OPTIONS FOR A STEADY-STATE COMPACT FUSION NEUTRON SOURCE

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The new approach in advancing the use of fusion, "Fusion for Neutrons" (F4N), is proposed. The application of a small or medium size Spherical Tokamak (ST) as a powerful steady-state fusion neutron source (FNS) is discussed. An overview of various conceptual designs of such neutron sources is given and they are compared with a recently proposed Super Compact Fusion Neutron Source (SCFNS). It is shown that SCFNS with major radius as low as 0.5 is feasible and could produce several MW of neutrons in a steady-state regime.

I. INTRODUCTION

Whereas the Fusion for Energy (F4E) programme currently struggles to achieve sufficient gain (power output over power input) to be viable as a power source, fusion still has a valuable role in the Fusion for Neutrons (F4N) approach. This is because the nuclear fusion reaction produces an abundance of high-energy neutrons (as mentioned in the original Blackman and Thompson Patent of 1946 [1]), and the Fusion Programme, with 60 years of R&D, is now ready to help in resolving the main problems of (Fission) Nuclear Power production: the emerging shortage of fissile fuel, disposal and storage of nuclear waste and proliferation of fissile materials.

A scheme originally proposed in the 1950's and reviewed by Bethe in 1980 [2] which has been revisited recently [3] because of the increasing dependence on nuclear power, is the fusion – fission hybrid reactor. By using the excess neutrons from the fusion reaction to cause a high-yield fission reaction in a surrounding subcritical fissionable blanket, the net yield from the hybrid fusion-fission process can provide a large gain over the input energy and yield sufficient heat output for economical electric power generation. Although the fusion equipment required will increase the construction cost of the reactor, the scheme has important control and safety advantages. In contrast to current commercial fission reactors, hybrid reactors potentially demonstrate inherently safe behavior because they remain deeply subcritical under all conditions; the fission is driven by neutrons provided by the fusion events, and is consequently not self-sustaining. The fusion rate can be readily reduced (for example by reducing the auxiliary heating supplied) and the fission then reduces instantly, eliminating the possibility of a runaway chain reaction such as occurred during the Chernobyl disaster.

In this paper we will focus on the steady-state fusion neutron source itself, rather than its applications, including in "hybrids". Freed from the requirement to produce much more electricity than used to drive, as required in the F4E approach, a fusion neutron source in the F4N approach could be efficiently used to support energy production by nuclear power. This can be achieved in several ways: by recycling high level nuclear waste from conventional nuclear fission reactors into new fissile fuel or low-radioactive waste and by breeding fuel from the existing large stocks of depleted uranium to top-up the diminishing world supplies of uranium for nuclear fission reactors. A reduction in the proliferation risk can be achieved by minimising the transportation of nuclear waste and fuel and removing Pu from the spent fuel. This combination of "fission + fusion" reactors becomes self-sufficient and environmentally clean, which dramatically improves both the safety and economics of nuclear energy production. The F4N approach, where Fusion is required only to produce the most valuable Fusion product, i.e. neutrons, can be implemented and commercialized much earlier than "pure" F4E or "hybrid" approaches.

Other possible applications of an F4N include scientific research (in particular for material studies), for the development of innovative neutron technologies like isotope production (e.g. medical isotopes), heat production for different applications (e.g. hydrogen production, desalination of water), radiotherapy, detection and diagnostics, for example, toxic waste detection and activation analysis; radiography etc.

Several options of a steady-state Fusion Neutron Source have been considered and are discussed in this paper. Auxiliary heating, tritium consumption and magnetic systems set the cost of a demonstration experiment. Classical tokamaks (with R/a > 2.5) [5-7] can be either pulsed or may use superconducting magnets for providing high toroidal field and a reduction of power dissipation, but require high Tritium consumption (due to the large device size required). Spherical tokamaks (R/a < 2.0) proposed in the 1980's by Peng [8] and first demonstrated by the START experiment at Culham [9] which demonstrated the very high efficiency of the ST concept – the ratio (beta) of the plasma pressure to magnetic field pressure reaching a tokamak record of 40% on START [10] - have been considered as a more favorable option as they typically require lower TF and so can use copper coils with water cooling and have smaller volume, so can be feasible at much lower fusion power and (importantly) much reduced Tritium start-up load and consumption [11-17, 19-25].

