FUSION DEVICES AS NEUTRON SOURCES FOR FFH(FUSION FISSION HYBRID REACTORS):ANALYSIS OF TOKAMAK PARAMETERS , READINESS LEVEL AND DESIGN OF VALIDATION EXPERIMENTS

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Abstract

The present paper summarizes the studies related to the development of the conceptual basis of tokamak neutron sources useful for fusion fission hybrid (FFH) reactors and the FFH concept experimental validation. The parameters for a tokamak neutron source are determined by a newly derived scaling laws, based on an extension of the Kadomtsev similarity principle to fusion reactors. The tokamak model obtained is then used as neutron source for a fusion fission hybrid reactor which uses fusion and fission blankets (which is operated in subcritical mode). This FFH model is simulated using MCNP to determine the tritium produced and the nuclear waste burned. An essential result of this evaluation is the strong (a factor 6) increase of tritium production in the fusion blanket when the nuclear fuel is present in the fission blanket. In parallel, we formulate a proposal of an experimental validation of the FFH concept by using a fusion source injecting neutrons in the core of TRIGA RC-1 reactor configured in subcritical operation mode.

1. INTRODUCTION

The fusion neutron sources needed for FFH (Fusion-Fission Hybrid) devices are not available so far, and the blankets integrating the fusion and fission characteristics are in the conceptual design stage. Consequently , there is the need to define a fulll validation path for the FFH concept. Starting from the figures of a neutron source needed for FFH, the paper is devoted to: i) the determination of parameters for a tokamak fusion source; ii) analysis of the technology readiness level [1] of tokamak as neutron sources , iii) the integration of the neutron source with the fusion and fission blankets; and iv) possible design of experiments for the validation of the FFH concept on presently available fission devices. Basic requirements for FFH neutron source are : Q=2-3 (Fusion gain factor), fusion power D-T of the order of 60 MW, Heating power 30 MW, power flux on the divertor < 5MW/m^2, blanket Li+nuclear fuel(Uranium or Thorium). The determination of optimal parameters of tokamak devices is linked to the scaling laws on the basis of the plasma state description. For reactor plasmas (deuterium-tritium) the α-particle power (P_α) must be introduced as an important contribution to plasma heating. In this case (the reactor plasma) P_α , the gain factor Q (=fusion power/heating power) and the slowing down time of the alpha particles (τ_{SD}) the characteristic time for transfer on energy from alpha particles to electrons, are parameters defining the plasma state[2]. The scaling parameter obtained , linking equivalent fusion plasmas, is: SFR =scaling parameter for fusion reactors = $R\ B^{4/3}\ A^{-1}\ Q0^{1/3}$. Where R is the major radius, B magnetic field, A aspect ratio, Q0 fusion gain factor. Following this scaling laws and using as reference the Q=10 ITER plasma parameters , a Q=2 device has major radius R=1.5m, magnetic field 8.5T, aspect ratio A=2.5 theoretically. According to these plasma parameters the corresponding neutron yield is 7E19n/s. In the present work , we use such neutron yield to study a conceptual FFH having a lithium alluminate fusion blanket for tritium breeding having a fission fuel assembly of 24 rods of MOX located into it.In this configuration (DD and DT) the FFH device is a net producer of tritium: a gain of respectively 4.33 and 5.66 improvement of tritium production is estimated when the fission rods are present: this is a remarkable result which is a by-product of the FFH model evaluation. The technology readiness level determination of the various subsystems of a tokamak is necessary. A TRL≈4 can be given to the plasma heating systems and superconductor magnets , while only to the electron cyclotron resonance heating can be given TRL≈6 . From the point of view of the FFH concept validation, the coupling of a fusion device to a multiplying fission medium (FFH) can be seen as one very specific case of the coupling of an intense high energy neutron source to a fission system. FFH concept validation experiments can be done on TRIGA RC-1 reactor operated in subcritical mode.New subcriticality measurements should also be envisaged, using techniques developed recently in different laboratories. These measurements are envisaged in the Casaccia TRIGA reactor. The structure of the rest of this paper is as follows: Section 2 Existing experience in Q<1 tokamaks and Basic requirements for a fusion neutron source for FFH; Section 3 Extension and application of the Kadomtsev scaling law; Section 4 FFH reactor

TRL assessments; Section 5 Analysis if a FFH concept using the parameters defined in sec.2 and tritium production by a FFH device; Section 6 Validation concept using the TRIGA reactor as sub-critical blanket; Section 7 Conclusions and suggestions for future work.

