HELIUM-3 - BASED FUSION PLASMA

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The experimental devices and conceptual designs of the field-reversed configuration (FRC), tandem mirror and spheromak as best solution for the low radioactive plasma, namely helium-3 based fusion plasma, are reviewed. Reactor schemes based on D-^{3}He-^{6}Li fuel with the possibility of ^{3}He mining on the Earth and Moon, including breeding and support reactors are proposed. ^{3}He acquisition, some estimation and resources are presented. Applications of D-^{3}He reactions and advanced-fueled alternative systems are discussed.
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INTRODUCTION

The most important technological advantages (blanket absence and possibility of using of the liquid first wall and direct conversion system) of power plant based on compact systems [1,2] – alternative scheme with low radioactive fuel [3-5] – in comparison with tokamak and other magnetic systems burning conventional D-T fuel are essential.

Theta-pinch, spheromaks merging and rotating magnetic field formation of FRCs [6-9] has been used successfully in previous experiments, but it extrapolates poorly to the fusion regime. Viable FRC startup and sustainment methods with reasonable input powers are being sought. Schematic D-^{3}He–fueled compact system is shown in Fig.1, where the separatrix has prolate shape and the plasma has the form of elongated quasi equilibrium.

Experimental plasma parameters for compact and linear machines (both with open filed lines) ranges: average beta $<\beta>\sim 5 – 95\%$, electron temperature $T_e \sim 0.02$ - 4 keV, electron density $n_e \sim 10^{16}$ - 10^{22} m^{-3}, energy confinement time $\tau_E \sim 0.01 – 2$ ms, external magnetic field $B_e \sim 0.005 – 15$ T, ion temperature $T_i \sim 0.03 – 10$ keV, length $l_s \sim 0.2$ - 12 m, radius $r_s \sim 0.01$- 0.5 m.

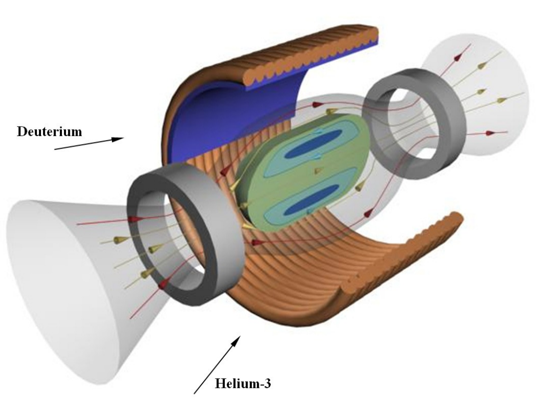

Fig.1. D-^{3}He field reversed configuration – prolate equilibrium with low radioactive fuel

EXPERIMENTAL AND FUSION PARAMETERS

Main experimental devices that can be used as D-^{3}He burn - compact tori as FRC and spheromak and open confinement system as tandem mirror - are shown in the Table. Some of experiments may be extrapolate to fusion regime. The name of Institute, Lab and University and the main functions and properties are indicated opposite the each device. The possibility of controlled fusion in a FRC using D-^{3}He fuel ($T_i \sim 50$ keV, $n_i \sim 10^{21}$ m^{-3}) is evident. High beta (the plasma to field energy density ratio) magnetic system burn D-^{3}He fuel is the best candidate for the fusion reactor.

Principal FRC, Mirror Trap and Spheromak experiments

FRC:	Linear Machine:	Spheromak:
CBFR – UC, Irvine, p-^{11}B	**AMBAL-M** - Budker Institute	**BCTX** – UC Berkeley, heat
FIREX - Cornell, **Munsat/Boulder** - Colorado U.	**CLM** – Columbia University	**BSX**, CT injection, Caltech
FIX – Osaka U., Stability, RMF	**GAMMA 10** – PRC,U.Tsukuba	**HIT-CT** – Himeji, Japan
NUCTE-3 – Nihon University, theta-pinch facilit	**MAP-II** – U. Tokyo, Hanyang	**CTIX** – UC Davis, acceleration
FRX-L – LANL, MIF/MTF high density	**GDT**, **SHIP** – BINP, LLNL, refueling	**HIT-SI** – U. Washington new formation
KT, **BN**, **TOR** – TRINITI, compression	**GOL-3** Multiple Mirror Trap – Budker	**SPHEX** – UMIST, pf, toroidal field
Lebedev Physical Institute RAS	**FLM** - Uppsala University	**SSPX**– LLNL, confinement
MRX – Princeton, oblate flux-conserver	**HANBIT** Device – KBSI	**SSSX**, multi-probe reconnection
TCSU, **STX** – U. Washington RMF, T, flux	**MultiCusp Trap** – Kurchatov Inst.	**TS-3,4** – Tokyo Univ., FRC, other TC

