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PROPULSION CONCEPTS FOR NUCLEAR MATTER COMPRESSION ENERGY AND "COLD" FUSION ENERGY SOURCES IN INTERSTELLAR FLIGHT†

M. Subotowicz

Institute of Physics, M. Curie-Skłodowska University, 20-031 Lublin and Polish Astronautical Society, 00-901 Warsaw, Poland

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Abstract—Various energy sources for interstellar flight are reviewed. Two more "non-conventional" energy sources were proposed in a recent paper: (1) energy delivery during "pionization" of nuclear matter through nuclear matter compression in heavy nuclei collisions and (2) generation of the energy in muon-catalysed "cold" fusion in compressed hydrogen. After a short discussion of the physical principles of the "pionization" of the nuclear matter, the engine design concept is sketched. It has some advantages in comparison to the annihilation propulsion. In laboratory reference system after nuclear matter pionization, all the pions and the resulting particles after decay of pions will move inside of the narrow pionization cone. Power supply of the heavy ion accelerator will extract some part of the energy from the nozzle of the propulsion engine. This would be the magneto-hydrodynamics (m-h-d) power unit based on the Hall effect. Muon-catalysed fusion as the energy source is possible thanks to the discovery of the multiple tritium + deuterium (T + D) synthesis catalysed by one muon. It is possible to combine muon-catalysed fusion with the nuclear fission process. Commercial fusion–fission hybrid reactor would require 100–300 fusions per muon. The principles of the muon-catalysed fusion are shortly discussed. The advantage of the muon-catalysis in T + D mixture is explained because existence of nuclear resonance in deuterium–tritium–muon fusion. This is the reason why the sticking probability muon–α particle is so small (0.4%). A conception of the muon-catalysed "cold" fusion reactor is presented. The pions and muons are produced and stopped in D + T fuel itself. Many technical details are discussed more briefly, e.g. the probability of negative pion production at various projectiles and targets, average energy to produce one negative muon, muon-catalysed fusion–fission systems, advantages of the fusion–fission systems. In the paper is shown a block scheme of the "cold" fusion reactor and propulsion unit.

1. INTRODUCTION

Many various energy sources have been proposed recently for interstellar flights: nuclear fission, nuclear fusion, matter–antimatter annihilation, laser photon propulsion, pulse propulsion through nuclear explosions of small A-bombs[1]. In all the above-mentioned energy sources, the mass to energy conversion rate is comparatively small with one exception, namely the matter–antimatter annihilation[2] where the mass–energy conversion rate is equal about 50%, because the remaining 50% of the energy is taken by neutrinos[1]. During the synthesis of helium isotopes from the hydrogen isotopes only 0.2% of all the rest mass is converted into energy. The annihilation fuel is very difficult to obtain, antiproton production rate in accelerators is very small and even for the production rate equal 0.01% (very high!) the costs of the production of 1 g antiprotons would be about 4×10^{16} $, very expensive indeed[1]. It remains also the problem of the confinement of antiprotons and "cooling" of the very energetic antiprotons[2,3].

In a recent paper by Subotowicz[1] the use of other energy sources in the interstellar flights than those mentioned above was proposed: (1) energy delivered through nuclear matter compression in heavy nuclei collisions and (2) energy generated in muon-catalysed "cold" fusion in compressed hydrogen. Let us discuss now the engine design concepts for both these energy sources.

2. ENGINE DESIGN FOR NUCLEAR MATTER COMPRESSION IN NUCLEI COLLISIONS

We take into the account that during heavy (uranium, thorium) ion collisions a phase transition occurs that means "pion condensation", producing pion field ("pion condensate"). The decay of this condensate (pion decay) is similar to that of proton–antiproton annihilation products. It means that the proposed propulsion has all the advantages of the annihilation propulsion without the disadvantages of the antiproton production, containment and storage.

The decay of the pions condensate is according to the following schemes: the initial particles are pions: π^+, π^- and π°. Their corresponding lifetimes are: $\tau(\pi^\pm) = 25$ ns, $\tau(\pi^\circ) = 0.1$ fs (of the order 10^{-16} s).

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One can expect the following chain of reactions and decays:

$$\pi^\circ \to 2\gamma,\quad \pi^+ \to \mu^+ + \nu_\mu,\quad \pi^- \to \mu^- + \bar{\nu}_\mu,$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu,\quad \mu^- \to e^- + \nu_\mu + \bar{\nu}_e,$$
$$e^+ + e^- \to 2\gamma(E_\gamma = 0.511\ \text{MeV}),\quad \tau(\pi^\circ) = 0.1\ \text{fs},$$

(order of magnitude 10^{-16} s).