We compare options for a steady-state Compact Fusion Neutron Source based on a small or medium-size Spherical Tokamak with aspect ratio R/a = 1.6 - 2.0. The most advanced design concepts, are medium-size STs with R~0.7-0.8m, based on VNS and CTF concepts developed at UKAEA, Culham Laboratory [12, 13]. A pioneering paper by Stambaugh et al [14] set out many relevant scalings, and developed the concept that small pilot plants with R ~0.5m can lead to production plants by merely scaling the size. However, as the objective was power production, very optimistic physics parameters (e.g. β_N ~ 8) were assumed, and wall loads were extremely high, so that the smallest device became impractical for energy production.

These ST designs are based on extrapolations from the successful STs: MAST at CCFE Culham, and NSTX at PPPL, Princeton. However in order to provide sufficient fluence to achieve their materials testing objectives, these devices have to operate at higher field, plasma current, and auxiliary heating power (each typically ~ 5 times more) than used on present STs and require very long pulse operation with typically hundreds of MW of electrical dissipation. Wall and divertor thermal and neutron loading are challenging in the steady-state operations. Hence they require a worthy but ambitious and costly advance in performance. We also consider as an option both a bigger device, like STEP [15] and US CTF proposals [16] and other proposals for a smaller device with R ~ 0.5m [12, 17]. The main parameters are compared in Table 1. Advantages and disadvantages of these different options are discussed in detail.

In this paper we also analyze a Super-Compact FNS (SCFNS) [20] which differs from these designs in significantly reduced input Neutral Beam Power (from 25-50MW to 5-10MW), output Fusion Power (from 25-40MW to 1-5MW), toroidal field (from 2.5-4.4T to 1.5-2T) and plasma current (from 6-8MA to 1-2MA). These changes result in:

- reduction of neutron wall load to ITER-scale values of below 0.5MW/m^2, which will allow use of existing first wall materials;
- reduction of requirements on NBI system to reduce the cost of the device and match industrial availability constraints and also improve plasma confinement due to reduced heating power;
- reduction of dissipation in the TF magnet, significantly reducing complexity of the magnet and running costs;
- reduction in Tritium consumption;
- removal of problems of ash accumulation and α-particle losses due to Alfven Eigenmodes by reducing the plasma current; this will also ease the current drive (CD) requirements.

The smallest SCFNS option with low TF and R ~ 0.5m looks the most attractive as a first prototype of a FNS. An important advantage of the ST path to Fusion Power is the possibility to progress from a prototype to a bigger device just by increasing the linear dimensions with no significant changes in design and technologies [14]. This suggests that a demonstration of the possibility for a reliable application of Fusion as a Neutron Source even at the level of a few MW will significantly advance the commercial exploitation of fusion power in nuclear industries and other neutron applications.

The mission of a Super Compact FNS is to show the feasibility and advantages of the ST concept as a powerful neutron source; to demonstrate and use a steady-state fully non-inductive regime; to operate with tritium, contributing with this to the mainstream Fusion research in many areas (T handling, material/component testing, diagnostics, safety, remote handling etc.) and to be the first demonstration of the commercial application of Fusion.

II. COMPARISON OF SCFNS WITH OTHER COMPACT ST NEUTRON SOURCES PROPOSALS

We first analyze two ST FNS designs closest in size to SCFNS (R < 0.6 m), the UKAEA compact option of a Volumetric Neutron Source (VNS) [12] and the smallest option of the GA ST Pilot Plant [14], Fig.1.

The motivation for a compact design is partly linked with the economics of a neutron source. The neutron shielding of the central post increases the size of the device, which would result in an unacceptably high Tritium consumption. An unshielded central post, which is the most favorable solution for an ST neutron source, is constrained by a heating limit (dissipation in the TF magnet) and a stress limit. The result of analysis in [12] is that the stress limit favours low R/a and low R. The limit on β_N due to stability requirements also favours lower R/a. However, the fluence of 6 MWa/m^2 demanded in [12] resulted in very high required H-factor, which forced an increase in size to R = 0.8 m. The SCFNS proposal does not have such high required fluence, so a small size is possible in SCFNS. We note that the main problems of the R=0.57 m UKAEA VNS are resolved in the SCFNS design:

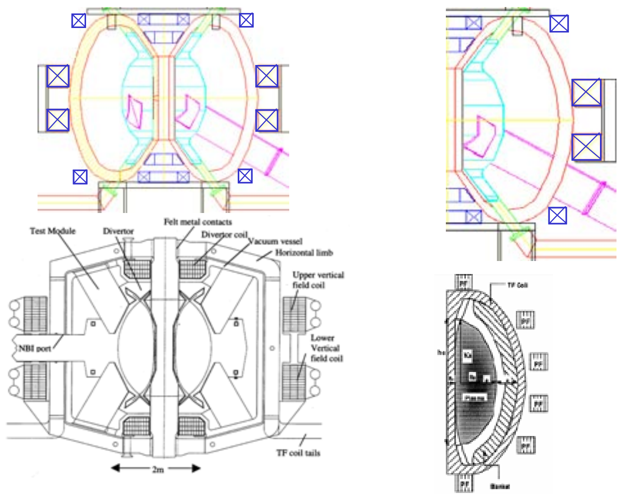

Fig.1. Outline (same scale) of UKAEA VNS and GA ST PP (bottom row) in comparison with the SCFNS (top).

- reduction of fusion power from 25MW to 1-3MW results in acceptable neutron wall load;
- reduction in heating power results in less thermal wall and divertor loads;
- higher availability can be achieved as no need to replace central rod, divertor targets and induction coils;
- no need for increased confinement because most neutrons are coming from the beam-plasma DT reaction, so much lower confinement is needed, H-factor ~ 1.4;
- lower I_p, so much less dissipation in PF coils, much less NBI power for current drive;
- α-particles are lost on the 1^{st} orbit, so no ash accumulation and no need for sawteeth or ELMs for ash removal, and no danger from the MHD induced by fast particles. In the SCFNS proposal there is no need to confine α-particles, as it does not rely on α-heating.

The similarity of UKAEA VNS and SCFNS means that engineering feasibility studies of the UKAEA VNS support the SCFNS design, allowing many results of VNS studies to be used for the SCFNS, providing optimistic feasibility predictions:
- stress analysis of VNS with NASTRAN code shows stress levels within the ASME III allowable values, which are even lower for SCFNS;
- MCNP neutronics analysis suggests that VNS magnets will survive for several years, hence longer for the SCFNS due to the much reduced fluence.

The aggressive GA design [14] suggests doubled central post heating limit compared with the UKAEA VNS, so allows higher TF at a smaller size. According to the GA studies, increase in the elongation from 2 to 3 allows a factor of 2 reductions in the plasma size. It was concluded that only the beta limit, not confinement, determines the performance. The high dissipation in magnets due to high TF and I_p made such small device not attractive for electricity production, however the compact GA ST studies confirms feasibility of the road map with the SCFNS as a first demonstration of a FNS and gradual increase in the neutron output and, probably, the device size can lead to future nuclear applications.

The SCFNS can be much more feasible and cheaper in capital and running costs than the UKAEA VNS or GA Pilot Plant, and still will be able to produce multi-MW neutron rates. At this first stage, the main goal of the SCFNS is to demonstrate reliable steady-state production of neutrons rather than power production or extreme fluence needed for Fusion and Fission reactors material tests, nuclear waste transmutation or breeding.

III. OPTIONS FOR SMALL AND MEDIUM SIZE ST FNS

To complete the comparative analysis of ST FNS, we look at bigger and more powerful proposed ST devices.

Azizov et al [11] propose series of large JUST devices with A = 2 and R = 2 m for transmutation of Minor Actinides and nuclear fuel production. An option of cryogenically cooled Al magnets has been considered which may be an alternative solution to superconductors if the necessary neutron shielding is provided. Wilson et al [22] extend the work of Hender [12], to propose a VNS (now termed a Component Test Facility, CTF) with A ~1.6, designed to consume < 1 kg of tritium per year and specifically to aid the fast-track approach to Fusion Power by testing components and materials. The device has R ~0.75m, I_p ~ 8MA, B_T ~ 2.8T, H~1.3, P_{NBI} ~ 60MW, and yields P_{fus} ~50 MW. Voss et al [13] develop the Wilson design, increasing the size slightly to R = 0.85m, a = 0.55m, with a slight decrease in current and field to 6.5MA and 2.5T, again assuming H=1.3, with P_{NBI} = 44MW and P_{fus} = 35MW. Dnestrovkij et al [21] provide ASTRA and DINA codes simulations of the Wilson CTF, and find that by using a different mix of NBI energies (6MW at 40keV and 44MW at 150keV) they can provide current ramp–up and, aided by a larger tritium fraction of 70% (cf 50%), obtain the same fusion output (50MW) but at considerably lower plasma current (5.5MA cf 8MA or 6.5MA). Although tritium is scarce and expensive, the option of using a larger tritium fraction to obtain the same neutron output but at lower plasma pressure (and hence improved plasma stability) may be attractive.

