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To cite this article: C. Bachmann *et al* 2026 *Nucl. Fusion* **66** 046015

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IOP Publishing | International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion **66** (2026) 046015 (6pp) https://doi.org/10.1088/1741-4326/ae4e46

Progress in the concept development of the VNS—a beam-driven tokamak for component testing

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Received 21 November 2025, revised 28 January 2026
Accepted for publication 6 March 2026
Published 17 March 2026

Abstract

The Volumetric Neutron Source (VNS) is a compact beam-driven tokamak with D–T plasma to generate a high neutron flux that will allow the testing and qualification of fusion nuclear components, in particular the breeding blanket. Recently, EUROfusion concluded a design study that confirmed the feasibility of VNS for construction and operation. Also, aspects were identified that require further development and assessment, and these have been key subjects of the on-going conceptual design phase. This article summarises the progress made in the design of VNS, including (i) the rationale for the small adjustments of major radius and aspect ratio, (ii) the configuration and performance of the equilibrium coils, (iii) the design of the in-vessel components including their remote handling concepts, (vi) design of the nuclear buildings and layout of the main plant systems including those related to the fuel cycle.

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Keywords: VNS, Volumetric Neutron Source, breeding blanket testing, DEMO, tokamak, remote maintenance

(Some figures may appear in colour only in the online journal)

1. Overview of VNS

1.1. Basic concept of VNS

Carrying out the validation of fusion nuclear components, the fuel cycle and the operation of a nuclear fusion plant in a Volumetric Neutron Source (VNS) in parallel to ITER had been proposed already in the 1990s [1]. The update to the first ITER operation phase with significantly reduced neutron production [2] has recently raised interest in a VNS acknowledging the prevailing testing needs e.g. for the breeding blanket (BB) [3]. VNS is to be built and operated in parallel to ITER. It implements a plasma scenario based on well-demonstrated beam-target reactions (e.g. in JET) and mature technologies and nuclear infrastructure. In particular, it does not require tritium self-sufficiency due to the low annual tritium consumption of less than 1 kg. During plasma operation the tritium inventory of the VNS fuel cycle is ≈400 g and VNS plant consumes 165 MW of electric power.

The European developments are summarised here. Russian developments of beam-driven neutron sources started already in 2010 and are led by the Kurchatov institute. These are based on hybrid fusion-fission. They resulted in the definition of two beam-driven tokamak VNSs, DEMO-FNS [4] and FNS-ST, a spherical tokamak [5].

1.2. Potential to advance the realisation of fusion energy

VNS would be the first fusion facility to continuously operate a D–T plasma generating an intensive flux of 14 MeV neutrons. VNS would therefore mimic the conditions of a fusion power plant and demonstrate its safe operation including a continuously operating fuel cycle during plasma operation and the management of tritium contamination during reactor maintenance. Ports are available for testing instrumented fusion components, in particular different concepts of the BB. In addition, the replacement of n-shield blankets with test BB segments is foreseen for qualification targeting a technology readiness level (TRL) of 7 'System prototype demonstration in an operational environment' [6]. Thanks to the plasma insensitivity to the physical presence and composition of the reactor core components, and to the machine's good accessibility, it would be possible to test a wider range of nuclear components. Although VNS is not intended for plasma physics experiments, its unique operating parameters allow research into fast particle physics, power exhaust and, more generally, D–T plasma operation and hydrogen isotope effects.

1.3. Plasma scenario

In VNS long plasma discharges are required for the qualification of the components, i.e. the pulse length must be sufficient to reach thermal equilibrium, typically of the order of few minutes. The VNS plasma is therefore based on a fully non-inductive scenario, since the relatively small space available for the central solenoid (CS) does not allow the sustainment of long discharges inductively. Neutral Beam Injectors (NBIs) have the twofold role of driving the plasma current and generating fusion reactions by injecting energetic particles in the bulk plasma—the so-called beam-target reactions—following the example of recent JET discharges [7]. To maximise fusion yield, NBIs are ideally operated with pure deuterium (D), while the bulk plasma is ideally composed of pure tritium (T). However, since the NBI unavoidably acts as a fuelling source, the resulting bulk plasma composition is foreseen to be ∼83% T and ∼17% D. Deuterium is expected to be injected with a share of ≈5% T given the expected processes in the tritium plant (see section 3.3). The plasma current is set as high as possible while compatible with the known stability limits (i.e. $q_{95} > 3$) and serves two main purposes: (i) provide a margin against destabilisation of resistive wall modes (RWMs) by maintaining low values of the normalised plasma pressure, β_N, and (ii) improve confinement of fast particles—both injected ions and fusion alphas—which is particularly critical in a small-size device as VNS.

