**UDC 621.039.574.3**

# DEVELOPMENTS FOR STELLARATOR-MIRROR FUSION-FISSION HYBRID CONCEPT

*V.E. Moiseenko[1], S.V. Chernitskiy[1], O. Ågren[2], N.B. Dreval[1], A.S. Slavnyj[1], Yu.V. Kovtun[1], A.V. Lozin[1], R.O. Pavlichenko[1], A.N. Shapoval[1], V.B. Korovin[1], M.M. Kozulya[1], N.V. Zamanov[1], A.Yu. Krasiuk[1], Y.V. Siusko[1], I.E. Garkusha[1]*

*[1]NSC Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
*[2]Uppsala University, Ångström laboratory, Uppsala, Sweden*

Conceptual development activities on a stellarator-mirror-based fission-fusion hybrid system (SM hybrid) are reviewed. Intended for transmutation of spent nuclear fuel and safe fission energy production, SM hybrid consists of a fusion neutron source and a powerful sub-critical fast fission reactor core. Its fusion component is a stellarator with an embedded magnetic mirror. The stellarator allows for the confinement of a moderately hot (1—2 keV) deuterium plasma. In the magnetic mirror, the hot sloshing tritium ions are trapped and fusion neutrons are generated. The magnetic mirror is surrounded by a fission mantle, where transmutation of minor actinides and energy generation take place. One candidate magnetic confinement device for the SM hybrid is the advanced DRACON magnetic trap system, which, unlike the «classical» DRACON version, has one short, rather than two longer mirrors with a relatively short size of 3—6 m. A comparative numerical analysis of collisionless losses occurring in the magnetic trap part of the single-mirror DRACON leads to a conclusion about the possibility for high-energy tritium ions to be fairly well confined in the magnetic trap area. The Uragan-2M (U-2M) stellarator is used to test the SM hybrid concept with experiment. To fit a magnetic trap into U-2M system, one of the toroidal coils had to be switched off. A radial escape of charged particles may spontaneously give rise to a weak radial electric field, which may result in closing the particles' drift trajectories and thereby substantially improve their confinement. Background plasma confinement without destructive instabilities is demonstrated in the stellarator-mirror regime of U-2M) operation. The sloshing ions driven by radio-frequency heating are detected in the mirror part of the device with NPA diagnostics. A novel fission mantle design for the SM hybrid is proposed.

**Key words:** fusion-fission hybrid, stellarator, magnetic mirror, nuclear transmutation.

DOI: 10.21517/0202-3822-2021-44-2-111-117

# РАЗРАБОТКА КОНЦЕПЦИИ СТЕЛЛАРАТОРНО-ПРОБКОТРОННОЙ ГИБРИДНОЙ УСТАНОВКИ СИНТЕЗА-ДЕЛЕНИЯ

*В.Е. Моисеенко[1], С.В. Черницкий[1], О. Агрен[2], Н.Б. Древаль[1], А.С. Славный[1], Ю.В. Ковтун[1], А.В. Лозин[1], Р.О. Павличенко[1], А.Н. Шаповал[1], В.Б. Коровин[1], М.М. Козуля[1], Н.В. Заманов[1], А.Ю. Красюк[1], Е.В. Сюсько[1], И.Е. Гаркуша[1]*

*[1]Национальный научный центр «Харьковский физико-технический институт», Харьков, Украина*
*[2]Упсальский университет, лаборатория Ангстрем, Упсала, Швеция*

