power in W / Puissance de fusion en W

 Df: Probable confinement time in s / Durée de confinement probable en s

 Nfs: Number of fusions per second in the reactor / Nombre de fusions par seconde dans le réacteur

 USELESS: during the confinement time, at least one fusion must occur,  otherwise it is useless

 pendant la durée de confinement au moins une fusion doit avoir lieu sinon c'est inutile}
```

{Constant data / Données constantes}

CONST Sigma_V:DOUBLE=1E-12;{Mean Sigma_V in mm3/s for D2+<->T2+ fusion/ Sigma_V moyen en mm3/s pour la fusion D2+<->T2+ }

CONST Li:DOUBLE=29;{Minimum confinement lenght at injection time in mm / longueur de confinement minimum lors de l'injection en mm}

CONST Le:DOUBLE=39;{Maximum confinement lenght (between terminal electrodes) in mm / longueur de confinement maximum (entre électrodes terminales) en mm}

{Intermediate variables / Variables intermédiaires}

VAR Lm:DOUBLE;{Mean confinement lenght in mm / longueur de confinement moyenne en mm}

VAR Sm:DOUBLE;{Mean speed of an ion (m/s) / Vitesse moyenne d'un ion m/s}

VAR Tre:DOUBLE;{Maximum round trip time (between terminal electrodes) (s) / durée maximum d'un aller-retour entre les électrodes terminales (s)}

VAR Tri:DOUBLE;{injection time over a round trip (s) / durée d'injection sur un aller-retour (s)}

VAR Q:DOUBLE;{Electric charge in Coulomb / Charge électrique en Coulomb}

VAR Ni:DOUBLE;{Number of ions in the reactor / Nombre d'ions dans le réacteur}

VAR Rc_mean:DOUBLE;{mean confinement radius in mm / rayon de confinement moyen en mm}

VAR Epf:DOUBLE;{Mean energy per fusion in MeV / Energie moyenne par fusion en MeV}

VAR Ef:DOUBLE;{Produced fusion energy (J) / Energie de fusion produite (J)}

```
VAR E:DOUBLE;{Probable fusion yield / Efficacité de fusion probable}

{Epc: Lost electric energy by collision of ions on terminal electrodes from the confinement loss (end of cycle) /

Perte d'énergie électrique par collision des ions sur les électrodes terminales à partir de la perte du confinement (fin de cycle)}

VAR Epc:DOUBLE;

VAR Ec_max:DOUBLE;{Maximum kinetic energy for a ion (J) / Energy cinétique maximum pour un ion}

VAR R:DOUBLE;{Ratio of the energy loss at the confinement loss compared to Ec_max / Ratio de la perte d'énergie à la perte de confinement
comparée à Ec_max}

BEGIN

 {Lm / Tre /Tri}

 Lm:=(Li+Le)/2;

 Sm:=3093*SQRT(U*1E6);

 Tre:=2*Le*1E-3/Sm;

 Sm:=3093*SQRT(Li*U*1E6/Le);

 Tri:=2*Li*1E-3/Sm;

// WRITELN('Tri ',Tri:12,' ','Tre ',Tre:12);


 {Rc_mean, experimental}
```

```
 IF Cd<0.6 THEN Rc_mean:=0.01972/Power(U,0.77)*Power((Cd/0.006),0.29) ELSE
 IF Cd<6 THEN Rc_mean:=0.08632/U*Power((Cd/0.6),0.29) ELSE
 rc_mean:=1.085/Power(U,1.3)*Power((Cd/6),0.29);
 Rc_mean:=Rc_mean*1.5;{expansion}
// WRITELN('Rc_mean ',Rc_mean:12);

 {Nfs}
 Q:=Cd/100*Tri;{1/100: cm2 --> mm2}
 Ni:=Q/1.60219E-19;{1.60219E-19: charge of one ion in Coulomb}
 Nfs:=SQR(Ni)*Sigma_V/(2*Pi*SQR(rc_mean)*Lm);
// WRITELN('Ni ',Ni:12); WRITELN('Nfs ',Nfs:12);

 {Fp}
 Epf:=17.08+0.31*U;{MeV, experimental}
 Fp:=Nfs*(Epf*1E6*1.60219E-19);{1.60219E-19: eV --> J}
// WRITELN('Epf ',Epf:12); WRITELN('Fp ',Fp:12);
```

```
 {Df, mainly experimental + Ef + USELESS}
 Df:=2E-7*(Le-Li)*Power(U,0.39)*Power(Cd,-0.69);
 Ef:=Fp*Df;
 IF Nfs*Df>1 THEN USELESS:=FALSE ELSE USELESS:=TRUE;
// WRITELN('Df ',Df:12,'  Ef ',Ef:12);


 {Epc, mainly experimental}
 R:=2.295*Power((U/5),-0.39)*Power((Cd/6),0.69)*Tre*1E6/Le;
 Ec_max:=1.60219E-19*(U*1E6);{qU is an overestimate / qU est un majorant}
 Epc:=R*Ec_max*Ni;
// WRITELN('R ',R:12,'  Ec_max ',Ec_max:12,'  Epc ',Epc:12);

 {Eg}
 E:=47.19/U+1.29;{experimental}
```

```
 Eg:=Ef/((Ef/E)+Epc);
// WRITELN('E ',E:12); WRITELN('Eg ',Eg:12);


end;
```