Simulation of a fusion reactor using an electrons cloud confined in a magnetic bottle

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Revision A

CONTENTS

1. Goal, presentation and notations used

The goal of this presentation is to describe a fusion reactor based on a magnetic bottle using magnetic confinement for electrons and electrostatic confinement for ions.

It produces nuclear fusions with a yield, unfortunately, extremely low, this one being defined by: “Kinetic fusion products energy / Electric energy consumed”.

This presentation relies on the Multiplasma particular simulator program version 1.10 (not public) developed by the author and used for the simulation of such reactor.

The studied reactor supposes the use of a Deuterium/Tritium fuel.

The problems of tritium regeneration, neutrons management relatively to materials and radiation hygiene are not addressed. This article is only concerned by the fusion aspect exclusively.

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),
- the square root of x is also indicated with SQRT(x)
- “§” for “chapter”
- « m » for the mass of an electron (9.11E-31 kg)
- « q » (1.60E-19 C, in absolute value) for the charge of an ion (D+ or T+) or an electron (= -q in fact)
- “V” for the speed

It is used the SI units or multiples.
In this paper, it is supposed that « 1 pixel = 1 mm » (default value, which could be modified from 0.1 to 10 mm). So thereafter, it will be equally spoken of “mm” or “pixel”.

2. Brief explanations of a few of the terms used:

- Deuterium (D or D2) / Tritium (T or T2): these are hydrogen isotopes comprising, besides one proton, either one neutron (Deuterium) or 2 neutrons (Tritium). As other elements, they are susceptible to produce fusions by collisions. The Deuterium is relatively abundant, in sea water, for example. It constitutes 0.01 % of hydrogen. The tritium is naturally present at traces amounts but it is produced (as a gaseous effluent) by fission nuclear centrals, in very small quantities.

- Interaction: it refers to the effect produced by two particles bumping each other : it can be an excitation, a dissociation or a radiation (not considered by Multiplasma), a collision, an ionization, a fusion.

- eV: the eV is a unit of energy quantity used in the particles domain.
  1 eV is equivalent to 1,602 10-19 J.

- Fusion: specific interaction where two particles (as D+) collide with sufficiently energy to be transformed in other particles with production of a certain quantity of kinetic energy (besides the initial kinetic energy of the particles colliding each other).
  Several fusion reactions are given below :

  - D+ + D+ ->T+ (+1.01 MeV) + p+ (+3.02 MeV) (at 50%)
  - D+ + D+ ->He3+ (+0.82 MeV) + n (+2.45 MeV) (at 50%)
  - D+ + T+ ->He4+ (+3.5 MeV) + n (+14.1 MeV)
  - H+ + B11+ ->3 He4 (+ 8,68 MeV) (aneutronic fusion)

- Ions: in our case, it can refer to an atom (D or T) having lost an electron. So it is an atomic ion (noted D+ or T+). It can also be a molecular ion if the molecule has lost an electron (D2+ or T2+). A molecule (D2) can be dissociated in atoms (D + D) and/or ionized (D+ + D+ or D2+).

- “Ions” is abbreviated to “I”. “Neutrals” (gas molecules) is abbreviated to “N”.

- Cross section: it refers to the collecting surface of the interaction. The larger it is and the more it will be produced interactions. It can also be seen as an interaction probability.

- Space charge: each ion and each electron creates its own electrical field to which all other charged particles are submitted. So, the space charge is equal to the sum of all these individual micro-electrical fields. In total, the particles of the same polarity tend to deviate from one another.

3. Simulator

This program developed by the author is called Multiplasma. It is at the moment (August 2019) at the 1.10 version but it is not public. It is a particle-in-cell 3D simulator, under Windows (W32), able to simulate particles trajectories (electrons and ions) and a certain number of interactions between particles (but not all, only the main ones).

Note that the Multiplasma version 1.6 is proposed to download in “freeware”, from the WEB page http://f6cte.free.fr/multiplasma_english.htm
However this 1.6 version does not manage magnetic devices.