Рассматривается концептуальный проект стеллараторно-пробкотронной гибридной системы синтеза-деления (СП-гибрид). Предназначенный для трансмутации отработавшего ядерного топлива и безопасного производства энергии при делении тяжёлых ядер СП-гибрид состоит из источника термоядерных нейтронов и мощной подкритической активной зоны реактора деления, работающего на быстрых нейтронах. Его термоядерный компонент является стелларатором со встроенным пробкотроном. Стелларатор позволяет удерживать умеренно горячую (1—2 кэВ) дейтериевую плазму. В пробкотроне горячие плещущиеся ионы трития захватывают и генерируют термоядерные нейтроны. Пробкотрон окружён мантией, в которой происходят деление тяжёлых ядер, трансмутация минорных актиноидов и генерация энергии. Одним из возможных устройств магнитного удержания для СП-гибрида является усовершенствованная система магнитной ловушки ДРАКОН, которая в отличие от «классической» версии ДРАКОНА имеет один короткий пробкотрон, а не два более длинных, имеющий размер в пределах 3—6 м. Сравнительный численный анализ бесстолкновительных потерь, возникающих в той части пробкотрона, где находится магнитная ловушка ДРАКОН, позволяет сделать вывод о возможности достаточно хорошо удерживать высокоэнергетические ионы трития в области этой магнитной ловушки. Стелларатор «Ураган-2М» (U-2M) используется для экспериментальной проверки концепции гибридной стеллараторно-пробкотронной системы. Для установки магнитной ловушки в систему U-2M необходимо было отключить одну из тороидальных катушек. Радиальный выход амбиполярных частиц может спонтанно вызвать слабое радиальное электрическое поле, которое может замкнуть траектории дрейфа частиц и тем самым существенно улучшить их удержание. Удержание плазмы без разрушительных неустойчивостей продемонстрировано в стеллараторно-пробкотронном режиме работы U-2M. Горячие ионы, появившиеся в результате радиочастотного нагрева, регистрируются в пробкотронной части этого устройства с помощью анализатора нейтральных частиц. Предложена новая конструкция ядерной части для СП-гибрида, в которой будет происходить деление ядер.

**Ключевые слова:** гибридная система синтеза-деления, стелларатор, пробкотрон, трансмутация ядер.

## INTRODUCTION

Current nuclear power plants rely mainly on $^{235}U$ fission for power generation. The ore reserves of this uranium isotope are not large, and the future of nuclear power production is associated with utilizing $^{238}U$

and $^{232}$Th, which are abundant. This situation has three implications. Number one is that the large amount of spent nuclear fuel already generated by the nuclear industry continues to grow. Today, the preferred option for nuclear waste management is long term geological storage with a view to keep the wasteisolated until the radionuclides have decayed to acceptable levels. However, the decay may last thousands of centuries, which is hardly acceptable. Therefore, geological storage should be looked upon as a way to gain some time before a full-scale incineration of spent nuclear fuel is in place. Unlike geological storage, incineration is consistent with the sustainability concept.

Number two is the inevitable need for introducing a new fuel cycle to allow $^{238}$U and $^{232}$Th to be used as a fuel. Both isotopes cannot be directly burned, and the first stage of this fuel cycle includes breeding of $^{239}$Pu and $^{233}$U. The fission of these isotopes, as well as many others, results in a twice as small fraction of delayed neutrons as the fission of $^{235}$U. This seriously hinders the controllability of critical reactors. Another need is for introducing a closed fuel cycle, in which, in the best-case scenario, waste would only consist of fission products. Such waste could be stored in a geological repository for a much shorter time of about 300 years. In the closed fuel cycle, all fissionable isotopes involved in the nuclear chain must be burned. This is only possible in fast reactors. Unfortunately, many fast reactor concepts are difficult to implement due to the positive reactivity accompanying a temperature increase. This, coupled with the shortage of delayed neutrons, has a serious impact on reactor safety. Implication number three is that $^{235}$U cannot be easily synthesized. If we burn it up completely, there will be no $^{235}$U left for future generations.

A solution is a subcritical fast reactor driven by an external neutron source. Inherently safe, it can be used for burning fertile components of spent nuclear fuel, nuclear breeding and energy generation under the closed fuel cycle. The neutron source for this reactor must be powerful and efficient. Two obvious candidates for the role of drivers of a sub-critical fast reactor are the spallation and fusion neutron sources, of which the latter are more compact, more feasible and less costly. In turn to, there are three major lines of fusion-fission hybrids (subcritical fission reactors driven by a fusion neutron source), i.e. tokamak, mirror and stellarator-mirror based hybrids.

