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Research on Fusion Neutron Sources

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Abstract. The use of fusion devices as powerful neutron sources has been discussed for decades. Whereas the successful route to a commercial fusion power reactor demands steady state stable operation combined with the high efficiency required to make electricity production economic, the alternative approach to advancing the use of fusion is free of many of complications connected with the requirements for economic power generation and uses the already achieved knowledge of Fusion physics and developed Fusion technologies. Fusion for Neutrons (F4N), has now been re-visited, inspired by recent progress achieved on comparably compact fusion devices, based on the Spherical Tokamak (ST) concept. Freed from the requirement to produce much more electricity than used to drive it, a fusion neutron source could be efficiently used for many commercial applications, and also to support the goal of producing energy by nuclear power. The possibility to use a small or medium size ST as a powerful or intense steady-state fusion neutron source (FNS) is discussed in this paper in comparison with the use of traditional high aspect ratio tokamaks. An overview of various conceptual designs of compact fusion neutron sources based on the ST concept is given and they are compared with a recently proposed Super Compact Fusion Neutron Source (SCFNS), with major radius as low as 0.5 metres but still able to produce several MW of neutrons in a steady-state regime.

Keywords: Fusion, fusion reactor, fusion-fission, spherical tokamak, neutron source.

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INTRODUCTION

The present world magnetic confinement fusion programme is focussed on ITER construction and exploitation, in pursuit of the ultimate goal of commercially viable fusion power for clean electricity generation. To obtain the fusion reactions required for economic power generation (i.e. much more power out than power in), the conventional tokamak has to be huge (as exemplified by ITER) so that the energy confinement time (which is roughly proportional to plasma volume) can be large enough so that the plasma can be sufficiently hot for thermal fusion to occur. The tokamak-based fusion reactor demands steady state stable operation combined with the high efficiency and high neutron fluxes (resulting in extremely high neutron wall loading) required to make electricity production economic. These conditions are especially difficult to achieve simultaneously, and the planned programme suggests many years of experimental research on big fusion devices like JET, JT60-SA and ITER, as well as theoretical and technological research. Materials studies on IFMIF and construction of a DEMO reactor have been proposed as essential steps towards this long term goal. To accelerate this programme and reduce risks it will be necessary to continue research on present facilities (to progress fusion science and technology) and to add more facilities, e.g. steady-state Fusion Neutron Sources as component test facilities (CTF) for material studies complementing (or substituting) IFMIF and significantly extending capabilities of existent and proposed low-power neutron sources.

The Fusion for Energy programme currently strives to achieve the sufficient gain (power output over power input) in a tokamak to be viable as a power source. However, tokamaks still have a valuable role in the Fusion for Neutrons (F4N) approach. This is because the nuclear fusion reaction produces an abundance of high-energy neutrons, and Magnetic Fusion, with 60 years of R&D, is now ready to contribute to energy production in a more general sense, by helping to resolve 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 - by utilizing the tokamak as a powerful neutron source.

In addition, there is a potentially important alternative Fusion for Energy route, the scheme originally proposed in the 1950s and reviewed by Bethe in 1970-80 [1,2] which has been revisited recently [3], namely 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.

A more immediate non-electrical application of fusion is the use of a fusion device as an intense neutron source. The application having received the most attention to date is as a Volume Neutron Source (VNS) or Component Test Facility(CTF) to test materials and components intended for use in future Fusion Power Plants, by subjecting them to powerful 14MeV neutron bombardment. There are however a wide variety of other applications: for the development of innovative neutron technologies like production of radioisotopes for medical applications and research, for detection of specific elements or isotopes in complex environments, radiotherapy, detection and diagnostics, for example, toxic waste detection and activation analysis; radiography, alteration of the electrical, optical, or mechanical properties of materials and in other material studies, heat production for different applications (e.g. hydrogen production via high-temperature electrolysis, desalination of water), production of tritium (scarce due to its short half-life), and many other non-electric applications of Fusion.