During this lifetime the following length l will be traversed: $l(\pi^\circ) = 3 \times 10^{-6}$ cm, $\tau(\pi^\pm) = 25$ ns and the length $l(\pi^\pm) = 7.5$ m and $\tau(\mu^\pm) = 2.2 \times 10^{-6}$ s and $l(\mu^\pm) = 660$ m. One should accept that during the decay of the pion condensate, about 50% of energy is taken away by neutrinos, 34% by γ-quanta and 16% by relativistic electrons and positrons of energy depending on the energy of incident heavy ions. Taking into the account full analogy of the decay products of the p–$\bar{\text{p}}$ annihilation and those of the nuclear matter compression, we can accept some similar engine design concepts in the case of the nuclear matter compression as in the case of p–$\bar{\text{p}}$ annihilation[2,4]. Some differences can appear in the energy distribution of the decay products and in their angular distribution, mainly that of e^+, e^- and γ-rays. As we well know, the rest annihilation products move isotropically, this is the case of the annihilation engine.

In the case of the nuclear matter compression after pion condensation, the decay particle (pions and all the following shower) in the laboratory frame of reference will move in a very narrow cone. The energy of the incident heavy ions is equal to about several GeV per nucleon. Then the energy of the pions in the beam will be from about few GeV to several tens of GeV. We should have at our disposal very well collimated beam of pions (about 1°), their momentum will be several tens of GeV/c. The forward direction of the particle emission (γ-quanta, neutrinos and electrons, e^+) occurs in very small angle.

Suppose that an accelerator pulse contains 10^{15} heavy ions and that there are 10^3pulse/h, beam collimation-up to 1′ or even 1″, depending on the energy of incident heavy ions. In comparison to the proton–antiproton rest annihilation where the directions of the resulting particles (pions) are isotropic, the situation in the case of the almost complete pionization of matter is more convenient. There is no necessity to construct the nozzle from magnetic fields to bend the charged particles exactly in the direction opposite to the direction of the relativistic rocket as is the case in the annihilation rocket. Even the neutrinos emitted in the "pionization" cone supply the rocket with the reaction in proper direction.

The accelerator should be supplied with the proper energy to accelerate the heavy ions to the high energy, several GeV pro nucleon. This would be possible to construct magneto-hydrodynamic power source in the nozzle on the base of the Hall effect (Fig. 1).

3. REACTOR FOR MUON-CATALYSED FUSION ENERGY

3.1. Introduction

In Ref.[1] the possibility of the "cold" nuclear synthesis in compressed hydrogen was discussed as the possible energy source for interstellar as well as interplanetary flights. This principle of energy delivery is based on the discovery by L. W. Alvarez (1956) that there exists the possibility to realize fusion reactions at low temperatures and to release a large amount of energy. Simultaneously but independently of[1] a review paper[8] was published where the principles and last results of multiple T + D synthesis catalysed by one μ-meson were described. It was reported that yields of the fusion energy release equal about 3 GeV per muon. One can expect even larger yields. It is about 25 times greater amount than the total energy of muon driving the fusion reactions. To produce one negative muon catalyst one should invest about 5 GeV energy by advanced technique. It is possible to combine muon-catalysed fusion with nuclear fission process. Commercial fusion–fission

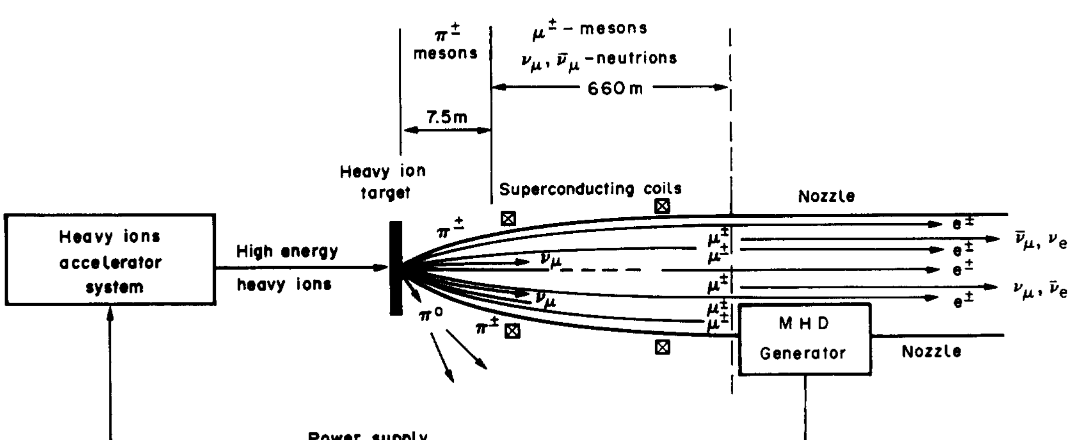

Fig. 1. Block scheme of the concept of the propulsion engine design for nuclear matter compression energy.