Tokamak [1] offers the best plasma confinement. However it allows an acceptable neutron budget to be only achieved with an excessive neutron production. Tokamak's another inherent weakness is the pulsed-mode operation with a long (~100 s) duty cycle.

In a mirror-based hybrid [2], plasma confinement is poor, which translates into the machine's low energy efficiency and huge size.

The SM hybrid [3, 4] has an acceptable plasma confinement, stationary operation and a very compact design.

## THE SM HYBRID

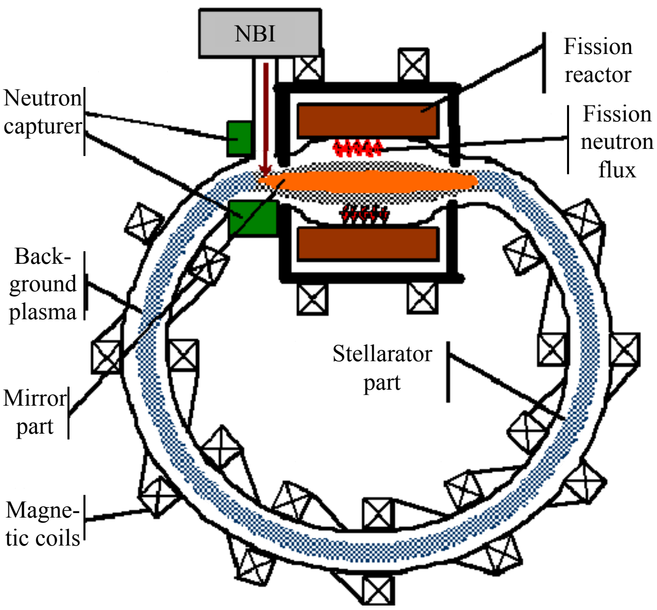


Fig. 1. Sketch of the fission-fusion hybrid

In the SM hybrid, fusion neutrons are generated in a deuterium-tritium plasma, confined magnetically in a stellarator-type system (Fig. 1). The plasma contains a warm electron component, and the majority of deuterium ions are in thermal equilibrium with electrons. The stellarator provides a steady-state operation and offers a relatively good confinement for such a warm Maxwellian plasma. Hot minority tritium ions are sustained in the plasma by a radio-frequency (RF) heating [5—8]. Considering the stellarator's inferior ability to confine high energy ions, it is proposed in [3] to integrate it with a magnetic trap with lower field. Hot ions mostly have perpendicular to the steady magnetic field kinetic energies. Because of the trapping effect, the hot (sloshing) ions' motion is restricted to the mirror part of the device. The containment of hot sloshing ions and, therefore, contraction the neutron production zone to the mirror part is favorable, as it makes it sufficient to only have the mirror part surrounded with a fission mantle. Furthermore, all sensitive plasma diagnostics and plasma control devices could be located at the stellarator part, but at a distance of the fission reactor zone, where the neutron flux is reduced.

It is not only RF heating that can sustain hot sloshing ions, but also a continuous neutral beam injection (NBI). The latter is implemented in both stellarators [9] and mirror machines [10].

For mirror-based hybrids, a quasi-tangential injection to the mid plane is typical. In comparison with normal injection, it allows the injection energy to be increased. However, a mid plane injection can seriously affect the reactor design, requiring either the reactor division into two independent nuclear reactor cores [11] or, in the case of a single reactor core, introduction of beam lines within the reactor core. Each of those modifications is a major engineering challenge.

Normal injection seems preferable, as it implies a smaller neutron loss from fission core and allows beam lines to be placed out side of the reactor core. To avoid beam shine-through, the shorter beam-plasma interaction distance is offset with a tolerable plasma density increase. The configuration with an NBI at the mirror ends, presented here, is similar to the scheme reported in [12]. The NBI is normal to the magnetic field and targets plasma just near the fission mantle border (see Fig. 1). Shined-through atoms, outnumbered by injected atoms, hit the armor made of refractory material (tungsten) and placed opposing to the NBI port.