Key to ensuring a high neutron production rate in VNS is a high electron temperature, T_e. The probability of beam target fusion reactions increases with a larger slowing down time, which is determined by electron–ion collisions and therefore scales as $T_e^{3/2}$. Thus, in addition to the 42 MW of NBI power [8], the plasma electrons are heated with 8 MW of electron cyclotron (EC) power, see table 1. The EC system provides also additional plasma control functions such as stabilisation against neo-classical tearing modes and reduction of the accumulation of tungsten. To achieve a high fusion power and to avoid the collapse of the VNS plasma it is essential to maintain low values of the effective charge, z_{eff}, and of the core radiation (stemming from tungsten and other impurities). For this reason, the impurity seeding foreseen to achieve a robust detachment of the VNS single null divertor must be carefully defined minimising the impact on the core z_{eff} [9]. The optimum impurity mix of the seeding gas is currently under investigation and Krypton has been identified as the best choice [10].

The energy content of the VNS plasma is small and comparable to the plasmas of existing experiments such as ASDEX-Upgrade. Therefore, the risk of possible damages of the wall components due to plasma disruptions is well-known and low in contrast to devices built to operate large plasmas with high energy contents like ITER or DEMO. The plasma current of VNS is much lower than what has been achieved in JET (≈7 MA), and experience shows that no major damages occur

Table 1. Parameters of VNS.

Major radius R	2.67 m	Auxiliary heating, $P_{NBI}\|P_{EC}$	42 MW ǀ 8 MW
Aspect ratio A	4.25	Beam energy E_B	120 keV
Plasma current, I_p	2.55 MA	El. density n_e (line averaged)	1.1×10^{20} m^{-3}
Plasma elongation, k_{sep} ǀ k_{95}	1.63 ǀ 1.45	El. temperature T_e (central)	12.91 keV
Toroidal field, B_0	5.6 T	Safety factor q_{95}	3.16
Fusion power P_{fus}	38.2 MW	Normalised beta β_N	2.7% T m MA^{-1}
Power to divertor P_{sep}	55.62 MW	D-fraction in the plasma	0.17
Neutron wall load, midplane	0.47 MW m^{-2}	Shafranov shift	0.18
Irradiation damage per full power year (in EUROFER)	3.6 dpa	Plasma thermal energy	7.9 MJ
		Plasma magnetic energy	3.5 MJ

at these levels of plasma energy. Due to the low plasma current also the risk of runaway electrons (REs) generation is expected to be low. In general, the loss of plasma control does not represent a major threat for the machine integrity. Instead, the loss of the divertor detachment would lead to excessive heat loads on the divertor targets, which could cause damages.

However, it is expected that this event can be reliably detected and that the heat loads on the divertor can be swiftly reduced by switching off the NBIs.

1.4. Operation concept

The primary purpose of VNS is to produce 14 MeV neutrons at reactor-relevant flux levels. This will enable the *testing* of instrumented test blanket modules (TBMs) and the *qualification* of BB segments. During plant commissioning, a standard, reliable plasma scenario will be defined and repeated throughout the operational phase. To further increase machine reliability, thermal cycling can be minimised by operating the plasma in a steady-state regime. Depending on the needs of testing and qualification, pulsed plasma operation will also likely be adopted at times. There will be regular shutdowns for ex-vessel maintenance, for example four times per year for one week. Furthermore, in-vessel components will be replaced when they reach the end of their radiation lifetime. Tentatively, a longer machine shutdown for replacement of in-vessel components is foreseen each 5 full power years. The replacement schedule of TBM port plugs and BB segments has not been defined yet, however, particularly for the port plugs a flexible replacement schedule can be realised.

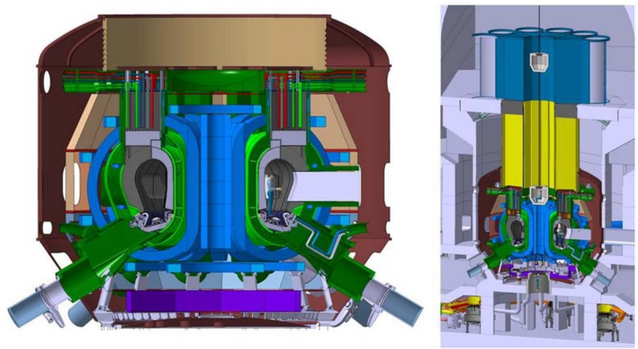

Figure 1. Left: VNS tokamak, right: personnel access to the joints of the magnet coils via shielding cabins to the central upper and lower areas of the cryostat.