4. Electrons Injection

Goal of the electrons injection
The thing is to create a very negative potential (-50 KV is aimed as a minimum) induced by electronic charges injected at the center of the device.
This -50 KV potential will permit to communicate to ions an average energy of about 10 KeV. At the time of D+/T+ frontal collisions at the center of the device, it will be reached a value of more than 30 KeV at the mass center level, value which corresponds to a correct fusion cross section for Deuterium/Tritium collisions.

This electronic cloud must have an axisymmetric shape (the magnetic bottle axis being directed along Y) and symmetric compared to the central plane (Y=0) so that the potential be maximal (in absolute value) at the very exact center of the device, i.e. on the axis and just between the solenoids (radius=0 and Y=0). In this way, ions will be in a potential well and all attracted towards the center of the device (in theory).

Accelerating voltage permitting to reach -50 KV
As previously indicated, the objective is to reach a minimum of -50 KV. The electrons cloud will roughly have a cylinder shape. By assimilating this shape to a sphere, it can be shown that the ratio between the voltage (« potential » in fact) induced at the “sphere” surface (so at the injector level) and the maximum voltage at the center of the electrons cloud is equal to 2/3 (see, for this subject, the link in reference [4]). So as a minimum, the accelerating voltage of electrons must be equal to 2/3 of the aimed induced voltage. But to avoid that electrons be too much slowed down at the injector output by the space charge, it will be selected an accelerating voltage superior to the absolute value of the aimed induced voltage, i.e. +100 KV here.

> Note 1 : with the progressive formation of the space charge, the initial electrons trajectories are going to be modified, some electrons being slowed down. So they will turn on smaller and smaller circles and will have a greater tendency to escape axially.
> Note 2 : experimentally, the voltage ratio is about half of the potential at the device center (rather than 2/3).

Minimum current permitting to reach -50 KV
What appears clearly in the numerous tests done by the author is that if the rate of the electrons loss is weak at start, it, afterwards, increases slowly, while the electrons cloud develops.

At worst, the loss rate could be such that the new injected electrons could not compensate electrons lost on the injector and those escaping radially and axially. So, it can be noticed that if the current is not sufficient, it is not certain that the voltage of -50 KV could be reached, the voltage induced by the space charge having the tendency to increase slowly and slowly, not to say to stabilize and even, afterwards, to slowly decrease.
Several (long) tests show that a minimum current of 350 mA is necessary to reach -50 KV.
In contrast, at 1 A it is easily reached -50 kV. So it will be considered 1 A to have some margin and to decrease the simulation duration. It has to be noted that any current superior to 1A will permit to necessarily reach -50 kV, see much more, but the injector would have to be of a diameter superior to 1mm and, hence, brings more losses by collisions with this one.

Description of the injector
It must be the finest possible to limit, at the maximum, collisions with electrons but it must not be too much fine to be able to carry the 1 A current required previously.
This one is composed of an injection neck which can be seen as a disk with a 1 mm diameter. It is preceded by a 1mm diameter tube with a length of 20 mm, sufficient so that the input end of that tube not be collided by electrons. So it can be connected the focusing line of the electron gun (not described, but supposed to permit to generate a 1A beam under 100 KV).
The author has made the hypothesis that it is possible to pass a 1 A current (maximum) through a tube of 1 mm interior diameter (the thickness of the tube magnetic shielding being neglected). On the one hand, 1 A is the maximum intensity of electrons beam welding systems and for these ones, it is admitted brilliances of 0.5 E10 A/(m^2.Sr) and more, especially with LaB6 cathodes. With this 0.5 E10 A/(m^2.Sr) hypothesis, it comes a product « maximum radius of the beam x maximum divergence angle » of 4.5 mm.mrad, sufficient to pass the 1A beam. It has to be noted that the beam « cross-over » will be located in the approximate middle of the tube (without any impact on the simulation). The tube output will be considered as a circular surface of 1 mm diameter, emitting electrons under a maximum angle of 20 mrad.

Injection principle
To get an induced voltage which can be maximal at the center of the device, it must be made so that all electrons trajectories cross the device axis, which will increase the probability of presence of electrons in this zone and consequently its relative weight in the space charge.