The first step in the study of the SM hybrid is to analyze the power balance [4, 13] and thereby estimate the plasma machine size, the magnetic field strength, power needed for the sustain of hot ions and the overall power efficiency. The analysis used the results of the ISS04 stellarator scaling [14] and kinetic calculation. The calculations resulted in a compact device with achievable characteristics. The parameters of the device chosen as a demo machine are given in [3]. They are as follows:

| | |
|---|---|
| Stellarator beta . . . | 0.01 |
| Mirror beta . . . | 0.15 |
| Tritium injection energy, keV . . . | 150 |
| Beam shine-through parameter (ratio of ion mean-free path to plasma radius) . . . | 1.5 |
| Background plasma temperature, keV . . . | 1.6 |
| Stellarator part magnetic field, T . . . | 4.1 |
| Mirror ratio . . . | 1.7 |
| Angle of rotational transform . . . | 0.8 |
| Inverse aspect ratio . . . | 0.05 |
| Plasma density, $cm^{-3}$ . . . | $1.5 \cdot 10^{14}$ |
| Tritium concentration (in mirror part) | 0.11 |
| Heating power, MW . . . | 20 |
| Fission power, MW . . . | 570 |
| Plasma minor radius, cm . . . | 20 |
| Torus major radius, m . . . | 4 |
| Mirror length, m . . . | 3.2 |
| Electric efficiency $Q_{el}$ (for nuclear mantle with $k_{\mathrm{eff}} = 0.95$) . . . | 4.8 |
| Estimated cost, M$ . . . | 500 |

This SM hybrid version is used for neutronic calculations and cost estimates.

## FUSION PART OF THE SM HYBRID

The SM hybrid's magnetic system is a combination of a stellarator and a mirror. It was first implemented as part of the U-2M stellarator at the Kharkiv Institute of Physics and Technology in Ukraine. There are two big questions about this magnetic system, viz. (i) whether it can have magnetic surfaces, and (ii) whether it can confine hot ions in its mirror part.

**Studies at U-2M**. Stellarator U-2M was involved in modeling such system, [15]. It has the advantage of a winding availability, which allows using an additional toroidal magnetic field. The winding accommodates

16 separate magnetic coils. The switching off of one of them produces a local mirror inside it with a proper mirror ratio of 1.5 [16].

First Biot-Savart magnetic calculations were done to model the field with the coil switched off. Several practically important cases were identified, where the field lines formed nested magnetic surfaces in the device. Next, experiments to measure the magnetic configuration had been performed [17], which verified the theoretical data and demonstrated the magnetic configurations of U-2M with an embedded magnetic mirror.

A theoretical study was carried out to analyze the behavior of fast ions in the mirror part of U-2M [18]. It involved Biot-Savart magnetic calculations and drift surface calculations based on motion invariants. The study confirms poor confinement properties of the magnetic mirror created in the U-2M stellarator by means of switching off one toroidal field coil. The created magnetic mirror had a flaw, namely, a curved magnetic axis. Calculated drift surfaces were not closed, hence, there was no radial confinement. Such a situation can be avoided if the embedded mirror would have a straight magnetic axis. Unfortunately, this cannot be realized in U-2M. Meanwhile, the radial electric field can improve the situation substantially in U-2M. It causes a particle drift in the poloidal direction which competes with the vertical magnetic drift. Above a certain value of the electric field, mean drift surfaces become closed, and particle confinement improves. This value can be obtained from $e\varphi \sim \mu\Delta B$, where $\varphi$ is the electric potential, $\mu$ is the magnetic moment and $\Delta B$ is the variation of the magnetic field across the confinement volume. To establish the electric potential in the plasma column, a very small amount of lost ions is sufficient. The electric potential seems to be small enough to perturb the diffusive character of confinement of the bulk plasma.

Such an opportunity to confine fast ions is checked experimentally at U-2M (see below). Since the RF heated ions are confined at the mirror part of U-2M, one can suggest that the regime with the radial electric field is realized in that case.