All the above studies employ NBI for current drive (providing heating, in conjunction with α-particle heating – note α-particles have low prompt losses at the high plasma currents employed in the first three studies), use well-understood technology (e.g. copper windings), and aspect ratios 1.4 ~ 1.6 (at which sufficient tritium can be bred without need of a centre-column blanket, although at the small sizes considered, tritium consumption is low and could be met from existing resources). Peng et al [16] proposed a larger CTF with R_0 = 1.2 m, A = 1.5, elongation k~3, with a range of parameters B_T = 1.1 - 6T, I_p = 3.4 - 10 MA, producing a driven fusion burn using 15 - 43 MW of combined neutral beam and RF heating power; performance P_{fus} ranged from 7.5MW to 150MW. This CTF also has an option of tritium breeding. Wu et al [23] proposed an ST for nuclear waste transmutation with R=1.4 m, A=1.4, k=2.5, B_t=2.5T, I_p=9.2MA, n_e=1.1 x $10^{20}m^{-3}$, bootstrap current fraction f_{bs} =0.81, heating power P_{NB} =19MW and the wall load P_{wall}=1MW/m^2. This design with an aspect ratio near the lower limit (due to limited space in the central post) requires an unshielded centre conductor post as a part of the toroidal field magnet. Feng and Zhang [24] propose a concept for a fusion-driven waste transmutation reactor (FDTR) based on a spherical tokamak with R = 1.05 m, R/a = 1.3, P_{fus}=85MW, wall load P_{wall}=0.8 MW/m^2. The engineering feasibility of the central post of a ST waste burner has been investigated. It has been shown that the proposed system has a high transmutation capability of 110 kg/FPY for MA waste at fusion power of 85 MW. They conclude that a small-scale, compact and low fusion power tokamak, based on an ST configuration, has attractive advantages if it is used as a nuclear waste burner. Most recently, Kotchenreuther et al [4] propose a larger CFNS with 100MW fusion output (R_o = 1.35 m, aspect ratio 1.8, B_T =2.9T, I_p = 10-14MA) using the 'Super X' divertor to solve the critical divertor thermal load problem. Their device is designed for use either as a CTF, the basis of a fusion-fission hybrid for transmutation, or for development of a pure fusion reactor. Galvao et al [15] study a 'Multi functional Compact Tokamak Reactor Concept' designed with similar objectives as our present study. They propose a device (STEP) of major radius Ro = 1.2 m (some 50% larger than MAST and NSTX), with A=1.6, I_p = 5MA, B_T = 3.5T, and obtain fusion gain Q_{fus} ~ 1 for a range of auxiliary heating powers from 5MW to 40MW. Interestingly, at lower powers the maximum Q_{fus} ~1 gain occurs at ever lower densities, whereas bootstrap current increases almost linearly with density, so the higher performance options have the advantage of largest self-driven current.

We summarize the ST options of a FNS in Table 1, which presents a list of some ST neutron sources, component test facilities and pilot plants with major radius R < 2 m and auxiliary heating and CD power < 50MW. Although the SCFNS has much less ambitious goals that other proposals presented, the advantages of the Super Compact ST as a FNS are that some of the big issues of large high-power devices are resolved:

- disruptions (lower I_p is required for smaller device, so lower stresses during disruptions);
- ELMs – low total energy in ELMs in SCFNS, so no need for mitigation;
- high beta in STs – so no conventional AEs, less EPMs (Energetic Particle Modes);
- low T consumption in the SCFNS, no need to breed T;
- small size – less problems with plasma formation due to lower inductance and higher electric field for the same loop voltage;
- small size, high elongation, high β_N – less demands on the current drive system.

