NOVEL HYBRID PILOT EXPERIMENT PROPOSAL FOR A FUSION-FISSION SUBCRITICAL COUPLED SYSTEM

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Fusion-fission hybrid systems (FFH) represent a coupling between a fusion device and a subcritical fission reactor driven by neutrons produced by fusion reactions. This kind of systems, in principle, can be useful for different purposes, for example, as energy amplifier or as nuclear waste burner. In this work, the preliminary characteristics and potentialities of a FFH based on a tokamak device characterized by high magnetic field ($B > 9$ T) and high-density plasma ($n > 10^{14}$ cm^{-3}) have been evaluated. During the years high magnetic field compact tokamaks have been designed, built and operated. Thanks to their characteristics, such as compactness, high field and high density plasma, these devices can produce intense neutron fluxes, and therefore are good candidates to be incorporated in FFH while operating in a sub-ignited regime. An additional advantage is that their design is based on relatively simple existing technology. In this work, a coupling between a tokamak (operating in DD-mode) and a subcritical molten salt fission blanket has been proposed. Molten salt reactor could be adapted for this purpose and could help the hybrid system to increase its energy balance. A model with a molten salt fission blanket ($k_{eff} = 0.92$, $P = 95$ MW) instead of the lithium one, has been considered and studied in terms of neutronic evaluations. Presented preliminary numerical calculations based on a neutron Monte-Carlo code confirm the potentialities of the system.

Key words: Fusion-fission hybrid system, subcritical molten salt fission blanket, nuclear waste burner, compact tokamak with high magnetic field and high density plasma, neutron Monte-Carlo code.

НОВОЕ ПРЕДЛОЖЕНИЕ О РАЗРАБОТКЕ ЭКСПЕРИМЕНТАЛЬНОЙ ПОДКРИТИЧЕСКОЙ ГИБРИДНОЙ УСТАНОВКИ СИНТЕЗА-ДЕЛЕНИЯ

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Гибридные системы синтеза-деления (ГССД) представляют собой объединение в одной установке термоядерного компонента и подкритического реактора деления, в котором реакция инициируется нейтронами, образующимися в результате реакций термоядерного синтеза. Такие системы, в принципе, могут быть полезны для различных целей, например, для увеличения производства энергии или сжигания ядерных отходов. В данной работе оценены характеристики и возможности ГССД на основе токамака с сильным магнитным полем ($B > 9$ Тл) и большой плотностью плазмы ($n > 10^{14}$ см$^{-3}$). В течение многих лет разрабатывались, строились и эксплуатировались компактные токамаки с сильным магнитным полем. Благодаря компактности, сильному магнитному полю и большой плотности плазмы такие токамаки могут генерировать интенсивные потоки нейтронов и, следовательно, являются хорошими кандидатами для включения в ГССД при их работе в подкритическом режиме. Их дополнительным преимуществом является то, что их конструкция основана на относительно простой существующей технологии. В этой работе был рассмотрен токамак, работающий на DD-реакции, с подкритическим бланкетом деления на основе расплавленной соли. Такой бланкет может увеличить выработку энергии в гибридной системе. Были изучены нейтронно-физические характеристики ГССД при замене литиевого бланкета бланкетом деления с расплавленной солью ($k_{эф} = 0,92$, $P = 95$ МВт). Предварительные численные расчёты на основе нейтронного кода Монте-Карло подтверждают потенциальные возможности системы.

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Ключевые слова: гибридная система синтеза-деления, подкритический бланкет деления на основе расплавленной соли, ядерное уничтожение радиоактивных отходов, компактный токамак с сильным магнитным полем и большой плотностью плазмы, нейтронная вычислительная программа Монте-Карло.

INTRODUCTION

Fusion-fission hybrid systems (FFH) [1] represent a coupling between a fusion device and a sub-critical fission reactor driven by neutrons produced by fusion reactions. This kind of systems, in principle, can be useful for different purposes, for example, as energy amplifier or as nuclear waste burner. In this work, we studied the characteristics and potentialities of a FFH based on tokamak device characterized by high magnetic field ($B > 9$ T) and high-density plasma ($n > 10^{14}$ cm^{-3}). During the years high magnetic field compact tokamaks have been built and operated (see for example FTU in Frascati (Italy) and C-MOD (MIT, Boston USA) and some like Ignitor [2—4] and Columbus projects [5, 6] have been designed. The latter two systems were originally conceived to explore the physics of burning plasmas with «Columbus» being a slightly enlarged version of Ignitor.

