Proposal of an electrostatic confinement reactor able to produce nuclear aneutronic fusions with a yield superior to 1

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Revision A

CONTENTS

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 aneutronic fusions of H+ <-> B11+ type, with a yield (kinetic fusion products energy / electric energy consumed) superior to 1.

This presentation relies on:

- the presentation done previously in reference [1],
- the Multiplasma 1.6 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.

One can, possibly, read the article aimed to Multiplasma users: http://f6cte.free.fr/Simulation_of_an_electrostatic_confinement_fusion_nuclear_reactor.pdf

In what follows, it is first presented the aimed objectives and the hypothesis made, then an abstract of different H+ <-> B11+ simulations done on the LKR1 reactor.

It is afterwards reminded the results and solutions obtained previously (issued from the reference [1]). This includes an improved reactor ("LKR1m3") able to reach a yield superior to 1 producing more power, as well as its working cycle.

A final test permits 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 « . »,
- the powers of ten are indicated with Ex or 10^x (for example 10^{-7} or E-7),
- "§" for "chapter".

2. Fusion type and yield objective

2.1 Type of aneutronic fusion

The aneutronic fusion reaction managed by Multiplasma 1.6 is the following :
H+ + B11+ ->3 He4 (+ 8,68 MeV)

It must be noted that Multiplasma includes the kinetic energy Ek of ions fusing in :

- the global fusion products energy: H+ + B11+ (+Ek) ->3 He4 (+ 8,68 MeV+Ek),
- the consumed electric energy.

The hydrogen nucleus « H+ » is a proton.

« B11+ » corresponds to a boron-11 atom (5 protons and 6 neutrons) ionized by loss of only one electron (ionization energy: 8.3 eV). It has not been considered the chemical problem of the B11+ atom production, knowing that the boron is under the gas form in the boranes (BH3 for example).

The reaction produces 3 helium-4 nuclei (2 protons and 2 neutrons) which are charged particles and so susceptible to be directed and slowed down. The kinetic energy generated by the fusion, for the whole nucleus He4, is equal to 8.68 MeV. The distribution of this energy among the He4 nuclei is probably random.

The chosen gas is the hydrogen (H2) because, possibly, fusions between B11+ and the nuclei of H2 could take place. However, the best is to have the lowest gas pressure to limit the problem of exchange of charges between ions and neutrals.

Hydrogen and bore-11 are abundant elements on Earth.

The other aneutronic reactions based on He3 have not been implemented in Multiplasma because the He3 element is only present on Earth in trace amounts.

2.2 Objectives in term of global yield

In reference [1], for fusion reactions (D-D or D-T), it has been made the (pessimistic) hypothesis that the conversion system was thermodynamic of efficiency 0.3. The same hypothesis is taken here, which justifies that the system global yield must be superior to 1 at worst, but superior to 3.333 (= 1 / 0.3) at best. We will adopt, a priori, a minimum yield objective of 3.333 (“Emin” thereafter).
In addition, the power fusion must be the largest possible.

2.3 Hypothesis made

There are several pieces of data that are not found in the accessible scientific literature. So the author has made the following hypothesis:

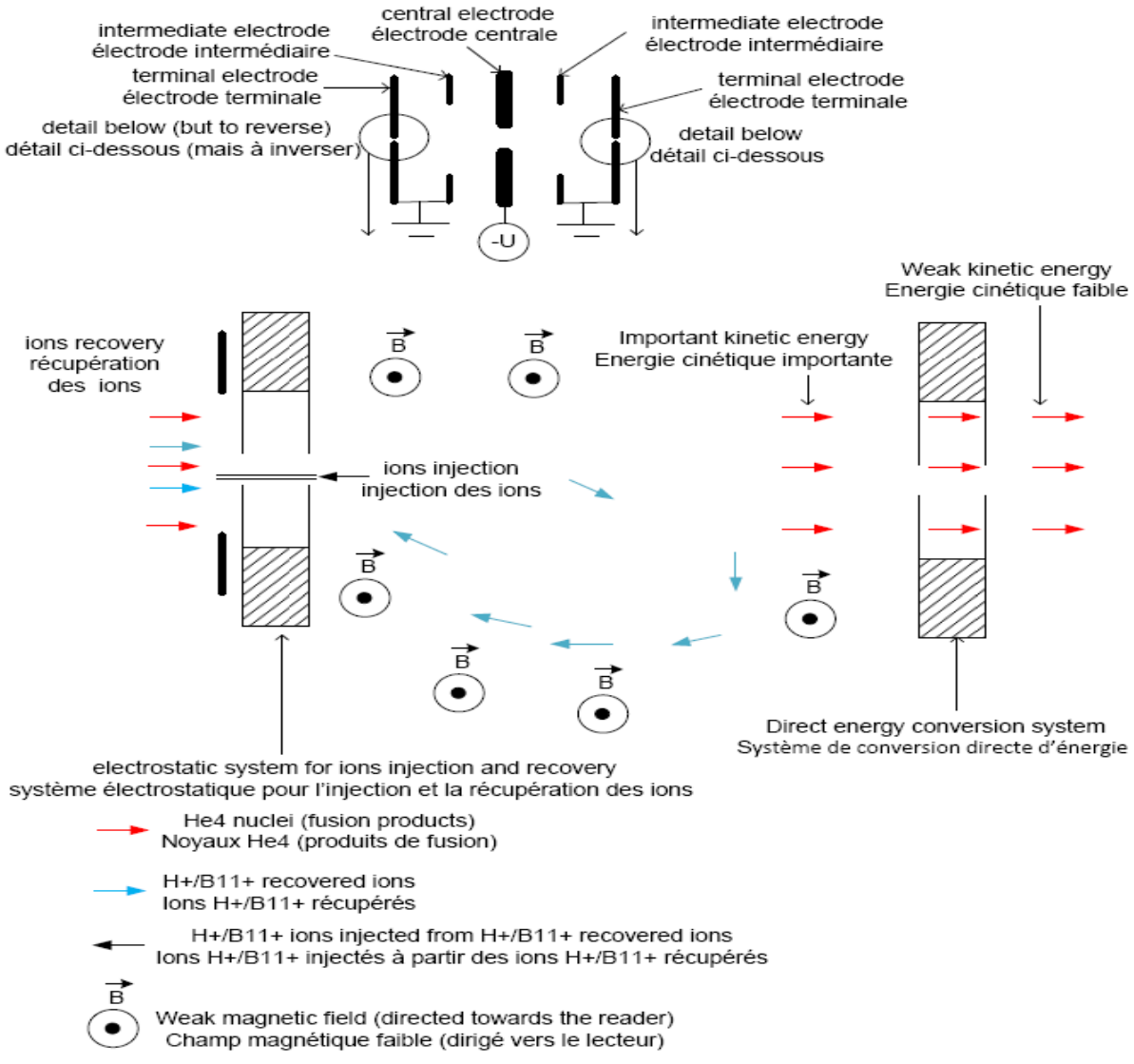
- the charge exchange cross section between B11+ ions and the H2 gas molecules is the same as between the H+ protons and the H2 molecules,

- the B11+ ions which have one electron missing don’t lose the other electrons (the B11 atom having initially 5 electrons), in collisions with neutrals or in the Coulomb collisions. If it was the case, the Coulomb collisions would be much more numerous. These ones would degrade the ions beam, so the number of fusions would decrease.

2.4 About the (abandoned) possibility to directly convert the fusion products energy in electricity

Because the He4 nuclei are charged particles, it would have been possible to make the hypothesis that their kinetic energy be converted in electricity in an electrostatic system (or other), with an efficiency close to 0.9 (direct energy conversion), which would be interesting for a spatial propeller. In this case, it would be enough that the reactor global yield be superior to 1.111 (= 1 / 0.9), instead 3.333. Unfortunately, the fusion products (the He4 nuclei) will probably diffuse in all directions (according to an unknown angular distribution) and will collide electrodes, without possibility to concentrate them along the device axis (Z axis) in order to make them cross a direct energy conversion system.
It must be noted that the He4 nuclei angular distribution will certainly be a narrow one around the Z axis, due to the fact that the B11 ions, being 11 times heavier than protons, will impose their motion amount along the Z axis to the He4 nuclei (but it is difficult to go further without experimentations).