**Plasma generation in U-2M in SM hybrid regime.** The U-2M — based experiments proved the possibility of background plasma production and confinement. A discharge was initiated by a RF pulse of a crankshaft antenna [19]. The discharge start-up was successful, as produced a $\sim 10^{12}$ cm$^{-3}$ plasma. The OV and CV lines showed up in the discharge. Their intense emission, especially that of the CV line, indicates an electron temperature of at least 100 eV. The parameters of the stellarator-mirror discharge are lower, but compatible with those of regular discharges.

**Experimental study of fast ion generation in the embedded mirror.** An experiment to generate sloshing ions in an embedded mirror was carried out on the U-2M stellarator. The magnetic beach approach was employed. A compressional Alfven wave was launched with a two-strap (W7-X like) antenna operated in monopole phasing. It is expected [5] that on the way to the embedded mirror, at a lower magnetic field, the wave reaches the ion cyclotron layer and accelerates the trapped ions. The neutral particle analyzer is used to detect high-energy ions.

The U-2M stellarator was recently equipped with a passive single-energy channel electrostatic small-angle 30° CX neutral particle analyzer (NPA) without mass separation similar to that described in [20]. Sweeping voltage NPA operating regimes [21] were used. A 2—5 ms analyzing voltage with triangular temporal shape was applied to electrostatic plates to enable a fast (2—5 ms) measurement of energy distribution using a single-energy channel analyzer. An additional 15 keV acceleration of ions after the electrostatic separation and ion-electron conversion allowed the suppression of the NPA collector energy sensitivity [21]. The NPA was located close to the switched off toroidal field coil and not far away from the W7-X like RF antenna, used for the ion cyclotron heating. Nitrogen was used in the NPA gas stripping cell. The 10—100 eV energy range was not covered by the NPA. Variations of line of sight angle allow us measuring the CX flux distribution from the plasma center to the edge. Very high CX fluxes in U-2M RF discharges allowed an analog NPA signal to be obtained. The NPA signal integration time was 0.1 ms, and its sampling rate was about 50 000 samples/s. Substantial CX flux as well as fraction of fast ions with perpendicular energy characterized by temperature of 400—500 eV was observed in pure hydrogen RF discharges in the U-3M stellarator [21], as well as in recent experiments involving the U-2M stellarator. Here we are demonstrating the strong transient CX flux in a «hybrid» configuration discharge, as shown in Fig. 2.

The CX flux radial distribution indicates that the energetic ions are localized in the centre of the plasma column. It should be admitted that the sweeping voltage of 1 kV corresponds to ion energy of 4.5 keV due to the NPA calibration coefficient [21, 22]. Ions with energies of 4.5 keV in the U-2M hybrid configuration are clearly seen in Fig. 2. Here we report the first experimental evidence of fast ions in a hybrid system. Although the presence of 0.5—4.5 keV ions is evident, some unclear points, e.g., different mechanisms of energetic ion generation in conventional stellarator and hybrid configurations are yet to be addressed.