Thanks to their characteristics, such as compactness, high field and high density plasma, these devices can produce intense neutron fluxes [7], and therefore are good candidates to be incorporated in FFH [8] while operating in a sub-ignited regime. An additional advantage is that their design is based on relatively simple existing technology. Preliminary numerical calculations based on a neutron Monte-Carlo code are presented, confirming the potentialities of a FFH based on the coupling of a compact, high field tokamak with a fission region based on the molten salt concept as a preliminary device to start to gain experience in operating fusion fission subcritical coupled systems.

IDEA AND BACKGROUND

Several hybrid reactor configurations have been evaluated in the past years in order to verify conceptual ideas and machine potentialities.

The aim of this proposal is to evaluate the main characteristics for a new FFH device having as main goal, if realized, to short-cut the demonstration of the first energy producing system based on a fusion device. The achievement of this goal is currently foreseen in the fusion roadmap with the DEMO demonstrator, where a thermal power production of several hundred MW should be achieved for a relatively long time, but still in pulsed mode. On the other hand, DEMO overall energy balance [9], due to the large amount of needed power for re-circulation, for cryogenic cooling under intense high energy radiation flow, to additional power systems and, in general to its high technological complexity level, may not be necessarily positive. In addition, the roadmap for such a pure fusion demonstrator is still affected by several physical and technological challenging problems [10] some of them far to be solved, with at least 10 years of ITER operating time and IFMIF/DONES material testing, i.e. probably far away in this century.

In this paper, an experimental machine configuration, ready to be designed for a relevant net thermal power production demonstration is presented, with as much as simple and cheap solutions as possible. This device could be the first hybrid experimental system to be realized with the possibility to produce a relevant quantity of power (comparable to DEMO) starting from a fusion system. With this option the cost, realization time, overall system complexity, and consequently affordability, will be extremely reduced. This machine, in principle, could ensure a positive power net balance due to the lack of strong power needs. Additional heating, in fact, is not essential to the ignition (or at least a remarkable neutron rate production), that could be reached by Ohmic heating alone. The presence of a few MW (3—5 MW) of ICRH system will expand the capabilities of the device.

This new proposed configuration has few open points from both the physical and technological point of view, and its detailed planning and construction could be started in a relatively short time.

According to these guidelines a fusion compact, high density, high magnetic field non superconducting machine has been considered. The main consequences of this choice are the following: i) cheapness: machine compactness together with the use of normal copper magnets reduce the cost and the complexity of the machine; ii) possibility to operate even in DD-mode with acceptable neutron production [11]. High density compact machine can achieve a neutron production useful for a first experimental power generation test, if coupled with a fission system as shown hereafter. The DD-regime reduces the system complexity caused by the management of large

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quantities of tritium and overcome the possible uncertainty on the lack of tritium for the starting of the operations (one of the DEMO challenges); in addition, due to DD operations, it would be possible to replace the original lithium blanket for tritium production with a blanket filled with circulating liquid molten salts mixed with fission elements placed partly inside the vacuum vessel, for higher neutron flow.

On the other hand, the non-superconducting choice limits the discharge time in a way non-compatible with a real reactor needs, limiting this system to the exclusive purpose of a demonstrator able to start the exploration of the hybrid experimental configuration. In addition, the generation of DD 2.45 MeV neutrons, instead of the DT 14 MeV, reduces the fission rate of 45% due to a reduced n-U235/238 cross-section. Even with these limits the configuration is able to produce in principle a relevant amount of power.

In Table I it is reported a parameter comparison between compact high-magnetic field tokamaks, which may be expected to be well-suited as neutron sources for hybrid systems (FIRE, Ignitor, Columbus), and the ITER tokamak presently under construction.