Several Government Reports [4-7] and reviews [8-13], have addressed the indirect benefits to society of these spin-offs that result from funding the Fusion programme. But the most obvious non-electric application of a Fusion neutron source is, as mentioned above, to aid the present expanding nuclear energy industry, which is rapidly both exhausting uranium fuel [14] and building up stores of radioactive waste. Application of fast fusion neutrons can convert the huge stockpiles of depleted uranium into fresh fuel, and can help reduce waste problems by transmutation [12, 13, 22, 32]. 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 [33]. 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 commercialised much earlier than FpureOF4E approaches.

Such applications have long been envisaged to the original fusion reactor patent of Thompson & Blackman in 1946 [15] recognised its value as a neutron source but have largely been neglected, in the desire to search for FpureOFusion as an ideal energy source. The use of fusion neutrons for non-electrical application and particularly to assist resolving nuclear power production problems has been proposed by Andrei Sakharov 1950 [16], H Bethe 1979 [2], many other authors later and recently by P-H Rebut 2005 [17]. Detailed design studies of large systems and their blankets have been performed by R Moir [18], D Stacey [19] and by Chinese and Russian groups [20-22].

Several options of a Fusion Neutron Source have been studied during the last decade. They include the UKAEA Volumetric Neutron Source (VNS) [23], CCFE Component Test Facility (CTF) [24, 25], Oak Ridge CTF [26], University of Texas CFNS [27] and TSUK/Kurchatov Institute Super Compact Fusion Neutron Source (SCFNS) [28, 29]. Their main features and feasibility are analyzed and discussed in this paper. Auxiliary heating, tritium consumption and magnetic systems largely determine the capital and running cost of a FNS, and it is shown that a small or medium size Spherical Tokamak (ST) provides significant advantages. The main physics and technology challenges, e.g. stability and confinement properties at high fast ion fraction and low collisionality, optimisation of an operating regime for the beam-plasma dominant neutron production, wall and divertor load at steady-state conditions, magnet design and power consumption, divertor design options and other issues will be discussed in detail.

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 [30]. This suggests that the demonstration of a reliable application of Fusion as a steady state Neutron Source in a compact ST even at the level of a few MW neutron output will significantly advance not only the mainstream Fusion for Energy research, but also the commercial exploitation of fusion power in nuclear industries and in a wide range of other neutron applications, which will be overviewed. Another major advantage of the ST route is that the initial SCFNS device is relatively cheap. Recent comparison of an ST-CTF with a conventional aspect ratio (DIII-D type) FDF shows that the ST-CTF is a machine ready to be constructed and is the smallest and lowest cost next step of the two [31].

In the present review we focus on the steady-state fusion neutron source itself, but not on details and technologies of its applications. 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 $R/a > 2.5$) [34-36] 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 1980s by Peng [37] and first demonstrated by the START experiment at Culham [38] 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 [39] - 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 [12, 20, 21, 23 - 26, 29, 30, 40-44].

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 [23-25]. A pioneering paper by Stambaugh et al [30] 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. $\beta_N \sim 8$) 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: START and 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 [12] and US CTF proposals [26] and other proposals for a smaller device with R ~ 0.5m [23, 30]. The main parameters are compared in Table 1. Advantages and disadvantages of these different options are discussed in detail below.

![FIGURE 1. Cut view of SCFNS](image-url)

In this paper we also analyze advantages of a Super-Compact FNS (SCFNS) [28, 29], Fig.1, which differs from the previous designs in significantly reduced input Neutral Beam Power (from 25-50MW or more 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 $\alpha$-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 [30]. 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.