2.EXISTING EXPERIENCE IN Q<1 TOKAMAKS AND BASIC REQUIREMENTS FOR A FUSION NEUTRON SOURCE FOR A FFH(FUSION FISSION HYBRID REACTOR)

The Fusion community has gained significant experience in the following areas: I)How to build and operate a pulsed tokamak (with short pulses of the order of 10s) Q<1 machine, heated with NBI (neutral beam injection) and RF (radiofrequency), ECRH (electron cyclotron resonance heating) and ICRH (ion cyclotron resonance heating) (~JET(EU)) ;II)How to build a low temperature superconductor device pulsed (of the order of 100s) Q=1 machine, heated with NBI and RF (ECRH) (EAST (China) , TORE SUPRA(Fr), JT60SA(JA-EU)) ;III)The MCF community is beginning to learn about High Temperature Superconductor magnets: this technology [6] will give access to high magnetic field fusion neutron sources. A summary of the basic requirements for a low power neutron source useful for a Fusion-Fission hybrid is given in Table I. As can be noted, the fusion power of the neutron source is relatively low, corresponding to a FFH total power(fusion+fission) of the order of 1GW. With reference to fig.1 (see also the discussion in sec.3), a Q~2 tokamak can have the following parameters: i) major radius R0=2.4m, magnetic field on axis B=6T, aspect ratio A=2.5 ; ii) major radius R0=1.5m, magnetic field on axis B=8.5T, aspect ratio A=2.5. In Tab.II the plasma parameters are detailed . The real point is related to the possibility of building a device which guarantees a quasi-continuous operation (long pulses or steady state) and a high reliability. This last point (high reliability) is connected to physics operation far from the instabilities which can cause disruptions or affect the neutron production. This means that the plasma operation must be realized far from the q, beta and density limits: in Table I such limits are identified as values of normalized beta $\beta_N<2.5$ and Greenwald fraction (ratio betwen the plasma density n and the Greenwald density limit nGr) n/nGr<0.8. The other important limit is the power flux density on the divertor which must be less than the damage limit of the presently available divertor materials, which could be put at a level of ~5MW/m^2, with a plausible erosion rate of the divertor surfaces. The maximum heat flux depends upon the thermal conductivity of the bulk material and the thickness of this material between the plasma-facing surface and the coolant channel (because of the temperature gradient through the material caused by the heat flux), which has to be larger if there is considered to be higher erosion between replacements.Any such nuclear tokamak must have a full remote handling capability for interventions inside the machine, and to be able to function properly with the plasma control achieved using the minimum possible number of sensors (radiation-tolerant diagnostic systems). Two potential problems clearly arise in pushing the design of FFH machines to small size. These are the power fluxes to the first wall and divertor target plates, long recognised as a severe problem for ITER and DEMO, and the tendency to compensate reduced fusion power gain by increasing the k_{eff} of the fusion-fission blanket. When k_{eff} is set very high but ostensibly maintaining a sub-critical assembly, the criticality (naturally unfamiliar to most pure fusion researchers) becomes very sensitive to the blanket distributions of neutron multiplying elements, both fissile (heavy metal and lithium-7) and non-fissile, and to neutron poisons such as boron, gadolinium and Xenon-135. These distributions necessarily vary with the degree of burn-up of the blanket. In addition variations in neutron moderation and reflection back into the blanket due to extraneous assemblies introduced for maintenance activities are likely to become significant issues for the safety case.