The diagram below shows the reactor if it would be possible to concentrate the He4 nuclei along the device axis or if the He4 nuclei angular distribution was very narrow along the device axis.



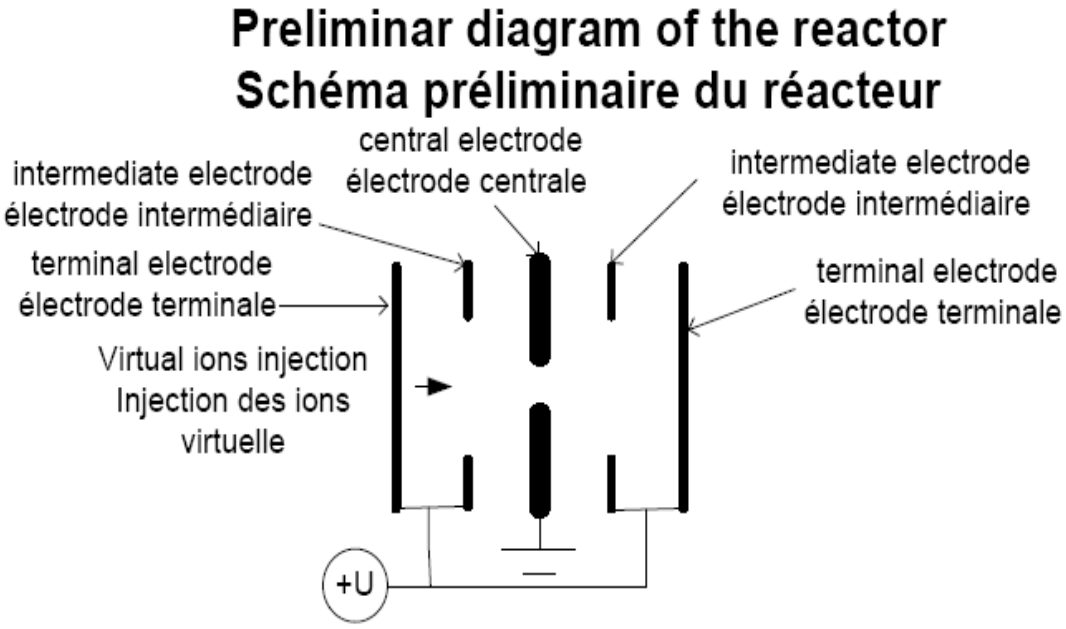
3. Simulation of aneutronic H+ <-> B11+ fusions

3.1 Generalities

In what follows, it is presented an abstract of different simulations done on the "LKR1" reactor (see description in the reference [1], §2), which permit to show the interest on this reactor, according to the voltage. For the reader, these results could be compared with the ones obtained in the reference [1] (§3 à 6), in comparable conditions.

Quick reminder of the "LKR1" reactor and its working

For this model ("LKR1"), the ions injection is done (in a virtual way) at 15 mm from the central electrode.



The 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).

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.

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

Simulation conditions

All simulations have been done on 10000 time steps.

The current density (Cd) is the maximum possible value:
- for the voltage (U),
- for the injection duration.

These tests give for a set of voltages, the maximum electric charge (Q) that the reactor can confine during a limited time, the yield and the fusion power.

3.2 Results of the simulation for H+ <-> B11+ 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 rapidly increases up to 6.835 for a voltage of 7 MV then slowly decreases.