T a b l e 1. **Comparison between ITER, FIRE, Ignitor and Columbus main parameters**

Relevant parameters	ITER	FIRE	Ignitor	Columbus
Pulse flat top t_{pulse}, s	400	20	6	11.4
Minor radius a, m	2	0.595	0.47	0.535
Peak el. temperature T_{e0}, keV	19	11	10.5	11.5
Peak ion temperature T_{i0}, keV	19	11	10.5	10.5
Peak density n, m^{-3}	10^{20}	5×10^{20}	9×10^{20}	9.5×10^{20}
Profile parameter α_T, parab	1	1	2	2
Purity parameter Z_{eff}	1.7	1.4	1.2	1.2
DD-neutron yield Y_{DD}, n/s	10^{18}	10^{17}	10^{17}	10^{18}
DT-neutron yield Y_{DT}, n/s	10^{20}	10^{19}	10^{20}	10^{20}

COMPACT DEVICE IN DD OPERATION MODE

Due to its physics characteristics, high magnetic field compact tokamaks can generally operate both in DT- and in DD-mode. Here we focus on the latter mode of operation, which has the advantage of not needing a tritium breeding region in addition to the fission blanket, to have an idea of the potential performances of DD-operational mode.

A simple evaluation of the neutron emission yield has been performed. Considering, for example, the following plasma parameters: i) density $n_e = 10^{15}$ cm^{-3} with parabolic profile; ii) $\langle\sigma v\rangle = 9 \times 10^{-20}$ cm^3/s (Fig. 1); iii) $V_{plasma} = 2.5 \times 10^7$ cm^3; iv) $T_{peak} \approx 10$ keV with parabolic squared profile (note that ion and electron temperature at that plasma density are equivalent); v) no additional heating; the reaction rate can be calculated as: $R = n^2/2 \; \langle\sigma v\rangle \; V_{plasma} = 2 \times 10^{18}$ DD/s. Since two equi-probable production channels are possible for the DD-reaction: i) D + D → ^{3}He + n; ii) D + D → ^{3}H + p; the neutron yield is about $Y = 10^{18}$ n/s.

Considering $E = 3.27$ MeV (^{3}He + n) and 4.03 MeV (^{3}H + p) as emitted energies for both production channels, fusion power can be estimated as 1.16 MW.

The design of a device like high magnetic field compact tokamak must be adapted to the requirements and goals of a FFH. In this contest, flat-top and cooling time duration represent crucial parameters for this configuration and have to be optimized in order to avoid molten salts freezing or complex heat exchanger addition to evacuate the excess heating.

New materials for the magnets might also be considered in order to increase magnetic flux availability and flat top duration, and the mode of operation (plasma temperature and density) should be adjusted to fit the requirements of a FFH.
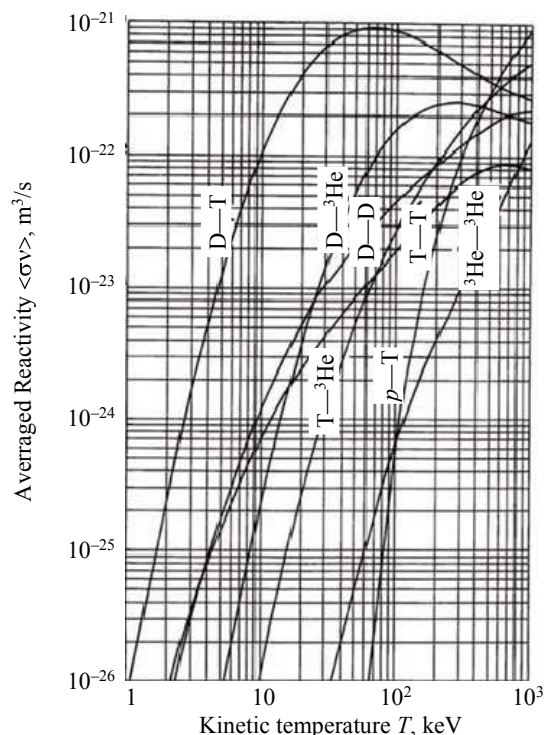

Fig. 1. $\langle\sigma v\rangle$ reaction rate as a function of plasma temperature for several fusion reactions

FUSION-FISSION HYBRID COUPLING

On the basis of the considerations presented in the previous paragraphs, high field tokamak characteristics fit in a very good way with hybrid device requirements.