There are two ways to transversely inject electrons:

- Either from the exterior of the magnetic bottle (see, for example, for a radial source, the reference [2] page 293), but the trajectory is instable,
- Or from the device interior by making cross the electrons beam through a tube magnetically shielded. Then, the beam can be precisely directed to have a stable trajectory.
  The problem is that the electrons are susceptible to turn until coming back to collide the injection tube.

It will be chosen the second solution so as to control the trajectories at best. Due to the space charge created by electrons, there is a modification (« thermalization ») of trajectories which avoid to lose all electrons. Reversely, due to this thermalization a certain number of accelerated electrons escape radially and even more a bigger number of slowed down electrons escape axially via the non confinement cone of the magnetic bottle (for this subject, see, for example, the reference [3]).

More precisely, it can be injected electrons with three different ways :

- Either with a purely azimuthal speed (Vθ), so that the electrons energy be minimal. It can be shown that in the theoretical case where it would be injected at the level of the device central plane (Y=0), perpendicularly to the axis (so without radial magnetic field), the position R for which it would be reached the center (r=0 and Y=0) is such that it checks the equation 2*Pi*m/q*Vθ*R=Φ(R,Y=0) with Φ the magnetic flow applying on a surface of radius R and center R=0,Y=0. It will be referred to documents [1] and [2] about the subject and the demonstration. However, an electron alone injected in the central plane will come back to the origin position and will collide the injector.

- Or from the central plane, with an azimuthal speed which permits to reach the axis (at the minimal energy) with which it is added a slight axial speed so that the electrons have a double azimuthal and axial movement, which permits to them a very big number of rotations before escaping (see the document [2] pages 294/295 about the subject). But the injector located on the central plane is susceptible to be frequently collided, when the number of electrons will be important. And there is no trivial solution to escape to this problematic.

- The method chosen by the author is to inject electrons, transversally in the magnetic bottle, with a purely azimuthal speed but from a certain height Y1>0 and not at the central plane level (Y=0) of the device. The injection position relatively to the center is such that the electrons cross the axis. The radial field will take down the electrons along the device until the symmetrical altitude (-Y1). Afterwards, the electrons will move up the device back to the altitude Y1 and this periodically. Thus, the volume comprised between Y1 and –Y1 will host the electrons trajectories. It will appear, finally, an electrons cloud roughly in form of cylinder. As the electrons cross always the axis, the density at the center will be a bit bigger than elsewhere in the cloud and the gradient along X and Y at the device center level will be a bit bigger than if the density was homogeneous. This is interesting to attract preferably ions towards the device center.

The advantage of this last method is that there is a simple solution to reduce the number of collisions with the injector, during and/or after the electrons injection.
This one is an adiabatic compression which consists to slowly increase the magnetic field (so as to keep the orbital magnetic momentum more or less constant on an orbit). As the magnetic field will progressively increase, the orbits radius will decrease and the electrons speed increase.

Indeed, by supposing that B0, V0 and Ui0 be, respectively, the start values of the magnetic field, the azimuthal speed and the induced voltage at the device center, giving an initial Larmor radius Rl0=m.V0/(q.B0), it can be shown that for any B (and for a negligible space charge):

- The azimuthal speed V=V0.SQRT(B/B0). In fact, this is true in case of absence of relativist correction.
  Note: in the program, the electrons are submitted to a relativist correction, but not ions which speed is weak.
- The Larmor radius is equal to : Rl=Rl0.SQRT(B0/B).
- The induced voltage is equal to Ui=Ui0.SQRT(B/B0) (due to the contraction of the electrons cloud volume).