2. Tokamak design

2.1. Adjustment of tokamak parameters

Based on various assessments of the previous tokamak and plasma configuration [11] the following parameters were modified, see also table 1: (i) The magnetic field was slightly increased to enable a higher plasma current and hence a better confinement and higher core temperature. Consequently, a significant contribution of thermal fusion is expected (≈5.5 MW). (ii) The β_N value is significantly reduced and the plasma has a margin to the stability limits [12]. (iii) The aspect ratio was reduced increasing the plasma minor radius, which significantly reduces the level of tungsten impurities. Furthermore, together with the increase of the plasma elongation, the electromagnetic plasma control and passive vertical stability improve significantly decreasing the issues control issues found in the previous configuration [13]. This allowed the poloidal field (PF) coils to be arranged outside the toroidal field (TF) coils in a conventional tokamak configuration.

2.2. Magnet system

The increase in size mitigated the issue of controllability and opened the possibility to reconsider a conventional (ITER-like) magnetic cage for VNS. In this context, the use of HTS and *in-situ* winding [14, 15] will be revisited only if necessary, depending on future developments. Implementing a conventional LTS system significantly reduces the overall machine complexity and improves its readiness. Despite quality assurance procedures, experience with existing superconducting devices suggests that defects may occur in the joints of the superconductors and of the cryo-distribution system [16–18]. In order to make these joints accessible for repair, the VNS magnet system is configured inside the cryostat so that all joints are located in the areas above and below the CS. The small gaps between the coils mean these areas are well protected from radiation. Personnel can reach them by special-purpose cabins, figure 1.

2.3. Vacuum vessel

The VV is a welded double wall structure made of 316L(N)-IG that is actively cooled by water. The two 30 mm shells are supported against the coolant pressure by poloidal ribs. Areas on the inboard side that are subject to local loads due to the support of the IVCs are reinforced by toroidal ribs. Ports structures are integrated into outboard side; the 12 lower ports support the VV weight from the cryostat pedestal ring.

To control the plasma vertical stability two so-called intra-VV coils are implemented in-between the VV shells, one above and one below the equatorial port. The conductors are assembled into the VV sectors during VV manufacturing and joints are made at the VV sector field joints during tokamak assembly. These coils are not maintainable. Each intra-VV coil is envisaged to be made up of 3 turns with separate power supplies for redundancy. The conductors are based on ITER technology i.e. a copper conductor with MgO insulation inside a stainless-steel pipe [19]. However, there is no internal cooling; instead, the Ohmic heating is reduced through increasing the copper section, and the conductor can be cooled externally by the VV coolant.

2.4. In-vessel components

The IVCs of VNS comprise 36 divertor cassettes, up to 60 shield blankets, the liner of the NB ducts, EC and diagnostic port plugs, BB test modules mounted on port plugs, and BB segments that replace outboard shield blankets. In addition, in-vessel diagnostics, the torus cryopumps, the NBI components, the in-vessel viewing system, shielding structures and pipes in the upper and lower ports are integrated inside the VV but are not usually considered to be 'in-vessel components'. The VNS shield blankets and divertor cassettes have tungsten as plasma-facing material. They are made of 316Ti for its availability, nuclear qualification, and good manufacturability, as well as its superior irradiation resistance compared to 316L(N). Technology, design and integration concepts of the VNS blankets and divertor cassettes are further described in [11, 20–23].

For the identification of in-vessel leaks a standard procedure is foreseen: (i) isolation of individual IVCs, (ii) water draining and pressurisation with helium, (iii) leak detection via torus cryopump (operating at increased temperature) with helium leak detector, (iv) replacement of identified IVC. The cooling loops are therefore designed with isolation valves, which allow each IVC to be isolated from the loop.

A fleet of remote-controlled and robotic tools carries out the various functions required for in-vessel maintenance, see also [22]: (i) the in-vessel viewing system operates within the VV and performs in vessel inspections between plasma pulses. (ii) Sealed casks transfer hot components in-between the VV and the active maintenance facility (AMF) (iii) Remote maintenance tools carry out tasks inside the VV e.g. pipe servicing. (iv) Various tools operate in the AMF hot cells to test, refurbish and decontaminate in-vessel components and to prepare them to be discarded as radwaste.