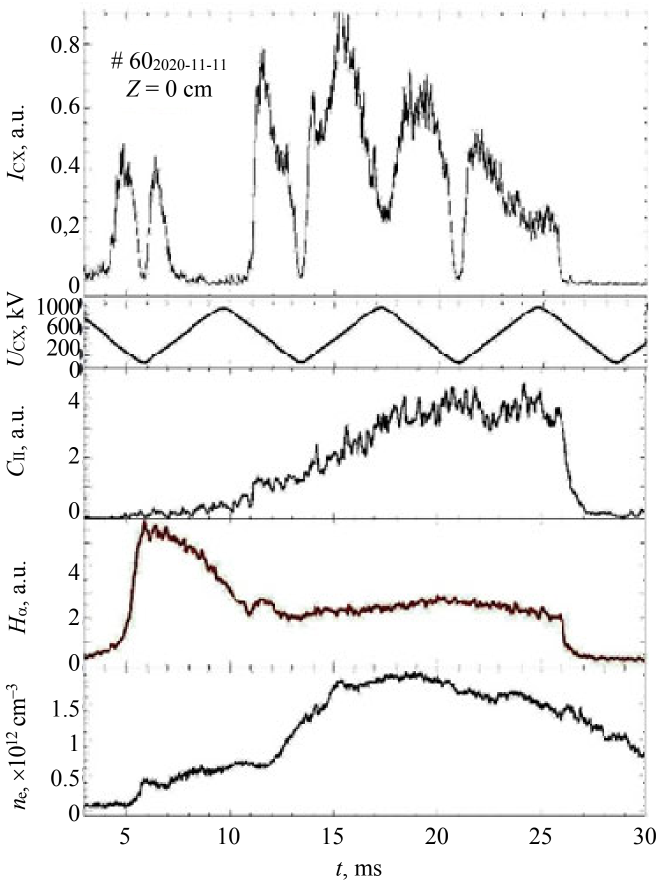


Fig. 2.Waveforms of the row NPA signal, NPA sweeping voltage, spectral lines $C_{II}$ and $H_\alpha$ emission and line-averaged density in hybrid configuration pure H discharge: $p = 2.4\times10^{-3}$ Pa, $B_0 = 0.38$ T, 2.5 ms (start of the pre-ionization with K-2 RF generator), 12.5 ms (shutdown) K-2: $f_2 = 5.36$ MHz, $U_a$ = 4 kV, RF power ~30 kW, 12.5 ms (start of main pulse with K-1 RF generator), 27.5 ms (shutdown) K-1: $f_1 = 4.9$ MHz, $U_a$ = 5.5 kV, RF power ~80 kW

**DRACON as a plasma confinement component of the SM hybrid.** One candidate magnetic confinement device for the SM hybrid is the DRACON magnetic trap system, which, unlike the «classical» DRACON version, has one short, rather than, two longer mirrors. The equilibrium stellarator configuration DRACON (see [18] and references therein) consists of two rectilinear regions and two curvilinear elements (known as CREL), which close the magnetic system and whose parameters are chosen so as to keep the Pfirsch—Schluter currents within the CREL and to prevent them from penetrating into the rectilinear sections. In order to improve plasma confinement, the magnetic field in the CRELs is higher than the field in the rectilinear parts. So, in fact the rectilinear parts represent two mirror traps, which are closed by the CRELs. Fusion reactions in such a device can be realized in the mirror parts, which help to confine the hot ion component (tritium) with high perpendicular energy. A comparative numerical analysis of collision less losses occurring in the magnetic trap part of the single-mirror DRACON [18] leads to a conclusion about the possibility for high-energy tritium ions to be fairly well confined in the magnetic trap area.

## FISSION PART OF THE SM HYBRID

The acquired knowledge of the fusion neutron source parameters can be used to obtain the initial conditions for a preliminary design of the hybrid's fission mantle part. The mantle design is mostly based on the results of engineering research described in [23].The cylindrical reactor is compact, with a 1.6-m radius and a 4-m length. Its major parts (Fig. 3), moving from the axis to the major radius, are the inner opening for the plasma column, the first wall, the LBE (lead-bismuth eutectic) buffer, the metal fuel-loaded, LBE-cooled active zone, the core extension zone (filled by LBE), and the reflector. Fuel for the fission

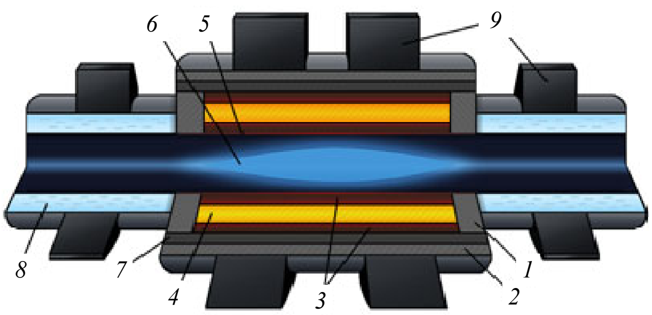

Fig. 3. Reactor part of the SM hybrid: *1* — axial reflector (HT-9 steel 70% and LBE 30%); *2* — 60:40 Vol.% mixture of the stainless steel S30467 tipe 304B7 with water, the steel contains 1.75% wt of natural boron; *3* — coolant (lead and Bismuth eutetic); *4* — fission blanket; *5* — first wall; *6* — neutron souce (D—T-plasma); *7* — radial reflector (HT-9 steel 70% and $Li_{17}Pb_{83}$ 30%, enrich 20% $^6$Li); *8* — borated water with B, 10 g/kg; *9* — magnetic coils