For the fusion plasma, an adaptation of the parameters to the requirements of an FFH is necessary, and this task will not be pursued here. For the fission zone, the following two main solutions could be considered:

— traditional reactor (with fuel rods) inside an external blanket, cooled by water;

— molten salt reactors (MSR) [12, 13] with fissile/fertile elements dissolved in the molten salt fluid.

Traditional reactors have the advantage in terms of technological knowledge and feasibility coming from decades of operation, but, in this kind of nuclear system, material stresses could represent a weak point especially for fuel rods cladding and structure. In particular, the pulsed behavior of the fusion machine could induce failures in the rod cladding. On the other side MSR solution could be better coupled to the tokamak geometry with the positioning of the blanket entirely, or partially, inside the machine. This has the advantage to intercept all the plasma produced neutrons and to shield the external structure from them.

There are many studies concerning MSR with different characteristics and designs, traditional or breeders, using many kinds of salt mixtures depending from the neutron spectrum inside the core (fast or moderated) [14—18].

The schematic view of MSR is reported in Fig. 2, in which it is possible to observe the molten salt circuit passing through the fission core and then in the heat exchanger loop.
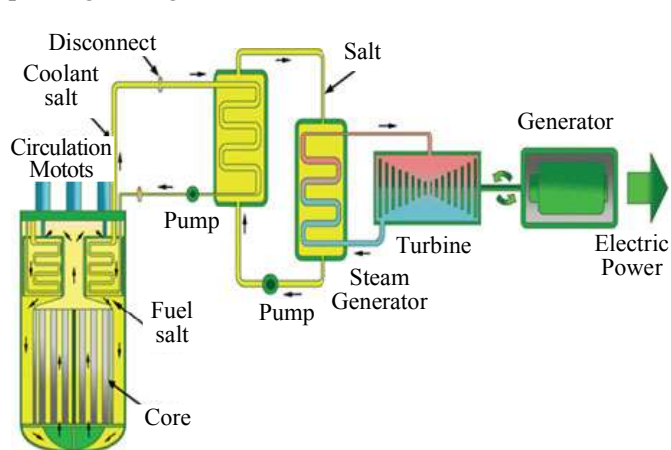

Fig. 2. MSR schematic view in which it is possible to observe the primary fuel loop passing through the reactor core, the secondary and the tertiary loops

A summary of the main features of MSRs which well fit the requirements of a FFH is the following:

— fissile isotopes contained in the salt mixture;

— possibility to use salt mixture containing different kind of isotopes (U/Pu/minor actinides);

— salt mixture chosen considering the fission blanket region temperature; MSR avoid the material stress on the traditional nuclear fuel rods, that could be very high due to the pulsed operational mode of the fusion system;

— salt online reprocessing keeping $k_{eff} < 1$.

Molten salt fission reactor with dissolved fuel has some limits in terms of system safety. The dissolved fuel may have density fluctuations that may lead the reactor in supercritical state. This is a well-known problem for fission reactor with sudden increase in power production. This difficulty is completely solved in a subcritical system, as the fuel density fluctuations will not be able to reach supercriticality.

SIMPLE HYBRID SYSTEM PRELIMINARY SIMULATIONS

In order to gain a preliminary understanding on the performances of the proposed hybrid system, a simplified simulation model has been considered. The model, as shown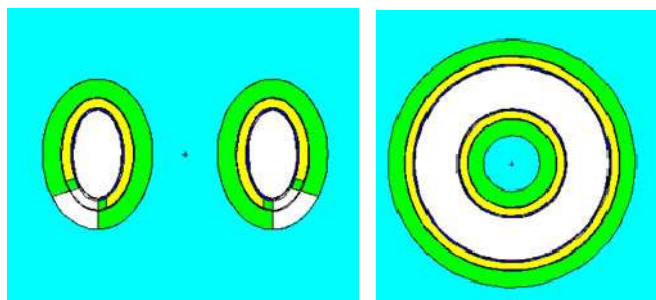 in Fig. 3, is based on a high magnetic field compact tokamak device with the following geometric characteristics: major radius $R = 200$ cm, minor radii $a = 54$ cm and $b = 100$ cm (vertical size of the plasma taking into account the elongation $\varepsilon = 1.85$). The first wall is composed by 1 cm thick tungsten, 3 cm thick AISI-316 followed by 29 cm thick molten salt fission blanket. This is supposed to be placed inside the machine vacuum vessel made with 2 cm steel. Just outside the vacuum vessel a 35 cm lead neutron reflector is positioned, to