hybrid reactor would require 100–300 fusions per muon. A pure fusion reactor based on muon catalysis would require about 1000 fusions per muon[9].

3.2. Muon-catalysed fusion

The molecule made up of one proton and one deuterium D atom ($D = {}^2H$) can be bound together by a negatively charged muon (μ^-). The Bohr radius is taken as the length parameter in atoms and molecules:

$$a = 4\pi\hbar^2/me^2$$

As the μ-meson has 200 times larger mass than the electron, the hydrogen and deuterium nuclei in the molecule are about 200 times closer to each other than in the case of the electron binding. Small distance of the proton and deuterium enables them to fuse together at ordinary terrestrial temperature forming ^{3}He and yielding about 5 MeV energy $\tau(\mu^-) = 2.2 \times 10^{-6}$ s. In the hydrogen bubble chamber, one muon could catalyse five fusion reactions before its radioactive decay. These five reactions deliver to small amount of the energy to pay for the energy of the accelerator to generate muons.

3.3. How to increase the catalysis reaction rate carried out by one muon

There are several factors determining the reaction rate carried out by one muon (a) slowing the muon, (b) slow-muon capture rate by proton, (c) muon transfer rate to deuterium, (d) muonic (pDμ) molecule formation rate by simultaneous electron ionization, (e) p–D–μ fusion rate, (f) probability of the repetition of the above cycle by the same released muon, (g) α–μ^- sticking losses (probability of the capture of μ^- by the ^{3}He atom), (h) relative composition of the hydrogen isotopes, (i) temperature of hydrogen isotopes mixture and (j) hyperfine effect.

The ultimate reaction rate of the muon-catalysed fusion is maximal in D + T mixtures and it depends on the α–μ^- sticking probability, ω_s, on D–T mixing ratio, density and temperature. For equal amounts of D and T, $\omega_s = 0.4\%$. It can be reduced up to $\omega_s = 0.1\%$. The reduction of sticking probability α–μ^- is possible because a nuclear resonance in D–T fusion effects the wave function in the D–T–μ molecular ion prior to fusion (Fig. 2).

In Los Alamos Meson Physics Facility (LAMPF) the average number of D–T fusions per muon equal 150 were achieved in 1984.

3.4. Propulsion concept for muon-catalysed fusion energy

As we have written above, there exists the possibility to build the hybrid fusion reactor[9]. It appears that about 5 GeV must be invested to produce one negative muon. Fusion–fission reactor requires 100–300 fusions per muon. A pure fusion reactor might require 1000 fusions per muon[8]. Grid to beam power conversion efficiencies up to 60% appear achievable. According to Fig. 3[9] high energy triton beam ~1 GeV nucleon enters one or more pressurized D–T gas targets. Magnetic mirror effectively confines the charged particles to a small volume (~0.1 m^3). The pions and muons are produced and stopped in D–T fuel itself. Produced in D–T fusion,