OPTIONS FOR COMPACT FUSION NEUTRON SOURCES

Several options can be considered for a Fusion Neutron Source on the basis of a tokamak with a fusion output of at least 1 MW, including:

a. tokamak with superconducting or non-superconducting magnets and an aspect ratio A = 3-4 (A=R/a - ratio of large radius R of the torus to a small radius a);

b. low aspect ratio tokamak with copper or superconducting magnets and an aspect ratio A ~ 2;

c. super compact (R ~ 0.5m) spherical tokamak with copper magnets and an aspect ratio A = 1.5 ÷ 1.8;

d. medium size (R < 1.5m) spherical tokamak with copper or superconducting magnets with an aspect ratio of 1.5 ÷ 1.8.

From a technical point of view, all options seem realizable, capable of providing the required power level. The cost of a demonstration experiment is set by the capital cost and running cost of the auxiliary heating system, magnetic systems and T consumption. (In a reactor, in principle, both T and electricity could be reproduced, making the device self-sufficient, but this is unlikely to be fully achieved in a demonstration experiment).

Option (a), classical tokamaks with R/a > 2.5, can produce a high neutron rate at acceptable neutron wall loads. Detailed design studies of large systems have been performed by P-H Rebut based on the ITER fusion core design [17], by D Stacey (SARB) [19], FEB and FDS groups (China) [20-21], V Kotov [22] and L Zakharov FFRF [51]. Neutron sources based on classical tokamaks (with R/a > 2.5) [20, 34-36, 51] 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). Using tritium, EAST would produce 5 MW fusion Power, JET has plans to produce 30 MW, FDF (GA) is designed to produce 250 MW [45] and ITER aims to produce up to 500 MW. The capital cost of a Fusion Neutron Source based on the conventional tokamak may exceed 1 billion euro and running costs will exceed 500 M USD for 100% load/year. Pulsed devices with lower availability may also be considered for a number of applications, and high-field options appear promising. The medium-sized IGNITOR project [46], now under development as a joint Russian ⊕ Italian project, is predicted to achieve short pulse ignition without need of extensive auxiliary heating, by virtue of its very high field Br ~ 13 Tesla at the plasma major radius (1.43m) and magnetic field ~ 20T at the edge of the centre stack, obtained by conventional copper magnets with a steel support structure.

Superconducting coils are possible for providing reduction of electricity use, but neutron shielding of the central post increases the size, which results in higher CD power needed for steady-state operations, and, due to increased input power leading to higher Fusion output (no low-power option), increased T consumption. High initial T load also increases the capital cost. Some of conventional aspect ratio tokamak neutron sources options are presented in Table 2.

Option (b), an ST with R/a ~ 2, has certain advantages in manufacturing, as well as the reduced cost of the tokamak, as compared to option (a). However, due to its large size, option (b) also has significant power requirements for the magnetic system and current generation system. This leads to higher operating costs as power dissipation in magnets and power consumption of other systems can approach 500 MW. The R/a=2 VECTOR project [47] has the advantage of superconducting magnets that reduces operating costs but increases technical challenges. A further increase in toroidal field in this type of device may have big benefits. Another R/a = 2 project, JUST [40], has an option of cryogenically cooled AI magnets which may be an alternative solution to superconductors if the necessary neutron shielding is provided.

Option (c) provides the smallest size with acceptable power requirements below 50 MW and minimum build cost, and delivers several megawatts of neutron power. Option (d) may prove to be even more efficient, as energy consumption can be further reduced by using superconducting (possibly high-temperature superconducting)
magnets. This option requires more space for magnets and in particular, for the central stack, which leads to increased major radius of the device compared to the super compact option (c).