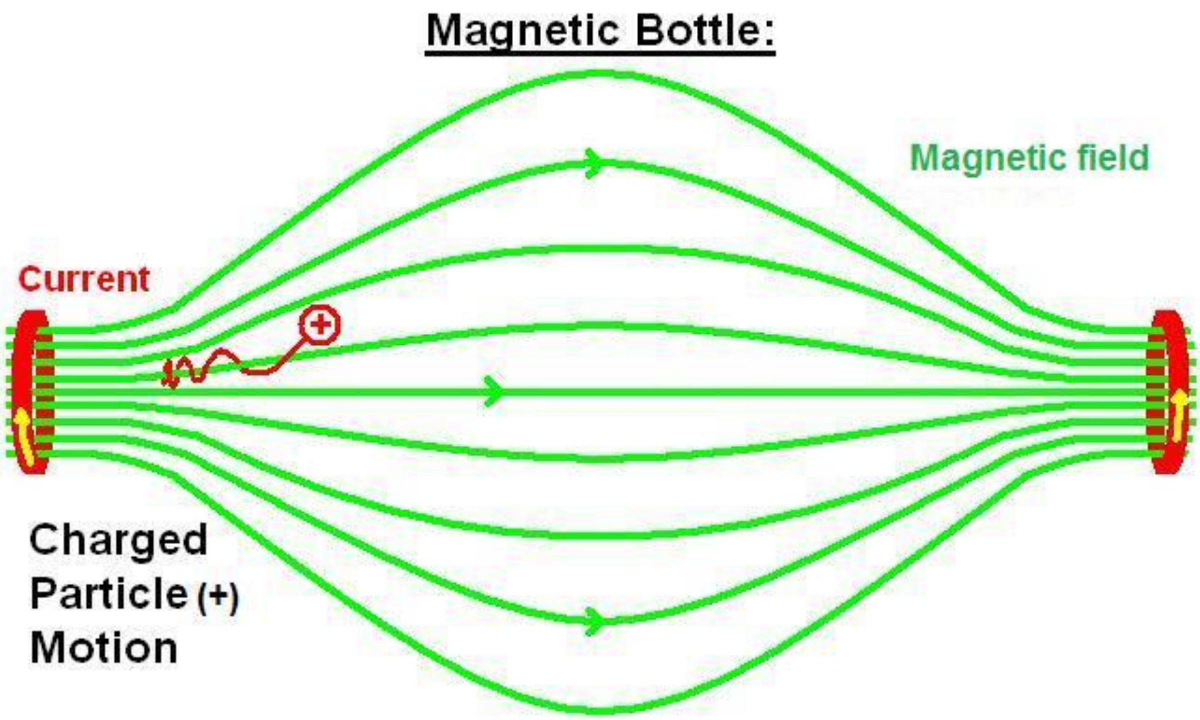
So when B increases, the speed and the induced voltage increase, the rotation radius (Larmor one) decreases and also the electrons cloud height due to the correlative increase of the radial field (and hence of the axial force on the electrons).
Due to the electrons cloud contraction, the injector is going to be cleared, so the number of percussions of the injector will go decreasing.

However, it has to be noted that from the moment when the continuous electrons emission stops, it can be compensated by injecting as many electrons than lost electrons, so as to maintain constant the number of electrons in movement counted at the moment when the continuous emission is stopped. So the number of electrons in the cloud remains constant, even if the trajectories are no more ideal because they don’t cross the axis anymore, due do the magnetic field increase. To force the electrons to cross the axis, it could be possible to correlatively increase the injection speed (taking also into account the space charge) but this would complicate the system. This necessary compensation and the space charge make that the adiabatic compression far to be perfect, but it reduces significantly the number of collisions on the injector.
Finally, the number of electrons will not be compensated during the test.

5. Reactor working principle

The basic principle is the « Fusor » (see the description under Wikipedia) for which it is created in the center of a spherical device, thanks to a spherical grid polarized negatively, a negative potential which permits to make circulate ions and, with a certain probability, to make them fuse. But here, the spherical grid is replaced by an electrons cloud, which forming a space charge, induces in its center a negative potential, as on the Polywell (see the description under Wikipedia). The advantage is that the electrons cloud is much more transparent than the spherical grid.

Unlike the Fusor and the Polywell, it is given more importance on one direction, the one on the axis of the magnetic bottle.
Unlike the Polywell, it is used here a simple magnetic bottle and not a magnetic 3D structure, at 6 solenoids, called « Magrid », where the fields of 2 solenoids in each of the three directions are in opposition (see « Biconic cusp » on Wikipédia).
It has to be noted that in a magnetic bottle, the fields of the two solenoids are going in the same direction.
So the reactor is built around a magnetic bottle (see « Magnetic mirror » on Wikipedia). Below, it will be found a magnetic bottle diagram (from WikiHelper2134, image in the public domain) :