component is produced by separating uranium and fission products from spent nuclear fuel. Actual fuel material is an alloy (TRU—10Zr) consisting of transuranic elements with 10% wt zirconium [24]. The active zone size is chosen using MCNPX calculations to achieve the effective neutron multiplication factor $k_{eff} \approx 0.95$. For the discussed reactor, the calculated fusion power multiplication factor is 65. There are only 5 t of transuranic elements in the fuel. This suggests that a nuclear plant operated at full capacity will need to refuel every 1—2 years.

## PRELIMINARY COSTS ESTIMATES

There is no point in doing the required experiments based on a downscaled prototype, as the hybrid machine itself is quite small. Taking the Wendelstein7-X stellarator's cost, EUR 1 billion (https://en.wikipedia.org/wiki/Wendelstein_7-X), as a reference and considering that:

— the SM machine is smaller;

— the diagnostic equipment is less advanced;

— the coils and the vacuum chamber are much simpler (in DRACON's case);

— the cost could be decreased to EUR 0.2—0.3 billion.

The fission mantle is expected to be installed after the completion of the «plasma part» test. Its cost can be put at EUR 0.2 billion based on the cost of the BREST-OD-300 (EUR 0.3 billion), the project carried out by Russia's Rosatom (https://www.riatomsk.ru/article/building_%20reactor_seversk). The total cost estimate for a hybrid with a fission mantle is then in the range of EUR 0.4—0.5 billion. This is less than the cost of the accelerator-driven MYRRHA system (around EUR 1.6 billion (https://en.wikipedia.org/wiki/MYRRHA)).

## DEMO MACHINE OPERATION PROSPECTS

The DEMO device needs 20 MW of RF power, which is high, but not exceptional: such a power is available, for instance, at the JET tokamak. Power supply could be provided by 1—2 MW modules and enlarged step by step to a total of 5 MW, needed for initial experiments. Frequency could be set at 27.2 MHz, the standard industrial value. It makes sense to start those experiments using the $^3$He—H mixture, a halved magnetic field and low power (5 MW). For a 3/4 magnetic field, the D—$^3$He mixture could be used. The fission mantle can be installed after the completion of the «plasma part» test.

With around EUR 0.5 billion of investment, the SM hybrid based on the spent fuel incineration technology could be developed in 10—15 years.

## SUMMARY AND CONCLUSIONS

The U-2M experimental studies suggest that the SM hybrid key properties are achievable. This machine offers the prospect of a successful implementation of the stellarator-mirror plasma trap technology. It is designed in such a way that the desired properties, including background plasma confinement and generation/confinement of hot ions at the mirror part are fully feasible. There is reason to be hopeful that developing an appropriate device is a realistic undertaking.

Calculations suggest that the plasma part of the SM hybrid could be a DRACON-like device with a single embedded mirror as short as needed.

The MCNPX calculations for the fission mantle are in line with a robust device design and operation, with no major engineering challenges looming.

The fuel mass is small enough, and refueling is needed every 1—2 years.

The estimated cost of the DEMO device for the SM hybrid is just EUR 500 million, which is the lowest for hybrid devices. It is just twice as large as the cost of a critical reactor of the same power. But the safety advantage could be a decisive argument in favor of hybrids to be used for regular power production under the closed fuel cycle.

### REFERENCES

1. **Kuteev B.V. et al.** — Nucl. Fusion, 2011, vol. 51, p. 073013.
2. **Ågren O., Moiseenko V.E., Noack K.** — Fusion Science and Technology, 2010, vol. 57, № 4, p. 326.