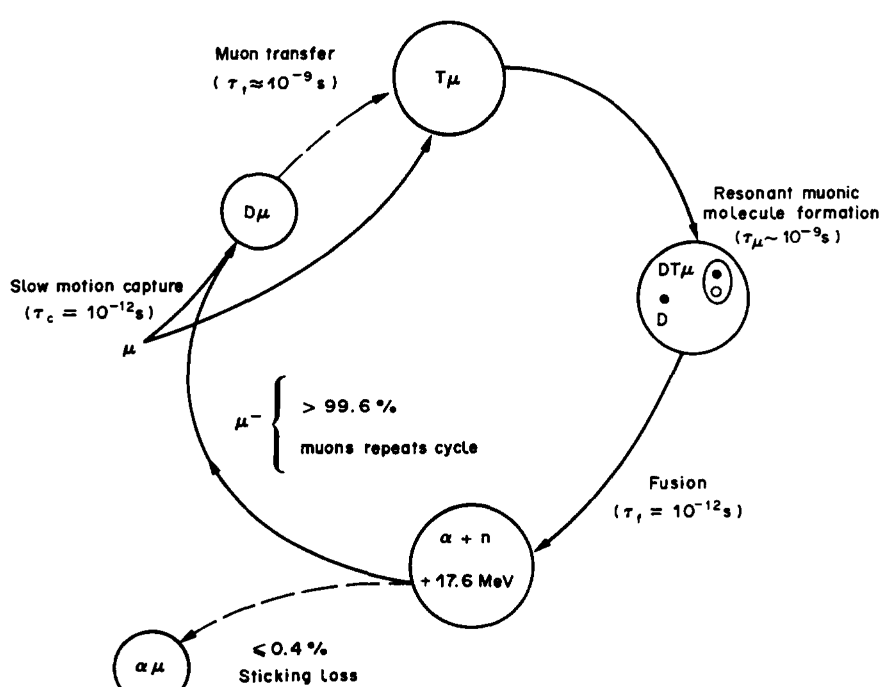

Fig. 2. Muon-catalysed D + T fusion[8].

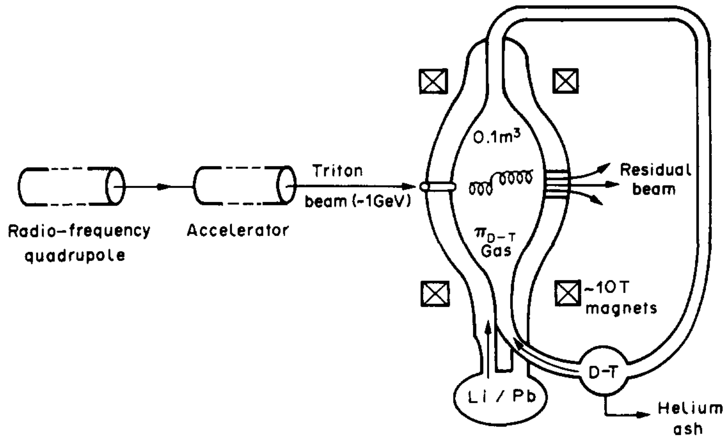

Fig. 3. A conception of the muon-catalysed fusion "cold" reactor with triton supply[9].

neutrons and α-particles are consumed in the reactor in following reactions:

$$^3He + n \rightarrow p + T$$

consumption of ^3He arising from tritium decay, $n + {}^6Li \rightarrow \alpha + T$ and $n + {}^7Li \rightarrow n + \alpha + T$. The circulating gas extracts heat and $^4He = \alpha$ particles, that are stopped in the dense gas. Thorium or uranium blankets produce after neutron capture additional heat in fission process. Energetic protons and neutrons following muon production can be used directly (neutrons would first produce energetic protons in the inelastic collisions).

The above-mentioned possibilities of the energy production in the muon-catalysed hydrogen fusion was possible, because at least 100–150 fusions per muon was achieved. It was possible thanks to the discovery of the resonance which allows muonic $DT\mu$-molecules to form in less than one-thousandth of muonic lifetime. The production of muons should be comparatively cheap (about 5 GeV per muon). It is interesting, do 150 fusions per one muon represent the limits of the "cold" fusion process?

3.5. *Negative muon generation*

We can produce muons colliding with a beam of high energy protons, about 10^3 MeV = 1 GeV, or other ions with a target (typically carbon). In these collisions, pions are produced decaying rapidly into muons. The yield of π^- production in p–p collisions is almost zero for the incident proton energies up to 1.5 GeV. The highest probability of π^- generation in p–n collisions is for proton beam energy of about 2 GeV. The maximum probability of π^- production equal to 30 mb is for n–n collisions. The "so-called" meson factories use beams at energies of 600–800 MeV. The negative pion production yield is there far below optimum. To produce negative pions more effectively, neutron-enriched nuclei should be used as projectiles and target, e.g. deutron or triton beams. Target dimensions should be selected in such a way that two-thirds of the incident beam particles undergo inelastic collisions because in the larger target π^- mesons would undergo unacceptable absorption. After π^- meson decay three-quarters of arising muons should be recovered. The experimental set up contains long solenoid where negative pions should decay and the arising muons are guided to a large deuterium–tritium reaction volume. It follows from the above considerations that the generation of one negative muon requires 5–8 GeV energy.

To establish a magnetic field which can collect negative pions leaving the target at various angles to focus them into a beam, large currents should be passed (10–100 kA) through the production Li target.

