FUSION-FISSION HYBRID REACTOR BASED ON HIGH FIELD TOKAMAK NEUTRON SOURCE

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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 need to be projected and validated. 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) design of a FFH reactor conceptual model useful for the study of the basic characteristics of an integrated FFH system . Basic orientative requirements for FFH neutron source are : Q=2-3 (Fusion gain factor), fusion power D-T >20MW, Heating power 10MW , power flux on the divertor <5MW/m2 , blanket Li+U238 or Th232. The determination of optimal parameters of tokamak devices is linked to the scaling laws on the basis of the description of a plasma state. For reactor plasmas (deuterium-tritium) the α-particle power (Pα) must be introduced as an important contribution to plasma heating. In this case (the reactor plasma) Pα , 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 articles to electrons, are parameters defining the plasma state. The scaling parameter linking equivalent fusion plasmas and derived developing this scheme are given in sec.3[1,2]. The structure 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 the scaling laws for tokamak neutron sources conventional (working in H-mode as well as L-mode) and spherical high filed tokamaks are derived and discussed; Section 4 Analysis of a FFH concept using the parameters defined in sec.2 and tritium production by a FFH device.

2. Experience in Q<1 tokamaks and Basic requirements for a fusion neutron source for FFH

Readers familiar with magnetic confinement fusion research will be aware that in 1994 Tokamak TFTR achieved 10MW of DT fusion power, largely (as always intended) from 100keV high-energy deuterium ions from the neutral beam injection interacting with the plasma tritons. This was followed in 1997 by JET in the EU producing 17MW of DT power, corresponding to a power gain Q ~ 0.6. Both these results were transient, however, with the time above 90% of those powers respectively 0.8 and 1.2 seconds. Power gain is broadly proportional to the triple product $nT_i\tau$ and the non-nuclear Japanese tokamak JT60U has since improved slightly upon the JET result in terms of the triple product. We can say that significant experience has been gained 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

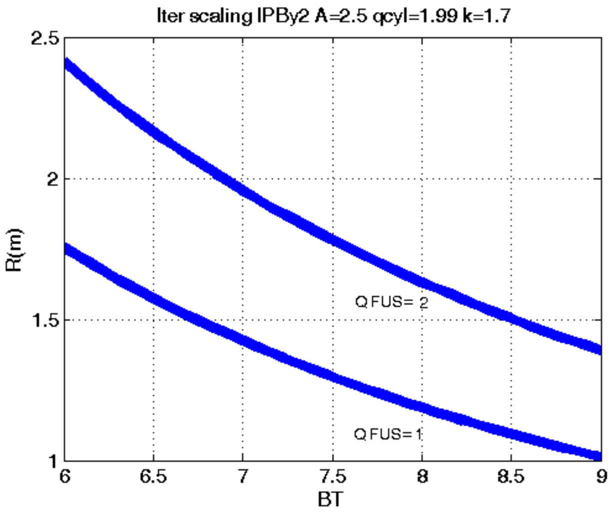

Fig.1. Major radius vs magnetic field of devices at QFus=1and 2 , aspect ratio A=2.5, qcyl=1.99, elongation k=1.7

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 0.5GW. 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 .

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	>20	>10	<2.5	<0.8	<5	Li+U238 or Th232	>3hr/steady state

Table I -Figures for a tokamak based neutron source useful for a Fusion-Fission hybrid reactor.

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:inTab I such limits are identified as values of normalized beta β_N<2.5 and Greenwald fraction (ratio between 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.

Table II Parameters of Q=2 Tokamaks A=2.5

	Q=2	Q=2
R(m)	1,5	2,4
A	2,5	2,5
B(T)	8,5	6
Ip(MA)	10	9,84
nG(10^{20} m-3)	6,28	3,4
n (10^{20} m-3) (0.8*nG)	5	2,7
Beta(%)	3,7	5,3
betaN(%)	2,1	3,1
Pfus (MW)	44	51,4
Pinput(MW)	22	25,7
T0(keV)	7,3	9,8
fi(dilution)	0,8	0,8
Neutron flux (10^{20}n/s)	0,158	0,183

3. **Scaling laws for fusion reactors**

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[1,2]: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 linking equivalent fusion plasmas is:

$$SFR = f_H(\Lambda_{SD}, \Lambda_{LH}, f\alpha, Meff) * R\ B^{4/3}\ A^{-1}\ Q0^{1/3}\ . \qquad (1)$$

The scaling laws (1) give approximately **the same weight to the magnetic field and aspect ratio**. The fig.1 has been obtained taking as reference the ITER parameters, 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. Applying the same conceptual scheme , but using the L-mode scaling law for energy confinement time (at the point 2) while Λ_{LH} <1 , the following scaling law for tokamak fusion reactors is obtained:

$$S_{FR}[LMODE] = f_L(\Lambda_{SD},,\Lambda_{LH}, f\alpha, Meff) * R\ B^{5/2}\ A^{-3/4} * Q_0^{-0.7} \qquad (2)$$

The meaning of the function f is given in sec.1. The fig.2 gives the major radius versus the magnetic field on axis at gain factors Q_0=0.5,1,2, for aspect ratio A=2.5 and qcyl=3.4. corresponding to the family of tokamaks having the scaling factor of eq.2. From the fig.2 the following parameters of devices can be deduced :i) Q=1, B=8T, R=1.5m, A=2.5, qcyl=3.47; ii) Q=2, B=8T, R=2.5m, A=2.5, qcyl=3.47.