We can compare the SCFNS parameters with those of the upgrades proposed for the largest STs MAST, NSTX (MAST-U, NSTX-U). First, we vary the size of the SCFNS, keeping the central post diameter not less than 40 cm and choosing other parameters aiming to satisfy the steady-state requirements. Table 2 shows results for devices with R=0.5m, 0.8m and 0.4m. The R=0.8m option is close to the MAST/NSTX geometry but with D/T and the toroidal field increased to 1.5T. The Valovic confinement scaling [18] has been used, which explains high H-factors in the R=0.8m case. Although experimental data from MAST and NSTX confirm favourable dependence on the toroidal field (which resulted in high confinement in simulations), there is no experimental evidence that this scaling will be valid at very low collisionality and this issue should be addressed in experiments on present STs. Although the volume has increased significantly, only a modest increase in the heating power was needed to achieve steady state. However, the neutron output is reduced, which can be explained by lower fast ion fraction that results in a reduction in the plasma-beam fusion reaction. The power dissipation in the R=0.8 m case was significantly higher than in the R=0.5m case, which makes the larger version less efficient.

For the lower size, R=0.4m, it was necessary to increase the toroidal field to achieve steady-state at lower plasma current of 1MA, which also explains the high H-factor. Reduction in H-factor to more conventional H=1.36 resulted in lower non-inductive current fraction and steady-state has not been reached. However, even in the smaller size version, the neutron output was within MW range. The increase in the aspect ratio may result in lower beta limit and higher demands on the vertical control. Unless engineering constraints are reduced, which will allow smaller central post diameter and so lower aspect ratio, this option looks less feasible.

This comparison shows that increase in the size does not give much benefit, apart from reduction in the wall load, but at the price of higher capital cost. The reduction of the size forces the simultaneous reduction in the plasma current to achieve steady-state. On the other hand, it may be easier to increase the input (and so the output) power in a bigger device, rather than in a smaller one. So, as discussed above, higher demands on the fluence may favor bigger devices. It may be easier to increase the toroidal field in a smaller device (due to lower power dissipation in the TF magnet) and with this compensate decrease in confinement due to lower volume. The superconductor option though is more feasible in a larger device. In brief, a compact device with R~0.5m may be a good option for a cost-efficient first step with more powerful larger next steps to follow. For sure, reduction in size is constrained both by engineering and physics.

IV. POSSIBILITY OF STEADY-STATE OPERATIONS IN THE SCFNS

Although (unlike in energy production) neutron sources do not require continuous operations, as the main aim is to achieve the necessary fluence, high availability, steady-state or long pulse operations are desirable for the SCFNS. In a spherical tokamak the main motivation for non-inductive operations is the lack of space in the central post for a solenoid to provide necessary loop voltage, and for sufficient shielding to protect the windings from neutrons. Specifically for the SCFNS, we would like to avoid any in-blanket materials that can absorb or slow down fast fusion neutrons. This requirement makes a conventional central solenoid impractical in our case. So it is necessary to resolve the current ramp-up and sustainment issues without relying on the inductive flux.

Two sources of non-inductive current drive can be considered: current drive from auxiliary systems (RF, NBI) and self-driven bootstrap current, fed by auxiliary heating from the same systems. Both require good plasma confinement for efficient heating of electrons for external CD and heating of both ions and electrons for the bootstrap. Moderately high electron temperatures are needed for neutron production from the beam-plasma reaction. Our analysis has shown that optimization of the non-inductive CD has the first priority, as when steady-state conditions are achieved, a MW-level neutron output will be self-consistently provided. ASTRA-NUBEAM modeling [20] has shown the feasibility of steady-state operations at $I_p = 1 - 1.5$ MA and $P_{NB} = 5 - 10$ MW. Fig.2 shows fusion output in the SCFNS vs injected power at 130 keV with D/T 50/50 mixture in steady-state for plasma current 1 MA (red) and 1.5 MA (blue), $n_e^{ave} = 10^{20}m^{-3}$. An increase in the plasma elongation from k =

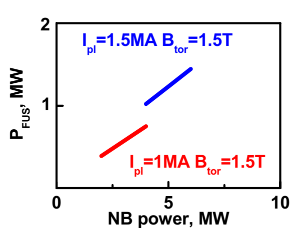

Fig.2. Fusion output in SCFNS vs injected power at 130keV with D/T 50/50 mixture in steady-state for plasma current 1 MA (red) and 1.5 MA (blue), $n_e^{ave} = 10^{20}m^{-3}$.