^{3}He ACTIVITIES

First analysis of D-^{3}He low radioactive systems and research on helium-3 resources have been started by I.N. Golovin [10] in USSR, H. Momota [11] in Japan and G.L. Kulcinski [12] in USA in the 1980th. Most of conceptual designs [7,11] on the D-^{3}He fuel assumed helium-3 from the Moon. Helium-3 supply on the Earth is just for couple years energy at full ^{3}He extraction from the atmosphere and underground gas [8] if we assume D-^{3}He thermonuclear power plant. Such situation may be improved by reactor schemes using catalyzed cycles and fusion cycles with ^{3}He getting in additional reactors (shown in Fig.2). ^{3}He has been produced in the auxiliary reactor and the part of the fusion power going to support the p-^{6}Li reaction: 1) D-^{3}He fusion power plant and self-sufficiency of helium-3 ; 2) Main reactor with D-^{3}He-^{6}Li mixture. This is a hybrid system - amplification factor is less than in the first case and part of ^{3}He will be delivered from the Moon. The third scheme (not shown here) assumed lunar helium-3.

If it is necessary ^{3}He will be produced on the Moon. Lunar soil [12], which contained desired isotope, covers the Moon (sea richer of helium, than highlands). History of helium-3 in brief: 1st Lunar Development Symposium, Atlantic City, 22 - 24 September 1986; 1st Wisconsin Symposium on Helium-3 and Fusion Power, 21 - 22 August 1990, Madison; US-USSR Workshop on D-^{3}He Reactor Studies, 25 September – 2 October 1991, Moscow; 2nd Wisconsin Symposium on Helium-3 and Fusion Power, 19-21 July 1993, Madison. The International Lunar Exploration Working Group (ILEWG) is a public forum created in 1994. The last 9th International Conference on Exploration and Utilisation of the Moon (ICEUM9) held 22 - 26 October 2007 in Sorrento.

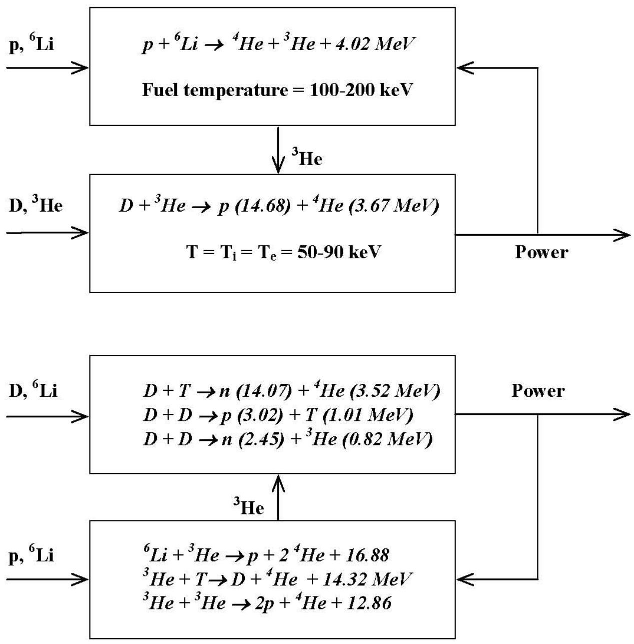

Fig.2. D-^{3}He-^{6}Li fuel fusion cycles.
*Scheme at the top shows main reactions, at the bottom - auxiliary reactions, small sigma*v and cross section for the reactions in the last box 2 stages reactor with ^{3}He recovery*

The price of helium and helium-3 is the separate question. Chemical-grade (99.9% pure) Helium-3 from ISOTEC Inc., Matheson company, Miamisburg, OH, USA (http://www.isotec.com/) now costs $220/liter.

So, the recent price is $1100/5l for ^{3}He, liquid ^{4}He ~ $5/kg, gas ^{3}He ~ 1.64M$/kg ($1.64 billion a ton).

The abundance of helium on the Earth are estimated as $3{\cdot}10^{10}$ m^3. In the crust, the concentration of He is in 200 bigger than in the atmosphere. Russian Federation total deep-laid gas estimated as ~ 48 · 10^{12} m^3 (1680 · 10^{12} f^3). East Siberia, Yakutia have resources of natural gas [13] ~ 30 · 10^{12} m^3 (helium-rich >0.5%).

Moon: ~ 1000 million tones (regolith). Uranium: ^{3}He/^{4}He = 1/3000, Jupiter: 10^{20} t (atmosphere), Saturn + asteroids + comets (asteroids more rich of helium-3).

Estimation for the two reactions ^{3}He(^{3}He,pp)^{4}He+12860 and ^{3}He(d,p)^{4}He+18353:

^{3}He-^{3}He reaction has reaction energy 12.86 MeV (2.06· 10^{-12} J). 1 gram ~ 2· 10^{23} particles of helium-3. 1 ton of ^{3}He: (12.86 ·10^6) x (1.6 ·10^{-19}) x (2·10^{29}) = 20.6·10^{16} J of heat energy. I.e., 1 t of ^{3}He is equivalent to 5.4 million tons of oil!