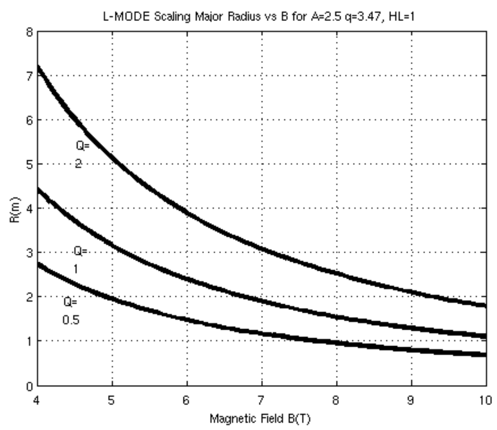

Fig.2. Major radius vs magnetic field on axis at gain factors,Q_0=0.5,1,2, for devices with aspect ratio A=2.5, qcyl=3.47 and following the L-mode ITER 97P confinement scaling.

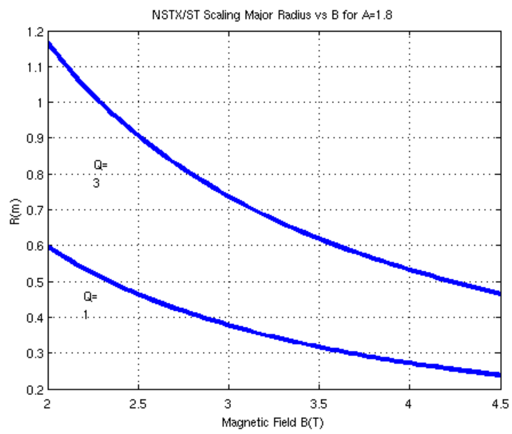

Fig.3.Major radius vs magnetic field B on axis for spherical tokamaks With aspect ratio A=1.8.

Finally using the NSTX scaling law for the confinement of spherical tokamaks we get the following scaling law for spherical fusion reactors :

$$S_{ST}[NSTX\ scaling] = C_{ST}\ R_{ST}^{1}\ Q_0^{0.61}\ B^{-1.13}\ A^{1.59}\ M_{eff}^{0.22}\ q^{0.4}$$

$$C_{ST} = \left(\frac{\Lambda_{SD}}{A_{SD}}\right)^{-0.036} \left(\frac{\Lambda_{LH}\ A_{lh}}{f_\alpha}\right)^{0.24} \qquad (3)$$

The fig.3 reports the major radius vs magnetic field , using the scaling (3) for Spherical tokamaks. Two sets of parameters can be deduced from fig.3 :i) A=1.8 B=2T Q=1 R=0.4m ; ii) A=1.8 B=3T Q=3 R=0.75m.

5. Analysis of conceptual model and improved tritium production in a FFH

A preliminary analysis of the FFH configuration starting from a tokamak neutron source with parameters listed in Tab.II can be done using a MCNP model[3] . The fig.2 shows the configuration of the machine load assembly together with the fusion and fission blanket. The composition of the fission blanket is made by a standard MOX and the fusion blanket is made by lithium aluminate .

The neutron source is operated with DT (deuterium -tritium) gas composition with neutron rate production of the order of 10^{19}neutron/sec.

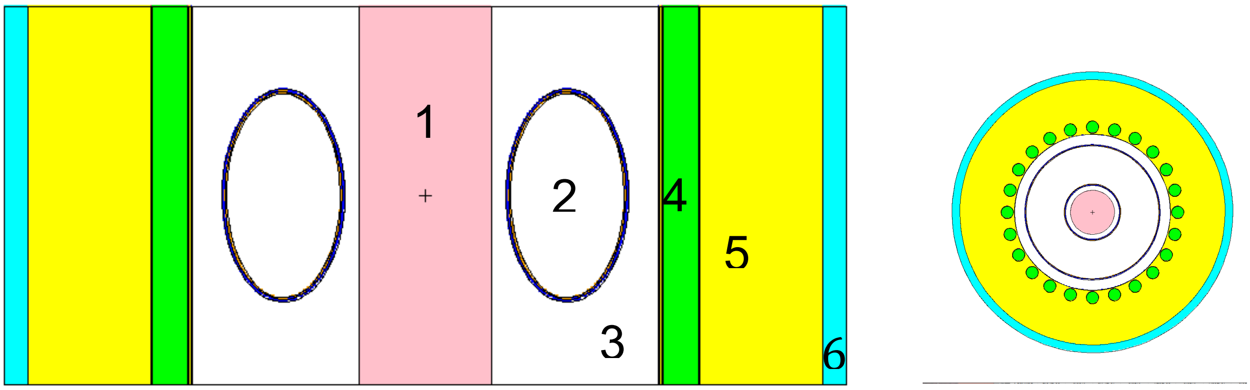

Fig.2. MCNP model for FFH conceptual design. The poloidal (left) and toroidal (right) views of the tokamak and blankets : 1-central solenoid;2-plasma chamber;3-torus first wall;4-fission fuel ;5-fusion blanket;6-reflector

There are 24 fuel rods surrounding the tokamak machine. The fission blanket is operated in subcritical mode with a neutron multiplication factor keff=0.9. The result from this configuration is that there is a net tritium production in presence of the fuel fission rods, in ref. [3] a factor 5 was evaluated. A study is in progress related to the precise evaluation of tritium production in the various models presented in sec.3. The authors specify that this work is only represented by a preliminary feasibility study and, at the moment, any experimental activity involving nuclear fuel is not considered.

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