Fig. 3. FFH poloidal and toroidal sections sketches. Molten salt blanket ( ), steel vessel ( ), lead reflector ( )

recover part of the out-flowing source or fission neutrons. In the following sketches a poloidal section (see Fig. 3) is shown with a void sector representing the space for divertor (not designed in this model and not necessarily required) positioning (in white).

The simulations have been performed by using the Monte-Carlo code MCNP6.1 with ENDF/BVII.0 libraries. For effective multiplication factor (k_{eff}) evaluation KCODE mode has been used, while, for neutron and fluxes calculations SDEF mode have been considered.

The isotropic neutron source (from DD-fusion reactions) emitting $Y = 10^{18}$ n/s over 4π solid angle has been implemented uniformly on a circumference passing from the center of the torus as shown in Fig. 4.
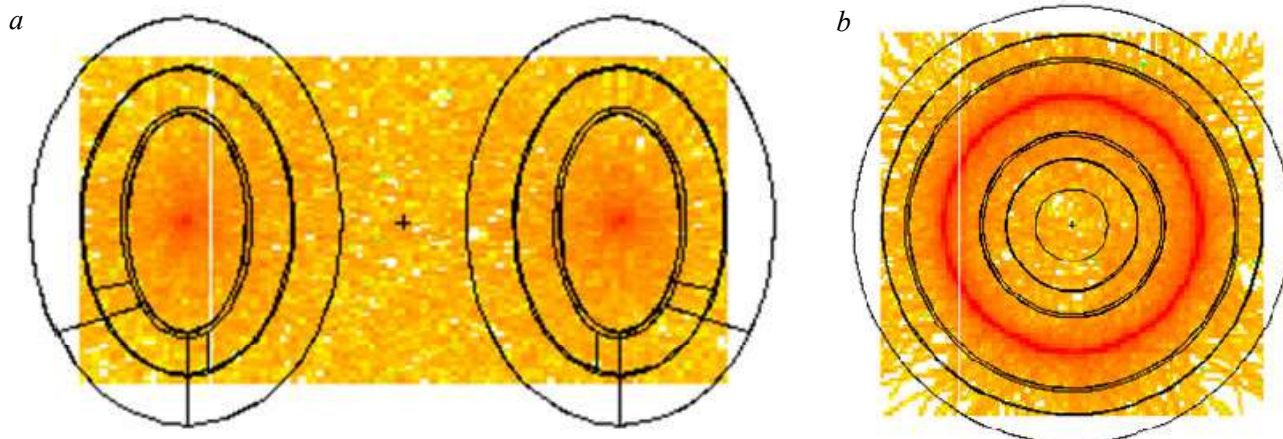

Fig. 4. Poloidal (*a*) and toroidal (*b*) views of the neutron emission from the circumference passing from the center of the torus

For this model, it has been considered a 34.5 cm thick fission blanket filled with molten salt mixture LiF—NaF—UF$_4$ (44.48%, 24.12%, 31.40%) molten % with 3.4 g/cm^3 density and the following mass composition [19]: 13.5% ^{235}U; 48.5% ^{238}U; 2% ^{7}Li; 31% ^{19}F; 6% ^{23}Na.

The effective multiplication factor for this fission system results to be about 0.92 (in order to guarantee a high safety level) , the integral neutron flux averaged on the whole molten salt volume is about $5{,}85\times10^{13}$ n/(cm^2·s) and the thermal power level is about 95 MW$_{th}$ (assuming a neutron yield of 10^{18} n/s).

In this scenario, the energy distribution for the neutron flux averaged on the whole molten salt volume is shown in Fig. 5.

A map of the integral flux intensities in the hybrid system is shown in Fig. 6.