Q Fusion Gain factor	PDT(MW) Deuterium-Tritium fusion power	Pheat Power Heating (MW)	β_N Normalized beta	n/nGr Greenwald fraction	Pdiv Power flux to the divertor MW/m^2.	Blanket Material of the blanket	Pulse duration
2-3	60-90	30	<2.5	<0.8	<5	Li+U238 or Th232	>3hr/steady state

TABLE I Figures for a Tokamak based neutron source useful for a FFH reactor.

Table II Q=2 Tokamak

R(m)	1,5
A	2,5
B(T)	8,5
Ip(MA)	10
nG(10 ^{20} m-3)	6,28
n (10 ^{20} m-3)	5
Beta(%)	3,7
betaN(%)	2,1
Pfus (MW)	44
Pinput(MW)	22
T0(keV)	7,3
fi(dilution)	0,8
Neutron flux (10 ^{20}n/s)	0,158

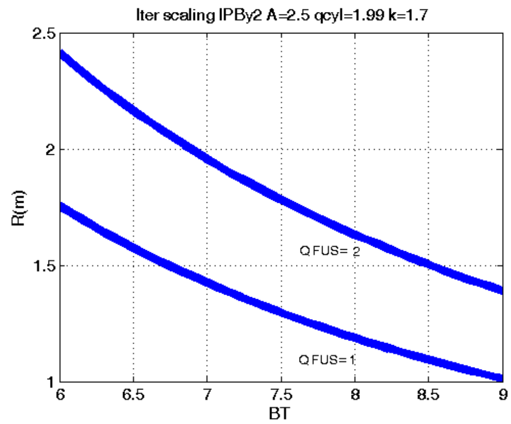

Fig.1. Major radius vs magnetic field of devices at QFus=1and 2 aspect ratio A=2.5, qcyl=1.99, elongation k=1.7

3.EXTENSION OF THE KADOMTSEV SIMILARITY PRINCIPLE AND APPLICATION TO FUSION REACTORS

The possibility of determining the optimal parameters of future devices is linked to the scaling laws on the basis of the description of a plasma state[2,3]. In fact the scaling laws for tokamak plasmas were introduced by Kadomtsev [4] noting that the energy confinement should depend upon the dimensionless parameters:

1.A = major radius / minor radius = R/a ;2.$\beta \sim nT/B^2$ = kinetic plasma pressure / magnetic pressure ; 3.ρ^* = Ion Larmor radius / machine minor radius=$(MT)^{1/2}A/(R\ B)$;4.ν^* = connection length / (trapped particle mean-free path) $\sim n\ R\ T^{-2}\ q\ A^{3/2}$; 5.q = safety factor $\sim R\ B\ \ k/(A^2\ I)$, Where R= major radius, B=magnetic field, I=plasma current, M=ion mass, k=elongation and T=temperature. Under this premise, devices with equal (β,ν^*,ρ^*,q) at fixed geometry should exhibit the same confinement properties.This means that equivalent devices (plasmas with similar confinement properties) can be obtained by taking fixed the scaling parameter:

$S_K = R\ B^{4/5}\ A^{-3/2}$. (1)

For reactor plasmas (deuterium-tritium) the α-particle power ($P\alpha$) must be introduced as an important contribution to plasma heating. In this case (the reactor plasma) $P\alpha$, the gain factor Q = Pfus/ Pin and the slowing down time of the alpha particles (τ_{SD}) must be introduced as parameters defining the plasma state. In practice we can define the following set of parameters as a basis for the definition of the scaling laws useful for fusion reactors:

1. Q=Q0 fixed ;2. $\tau_{SD} = \Lambda_{SD}\ \tau_E$.($\Lambda_{SD} \leq 1$) (slowing down time of alpha particles ≤ energy confinement time. This is true for JET-DTE1, ITER, DEMO PPCS and EU-DEMO, Te≤20keV); Λ_{SD}. is NOT a constant but depends upon the device. 3. $P\alpha = \Lambda_{LH}\ P_{LH}$ ($\Lambda_{LH} > 1.5$), the alpha heating is sufficient to keep the plasma in H-mode. 4. The energy confinement scaling law is ITER IPB98y2 and the scaling for the power threshold for the transition to the H-mode scaling $P_{LH} \approx A_{lh}\ B\ n^{3/4}\ R^2$. We find that the scaling parameter for equivalent fusion plasmas is:

S_{FR} =scaling parameter for fusion reactors = $R\ B^{4/3}\ A^{-1}\ Q0^{1/3}$. (2)

Both scaling laws (1) and (2) give approximately the same weight to the magnetic field and aspect ratio. The fig.1 has been obtained taking as reference the ITER parameters[5], obtaining the scaled devices the eq,2 is used , and the parameters showed in Table II are obtained using the power balance equation. The stronger dependence upon the magnetic field contained in the new scaling law for fusion reactors (eq.2) permits a reduction of the device dimensions for the same Q.

4.FUSION FISSION REACTOR (FFH) TECHNOLOGY READINESS LEVEL(TRL) ASSESSMENTS

Here the following type of machine is in consideration:

1. Q~2-3 machine with long pulses (say > 3 hrs)/steady state, DT plasma P_{DT}~80-100MW , P_{in}~30MW

1.1. Low level of probability of disruptions: plasma parameters chosen to be away from strong MHD and density limits (for example with $\beta_N<2.5$, $n/n_{Gr}<0.8$)

2. Power on the divertor definitely lower than 5MW/m^2: in this case the problem of the divertor is easier.

3. A blanket for tritium breeding with power gain and neutron multiplication from fission

4. A machine with high reliability, working continuously

5. All maintenance by remote handling

6. Modularity (facilitating rapid interventions on the divertor)

7. Few and simple diagnostics (the acceptable level of complexity of the diagnostics and controls depends on the plasma scenario and on the physics model).

The meanings of the different Technology Readiness Levels are as described in [1].

The Table IV shows the TRL for the main subsystems of a tokamak neutron source for FFH: it seems that only ECRH (electron cyclotron resonant heating) systems are in a certain level of engineering maturity for the insertion in a FFH, while the other main systems need to be demonstrated in a neutron flux environment. Table V shows the TRL for the plasma scenarios: here only the H-mode demonstrated on JET DTE1 at Q<1 can be considered for FFH reactor designs. The other scenarios need a demonstration at least at low power.

Subsystem	TRL 100s	Comments
Superconducting magnets	4	Not demonstrated in a neutron flux environment.
NBI (100keV)	4	Need to demonstrate immunity to gamma and neutron effects (e.g. grid flash-over due to the ionising radiation or grid insulation degeneration).
ECRH (1MW gyrotron)	6	The gyrotrons are not in any radiation field and steady state operation has been demonstrated at the developer's works, for hours if not months, but only on test-beds.
ICRH (1MW)	4	As NBI but for antenna operation; also parasitic currents may inject antenna material into the plasma.

Table IV. Technology Readiness Level for prototype with 100-second pulses

Scenario	TRL	Comments
H-Mode	6	OK in JET at Q~0.6, needs demonstration at Q~2
Hybrid mode	4	Needs demonstration in relevant Q>1 environment – possibly JET DTE2
Advanced mode	3	To be demonstrated in a near steady-state machine