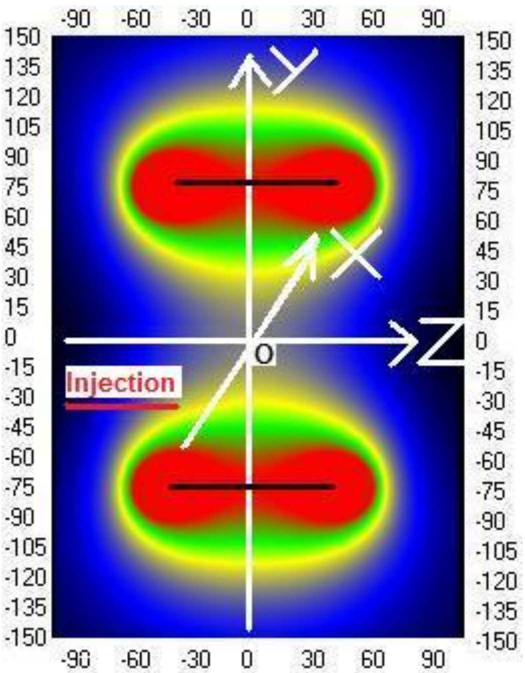


Comment about the image (from WikiHelper2134) : this image shows the magnetic field lines (in 2D) inside a magnetic bottle. Each end consists of a dense magnetic field which charge particles can be reflected from. Particles corkscrew along these magnetic field lines, are internally reflected and trapped. They can escape if they come it at certain angles to the magnetic field.

For a study of these magnetic bottles, refer to the book in reference [3]. For historic elements about their use in the fusion domain, refer to the book in reference [6].

The solenoids diameter is equal to 50 mm. The distance between the 2 solenoids is equal to 75 mm. The initial magnetic field value at the solenoids center is equal to 224 mT and 224/3.02=74 mT at the center of the bottle. There are no intermediate solenoids because a constant field in the middle of the bottle is not strictly necessary. It has to be noted that this addition would be certainly interesting (by lengthen the plasma height) but it has not been studied by the author.

The magnetic field of this magnetic bottle has the indicated shape on the following diagram, with the red for the maximum field around the solenoids and the black for the minimum magnetic field. It has been also indicated the direct system of axes used, the solenoids by two black dashes and the electrons injection tube with a red dash.
In the example below, the end of the tube permitting the electrons injection is at 30 mm from the center and a height (along Y) of 15 mm, so at the coordinates
X=-30, Y=15, Z=0. The 20 mm tube is parallel to the Z axis (between Z=-21 and Z=-1 at X=-30 and Y=15 constant).



Working
The selected time step for the simulation is equal to 60 ps, which corresponds to a very mediocre but acceptable accuracy.

Until t=120 ns :

- It is injected electrons in a continuous emission, from Y=15 mm, so as to obtain an induced voltage of more than -50 KV at the center of the device.

- The magnetic field increases (adiabatic compression) at a rate of x1,00072/step (so as to reach 945 mT at t=120 ns). The electrons cloud is going to contract and the induced voltage to slightly increase.

- Ions are symmetrically injected (a D+/T+ pair per step). The D+ ion will be injected on the axis, at the point Y=+20 , X=Z=0 whereas the T+ ion will be symmetrically injected from the point Y=-20, X=Z=0. The ions are initially accelerated at 1 kV. The ions intensity (1 mA) is much more weaker than the electrons one (1 A) and will modify only very weakly the potential induced by the electrons.

At t=120 ns, the electrons continuous emission and the magnetic field increase are stopped. Note that at this moment the injector is enough cleared.
The ions injection is left in service.

The ions density is going to slowly increase and the ions are going to fuse. It has to be noted that ions, due to their mass compared to the electrons one, are very little sensitive to the magnetic field.

At t=600 ns, the simulation is stopped.

6. Gas pressure

The gas pressure (D2) must the weakest possible. It is just an inconvenience because the aimed fusions are only the ones between ions nucleus, but in no way the ones between ion nucleus and neutral nucleus.

