Physics basis of a Volumetric Neutron Source (VNS) for component testing and qualification

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Abstract

A study is being carried out within EUROfusion to address the feasibility of a Volumetric Neutron Source (VNS). In its current shape, VNS is a medium-size tokamak (R = 2.67 m, B_0 = 5.6 T, A = 4.25, I_p = 2.54 MA) operating D-T plasmas, aiming to achieve a significant neutron wall load (approximately 0.5 MW/m^2) on long pulses. In terms of time scales, VNS is conceived to be built and operated in parallel to ITER. Purpose is to test and qualify in-vessel components, in particular breeding blanket modules and divertor, under large neutron irradiation, fluence and heat flux in a reactor-relevant environment. VNS is based on beam-target fusion reactions, which enable a significant fusion power despite the reduced device size. Neutral beams (NBI) are employed to generate the beam-target reactions (as in JET D-T fusion energy record [1]), and to drive the plasma current to sustain a fully noninductive scenario. Additional EC power is installed to keep the electron temperature high and for control reasons. This paper illustrates the design-driving criteria according to which the current VNS design point has been identified. In addition, it discusses the workflow employed for the definition of the design point, which involves codes of different level of fidelity up to integrated modelling. This approach allows a rigorous identification of all critical design aspects, thus ensuring the robustness of the point or driving future design modifications.

Introduction

Complementary to ITER and DONES [2], the role of the Volumetric Neutron Source (VNS) proposed by EUROfusion is the testing and qualification of entire in-vessel components, e.g. breeding blanket and divertor modules, at intense neutron flux and reaching high levels of neutron fluence. In general, the fusion nuclear components would be tested as close as possible to the expected reactor conditions. An extensive discussion of the role of a VNS in the path to the commercialisation of nuclear fusion energy can be found in [3]. The need for a VNS was identified as early as 1985 [4] and its role to complement ITER was indicated [5] [6]. EUROfusion VNS has been conceived as a high aspect ratio tokamak with medium size plasma ($R \cong 2.5$ m, $a \cong 0.5$ m) which mainly relies on beam-target reactions. The small size is key to keep the tritium consumption low while keeping high Neutron Wall Load (NWL) to efficiently test the components. The performance requirements of VNS are discussed in detail in [7] and references therein, while a description of the machine present architecture can be found in [8]. Requirements are similar to those defined for the ITER test blanket module (TBM) program: intensity of the neutron flux, i.e. NWL ≈ 0.5 MW/m^2, and long pulses to reach thermal equilibrium conditions in the test blanket modules. This paper discusses the design driving criteria considered in the definition of the present VNS design point. Furthermore, the workflow for the validation on JET T rich and the verification against higher fidelity modelling for the identification of the design challenges is presented.

VNS design-driving criteria

The reference design point identified, which served as a basis for all physics and engineering activities carried out in EUROfusion so far, has been required to fulfil the following high-level criteria:

- Peak NWL >= 0.5 MW/m^2

- β_N < = 3.5 % Tm/MA
- Fully noninductive plasma scenario
- Minimize T consumption (below 3 kg per full power year)

The first requirement refers to the peak NWL at the outer midplane, i.e. where the test modules will be located (equatorial ports) [8]. The second requirement is connected to global MHD plasma stability. While, normally, a value of $\beta_N = 3.5\%$ mT/MA is considered marginal with this respect, one must note that VNS plasma is characterised by a large fast particle population (beams and α's), which contribute for a very significant fraction of the total plasma β and are in general beneficial in terms of pressure driven modes stability. The third requirement is linked to the need of stationary plasma operation, or at least significantly longer than the time required to thermalize the test blanket modules (i.e. tens of minutes). In view of the small size of the device (which is a consequence of the fourth requirement, as discussed below), and of the very limited space for the CS on the inboard (where toroidal field coils inner legs and, especially, a thick neutron shielding have to be hosted [7]), it is quite easy to conclude that any inductive discharge could be sustained only for very short time in this device. In view of the large NBI power installed on the device, a high current drive potential can however be anticipated.

The VNS plasma, ideally, consists in a pure tritium plasma target where 120 keV deuterium ions are injected, similarly to JET T rich experiments [1][9]. This solution maximises the fusion power yield by maximising the collision energy in the centre of mass reference frame, as explained in [10]. However, beam also contribute to plasma fuelling, diluting the bulk plasma with D ions. The fusion power per unit volume Y_f in a beam-target device can be written as

$$Y_f \propto n_T \dot{n}_D \tau_{sd}$$

where n_T is the background tritium density, $\dot{n}_D$ is the injection rate of the deuterium (beam) ions and τ_{sd} is the slowing down time of the fast beam ions, in turn proportional to $T_e^{3/2}/n_e$ and moderately decreasing with Z_{eff} [11]. The performance of the device depends therefore strongly on the electron temperature profile (which must be high), but also on the plasma density. The latter does not appear explicitly in the formula for Y_f (n_T essentially cancels out with the $1/n_e$ dependency in τ_{sd}), but it plays a crucial role in determining the beam deposition profiles, and also must be compatible with the power exhaust requirements. The reference design point has been chosen with the following driving criteria:

Major Radius: The machine size has to be as small as possible to maximise NWL while minimizing the T consumption. Since in the testing phase one cannot rely by definition on the self-production of T, the whole T amount has to be provided by external sources. Each MW of fusion power corresponds to a T consumption of 55 g/fpy (full power year). Since the *entire* world production of T is at the moment lower than 5 kg/year [12], the fusion power in VNS must be limited to few tens of MW to ensure T availability.

