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CRYOGENIC REACTOR FOR THE INS PROJECT

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Introduction

The intense 14 MeV neutron source (INS) [1] based on muon catalyzed fusion (MCF) was considered in 1993 by ENEA (Italy), PSI (Switzerland) and RRC KI (Russia). The intensity of the source would be ~10^{17} neutrons/sec. The monochromatic neutron source is a tool of study of the behavior of fusion reactor materials under neutron irradiation in the frame of ITER program (first wall problem). It can also be used to study the incineration of nuclear wastes. The design of the reactor for neutron source become quite a task because of the radiation safety requirements imposed on the installation besides muon beam requirements. The choice of cryogenic reactor for INS is based on the ideas born in the experiments on muon catalyzed fusion. It is sufficiently to mention that first maximum experimentally measured neutron output with respect to single incident muon (~100 neutrons/muon) was obtained in LAMPF (USA) [2] with liquid D/T mixtures. Further progress in MCF experiments gives easy to handle D/T fusion cryogenic devices built in PSI (Switzerland) [3] , JINR (Russia) [4] and RIKEN-RAL (U.K.) [5]. In the scope of the article is shown how cryogenics helps to solve a variety of problems aroused while the creation of the fusion neutron source.

Principles of MCF reactor operation

A middle range accelerator produces deutrons. Deutrons strike primary (carbon) target T (Fig.1) and produce negative pions. Negative pions decay resulting in negative muons. Negative muons stop in liquid D/T mixture (R in the Fig.1). Muons catalyze a cycle of fusion reactions $D+T={}^4He+n$ via Vesman mechanism [6]. Demands to the purity of the reacting mixture are high enough (10^{-7} in respect to admixtures with $Z>2$, 10^{-4} – $Z>1$). Muons stick to impurities and fall out from fusion cycle. Normally one should use diffusion purification of the hydrogen mixture (say with the aid of the palladium filters [7]). Tritium containing in the reacting mixture undergoes β-decay and results in ^3He. At a times one should remove this helium ($Z=2$) from the reacting mixture. The density of the reacting D/T mixture should be as high as possible to provide sufficient neutron yield. The thickness of the walls of the D/T cell A (central part of the reactor) should be minimized to provide muon stops in hydrogen isotope mixture rather than in the walls of the D/T cell. One should remove heat from reacting volume including heat input of stopping muons (15 kW) and heat released by fusion products ^4He and n (45 kW). Special measures should have been taken to provide radiation safety of the device because of tritium radiation activity (18 keV β-source).

How cryogenics helps to decrease heavy duties of the reactor

Filling of the reactor with liquid D/T mixture is preferable than with gas by the reasons.

The density of the liquid D/T is close to the liquid hydrogen density (LHD $4.25*10^{22}$ atoms/cm^3) – highest density achieved by everyday means. The temperature of the reacting mixture should be higher than 20.6 K because tritium freezes at 20.6 K.

Vapor pressure above liquid hydrogen mixture for example at 25 K do not exceed 5 bar while at same density gas would give the pressure up to 1000 bar. Thickness of the wall of the cryogenic reactor could be smaller as compared to the reactor filled with relatively warm gaseous mixture. So the construction could bear the appropriate loading at less thickness of the wall of the D/T cell.

The desired purity of the mixture could be easily achieved at cryogenics with cold adsorbents rather than that at higher temperatures. It is possible to make *in situ* purification of the mixture. As to fusion and decay product removal (^{3}He, ^{4}He, Z=2) it was recently shown [5] that helium comes mostly out of the liquid D/T mixture to gaseous phase and at least would not spoil the fusion cycle. So there would be no need to recycle the reacting mixture much.

Heat removal can be done more easily with cryogenics because of thermodynamic resistance (Re numbers) of the reacting mixture is less in heat and mass transfer (low temperature)

Safe operation of the reactor taking into account the tritium activity is much better attainable in case of cryogenic reactor (low pressure) as compared to a «warm» device at same density of the reacting D/T mixture.