However it must be considered a certain pressure. It is good to have some values in mind (not guaranteed…):

- 10 pPa is the minimum value of pressure obtained in laboratory. It is also the pressure at an altitude of 10000 km,
- 1000 pPa is the minimum obtained industrially,
- 10000 pPa is the vacuum obtained in the particles accelerators. It is also the pressure at an altitude of 1000 km,
- 10 µPa is the vacuum obtained relatively easily with a turbo-molecular pump. It is also the pressure at an altitude of 400 km.

It has been supposed, by default, a pressure of 40000 pPa which is possible to obtain (but with difficulty).

7. Radiation

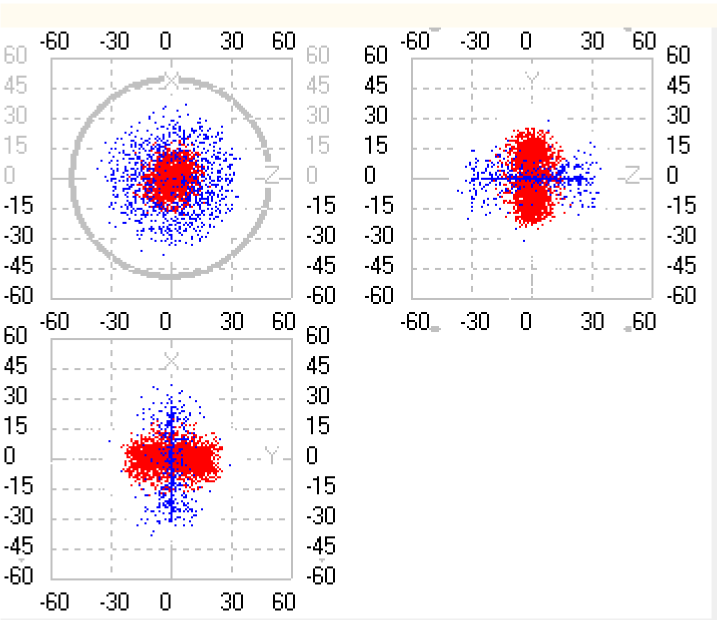
Interactions (by excitation…) supplying a radiation are not taken into account by the program.

Furthermore, these simulations ignore the Bremsstrahlung (braking radiation) and the synchrotron radiation. The relative power of these radiations is negligible for the D+/T+ fusion (see, about this subject, the document in reference [5] pages 42 and 43).

8. Results of the simulation for D+/T+ fusions at a gas pressure of 40000 pPa and conclusion

After many experimentations, the author has determined a configuration considered as correct and made a test on this one.

The following snapshot shows how are the ions (in red) and electrons (in blue) when the simulation stops. The electrons are relatively concentrated on a disk at the center of the device (at Y=0). Ions are little radially confined.



The efficiency is very bad, around 7E-9 , due to a weak number of fusions and a not negligible loss of electrons, due mostly to collisions on the injector.