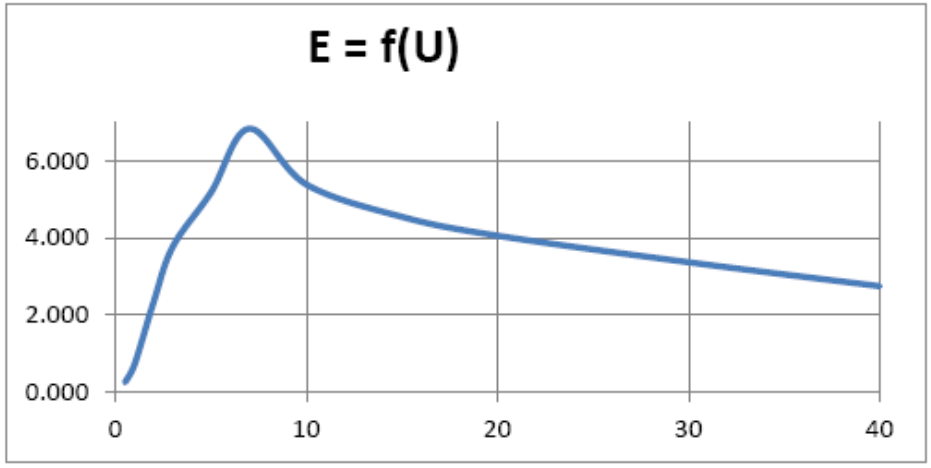
The ideal value for the voltage U is the one for which the exploitable power EP is maximum. For the minimum yield Emin=3.333, the exploitable power is equal to 0 W. For E>3.333, the supplied electric power is equal to P/3.333, the consumed electric power is equal to P/E and so the exploitable power is 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.

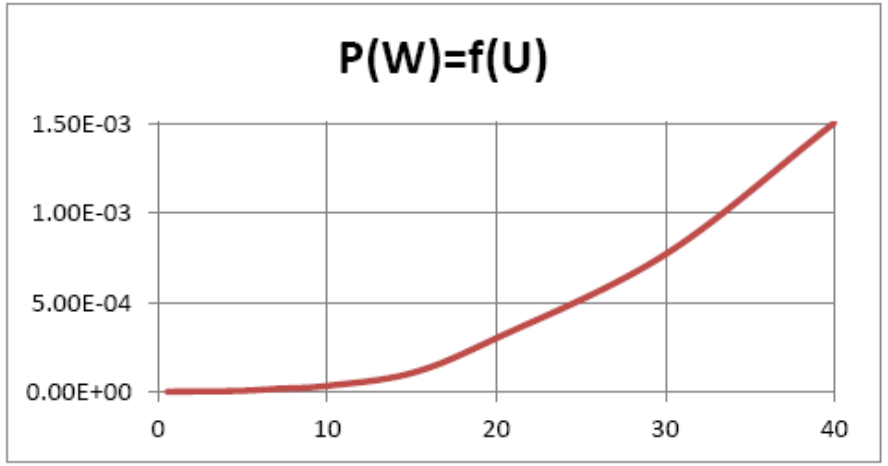
It can be noticed that the maximum confined electric charge (Q) is approximately proportional to the voltage.

Reminder: 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.

Study of E and P = f(U) for H+ <-> B11+ at Pgas=10pPa / Etude de E et P = f(U) pour H+ <-> B11+ 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	1664	1.997E-09	0.237	1.09E-08	-4.27E-08
1	12	20	1764	4.234E-09	0.707	6.61E-08	-7.37E-08
2	35	10	2496	8.736E-09	2.334	5.89E-07	-7.57E-08
3	64	10	2038	1.304E-08	3.767	1.71E-06	5.92E-08
5	120	10	1578	1.894E-08	5.180	4.77E-06	5.10E-07
7	250	6	2223	3.335E-08	6.835	1.56E-05	2.40E-06
10	370	6	1861	4.131E-08	5.384	3.23E-05	3.69E-06
15	700	6	1519	6.380E-08	4.543	1.04E-04	8.33E-06
20	1300	3	2632	1.026E-07	4.053	2.99E-04	1.59E-05
30	2200	3	2150	1.419E-07	3.362	7.69E-04	1.97E-06
40	3050	3	1865	1.706E-07	2.740	1.51E-03	-9.79E-05