For efficient production of negative pions, neutrons as incident particles should be used. But neutrons cannot be accelerated. The best way is to accelerate a beam of deutrons or even better, tritons. Thin target, such as falling lithium sheet, can separate protons and neutrons. Protons do not produce negative pions efficiently. Their energy, after collection of protons, can be easily converted to electrical power or used in the spallation reactor. Neutrons falling on the target produce negative pions (π^-). One neutron colliding inelastically with Li produces on average 0.6 π. Assuming that neutrons contribute more than in 80% in pion production on the target, and that two-thirds of the collisions are inelastic, and that 60% of muons are recovered following the negative pion decay, then—by 50% accelerator efficiency—the approximate amount of energy per one muon would be about 3 GeV. The target is less heated by incident neutrons but more seriously by a charged-particle beam. Uranium or thorium target allow use of spallation nucleons to induce fission. In low-density targets such as lithium, the probability of the pion escape the target is larger. In tritium n/p = 2, the highest ratio in nature. Let us take colliding deuterons or tritons, where neutrons are excited primarily to delta particles $\Delta = 1232$, decaying into protons and pions:

$$T + T \rightarrow 3n + 3p + \pi^-$$

The center-of-mass c.m. energy is equal to about 400 MeV. In colliding beams, each beam should have the energy about 200 MeV. At the stationary target the equivalent c.m. energy of a beam would be 830 MeV. Muons produced would represent a broad range of momenta and energies. To stop muons of all energies in the fuel and to have comparatively short reaction vessel one should use proper magnetic fields and properly shaped degrader. Muons of various momenta will be focused in slightly different beam. High-density deuterium–tritium fluid of moderate path-length can stop muons. Small spread of momenta enables μDT reactions throughout the volume of the reaction vessel.

3.6. *Muon-catalysed fusion–fission systems*

It is possible to now use the high power accelerators (up to gigawatt) because of the invention of the radiofrequency quadrupole preaccelerator. The target vessel should contain D–T mixture at the pressure up to $1000\,\text{atm} = 103\,\text{MPa}$ at temperature up to 800 K. The vessel had to withstand thermal cycling from 14 to 800 K.

Gas purity for helium should be $< 10^{-4}$ and for higher Z gases $< 10^{-5}$. Gas volume should stop muon beams with 30 mm dia. Inner diameter of the chamber is 51 mm. Single volume of the target vessel contained 90% T and 10% D. Activity of tritium was 54 kCi. A palladium filter was used to remove ^{3}He from tritium.

Neutrons are moderated from the energy 14.1 MeV to near-thermal energies by more than 40 cm thick gas layer of the hydrogen isotopes. The neutron-heating of gas require circulating the gas through a heat exchanger. The removal of ^{3}He occurs via the reaction: $^3\text{He} + \text{n} \rightarrow \text{T} + \text{p} \cdot (\text{D} + \text{T})$ fuel eliminates high-energy neutron damage of the inner wall of the vessel. In the (D + T) fuel the neutrons will multiply and tritium will be bred according to the reaction: $\text{D} + \text{n} \rightarrow \text{T}$. Thermal neutrons will be captured in lithium–deuteride liner and bred tritium. There exists the possibility to couple muon-catalysed fusion with a linear accelerator-driven spallation breeder reactor. Both concepts can employ the same accelerator. Twenty per cent of the beam energy can be used for pion production. Coupling the muon-catalysed fusion with the induced fission the high-energy protons and neutrons and breeding fissile material in subcritical amounts of natural or deplated uranium (or thorium), all the possibilities to produce energy effectively can be exploited[9]. Spallation breeding requires the nucleons of energy larger than 700 MeV. Uranium nuclei could be spalled to produce neutrons. As we have seen before, tritium breeding is possible with the residual nucleon beam or together with fissile-fuel breeding. Because both parts of the processes, fusion and fission are driven by the accelerator beam, a fraction of the produced power should be taken to drive the accelerator. Jones[9] lists the following advantages of the above discussed fusion–fission power system driven mainly by muon-catalysed fusion:

(1) fusion proceeds without plasma;

(2) highly advanced safety: no thermal runaway, easy stopping the reaction (switch off muon flux), self slowing down the muon-catalysed fusion process with the increasing fuel temperature;

(3) fission part of the power production occurs in subcritical region; this system can be easily accepted by the society;