In Table 2, the integral flux and the integral flux evaluated for three energy bins with their relative percentages in terms of absolute flux are reported to have a quantitative idea of the neutron energy distribution inside the fission blanket.
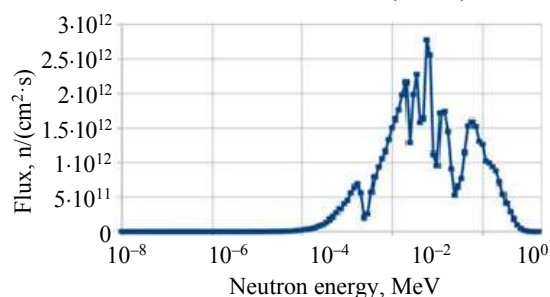

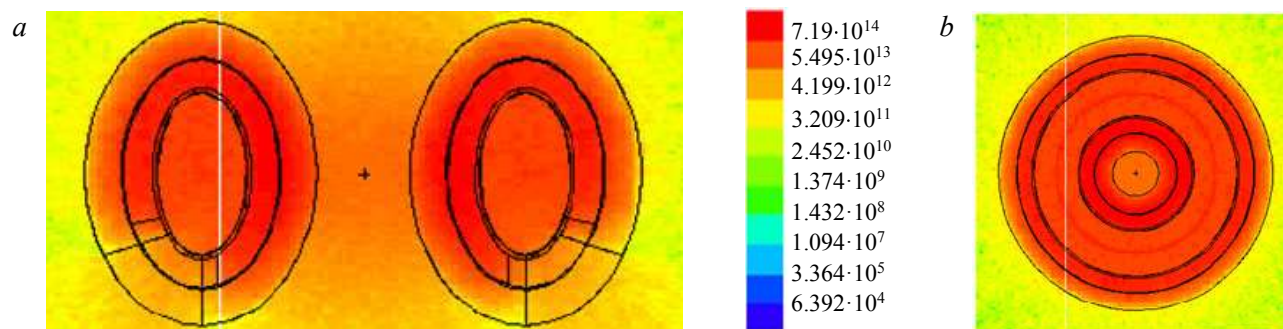Fig. 5. Neutron energy distribution averaged over the whole molten salt volume

Fig. 6. Poloidal (*a*) and toroidal (*b*) integral flux intensities in the hybrid system in the legend the flux intensities are reported in n/(cm^2·s)

T a b l e 2. **Flux values for different energy bins with their relative percentage with respect to the integral one**

Parameter	Integral	<1 eV	1 eV — 100 keV	>100 keV
Flux, n/(cm^2·s)	5.85×10^{13}	7.36×10^7	2.54×10^{13}	2.31×10^{13}
Percentage, %	100.0000	0.0001	60.4550	39.5448

Such a fission blanket can provide a relatively high intensity flux with a good component in the range of fast reactors.
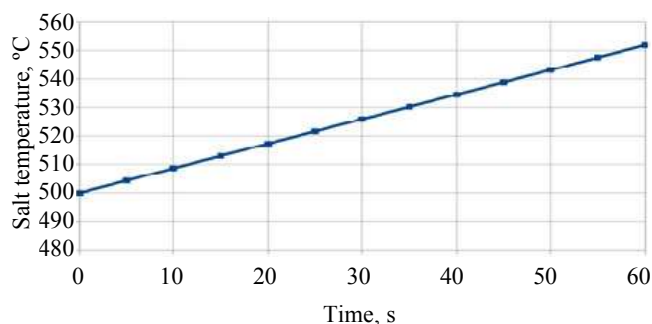

Fig. 7. Salt temperature increase as a function of shot duration

To have a more detailed and quantitative evaluation, starting from a temperature of about 500 ºC (higher than fusion temperature) and considering the thermal power generated inside the salt mixture (95 MW_{th}) in stationary situation, the temperature increase as a function of pulse duration is shown in Fig 7.

An optimization regarding the pulse and the cooling time durations can be fundamental for the definition of the hybrid device operation mode in a more detailed model. In this framework, the magnets have to be actively cooled by liquid nitrogen flow during and in between the pulses as already done in the FTU machine [20]. Thermal insulators are still not considered in this preliminary version, but in a more detailed work, could be considered as a fundamental component of the system.