3. Nuclear buildings and safety provisions

3.1. Site and nuclear buildings

The tokamak building is the centre of the VNS site, figure 2. It has an octagonal shape with four longer and four shorter side lengths. The diagnostic building and the three other nuclear buildings are arranged along the longer side lengths i.e. the tritium plant, the AMF, and the chemical volume and control system (CVCS). Smaller buildings requiring good access to the tokamak building are arranged along the shorter side lengths: The tokamak assembly hall is connected during construction and non-nuclear operation via an overhead crane, the gyrotron building routing the EC waveguides, a personnel access building, and the NB power supply building. Systems in other buildings are connected to the tokamak building via bridges and trenches i.e. safeguard buildings hosting equipment to bring and keep the plant in a safe state, and buildings hosting plant systems e.g. heat rejection.

The tokamak building has external walls, and a circular dome of reinforced concrete designed to resist to an airplane impact as in fission power plant. A double-wall bioshield encloses the tokamak protecting external areas from radiation. The activated tokamak coolant is segregated from other plant areas. It is routed in the bioshield interspace to the upper pipe chase which has sufficient volume to prevent over pressurisation in the event of a pipe break. Heat exchangers, pumps and other cooling system equipment is integrated in the upper building levels. Port cells are arranged outside the tokamak ports. External galleries are used for the transfer of casks to and from the AMF and for the routing and hosting of auxiliary plant systems. The basement level is non-nuclear except the zone directly below the tokamak. It hosts all magnet feeders and the cold valve boxes of the cryopumps. It is connected to the coil power supply building and the cryoplant via trenches, and to the magnet fast discharge resistors that are located in the diagnostic building.

3.2. Safety provisions

The safety provisions implemented in the VNS plant aim at minimising (i) the release of tritium into the environment both in normal operating condition and in worst case accidental scenarios, and (ii) the produced amount of radwaste, which consists mainly of metallic structures that were exposed to n-irradiation. The following approaches are implemented: (i) protection of the VNS plant against external events (fire, flooding, airplane crash, earthquake, etc), (ii) implementation of two physical confinement barriers in all plant states, (iii) segregation of building sectors that may be subject to contamination, (iv) ventilation system in the nuclear buildings that can be connected to the air detritiation system, (v) Chemical

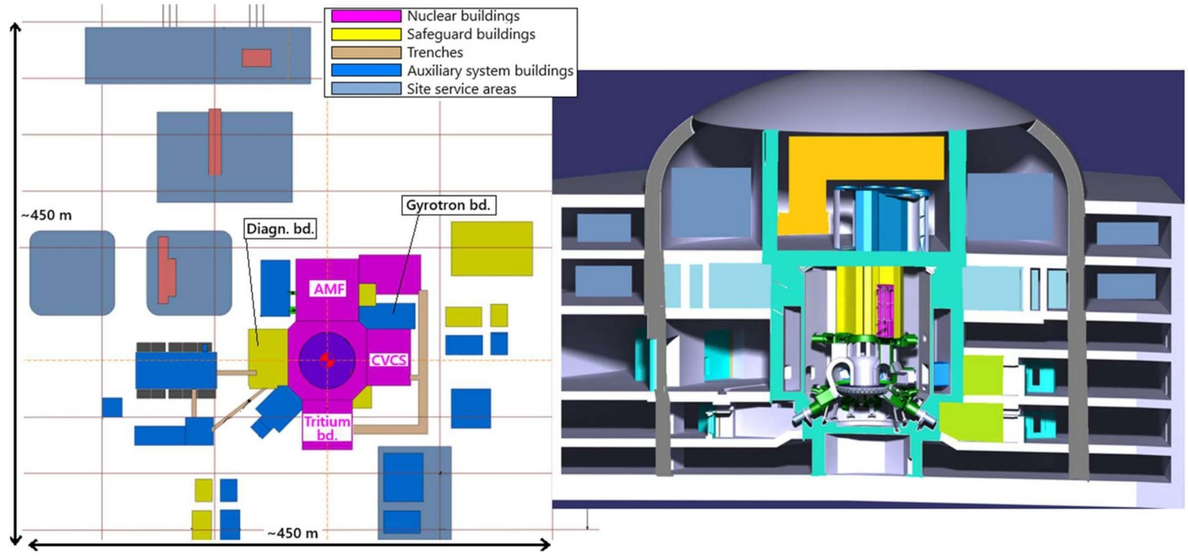

Figure 2. Left: VNS site with arrangement of nuclear buildings, buildings hosting tokamak auxiliary systems, and power supply and heat rejection installations, right: section of the left side of the tokamak building.