**Options for Small and Medium Size FNS Based on the ST**

To do a comparative analysis of ST-based FNS, we look at different small and medium size proposed ST devices. Azizov et al [40] 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 [25] extend the work of Hender [23], to propose a VNS (now termed a Component Test Facility, CTF) with \( A \sim 1.6 \), 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 \( R \sim 0.75 \) m, \( I_p \sim 8 \) MA, \( B_T \sim 2.8 \) T, \( H = 1.3 \), \( P_{NB} \sim 60 \) MW, and yields \( P_{\text{fus}} \sim 50 \) MW. Voss et al [24] develop the Wilson design, increasing the size slightly to \( R = 0.85 \) m, \( a = 0.55 \) m, with a slight decrease in current and field to 6.5 MA and 2.5 T, again assuming \( H = 1.3 \), with \( P_{NB} = 44 \) MW and \( P_{\text{fus}} = 35 \) MW. Dnestrovkij et al [42] provide ASTRA and DINA codes simulations of the Wilson CTF, and find that by using a different mix of NBI energies (6 MW at 40 keV and 44 MW at 150 keV) they can provide current ramp up and, aided by a larger tritium fraction of 70% (cf. 50%), obtain the same fusion output (50 MW) but at considerably lower plasma current (5.5 MA cf 8 MA or 6.5 MA). 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 \( \alpha \)-particle heating) note \( \alpha \)-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 \( 1.4 \sim 1.6 \) (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 [26] proposed a larger CTF with \( R_s = 1.2 \) m, \( A = 1.5 \), elongation \( k = 3 \), with a range of parameters \( B_T = 1.1 - 6 \) T, \( I_p = 3.4 - 10 \) MA, producing a driven fusion burn using 15 - 43 MW of combined neutral beam and RF heating power; performance \( P_{\text{fus}} \) ranged from 7.5 MW to 150 MW. This CTF also has an option of tritium breeding. Wu et al [21] proposed an ST for nuclear waste transmutation with \( R = 1.4 \) m, \( A = 1.4, k = 2.5, B_s = 2.5 T, I_p = 9.2 \) MA, \( n_e = 1.1 \times 10^{20} \) m\(^{-3} \), bootstrap current fraction \( f_{\text{bs}} = 0.81 \), heating power \( P_{\text{NB}} = 19 \) MW and the wall load \( P_{\text{wall}} = 1 \) MW/m\(^2\). This design with an aspect ratio near the lower limit requires (due to limited space in the central post) an unshielded centre conductor post as a part of the toroidal field magnet. Peng and Zhang [43] propose a concept for a fusion-driven waste transmutation reactor (FDTR) based on a spherical tokamak with \( R = 1.05 \) m, \( R/a = 1.3 \), \( P_{\text{fus}} = 85 \) MW, wall load \( P_{\text{wall}} = 0.8 \) 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 [27] propose a larger CFNS with 100 MW fusion output (\( R_s = 1.35 \) m, aspect ratio 1.8, \( B_T = 2.9 \) T, \( I_p = 10-14 \) MA) using the super X-\( \phi \) 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. Galvo et al [12] study a Multi functional Compact Tokamak Reactor Concept designed with similar objectives as our present study. They propose a device (STEP) of major radius \( R_o = 1.2 \) m (some 50% larger than MAST and NSTX), with \( A = 1.6, I_p = 5 \) MA, \( B_T = 3.5 \) T, and obtain fusion gain \( Q_{\text{fus}} \sim 1 \) for a range of auxiliary heating powers from 5 MW to 40 MW. Interestingly, at lower powers the maximum \( Q_{\text{fus}} \sim 1 \) 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 < 50 MW. 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 stress during disruptions);
- ELMs (low total energy in ELMs in SCFNS, so no need for mitigation);
- high beta in STs (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 the lower inductance and higher electric field for the same loop voltage);
- small size, high elongation, high $\beta_n$, 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 3 shows results for devices with $R=0.5$m, 0.8$m$ and 0.4$m$. The $R=0.8$m option is close to the MAST/NSTX geometry but with $D/T$ and the toroidal field increased to 1.5T. The Valovic confinement scaling [48] has been used, which explains the high H-factors in the $R=0.8$m case. Although experimental data from MAST and NSTX confirm favorable dependence on the toroidal field (which resulted in high confinement in simulations), there is as yet 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 the 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 $R=0.5$m case, which makes the larger version less efficient.