Table V. Technology Readiness Level for possible operational scenarios

5.PRELIMINARY CONCEPTUAL DESIGN OF FFH REACTOR MODEL FOCUSED ON THE BOOSTING THE TRITIUM PRODUCTION

An FFH configuration attempt, whose driving neutron source is the tokamak proposed in this paper (see Table II for the parameter's list), has been implemented into the MCNP formalism to model its neutronic feature. As reported in Figure 2, the 24 fuel rods of the subcritical fission assembly (neutron multiplication factor keff=0.96) are within a gamma-lithium aluminate fusion blanket radially wrapped by a graphite reflector (see Tab.VI). The MCNP simulations performed using both the DT (deuterium-tritium) and DD (deuterium-deuterium) neutron sources, including and excluding the fuel rods, produce the estimates of the neutron flux's energy distribution in Fusion Blanket (FSB) and Tritium yields for all the considered cases. Fig.3.Neutron spectrum generated inside the fusion blanket for both DD and DT gas mix used in the main fusion plasma chamber. As reported in Figure 3, the neutron fluxes for the case of the coupling of the DT source with the fuel rods is one order of magnitude higher than the flux obtained with the same fusion source without the fuel rods. The DD source shows the same behaviour, although the fluxes are two order of magnitude less intense than the DT source. As expected, both fusion sources show a marked effect of flux intensity amplification due to the fuel rods' presence. From the spectral point of view, the presence of a 14.1 MeV sharp peak (Blue and Red curves of Figure 3) denotes uncollided fusion neutrons existence within the FSB. When the fuel rods are not present, the peak signals the energy spectrum's upper boundary (red curve fig. 3). Conversely, the fuel rods' presence causes the energy range extension up to 20 MeV because of the fission high energy tail that is more clearly visible in the DD case (green curve of Figure 3).

MCNP estimates the tritium yield in FSB according to the following relation:

$$\frac{dR}{dt} = \int \Phi(E)\sigma(E)dE,$$

$\frac{dR}{dt}$ =Tritium yield;
$\Phi(E)$ = Neutron spectrum;
$\sigma(E)$ = ^{6}Li(n,α)T cross- section;

Comparing the Tritium yields obtained in the fuel rods' presence with the one obtained without them, we found a significant increase in tritium production, a factor 5.66 gain for the DT gas mix, and a factor of 4.33 DD gas mix.

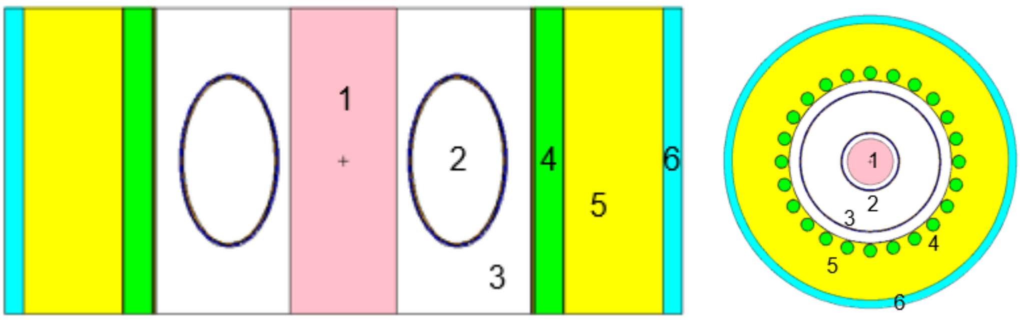

Fig.2. MCNP model for FFH conceptual design. The poloidal (left) and toroidal (right) views of the tokamak and blankets : 1-central solenoid;2-plasma chamber;3-torus first wall;4-. fission fuel ;5-fusion blanket;6-reflector.

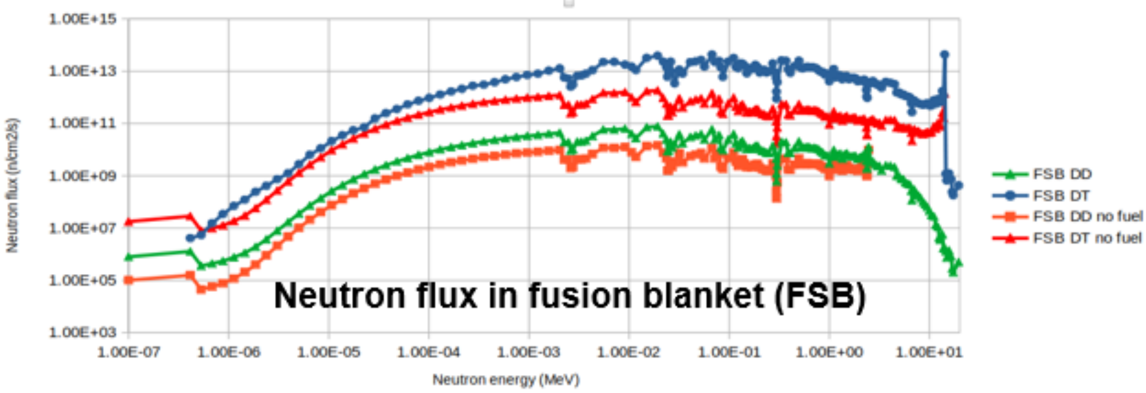

Fig.3.Neutron spectrum generated inside the fusion blanket for both DD and DT gas mix used in the main fusion plasma chamber.