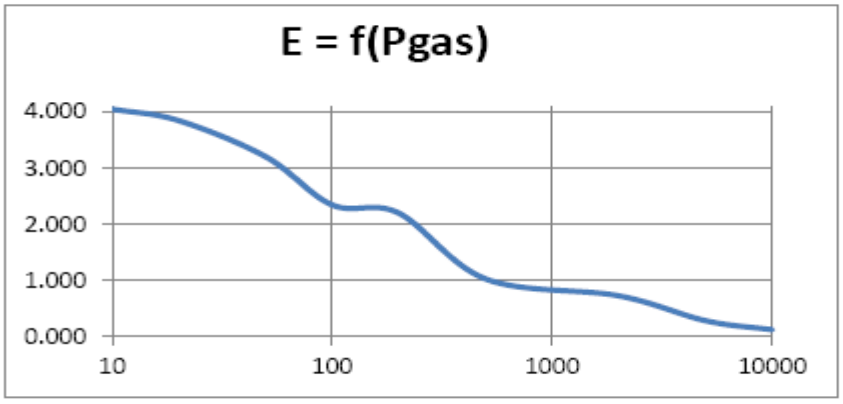
3.2 Results of the simulation for H+ <-> B11+ fusions at different gas pressures

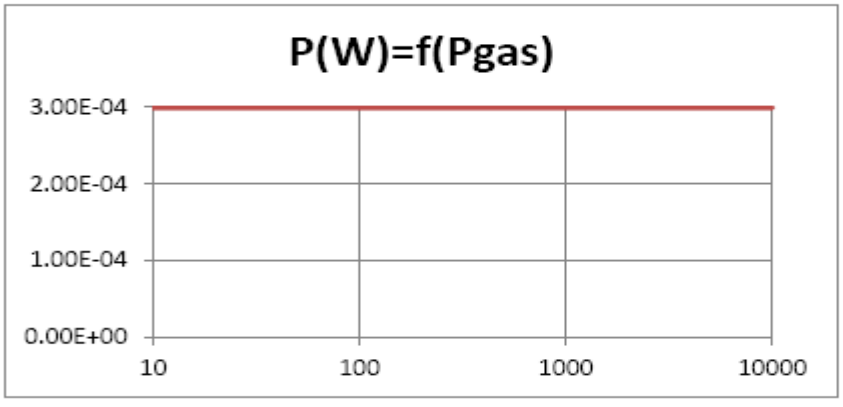
It will be considered the “best” solution determined previously so a voltage of 20 MV, a current density of 1300 A/cm^2 under a pressure of 10 pPa and we will see the evolution of E and P according to the gas pressure. It is expected a degradation of the reactor performances due mainly to the Ions-Neutrals charge exchanges but also to Ions-Neutrals elastic collisions.

The following panel gives an abstract of the results obtained. It can be seen that a maximum of 20 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 H+<->B11+ / Etude de E et P = f(Pgaz), pour H+<->B11+
All tests done at 20 MV Cd=1300 A/cm2
Tous les tests faits à 20 MV Cd=1300 A/cm2

Gas pressure / Pression du gaz Pgas (pPa)	Yield / Efficacité E	Fusion power / Puissance de fusion P (W)
10	4.053	2.99E-04
20	3.849	2.99E-04
50	3.200	2.99E-04
100	2.342	2.99E-04
200	2.199	2.99E-04
500	1.019	2.99E-04
2000	0.721	2.99E-04
5000	0.274	2.99E-04
10000	0.114	2.99E-04





4. Abstract of results and solutions obtained previously

Below it will be found an abstract of the problems and solutions explained more in details in the reference [1] (§7 to 12).

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). The energy exchange between particles when they collide (Coulomb collisions I-I), is the other source of energies «thermalization », overall at low intensity.
One can try to limit the thermalization but it can't be avoided.
The main parameter to follow from the Multiplasma program is « dmax » (maximum distance from the center).

Solution consisting to increase the confinement time

The confinement time can be increased by limiting the space charge and the Coulomb collisions by reduction of the electric charge stored.

Effectively by decreasing significantly the electric charge, the confinement time can be widely increased. But the fusion power produced will be extremely weak and without any practical interest.

So this solution is abandoned. Reversely, it will be ignored the fusions regularly created. It will only be taken into account the fusions created during the injection and a bit after (before ions dispersion). This means that the confinement time 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.