D-^{3}He – 18.36 MeV. 1 ton of ^{3}He: (18.36·10^6) x (1.6·10^{-19}) x (2·10^{29}) = 59·10^{16} J of thermal energy. One ton of ^{3}He ~ 15.5 million tons of oil!

Oil costs ~ $100/bar. Urals (main Russian brand) coefficient ~ 7.28 bar/t. 1 oil ton costs 728$.

At one billion dollars a t, the energy cost of ^{3}He is equivalent to oil at ~ $9 per barrel! We can go up to $10 billion/t for helium-3 from the Moon!

Even, for Wittenberg figures [12] (7·10^{-10} for ^{3}He Volume Fraction in natural gas) we have:

Just for Siberia (30 ·10^{12}) x (7 ·10^{-10}) = 21· 10^3 m^3 of ^{3}He 2.8· 10^3 kg, i.e. 2.8 t !

Irkutsk region (He reserve in 2025) ~ 30·10^6 m^3.

World: (27.8·10^9) x (1.4·10^{-6}) x 0.134 = 5.2 t of ^{3}He !!! It’s enough even for Demo reactor. To cover the energy supply of one country (taking into account 20 percent of usage thermonuclear reactors of general part) 10 tones per year of helium-3 is required and enough for Russia. Other countries also have helium (reserve and resource): US + Algeria + Canada + Japan (Niigata basin – ^{3}He/^{4}He higher ratio) + China + Australia.

Approximate power inputs on helium detachment (low temperature separation or produced rectification) from gases contained 0.02; 0.05; 0.5% He - 250, 100 and 10 kW·h/m^3.

Applications of helium-3 based plasma [14] unlimited and may lead to new era in medicine and space propulsion. Near term – proton source and medical isotope production, cancer therapy, FRC fueler for tokamak design, detection of explosives and chemical wastes. $^{18}O + p \rightarrow n + {}^{18}F$; $^{94}Mo + p \rightarrow n + {}^{94m}Tc$; $^{14}N + p \rightarrow {}^4He + {}^{11}C$; $^{16}O + p \rightarrow {}^4He + {}^{13}N$; $^{13}C + p \rightarrow n + {}^{13}N$; $^{15}N + p \rightarrow n + {}^{15}O$. Mid term – destruction of fissile material and radioactive wastes, material and technology issues, including thick liquid walled commercial power plant (low recycling/ wall pumping).

CONCLUSIONS

Aneutronic/ low radioactive fuel is the way to clean and cheap energy in the future. An alternative fueling scheme using accelerated compact-toroids (CT) – FRC or sheromak injection - may be applied for the reactor based on any magnetic confinement system. Even more, any fusion concepts, including magneto inertial fusion (MIF)/magnetized target fusion (MTF) might use advantages of D-^{3}He fuel. Examples of the subsidiary reactor for the D-^{3}He-^{6}Li fuel cycle: breeder, polarized beams, plasma accelerator, colliding beam, also are open for discussion.

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ТЕРМОЯДЕРНАЯ ПЛАЗМА НА ОСНОВЕ ГЕЛИЯ-3

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Рассмотрены экспериментальные установки обращенной магнитной конфигурации (FRC) и сферомак, составляющие класс магнитных систем, называемый "компактный тор", и зеркальные ловушки, как наиболее перспективные и, в то же время, надежные и простые кандидаты в качестве термоядерных реакторов с улучшенным топливом. Представлены реакторные схемы с комбинированным D-^{3}He-^{6}Li топливным циклом с возможностью получения гелия-3 на Земле, включая реакторы-бридеры, и накопления ^{3}He в результате побочных реакций, а также с учетом лунного гелия. Показаны расчеты стоимости He-3 при получении его из природного газа, а также история вопроса и полная и энергетическая цена гелия-3. Обсуждены концепция электростанции с малонейтронным топливом и различные приложения малорадиоактивной плазмы на основе гелия-3.

ТЕРМОЯДЕРНА ПЛАЗМА НА ОСНОВІ ГЕЛІЮ-3

С.В. Рижков

Розглянуто експериментальні установки зверненої магнітної конфігурації (FRC) і сферомак, що складають клас магнітних систем, названий "компактний тор", і дзеркальні пастки, як найбільш перспективні і, у той же час, надійні і прості кандидати як термоядерні реактори з поліпшеним паливом. Представлено реакторні схеми з комбінованим D-^{3}He-^{6}Li паливним циклом з можливістю одержання гелію-3 на Землі, включаючи реактори-брідери, і накопичення ^{3}He у результаті побічних реакцій, а також з урахуванням місячного гелію. Показано розрахунки вартості He-3 при одержанні його з природного газу, а також історія питання і повна й енергетична ціна гелію-3. Обговорено концепцію електростанції з малонейтронним паливом і різні додатки малорадіоактивної плазми на основі гелію-3.