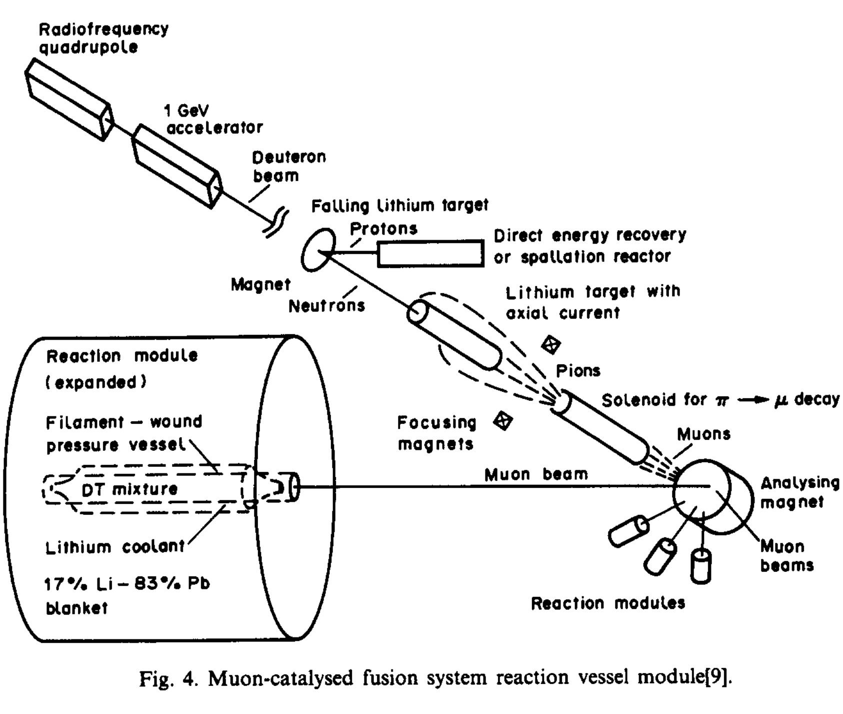

Fig. 4. Muon-catalysed fusion system reaction vessel module[9].

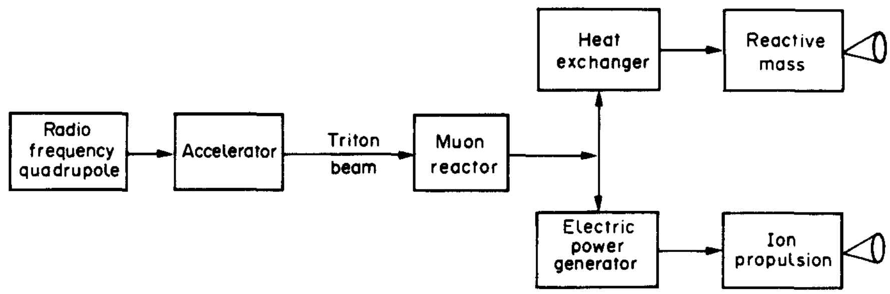

Fig. 5. Block diagram of the muon-catalysed propulsion system.

(4) amount of the fission energy extraced from uranium or thorium increased substantially. Therefore our fusion–fission system can run for long time;

(5) Our system does not contain the plasma stage in its running.

The system is highly stable in comparison to the instabilities and difficulties of the plasma confinement in other "typical" controlled fusion system.

3.7. Block scheme of the "cold" fusion reactor

Our accelerator-driven system contains both nuclear processes: fusion and fission but working distinctly, optimizing use of the accelerated beam of neutrons and protons. Such a combination are called "symbiont".

Principally, there are possible fusion–fission "*hybrids*" having a fertile/fissile blanket around a fusion-reactor core. These types of hybrid systems have also been studied[9], assuming 100–300 fusions per muon. It follows from these investigations that it would be possible to build commercially viable fusion/fission reactor.

General impressions which kind of blocks should contain the muon-catalysed fusion reactor is given in Fig. 4.

The most difficult part to design is the deuterium–tritium high pressure vessel capable of admitting muons and removing heat and helium from the D–T mixture. To have some idea on the values of various parameters the reaction vessel is characterized as follows: No. of modules—10; power output per module–100 MW; modules dia—14 cm; length—200 cm; muon entry window thickness—1 cm; muon heating rate in window—40 W/cm^3; gas-heating rate (α-particles)—16 MW; gas purity: helium—$<10^{-4}$; high—Z gases $<10^{-5}$; side-well heating rate (neutrons)—6.4 MW/m^2; tritium inventory—0.8 kg; volumetric heating in 17% Li and 83% Pb blanket—15 MW/m^3 (Fig. 5).

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