Problem of collisions on central electrode and solution

Due to "thermalization" phenomena, the turnaround point of ions circulating in the reactor (i.e. where their speed becomes nil and they turn back), is going to have the tendency to move away from the center until collision with a terminal electrode. From the energy balance point of view, the loss is weak because ions have a weak speed when they collide.
In the same way, due to thermalization, some ions will not have enough kinetic energy and will end up colliding the central electrode. From the energy balance point of view, the loss is elevated because these ions have a very elevated speed when they collide. So collisions of ions with the central electrode must be avoided.

Experimentally, it has been noticed that to avoid collisions with the central electrode, the current density must be limited to $1/6^{th}$ of the maximum current density, for a charge confined at least 100 ns. In that case, ions collide always the terminal electrodes.

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. This solution has been adopted and implemented on Multiplasma.

If we apply a linear injection, limiting the current density to about 1/6th of the maximum current density, for a charge confined at least 100 ns, then the confinement volume will be in form of cylinder (i.e. a “red dash” on the reactor sectional view) of mean radius inferior to 0.05 mm, so consequently:

- in one hand, it is avoided collisions with the central electrode,
- in the other hand, the number of fusions is maximized.

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. This solution has been adopted and implemented on Multiplasma.

Control of the reactor with the voltage (for ions injection and recovery) and reactor principle diagram

If the collision speed on terminal electrodes could be controlled, the lost energy could be made negligible (ideally nil). In this case, it would be obtained the best yield possible.

This control is possible simply by increasing or by decreasing slowly the voltage, following a ramp. This has been checked on simulation. Experimentally, it is found that for a ramp-up voltage there is a contraction along the Z axis of the confinement cylinder and reversely for a ramp-down voltage. These evolutions depend on the chosen model.

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 in form of cylinder (see the previous page).

Moreover, this control can be used for the introduction of ions in the reactor:

- 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).

Once the central electrode is 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.

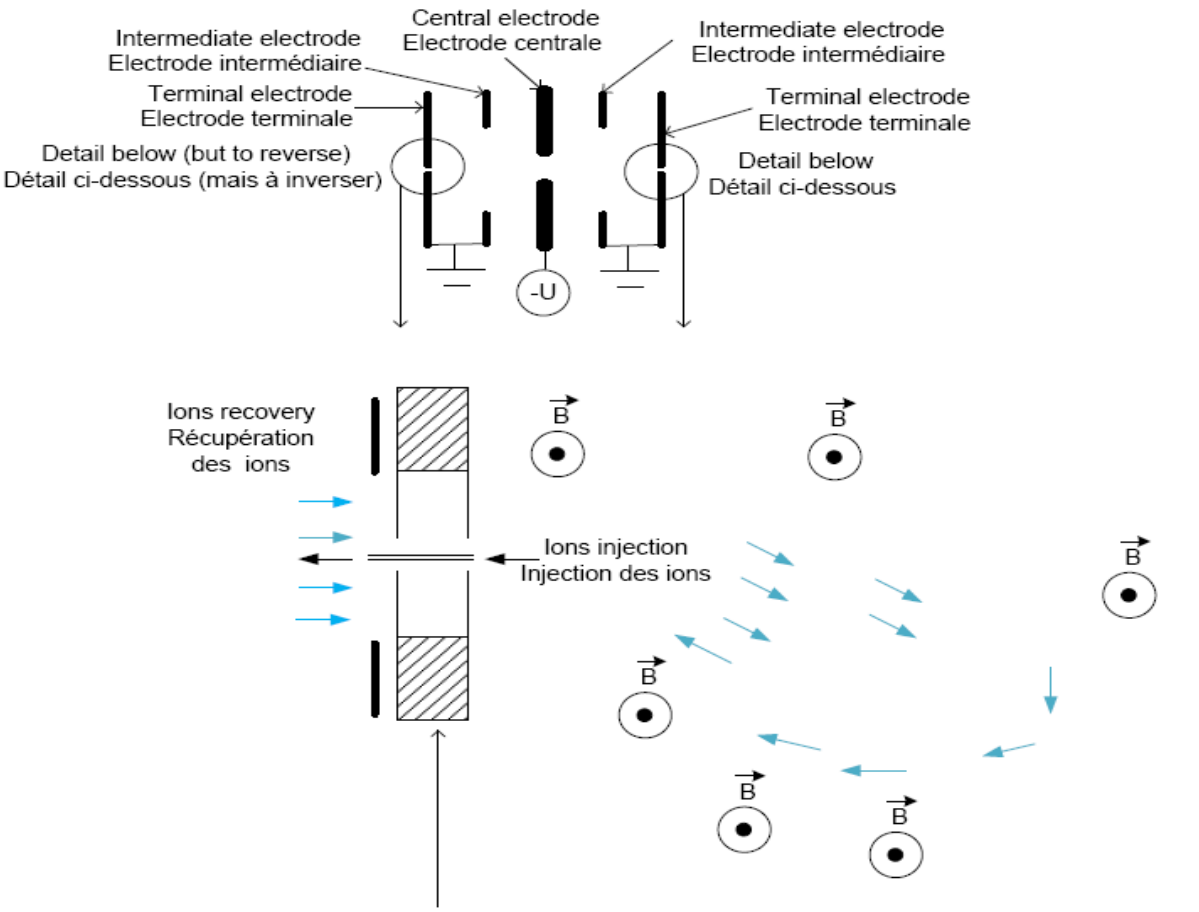
Note that orifices on terminal electrodes will permit to recover ions not fused at the end of cycle, rather than let them collide on terminal electrodes.