Cooling of the reactor

There are two possible ways to cool the reacting mixture. First is cooling of the reacting mixture by pumping through the heat exchangers. Second is cooling by condensation of the vapor. The second way is preferable for two reasons. Firstly because of high efficiency of condensation cooling and finally in this case the reacting mixture would reside mostly in the reacting volume A (D/T cell). Besides it is possible even to increase the cooling efficiency adding small amount of protium (H_2) to the reacting mixture, thus using heat effect of hydrogen isotope solution [8]. For the safety sakes is necessary two stage cooling system with intermediate cooling agent (hydrogen). In the suggested scheme the D/T cell itself should be a part of the rotating tube A-C the diameter being ~10 cm (Fig.1). The main features of such devices (heat tubes) can be found elsewhere in [9].

The liquid D/T reacting mixture under rotation ω (600-6000 rpm) leans along to cylindrical surface of the tube. The warm corner A of the «heat tube» A-C is more wide in diameter than cold corner C to make liquid reacting mixture reside under rotation mostly in the reacting volume A. In the middle of the tube there is gaseous phase of the D/T mixture blowing from A to C. Rotation of the tube segregates liquid reacting mixture from gas. The tube is placed in the axial magnetic field (~10^4 Gs) in the reacting volume created by the superconducting magnet M. Muons originating in pion decay travel along the magnetic field in circular trajectories strike the tube and stop in the liquid D/T mixture. The lower corner of the tube C is cooled by intermediate cooling agent (liquid hydrogen). The tube rotates in bearings B and is tightened in a labyrinth manner LT. The volume above the labyrinth tightening is pumped to provide gaseous phase of hydrogen in between the cylinders. This also helps to orient the rotating tube at will with respect to a horizon. The volume of the hydrogen heat exchanger HH is connected to the hydrogen receiver REC.

Liquefier-refrigerator

It is possible to use hydrogen, helium or neon as main cooling agents. Hydrogen is cheaper, helium and neon are more safe. In the Fig 1 is shown the refrigeration scheme with helium as a main cooling agent.

Pressurized and purified gaseous helium (^{4}He) following by the valve V1 is lead through the heat exchanger HE1, turbo expander ET1, HE2, bath of liquid nitrogen, HE3, ET2, HE4, ET3. This part of helium refrigeration flux comes to the hydrogen heat exchanger HH through valve V5, cools liquid hydrogen and returns to the bath of liquid helium passing

V8 and HE5, finally being throttled with V6. The second part of helium flux passes V2, HE1, HE2, bath of liquid nitrogen, HE3, HE4, HE5 and is throttled in V7. Then being cooled in the bath of liquid helium this flux cools the magnet M in the loop V10, V11. Throttle V4 is used to adjust the refrigeration cycle.

Thermal calculations

There are following liquefier-refrigerators [10] created up to now: FNAL, Batavia (4000-5400 liters of liquid helium per hour at 3.56 K); CERN, Geneva (12/18 kW at 4.5 K); TESLA, Germany, USA (77 kW at 2 K, 67 kW at 4.5 K, 352 kW at 40/80 K) in production. The listed above liquefier-refrigerators is quite comparable to the suggested one.

Here are calculated characteristics of the helium liquefier-refrigerator (60 kW, 25 K):

- specific power consumption – 50 MJ/l (liquid helium);
- gaseous helium flux – 8000 m^3/hour;
- liquid helium output – 1000 l/hour;
- liquid nitrogen consumption – 1000 l/hour;
- cooling water consumption – 200 m^3/hour;
- specific heat input from the environment – 5 J/mole (helium);
- helium losses in the cycle – 5-10%.

Radiation safety

A set of measures should be taken to provide radiation safety in the design of cryogenic neutron source:

- two contours of safety, first entirely metal to contain tritium mixtures, second to hold tritium mixtures in case of malfunction of the first contour;
- using of an intermediate cooling agent in two stage cooling scheme;
- using of a buffer volumes connected to devices filled with tritium mixtures and intermediate cooling agent to make sure normal operation of the device in case of accidental warming up;
- using high quality pumping and recycle systems to ban tritium conversion to a heavy water.

All measures of safety are pointed to exclude the possibility of the penetration of the tritium mixtures into atmosphere.