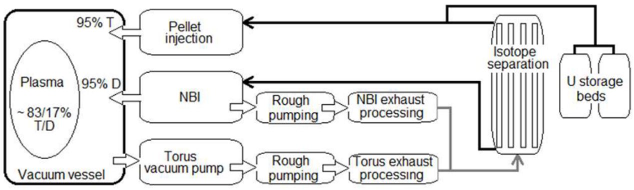

Figure 3. Block diagram of basic VNS D–T fuel cycle.

Volume & Control System for the cooling water to control the level of activated corrosion products, (vi) detritiation of radioactive waste prior to processing and storage, (vii) minimisation of exposure of personnel to radiation and tritiated atmosphere: All in-vessel maintenance operations will be carried out by robotic tools following the sealed environment approach based on sealed casks for the transport of contaminated IVCs.

3.3. Fuel cycle systems

The VNS tritium (T)–deuterium (D) plasma is fed with T in the form of pellets (95% T/5% D) and D (95% D/5% T) from the neutral gas beam of the NBI [24], see figure 3. The total throughput is pumped out via cryopumps. It much depends on the chosen operating point, early estimates predict $\approx 3 \times 10^{22}$ atoms s^{-1} [9]. The torus cryopumps remove the plasma exhaust gases, the NBI cryopumps remove the excess gases used in the NB neutraliser. The gas stored on the surfaces of the cryopumps are removed regularly. The cryopanels are regenerated by the separation of either the torus cryopump housing or the NBI box, heating the panels and pump-out of the isolated volume by the rough pumping system. The exhaust gas mixtures are processed in a closed fuel cycle loop in the tritium plant.

Foreseen technologies: Centrifugal pellet accelerators are currently planned, as they do not introduce additional gases into the fuel cycle and enable effective feeding of the plasma core. ITER-like cryopanels with char-coal coating are suitable to create the high vacuum condition. The VNS torus cryopump will adopt the design of the ITER model pump to shorten the development programme. The roughing pump system will use a combination of roots- and scrollpumps that are suitable for continuous operation, compatible with tritium and do not require purge gas. Cryogenic distillation columns in the tritium plant separate the hydrogen isotopes D and T. Depleted uranium beds store tritium and recover it from the fuel cycle system during machine shutdown.

The expected total tritium inventory in the fuel cycle during plasma operation of $\approx$400 g is distributed as follows: cryogenic distillation columns $\approx$350 g, NBIs $\approx$ 12 g, TCPs $\approx$ 30 g, and pellet injector $\approx$23 g [24]. In addition, depending on the supply of the expected tritium consumption of up to 1 kg yr^{-1}, several hundred grams will be stored in the uranium beds.

4. Summary

The VNS is proposed to operate in parallel with ITER, designed to validate fusion nuclear components, the tritium fuel cycle, and safe plant operation under fusion power plant conditions. Using a mature, fully non-inductive plasma scenario with a total of 50 MW of NB and EC auxiliary heating, VNS achieves high neutron yields with low operational risks from disruptions or REs. Addressing ITER's reduced neutron output, VNS will operate be the first continuous D–T plasma producing an intense 14 MeV neutron flux—enabling BB qualification to TRL7. The fuel cycle integrates technologies developed for ITER and fission applications, with an annual tritium consumption below 1 kg. VNS bridges the gap between ITER and DEMO, accelerating fusion energy realisation while offering a near-term platform for component qualification and operational experience.

The facility requires a 450 m × 450 m site, ≈165 MW power supply, licensing of a fuel cycle with a tritium inventory of ca. 400 g, and the possibility of storage of up to ∼2000 tons of low and intermediate level waste. Safety provisions include two physical confinement barriers, robotic in-vessel maintenance, and advanced detritiation systems.

The VNS design has been adjusted with respect to [11] in e.g.: (i) increasing the plasma current and minor radius to reduce tungsten impurities, (ii) lowering β_N to avoid plasma instabilities, (iii) implementing a conventional coil configuration and conductor technology (Nb_3Sn, NbTi), and (iv) adopting an octagonal design of the tokamak building with a circular dome inspired by the design of fission power plant buildings. The implementation of ion cyclotron heating to increase the fusion yield is currently investigated.

Acknowledgment

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200—EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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