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 can 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 towards 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)

Recovered ions to be re-injected
Ions récupérés pour être réinjectés

Ions injected from recovered ions
Ions injectés à partir des ions récupérés

$\vec{B}$ Weak magnetic field (directed towards the reader)
Champ magnétique faible (dirigé vers le lecteur)

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.

Working cycle

It is composed of 3 phases, as described precisely in reference [1] §11.2:

- First phase: injection of ions.
  From the internal face of the terminal electrodes left and right, the two ions sources begin to inject into the equipment. It is injected along the Z axis a given number of ions (mixture of 50% H2+ and 50% B11+ ions) corresponding to a certain electric charge and, in parallel, the voltage is slowly increased.

- Second phase (from the end of the voltage increase): stabilized circulation of ions and fusions.

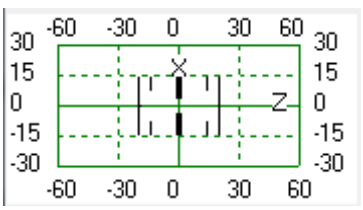
- Third phase: circulating ions recovery, through the two terminal electrodes orifices.

The cycle duration is very short: 1 µs or less.

Improvement of the LKR1 model

The reactor model LKR1 is not adapted to the working described previously. It will be determined a better model on its capacity to confine the plasma in the most concentrated way along the device axis, from an injection point located at the internal face of the terminal electrodes left and right.

This new model, correct up to about 200 A/cm2, is named “LKR1m3” (with “m” for “modified”).



Determination of the reactor global yield for the complete working cycle (Eg)

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=Ef/((Ef/E)+Epc) with:

- Eg: global yield of the working cycle, i.e. the ratio between the energy supplied by the fusion products and the consumed electric energy, for the complete cycle.

- Ef: energy (J) produced by fusion products.
  It is a piece of information supplied by the Multiplasma program.

- E: yield of the fusion process, i.e. the ratio between the energy supplied by the fusion products and the consumed electric energy, for the two first phases of the cycle.
  It is a piece of information supplied by the Multiplasma program.

- Epc: energy (J) lost by collision of ions on terminal electrodes, or during ions recovery, from the confinement loss (at the end of the cycle).
  It is an estimated piece of information.

5. Simulation of the two first phases, results and comments

Although the configuration possibilities for the two first phases be numerous, it is proposed three examples aimed to have a variety of cases.

Simulation conditions:

- The model used is the “LKR1m3” one.
- The targeted voltage is -U=-20 MV (first case), -40 MV (second case) or -50 MV (third case) on the central electrode, with a maximum ions turnaround position between 19 mm and 19,5 mm (19,5 mm being the position of collision or recovery).
- The current density Cd is the one which permits to have the biggest fusion energy Ef for the chosen voltage –U, independently to the yield. It is reminded that the current in the reactor is 100 times weaker (for example 2 A for Cd=200 A/cm2).
- The time step is equal to 3 ps for the 3 voltages.
- The number of ions packets is equal to de 3432 at -20 MV, 2665 at -40 MV and 2350 at -50 MV.
- The initial voltage is equal to 90 % of the nominal voltage and the voltage is linearly increased up to 100 % of the nominal voltage in 6 ns (2000 time steps).
- The injection is done symmetrically from the internal face of the terminal electrodes left and right, in linear mode. The radius of injection is 7 microns at -20 and -40 MV and 3 microns at -50 MV.
- The simulation lasts 3500 time steps so 10,5 ns.