Beam Energy = 120 keV. This value has been chosen to allow a sufficient neutralisation efficiency – which affects the overall electricity consumption - without recurring to negative ion beam technology [13]. Beams are supposed both to drive the fusion power and the plasma current. For this reason, a tangential injection is foreseen [7][8], which generates a significant torque and, subsequently, plasma rotation.

EC Power: its function is to increase the electron temperature, which increases in turn the slowing-down time of the beam particles boosting the fusion power yield – see above. Also, EC is necessary to prevent tungsten accumulation, and for control reasons in general.

Plasma current: plasma current must be large enough ensure a reasonable confinement of the fast particles (both beam and fusion α's). A sufficiently high toroidal field to sustain the current is therefore required.

$\boldsymbol{Z_{eff}}$: the effective charge in the core must be kept as low as possible, both because it increases the loop voltage making the CD more challenging, but also because it affects the slowing-down time of the beam (see above), and thus the fusion yield. Also, fuel dilution is not beneficial for the fusion power yield.

Elongation and shape control: too high elongation can be critical for the vertical stability. On the other hand, a too low value could complicate the feasibility of the magnetic equilibrium, making the plasma too small as compared to the large distance between plasma and PF coils, mainly due to the presence of a thick neutron shielding. An exhaustive discussion on this point can be found in [14].

Two important machine parameters require careful optimisation, namely the density and the aspect ratio. Concerning aspect ratio: from a purely geometrical standpoint, reducing the minor radius a at given major radius R can significantly increase the NWL, since the surface decreases while the beam-target fusion power roughly remains unchanged (assuming a satisfactory beam penetration). Also, a high aspect ratio allows for more space in the inboard, thus simplifying to some extent the radial build constraints and eventually allowing a higher toroidal field on axis. However, the value of β_N increases as A at constant q and β, compromising the MHD stability at higher A. Concerning plasma density: as discussed above, the beam-target fusion power rate is known to be almost independent of plasma density, since the $1/n_e$ dependency of the slowing-down time cancels out with the plasma density itself. However, at fixed heating power, a high density causes a reduction of the electron temperature, which negatively affects the beam slowing down time and thus the fusion power yield. Plus, a too high density might hamper the beam penetration, strongly affecting the achievable fusion power and current drive. On the other hand, at fixed beam power, a high plasma density (i.e. T-density) reduces the D dilution by the beam fuelling, having thus a positive effect on the achievable fusion power. The optimal plasma density is therefore found as a trade-off between all these effects. Plus, it also has to be compatible with the power exhaust requirements [15].

Design point definition

The table below lists the parameter of the current VNS design point. In terms of plasma scenario, the point has been evaluated with the 0.5 D code METIS [16], using ad-hoc density profiles, constraining the energy content to the H_{98} scaling law with $H = 1$ and fixing the pedestal top. As a first insight on the uncertainties, 2 different settings of METIS have been used: one without a pedestal in density and assuming all NBI D at 120 keV (label: *H=1*) and another one tuned to reproduce the profiles and fusion power obtained in the JET 99971 beam-target experiment [1] (label: *JETlike*). The corresponding values of fusion power and NWL are provided in the table for the two cases.

Major radius	2.67		[m]
Toroidal field	5.6		[T]
Aspect ratio	4.25		[]
Plasma elongation (separatrix)	1.6		[]
NB power/EC power/ NB energy	42.5/8/120		[MW]/[MW]/[keV]
Density/Greenwald fraction	11/0.53		[1e19m-3]/[]
Central electron temperature	12.91		[keV]
Fusion power (*H=1* | *JETlike*)	38.22	25,98	[MW]/
Peak NWL (*H=1* | *JETlike*)	0.5 | 0.34		[MW/m2]
Plasma current	2.54		[MA]

Given the impact of the settings in such 0.5D approach, higher fidelity modelling has been carried out and is reported in [17]. As a consequence, an update of this design point is currently ongoing – cf. next section.

Workflow: from low to high fidelity

Given the uncertainties in simplified 0.D modelling reported above, we have employed higher fidelity codes to study some peculiar aspect in isolation (e.g. SOLPS for power exhaust [15]), but also moving towards high-fidelity integrating modelling – ASTRA with TGLF to model the turbulent transport coupled with RABBIT for the NB modelling and FACIT for the W transport [17]. The ASTRA-TGLF-RABBIT-FACIT workflow applied on JET 99971 at 10 s has reproduced the measured profiles as well as the fusion power and the radiated power. This validated framework allows to address accurately the VNS complex interplay between i) the density profile and the beam penetration, ii) the torque and the NBI power loss, iii) the loop voltage and the NBI radius of tangency and iv) the rotation and the tungsten transport, and further aspects. Within this framework, to obtain a loop voltage compatible with the flux available on flat top (V_{loop} < 2mV), the NBI energy had to be increased to 150 keV, the ECRH to 10 MW and used for current drive and the density had to be reduced to allow for NBI penetration. The steady-state solution presented above, once assessed with high fidelity tools, exhibits a fusion power of 24 MW and a density presently not compatible with the exhaust solution with relies on high T flux and high separatrix density [15]. Moreover, the current profile compatibility with MHD stability still needs to be assessed – keeping in mind the effects of massive current drive on the q −profile shape. Last, but not least, the fast particles (both beams and α's) could drive MHD modes as well as fast particle losses, requiring particular attention [18]. Dedicated investigations on all these aspects are currently ongoing. In view of these more advanced physics assessment of the present VNS design point, METIS has now been modified to capture the high-fidelity integrated modeling results, and is presently used to re-explore the design space along the guiding principles presented here.

Acknowledgments

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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