3. **Moiseenko V.E., Noack K., Ågren O.** — J. Fusion Energy, 2010, vol. 29, p. 65.
4. **Moiseenko V.E., Kotenko V.G., Chernitskiy S.V. et al.** — Plasma Phys. Control. Fusion, 2014, vol. 56, p. 094008 (11p.).
5. **Moiseenko V.E., Ågren O.** — J. of Physics: Conference Series, 2007, vol. 63, p. 012004.
6. **Moiseenko V.E., Ågren O.** — Phys. Plasmas, 2005, vol. 12, p. 102504.
7. **Moiseenko V.E., Ågren O.** — Phys. Plasmas, 2007, vol. 14, p. 022503.
8. **Moiseenko V.E., Ågren O.** — AIP Conf. Proc., 2012, vol. 1442, p. 199. doi:http://dx.doi.org/10.1063/1.4706869.
9. **Yamada H. et al.** — Nucl. Fusion, 2003, vol. 43, p. 749.
10. **Zuev A.A. et al.** — Plasma Phys. Rep., 2002, vol. 28, p. 268.
11. **Noack K. et al.** — Annals of Nuclear Energy, 2008, vol. 35, p. 1216.
12. **Ryutov D.D., Molvik A.W., Simonen T.C.** — J. Fusion Energy, 2010, vol. 29, p. 548.
13. **Moiseenko V.E., Ågren O.** — Fusion Science and Technology, 2013, vol. 63, № 1T, p. 119.
14. **Yamada H. et al. —** Nucl. Fusion, 2005, vol. 45, p. 1684.
15. **Bykov V.E. et al.** — Fusion Technology, 1990, vol. 17, p. 140.
16. **Kotenko V.G., Moiseenko V.E., Ågren O.** — AIP Conf. Proc., 2012, vol. 1442, p. 167.
17. **Lesnyakov G.G. et al.** — Problems of Atomic Science and Technology. Series: Plasma Physics, 2013, vol. (83), № 1, p. 57.
18. **Moiseenko V.E. et al.** — Plasma Phys. Control. Fusion, 2016, vol. 58, p. 064005 (8 p.).
19. **Moiseenko V.E. et al.** — Nukleonika, 2016, vol. 61(2), p. 91.
20. **Afrosimov V.V. et al.** — Soviet Phys. Tech. Phys., 1961, vol. 5, p. 1378.
21. **Dreval M., Slavnyj A.S. —** Plasma Phys. Control. Fusion., 2011, vol. 53, p. 065014.
22. **Slavnyj A.S. et al.** — Problems of Atomic Science and Technology. Series: Plasma Physics, 2021, vol. 131, № 1, p. 25.
23. **Chernitskiy S.V. et al. —** Annals of Nucl. Energy, 2014, vol. 72, p. 413.
24. **Stacey W.M. et al.** — Fusion Science and Technology, 2002, vol. 41, p. 116.

**AUTHORS**

**Uppsala University, Ångström laboratory, Box 534, SE 751 21 Uppsala, Sweden**
Olov Ågren, Olov.Agren@angstrom.uu.se

**Institute of Plasma Physics, National Science Center «Kharkiv Institute of Physics and Technology», 61108 Kharkiv, Ukraine**

V.E. Moiseenko, moiseenk@ipp.kharkov.ua; S.V. Chernitskiy; M.B. Dreval; A.S. Slavnyj; Yu.V. Kovtun; A.V. Lozin; R.O. Pavlichenko; A.N. Shapoval; V.B. Korovin; M.M. Kozulya; N.V. Zamanov; A.Yu. Krasiuk; Y.V. Siusko; I.E. Garkusha

Статья поступила в редакцию 15 января 2021 г.
После доработки 16 марта 2021 г.
Принята к публикации 25 марта 2021 г.
Вопросы атомной науки и техники.
Сер. Термоядерный синтез, 2021, т. 44, вып. 2, с. 111—117.