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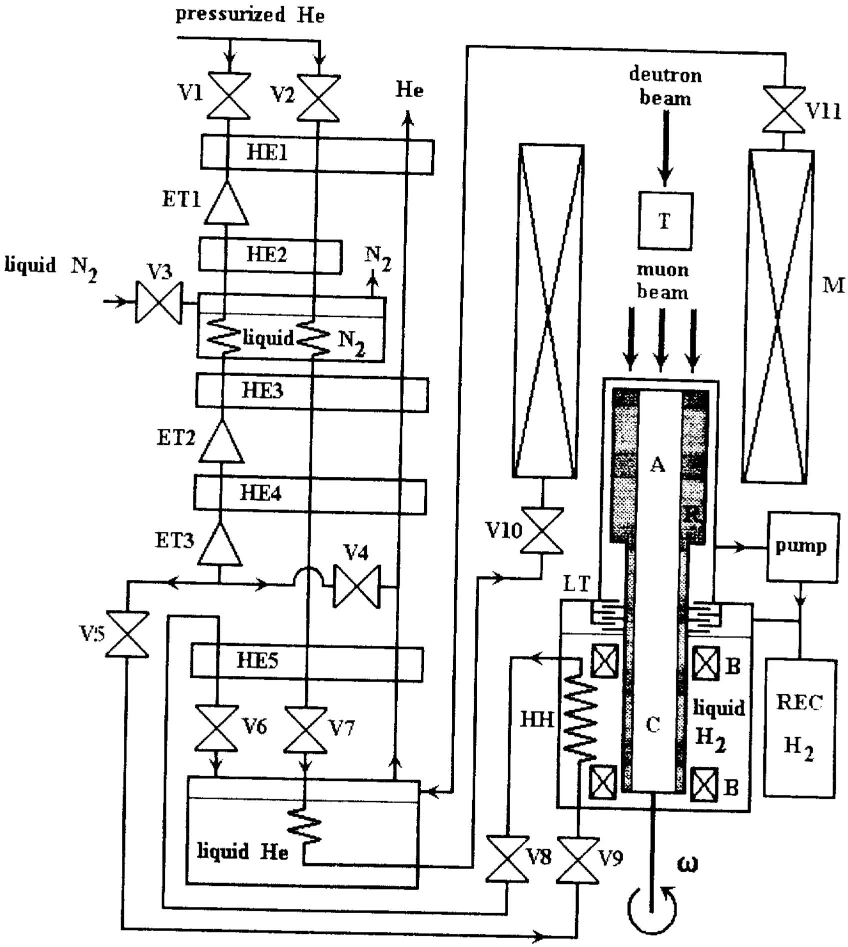

Fig. 1. Schematics of the liquefier-refrigerator and the cryogenic reactor

References

[1] C. Petitjean, F. Atchison, G. Heidenreich et al., Fusion Techn. **25**(1994)437

[2] A.J. Caffrey, S.E. Jones and K.D. Watts, Bull. Am. Soc. **28**(1983)646.

[3] C. Petitjean, P. Ackerbauer, W.N. Breunlich et al., SIN Report PR-87-07(1987).

[4] N.N. Grafov, V.G. Grebinnik, D.L. Demin et al., JINR Preprint P13-97-343(1997).

[5] K. Nagamine et al., RAL (1997), to be published

[6] E.A. Vesman, Pisma Zh. Eksp. Teor. Fiz. **5**(1967)113

[7] A.A. Yukhimchuk, V.N. Lobanov, Hyp. Int. **101/102**(1996)661

[8] V.G. Grebinnik, D.L. Demin, V.G. Zinov et al., JINR Preprint P8-97-7(1997)

[9] S.S. Kutateladze, «Teploperedacha i gidrodinamicheskoe soprotivlenie», Energoatomizdat (1990) 322.

[10] Proceedings of the XV International Cryogenic Engineering Conference, Genova, Italy, 1994.

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Криогенный реактор для проекта INS

Рассмотрена схема криогенного реактора, основанного на явлении мюонного катализа, для интенсивного источника 14 МэВ нейтронов (INS). Особое внимание уделено радиационной безопасности при работе нейтронного источника.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Cryogenic Reactor for the INS Project

The feasible scheme of a cryogenic reactor based on muon catalyzed fusion for the intense 14 MeV neutron source (INS) is considered. Special attention is paid to provide safe operation of the neutron source.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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