Fuel	Fresh MOX (Natural U + 5 % 239Pu oxides, density 7.91 g/cm3) , 24 fuel rods (Height=400 cm, Radius=19 cm)
Coolant	Helium
Fusion Breeder	γ lithium aluminate
Neutron yield (n/s)	7.60E+19 (DT) 7.60E+17 (DD)

Table VI The design parameters of the FFH model with fusion and fission blankets

6.VALIDATION CONCEPT OF A FFH REACTOR USING THE TRIGA RC-1 REACTOR AS SUB-CRITICAL BLANKET

From the point of view of the validation of the FFH concept[6], the coupling of a fusion device to a multiplying fission medium can be seen as one very specific case of the coupling of an intense high energy neutron source to a fission system. In the recent past the case of ADS[7] was considered, in particular in the frame of waste management strategies. A preliminary evaluation, by means of the MCNP code, has been carried out by considering the coupling of a mono-energetic external fusion source (DD, E_n =2.45 MeV, or DT type, E_n =14.1 MeV) with the TRIGA RC-1 reactor in subcritical configuration, in order to compare the neutron spectra in different TRIGA RC-1 positions, and for different source positions, with the fusion spectra emerging from the fusion reactor first wall ad subsequently entering in a fusion blanket of a hybrid system. Two different positions for the external source have been considered: one in the Central Channel (named Source CC, green in figure) and one in the Radial Channel A (named Source PC, red in figure) for both DD and DT spectra. Once defined the TRIGA RC-1 subcritical configuration (k_{eff} ~ 0.95), obtained by removing all the six fuel elements in the first ring plus four elements in the second ring, as shown in Fig. 5 (light blue elements in figure 5), the neutron spectra in some elements, highlighted in Fig. 5, have been evaluated for each external source position and type (DD or DT). The neutron spectra calculated in various positions (denoted in fig.5) for 14.1MeV fusion DT generated by the tokamak are shown in fig.6. In Table VII, the percentages of neutron fluxes shown in figure 6, for three different energy bins (0-100 keV, 100 keV-500 keV, 500 keV-20 MeV) are reported in order to observe the similarities and the differences between the considered spectrum shapes for DT source. The comparison shows many similarities between the spectrum entering the fusion blanket and the TRIGA RC-1 subcritical spectrum evaluated in position C11 with the DT external source in Central Channel position (blue curve in figure) and the spectrum evaluated in position D03 with the DT external source in Radial channel A position (green curve in figure). The previous mentioned evaluation can be very useful for the FFH concept validation. A similar research reactor (like TRIGA-RC1) configured in a subcritical mode, coupled with a neutron generator could offer some measurements possibilities (subcriticality, neutron fluxes and neutron energy distributions in the fission core) to study in a detailed way the hybrid in the frame of a pilot experimental proposal.

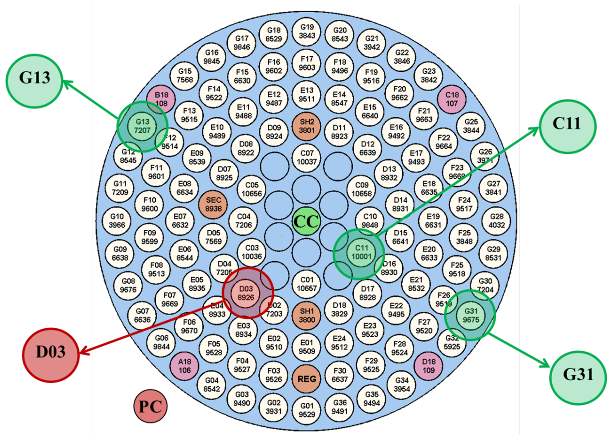

Fig. 4. TRIGA RC-1 subcritical configuration coupled with DD (2.45 MeV) or DT (14.1 MeV) external sources.