Simulation results:

The main results are given under in the form of a table:

Voltage –U (MV)	Current density Cd (A/cm2)	Fusion yield E	Fusion energy Ef (J)	Maximum ions turnaround position (mm)	Mean confinement radius (mm)
-20	50	3.486	1.399 E-10	19.237	0.01962
-40	180	2.155	2.589 E-9	19.360	0.02554
-50	205	2.034	8.112 E-9	19.384	0.02756

Example of global yield calculation at -20 MV
If we suppose that Epc=Ef/10=1.399 E-11 J, then the global yield will be equal to Eg=Ef/((Ef/E)+Epc)=2.58.
If Epc=Ef/100=1.399 E-12 J, then Eg=3.37.

Calculation of the mean fusion power for the cycle
If we suppose that the recovery lasts 9.5 ns, then the cycle will last 10.5+9.5=20 ns so the mean fusion power for the cycle Pfm will be equal to:

- at 20 MV: Pfm = 1.399 E-10 / 20 E-9 = 7.00 E-3 W
- at 40 MV: Pfm = 2.589 E-9 / 20 E-9 = 0.129 W
- at 50 MV: Pfm = 8.112 E-9 / 20 E-9 = 0.406 W

Comments

- We see that apparently, between U=20 and U=50 MV, the fusion power Pfm increases very rapidly according to the approximate formula:
  Pfm (W) = $(U/20)^{4,4}$ x 0.007, which would give at U=100 MV a probable mean fusion power Pfm=8.3 W.

- We clearly see that the yield is maximum at U=20 MV and slowly decreases with the voltage, which confirms the results of the §3. So there is a compromise to do between power and efficiency.

- For even more power and/or fusion yield, it would be necessary to change of model (other than LKR1m3), to determine, the author having only tested a tiny fraction of all the possibilities.

- the three test configurations are stored in the LKR1m3_H_B11_20_MV.SER, LKR1m3_H_B11_40_MV.SER and LKR1m3_H_B11_50_MV.SER files of the sub-directory CONFIGURATIONS of MULTIPLASMA.

6. Conclusion

The H+<->B11+ aneutronic fusion in a reactor LKR1m3 type, controlled in voltage (cf. §4 and 5), permits to reach a fusion yield superior to 1 and rather between 2 and 4 according to the voltage used (cf. §3 and 5).

In §3, it has been determined that the ideal value for the voltage is the one for which the exploitable power is maximum, so 20 MV. It has also been noticed that the yield remains superior to 3.333 as long as the gas pressure remains inferior or equal to 20 pPa.

Furthermore, by lack of data in the scientific literature at the author's knowledge, it has been made a certain number of hypothesis (cf. §2), which adds uncertainty to the technical feasibility of such reactor.

However, there is a large amount of latitude to improve this reactor, thanks to Multiplasma simulations or, possibly, experimentations.

The most interesting improvement would be to find a way to convert the kinetic energy of He4 nuclei in electricity with a direct energy conversion system (see §2.4).

Reactors in parallel
What has been described corresponds to only one reactor of small dimensions (several cm), for an ions beam of less than $1/10^{th}$ of mm of diameter.
In a possible practical application, thousands of devices might be set in parallel. An objective of one reactor per cm^2 and consequently 10000 reactors per m^2 could be aimed.

7. References

Preliminary note: for a complete list of references, refer to the §14 of the reference [1], below.

[1] « Proposal of a new type of electrostatic confinement reactor able to produce nuclear fusions with a yield superior to 1" by Patrick Lindecker: http://f6cte.free.fr/Proposal_of_a_new_type_of_fusion_reactor.pdf

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