This simple analysis has to be better detailed but could highlight the possible compatibility between a high magnetic field tokamak and a molten salt fission blanket in order to start to gain experimental confidence with a simple fusion fission coupled system with increasing level of criticality.
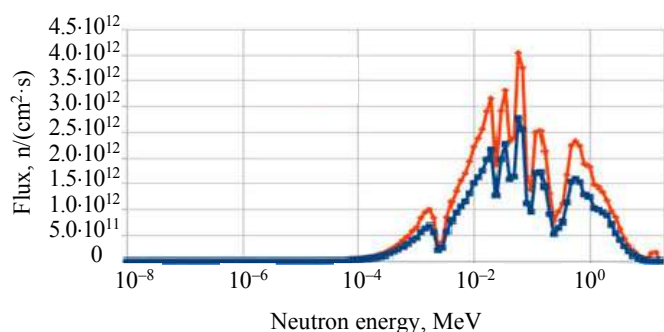

Fig. 8. Neutron energy distributions averaged over the whole molten salt volume for DD source (——) and for DT source (——)

To have an idea of the differences due to the use of 14.1 MeV neutrons instead of considering 2.45 MeV, (as briefly recalled above), the comparison of the neutron spectra sampled inside the fission blanket obtained starting from DD- and DT-fusion reactions is reported in Fig. 8.

Neutron integral flux and thermal fission power in the case of DT-fusion source are 45% higher than in the case of DD-source (maintaining the same neutron intensity of 10^{18} n/s for both cases).

From this comparison, performed by maintaining the same neutron intensity, the better behavior of DT-source is clear, 14.1 MeV neutrons are more efficient for inducing fission reactions inside the fuel. Another important factor is that the neutron intensity is much higher for DT-fusion with respect to DD. In any case, for a first experimental demonstration DD fuel appears to be suitable to drive the fission system.

CONCLUSIONS

In this paper the idea of considering a tokamak neutron source operating with DD fuel coupled with a molten salts fission blanket for a fusion-fission hybrid system preliminary experimental activity has been described. This solution could represent a short-cut towards a first experimental system based on a fusion machine generating an appreciable value of power with a positive overall energy balance. In this way it could be possible to reach the fusion power experimental generation conceptual demonstration several decades ahead of schedule as foreseen in the mainstream fusion roadmap.

High field non-superconducting tokamaks, for their peculiar properties, can act as neutron sources for FFH due to their compactness, their relative technological simplicity and their high neutron emission. An optimization in parameter space is however required in order to adapt the original already existing (i.e. Columbus) high field tokamak design to the hybrid purposes. The simple and feasible technology represents a crucial point with regard the realization of a FFH pilot experiment. Configuration optimization could be performed by modifying the magnetic field intensity and by considering new solutions and materials for the molten salt reactor technolo-

gies, but the proposed technologies are well tested and available and allow to start with a simple and cheap system the coupling studies between fusion sources and fission energy generation module.

A simplified model simulation has been performed by using the MCNP6.1 code concerning a $k_{eff} = 0.92$. The results of these simulations provide some preliminary insights on the main neutron parameters concerning the fission blanket in terms of geometric characteristics, thermal power and fluxes. A power production of about 95 MW_{th} has been calculated along the plasma shot duration, sufficient for the first relevant power production demonstration with a fusion based system. The simulations have given inputs on the required characteristics concerning the fusion device, the geometrical disposition and the neutron emission intensity, providing a starting point for the definition of a pilot FFH experiment, its main characteristics and its operation mode. An important point is represented by molten salt thermal cycle: from a preliminary evaluation seems that the high magnetic field tokamak operation characteristics can match in a good way with the thermal properties of the salt in stationary conditions also allowing to increase, step by step the k_{eff} of the system. A fusion shot of about few tens of seconds in case of an increased k_{eff} could theoretically reach a significantly higher power production. A proper design of the copper magnets cooling system can help to increase the flat-top duration and to reduce the cooling time, in order to improve the FFH operation mode.

Of course, additional studies for a further detailed planning are needed.

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