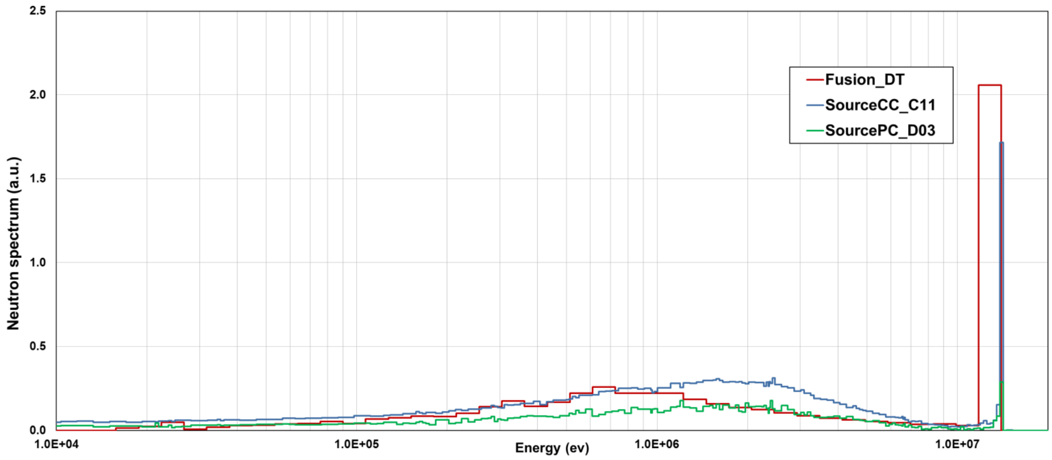

Fig. 5. Neutron spectra comparison between fusion blanket and TRIGA RC-1 reactor in subcritical configuration driven by an external DT source.

DT source	% flux in energy range		
Position	0-100 keV	100-500 keV	500 keV-20 MeV
Fusion	5.51%	16.00%	78.49%
D03 (PC)	15.40%	20.69%	63.91%
C11 (CC)	14.38%	20.70%	65.38%

Table VII. flux percentages in three energy bins for the spectrum shapes reported in figure 9 (DT source)

7.CONCLUSIONS AND FUTURE WORK

The present paper summarizes the studies related to the development of the conceptual basis of tokamak neutron sources useful for fusion fission hybrid (FFH) reactors and the FFH concept experimental validation. The parameters for a tokamak neutron source are determined by a newly derived scaling laws, based on an extension of the Kadomtsev similarity principle to fusion reactors: the derivation given in sec.3, leads to the definition of the fusion reactor scaling parameter S_{FR} =scaling parameter for fusion reactors = $R\ B^{4/3}\ A^{-1}\ Q0^{\ 1/3}$. Similar fusion reactors have the same scaling parameter. The tokamak model obtained , whose parameters are given in Tab.II, is then used as neutron source for a fusion fission hybrid reactor which uses fusion and fission blankets: the fission blanket is operated in subcritical mode. The fusion blanket is made by γ lithium aluminate, while the fission blanket by Fresh MOX (Natural U + 5 % 239Pu oxides, density 7.91 g/cm3). This FFH model is simulated using MCNP to determine the tritium produced and the nuclear waist burned. An important result of this evaluation is that the strong (a factor 6) increase of tritium production in the fusion blanket when the fuel is present in the fission blanket. The experimental validation of the FFH concept will be carried out using a DT neutron source injecting 14.1 MeV neutrons in the subcritical core of TRIGA RC-1 reactor. The study presented shows that the neutron spectra produced inside the TRIGA RC-1 reactor , where a 14.1 MeV neutrons are injected, is very similar to that produced in a fusion blanket : in this way the interaction of the fission blanket with this neutron spectrum can be studied in detail through the measurements of the elements transmutation, as well as the subcriticality level of the fission blanket.

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