TABLE 1. Main parameters of several proposed ST-based Compact Fusion Neutron Sources.

	R/a, m	I_p/B_t, MA/T	k	P_{in}/P_{fus}, MW
VNS UK	0.8/0.5	13.4/3.5	2.3	69/32
CFT UK	0.85/55	6.5/2.5	2.4	44/35
CTF US	1.2/0.8	12/2.5	3.2	47/150
CFNS US	1.35/0.75	14/2.9	3	50/100
STEP UK	1.2/0.75	5/3.5	3	40/30
JUST RF	2/1	5.3/3.9	1.6	45/62
STPP US	0.7/0.5	11/3	3	30/300
CVNS UK	0.57/0.35	6.8/2.5	2.3	25/16
TIN RF	0.47/0.28	3/1.35	3	15/2
CSTPP US	0.47/0/28	14/9.6	3	50/310
SCFNS UK	0.5/0.3	1.5/1.5	2.75	6/2

TABLE II. SCFNS options.

		SCFNS	larger size	smaller size
R/*a*	m/m	0.5/0.3	0.8/0.5	0.4/0.2
<n>	$10^{20}m^{-3}$	1	1	1.5
I_{pl}	MA	1.5	1.5	1
B_{tor}	T	1.5	1.5	1.87
E_{beam}	keV	130	130	130
P_{beam}	MW	6	8	4
R_{beam},	m	0.6	0.9	0.45
Elong		2.75	2.75	2.75
Trian		0.5	0.5	0.5
Te0/Ti0	keV	4.7/7.9	4.4/5.5	7.5/16.9
P_{input}/P_{abs}	MW	3+3+1/6.5	4+4+1/6.8	2+2/3.4
I_{cd}	MA	1.1	0.4	0.65
I_{boot}	MA	0.5	1.1	0.58
H-factor		1.37	1.9	1.97
TauE,	ms	43	151	47
li3		0.42	0.44	0.61
W_{th}/W_{tot}		0.58	0.86	0.66
β_N		4.9	4.3	5.96
Neutrons	10^{17} s^{-1}	5.2	4.5	4.52

2.75 to k = 3 will also lead to higher performance, although k=2.75 is presently favored as it has been demonstrated in long-pulse discharges in NSTX [26]. The regimes have β_N <5, which is below stability limits [20]. KINKS and SPIDER vertical stability analysis [20] has shown that the vertical stability, supported by a high natural elongation of ST plasmas, can be provided with the aid of 2cm CuCrZc passive stabilization plates positioned ~ 7 cm from the plasma edge.

Another important issue connected with steady-state operations is power load, both neutron and thermal, on the vessel wall and divertor. With the surface of ~ 10 m^2, the neutron load on the wall is low. The high thermal load ~ 1 MW/m^2 is within the range of ITER load, and ANSYS analysis has shown that removal of the heat with water cooling should not by a problem as the total load power is quite low [20]. Similar analysis shows feasibility of the divertor. However, extrapolation to higher power next-step ST neutron sources will probably require more advanced approaches, e.g. liquid Li divertor plates.

V. CONCLUSIONS

Comparative analysis of Fusion Neutron Sources based on a spherical tokamak shows that many feasible options can be considered. It is shown that reduction in a FNS size down to R= 0.5m is not constrained by stress, heat, wall & divertor load, confinement or stability. In SCFNS, it is possible to produce MW-level of neutron output in steady-state regime with high availability, and with (importantly) minimum demands on tritium consumption. UKAEA CTF, GA Pilot Plant, SCFNS and Kurchatov TIN design studies all confirm feasibility; hence the road map for commercial application of fusion as a neutron source can start from a Compact ST with major radius as low as 0.5 m and NBI power 5-10 MW. Neutron sources with rates of 10^{17} n/s will have a very strong influence on the global energy production strategy as well as on the development of fusion & nuclear science and innovation technologies.

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