For the lower size, $R=0.4$m, 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 the decrease in confinement due to lower volume. The superconductor option though is more feasible in a larger device. In brief, a compact device with $R=0.5$m 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.

![FIGURE 2. Outline (same scale) of UKAEA VNS and GA ST Pilot Plant (bottom row) in comparison with the SCFNS (top).](image)

**Comparison of SCFNS with Other Compact ST Neutron Sources Proposals**

We analyze two ST FNS designs closest in size to SCFNS ($R < 0.6$m), the UKAEA compact option of a Volumetric Neutron Source (VNS) [23] and the smallest option of the GA ST Pilot Plant [40], Fig.2.
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 [23] is that the stress limit favors low R/a and low R. The limit on $\beta_n$ due to stability requirements also favors lower R/a. However, the fluence of 6 MWa/m² demanded in [23] 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.

- 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 [49], H-factor $\sim 1.4$;
- lower $I_p$, so much less dissipation in PF coils, much less NBI power for current drive;
- $\alpha$-particles are lost on the 1st 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 $\alpha$-particles, as it does not rely on $\alpha$-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 [30] 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 devices unattractive for electricity production, however the compact GA ST studies confirms the feasibility of the road map with the SCFNS as a first demonstration of a FNS; and a gradual increase in the neutron output and, probably, the device size could 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 the extreme fluence needed for Fusion and Fission reactors material tests, nuclear waste transmutation or breeding.

### 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 the 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 current. 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 [41] has shown the feasibility of steady-state operations at \( I_p = 1 \pm 1.5 \) MA and \( P_{NB} = 5 \pm 10 \) MW. Fig. 3 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), \( n_{e\text{ave}} = 10^{20} \text{m}^{-3} \). An increase in the plasma elongation from \( k = 2.75 \) 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 [50]. The regimes have \( \beta_N < 5 \), which is below stability limits [41]. KINKS and SPIDER vertical stability analysis [41] 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 \( \sim 10 \text{ m}^2 \), the neutron load on the wall is low. The high thermal load \( \sim 1 \) 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 be a problem as the total load power is quite low [41]. 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.

**IV. 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 \( R = 0.5 \)m is not constrained by stress, heat, wall & divertor load, confinement or stability. In SCFNS, it is possible to produce MW-levels of neutron output in a 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.

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

<table>
<thead>
<tr>
<th>Source</th>
<th>( R/a, \text{m} )</th>
<th>( I_p/B_{tor}, \text{kA/T} )</th>
<th>( k )</th>
<th>( P_{in}/P_{fus}, \text{MW} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNS UK</td>
<td>0.8/0.5</td>
<td>13.4/3.5</td>
<td>2.3</td>
<td>69/32</td>
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<td>CFT UK</td>
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<td>6.5/2.5</td>
<td>2.4</td>
<td>44/35</td>
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<tr>
<td>CTF US</td>
<td>1.2/0.8</td>
<td>12/2.5</td>
<td>3.2</td>
<td>47/150</td>
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<tr>
<td>CFNS US</td>
<td>1.35/0.75</td>
<td>14/2.9</td>
<td>3</td>
<td>50/100</td>
</tr>
<tr>
<td>STEP UK</td>
<td>1.2/0.75</td>
<td>5/3.5</td>
<td>3</td>
<td>40/30</td>
</tr>
<tr>
<td>JUST RF</td>
<td>2/1</td>
<td>5.3/3.9</td>
<td>1.6</td>
<td>45/62</td>
</tr>
<tr>
<td>STPP US</td>
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<td>11/3</td>
<td>3</td>
<td>30/300</td>
</tr>
<tr>
<td>FDF China</td>
<td>1.4/1.0</td>
<td>9.2/2.5</td>
<td>2.5</td>
<td>19/100</td>
</tr>
<tr>
<td>CVNS UK</td>
<td>0.57/0.35</td>
<td>6.8/2.5</td>
<td>2.3</td>
<td>25/16</td>
</tr>
<tr>
<td>TIN RF</td>
<td>0.47/0.28</td>
<td>3/1.35</td>
<td>3</td>
<td>15/2</td>
</tr>
<tr>
<td>CSTPP US</td>
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<td>14/9.6</td>
<td>3</td>
<td>50/310</td>
</tr>
<tr>
<td>SCFNS UK</td>
<td>0.5/0.3</td>
<td>1.5/1.5</td>
<td>2.75</td>
<td>6/2</td>
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TABLE 2. Main parameters of several proposed conventional Fusion Neutron Sources.