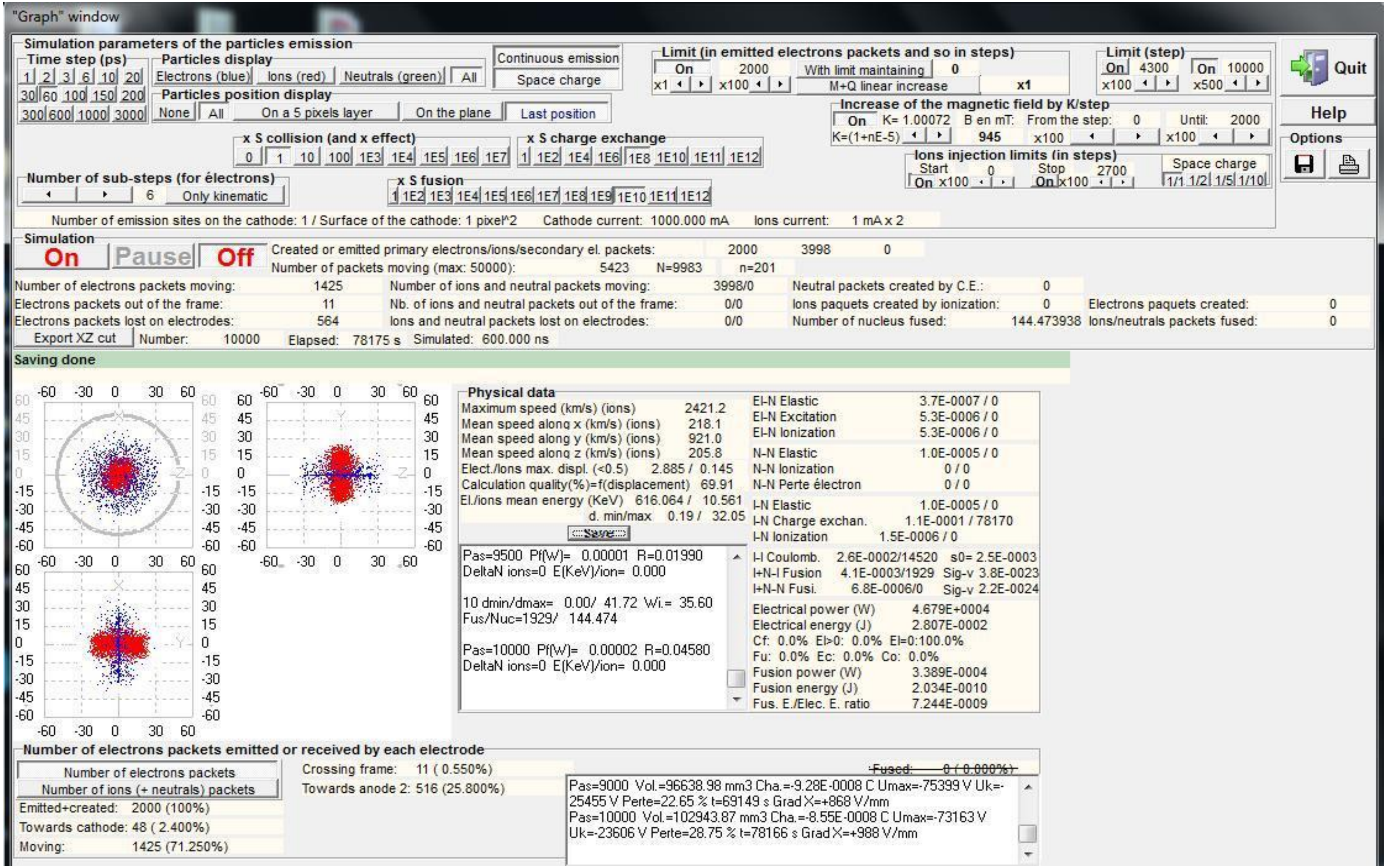
The ions confinement is not very good because the radial gradient is not sufficient (<1000 V/mm), which explains the weak number of fusions.

It has to be noted that the calculation uses a time step (60 ps) much too big for electrons simulation (but nice for ions simulation), which deteriorates the calculation accuracy and makes it very pessimistic. But it cannot be done in another way, so as not to pass one day of simulation.

Even with a such calculation deterioration, it can be concluded that such a way does not permit to reach an efficiency of 1.

The different parameters and results used in this simulation cannot be given because there are too many. Moreover, they are not very important as the goal is just to give an idea about this possibility of fusion.

But, for information, it is displayed in the following page, a snapshot of the main window.