<table>
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<tr>
<th></th>
<th>SABR</th>
<th>FDS-1</th>
<th>Rebut</th>
<th>FDF</th>
<th>FEB</th>
<th>FFRF</th>
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<tr>
<td>R, m</td>
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<td>4</td>
<td>6.2</td>
<td>2.49</td>
<td>4</td>
<td>4</td>
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<tr>
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<td>4</td>
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<td>4</td>
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<tr>
<td>k</td>
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<td>1.78</td>
<td>1.6</td>
<td>2.31</td>
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<tr>
<td>I_p, MA</td>
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<td>6.3</td>
<td>15</td>
<td>6.5-9.3</td>
<td>5.7</td>
<td>5</td>
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<tr>
<td>B_r, T</td>
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<td>4.4-6.0</td>
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<td>SC</td>
<td>Cu</td>
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<td>SC</td>
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<tr>
<td>Pulse, s</td>
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<td>1000</td>
<td>600-s/s</td>
<td>s/s</td>
<td>2h-s/s</td>
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<tr>
<td>P_in, MW</td>
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<td>50</td>
<td>80</td>
<td>20-67</td>
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<td>120</td>
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<tr>
<td>P_fus, MW</td>
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<td>150</td>
<td>300-500</td>
<td>120-400</td>
<td>143</td>
<td>50-100</td>
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TABLE 3. Main parameters of SCFNS options

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<tr>
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<th>larger size</th>
<th>smaller size</th>
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<td>R/a</td>
<td>m/m</td>
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<td>0.8/0.5</td>
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<td>&lt;n&gt;</td>
<td>10^20 m^-3</td>
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<td>1</td>
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<tr>
<td>I_pl</td>
<td>MA</td>
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<td>1.5</td>
</tr>
<tr>
<td>B_tor</td>
<td>T</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>E_beam</td>
<td>keV</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>P_beam</td>
<td>MW</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>R_beam</td>
<td>m</td>
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<td>0.9</td>
</tr>
<tr>
<td>Elong</td>
<td></td>
<td>2.75</td>
<td>2.75</td>
</tr>
<tr>
<td>Triangular</td>
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<td>0.5</td>
</tr>
<tr>
<td>Te0/Ti0</td>
<td>keV</td>
<td>4.7/7.9</td>
<td>4.4/5.5</td>
</tr>
<tr>
<td>P_in/P_abs</td>
<td>MW</td>
<td>3+3+1/6.5</td>
<td>4+4+1/6.8</td>
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<tr>
<td>I_cd</td>
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<td>0.4</td>
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<tr>
<td>I_boot</td>
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<td>H-factor</td>
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<td>W_th/W_tot</td>
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<td>β_N</td>
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ACKNOWLEDGMENTS

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REFERENCES

4. "Non-Electric Applications of Fusion Energy Report to FESAC, July 31, 2003"
32. B. McNamara. A briefing on futures with Fission & Fusion hosted at: http://gtmhr.ga.com as Fission & Fusion Futures
41. B. V. Kuteev et al., Tokamak-based MW-Range Fusion Neutron Sources at DOE Workshop on Fusion-Fission Hybrid Reactors, Gaitersburg, Maryland, USA, September 30 – October 2, 2009.
44. A. A. Golikov, B. V. Kuteev, VANT, ser. Thermonuclear Fusion, 2, 50 (2010).