"Graph" window
Simulation parameters of the particles emission
Time step (ps)
Particles display
Electrons (blue) Ions (red) Neutrals (green) All
Continuous emission
Space charge
Particles position display
None All On a 5 pixels layer On the plane Last position
Limit (in emitted electrons packets and so in steps)
On 2000 With limit maintaining 0
M+Q linear increase x1
Limit (step)
On 4300 On 10000
Quit
Help
Options
Increase of the magnetic field by K/step
On K= 1.00072 B en mT: From the step: 0 Until: 2000
K=(1+nE-5) 945
x S collision (and x effect)
x S charge exchange
Ions injection limits (in steps)
Start 0 Stop 2700
Space charge
Number of sub-steps (for électrons)
6 Only kinematic
x S fusion
Number of emission sites on the cathode: 1 / Surface of the cathode: 1 pixel^2 Cathode current: 1000.000 mA Ions current: 1 mA x 2
Simulation
On Pause Off
Created or emitted primary electrons/ions/secondary el. packets: 2000 3998 0
Number of packets moving (max: 50000): 5423 N=9983 n=201
Number of electrons packets moving: 1425
Number of ions and neutral packets moving: 3998/0
Neutral packets created by C.E.: 0
Electrons packets out of the frame: 11
Nb. of ions and neutral packets out of the frame: 0/0
Ions paquets created by ionization: 0
Electrons paquets created: 0
Electrons packets lost on electrodes: 564
Ions and neutral packets lost on electrodes: 0/0
Number of nucleus fused: 144.473938
Ions/neutrals packets fused: 0
Export XZ cut Number: 10000 Elapsed: 78175 s Simulated: 600.000 ns
Saving done
Physical data
Maximum speed (km/s) (ions) 2421.2
Mean speed along x (km/s) (ions) 218.1
Mean speed along y (km/s) (ions) 921.0
Mean speed along z (km/s) (ions) 205.8
Elect./Ions max. displ. (<0.5) 2.885 / 0.145
Calculation quality(%)=f(displacement) 69.91
El./ions mean energy (KeV) 616.064 / 10.561
d. min/max 0.19 / 32.05
Save
El-N Elastic 3.7E-0007 / 0
El-N Excitation 5.3E-0006 / 0
El-N Ionization 5.3E-0006 / 0
N-N Elastic 1.0E-0005 / 0
N-N Ionization 0 / 0
N-N Perte électron 0 / 0
I-N Elastic 1.0E-0005 / 0
I-N Charge exchan. 1.1E-0001 / 78170
I-N Ionization 1.5E-0006 / 0
I-I Coulomb. 2.6E-0002/14520 s0= 2.5E-0003
I+N-I Fusion 4.1E-0003/1929 Sig-v 3.8E-0023
I+N-N Fusi. 6.8E-0006/0 Sig-v 2.2E-0024
Electrical power (W) 4.679E+0004
Electrical energy (J) 2.807E-0002
Cf: 0.0% El>0: 0.0% El=0:100.0%
Fu: 0.0% Ec: 0.0% Co: 0.0%
Fusion power (W) 3.389E-0004
Fusion energy (J) 2.034E-0010
Fus. E./Elec. E. ratio 7.244E-0009
Pas=9500 Pf(W)= 0.00001 R=0.01990
DeltaN ions=0 E(KeV)/ion= 0.000
10 dmin/dmax= 0.00/ 41.72 Wi.= 35.60
Fus/Nuc=1929/ 144.474
Pas=10000 Pf(W)= 0.00002 R=0.04580
DeltaN ions=0 E(KeV)/ion= 0.000
Number of electrons packets emitted or received by each electrode
Number of electrons packets
Number of ions (+ neutrals) packets
Emitted+created: 2000 (100%)
Towards cathode: 48 (2.400%)
Moving: 1425 (71.250%)
Crossing frame: 11 (0.550%)
Towards anode 2: 516 (25.800%)
Fused: 0 (0.000%)
Pas=9000 Vol.=96638.98 mm3 Cha.=-9.28E-0008 C Umax=-75399 V Uk=-25455 V Perte=22.65 % t=69149 s Grad X=+868 V/mm
Pas=10000 Vol.=102943.87 mm3 Cha.=-8.55E-0008 C Umax=-73163 V Uk=-23606 V Perte=28.75 % t=78166 s Grad X=+988 V/mm

9. <u>References</u>

[1] « Etude de la capture temporaire d'un faisceau d'électrons dans une configuration magnétique à miroirs » by Jean Jacques Gourden
Rapport CEA-R-3568 / EUR-3870 f

[2] « Etude des trajectoires d'ions dans une configuration magnétique à miroirs – Première partie. Possibilité de capture temporaire par une configuration magnétique d'une particules chargée provenant de l'extérieur » by C. Gourdon
J. Phys. Radium, 1962, 23 (5), pp.291-296. <10.1051/jphys-rad:019620023005029100>. <jpa-00236628>

[3] « Plasmas collisionnels » by Michel Moisan and Jacques Pelletier

[4] Cours d'électrostatique - http://www.uvt.rnu.tn/resources-uvt/cours/physique-electrecite1/html/tome%201/chap2/III_4.htm

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