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Assessing the feasibility of a high-temperature, helium-cooled vacuum vessel and first wall for the Vulcan tokamak conceptual design

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ABSTRACT

The Vulcan conceptual design ($R = 1.2$ m, $a = 0.3$ m, $B_0 = 7$ T), a compact, steady-state tokamak for plasma–material interaction (PMI) science, must incorporate a vacuum vessel capable of operating at 1000 K in order to replicate the temperature-dependent physical chemistry that will govern PMI in a reactor. In addition, the Vulcan divertor must be capable of handling steady-state heat fluxes up to 10 MW m^{-2} so that integrated materials testing can be performed under reactor-relevant conditions. A conceptual design scoping study has been performed to assess the challenges involved in achieving such a configuration. The Vulcan vacuum system comprises an inner, primary vacuum vessel that is thermally and mechanically isolated from the outer, secondary vacuum vessel by a 10 cm vacuum gap. The thermal isolation minimizes heat conduction between the high-temperature helium-cooled primary vessel and the water-cooled secondary vessel. The mechanical isolation allows for thermal expansion and enables vertical removal of the primary vessel for maintenance or replacement. Access to the primary vessel for diagnostics, lower hybrid waveguides, and helium coolant is achieved through ~1 m long intra-vessel pipes to minimize temperature gradients and is shown to be commensurate with the available port space in Vulcan. The isolated primary vacuum vessel is shown to be mechanically feasible and robust to plasma disruptions with analytic calculations and finite element analyses. Heat removal in the first wall and divertor, coupled with the ability to perform in situ maintenance and replacement of divertor components for scientific purposes, is achieved by combining existing helium-cooled techniques with innovative mechanical attachments of plasma facing components, either in plate-type helium-cooled modules or independently bolted, helium-jet impingement-cooled tiles. The vacuum vessel and first wall design enables a wide range of potential PFC materials and configurations to be tested with relative ease, providing a new approach to reactor-relevant PMI science.

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1. Introduction

Plasma–material interaction (PMI) science is critical to the development of magnetic fusion reactors. PMI processes such as material erosion, hydrogenic fuel retention, and impurity production pose significant challenges for both plasma operations and material longevity, especially in the divertor. Reactors must operate in steady state, requiring greater understanding of long-term PMI issues resulting from high particle fluence and thermal loads. The main purpose of the Vulcan conceptual design (Vulcan hereafter), a compact, steady-state tokamak (see Table 1), is to explore reactor-relevant PMI issues [1].

An important design feature for a PMI research tokamak is a high-temperature (~1000 K) plasma-facing first wall. Reactors will maximize their structural operating temperature in order to achieve high thermodynamic efficiency for economical power production. High-temperature operation, however, has significant consequences for plasma performance and plasma-facing materials (PFM) because the physical chemistry that governs PMI is strongly temperature-dependent. For example, phase transitions and recrystallization are set primarily by temperature, while fuel retention, diffusion, and erosion processes have rates that vary exponentially with temperature, which strongly determine the performance of PFMs in fusion devices [2].

Operating a compact tokamak with a high-temperature first wall and vacuum vessel poses a unique set of engineering challenges. The vacuum vessel (VV) must maintain high vacuum and uniform temperature while minimizing conductive and radiative heat transfer to the surrounding structures, especially the cryogenic superconducting magnets. The vacuum vessel and support structure must be assembled at room temperature and then heated to the desired operating temperature. This temperature must then be

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Table 1
Engineering and plasma parameters for three example operational scenarios for Vulcan. The "A" scenario is full Vulcan performance; the "B" and "C" scenarios are more conservative for the first wall and for the current drive system, respectively.

Parameter	Scenario		
	A	B	C
Plasma major radius, R (m)	1.20	1.20	1.20
Plasma aspect ratio, R/a	4.0	4.0	4.0
Plasma elongation, κ_{95}	1.7	1.6	1.6
Plasma triangularity, δ_{95}	0.7	0.7	0.7
LCFS surface area, S (m^2)	19.8	19.0	19.0
Plasma volume inside LCFS (m^3)	3.6	3.4	3.4
LCFS power flux, P/S ($MW\,m^{-2}$)	1.0	0.75	1.0
Total heating + CD power, P_{ext} (MW)	19.8	14.2	19.0
On-axis magnetic field, B_0 (T)	7.0	7.0	7.0
Assumed H-factor, H_{98}	1.2	1.0	1.0
Energy confinement time, τ_e (ms)	94	61	35
Vol.-avg. electron temp., $\overline{T}_e$ (keV)	2.7	1.6	3.0
Fraction of reactor-similarity density	1.0	0.75	0.30
Vol.-avg. electron density, $\overline{n}_e$ ($\times 10^{20}\,m^{-3}$)	3.95	3.22	1.38
Safety factor, q_*/q_{cyl}	3.0/1.54	4.0/2.25	4.0/2.25
Total plasma current, I_p (MA)	1.70	1.17	1.17
Assumed plasma charge state, Z_{eff}	1.3	1.3	1.3

maintained by active heating or cooling, depending on the plasma conditions. In addition, the design of the vacuum vessel must provide sufficient access for helium coolant, lower hybrid current drive (LHCD) waveguides, and diagnostics, as well as accommodate thermal expansion of the vessel structure.

Engineering challenges are also significant in the design of the plasma-facing first wall, especially in the divertor. In addition to an actively cooled first wall, the Vulcan divertor will need to handle heat loads similar to those expected for a reactor, with steady-state heat fluxes up to 10 $MW\,m^{-2}$. In an experimental PMI science tokamak such as Vulcan, the design of the plasma-facing components (PFCs) in the first wall and divertor should facilitate in situ maintenance for device availability and modular replacement for scientific purposes.

2. Conceptual design of the vacuum vessel

The conceptual design of the vacuum vessel for Vulcan proposes an innovative double VV configuration that meets the difficult requirements required for a PMI tokamak: high-temperature operation of the first wall; low heat transfer to surrounding structures; accessibility for coolant, waveguides, and diagnostics; and accommodation of thermal expansion. The inner (or primary) vessel can be maintained at the high temperature required for PMI science, while providing high vacuum for plasma operations and support structure for the PFCs. The outer (or secondary) vessel is separated from the primary vessel by a rough vacuum gap that, unlike other double-walled vacuum vessel designs such as that of ITER [3], is intended to provide mechanical and thermal isolation from the primary vessel. The secondary VV also provides a low-temperature support structure for the poloidal shaping/equilibrium coils, shielding, and other necessary hardware. In addition to the isolation, the gap also provides clearance to allow for vertical removal of the primary VV for maintenance, and accommodates thermal expansion during high temperature operation. An exploded illustration of the Vulcan double VV configuration is shown in Fig. 1.

The remainder of this section is structured as follows: Section 2.1 presents material considerations for the VV; Section 2.2 describes the motivation for thermally isolating the primary VV with a vacuum gap and its impact on the design; and Section 2.3 describes the mechanical design of the VV, including the design and accessibility of required connections to the primary VV.

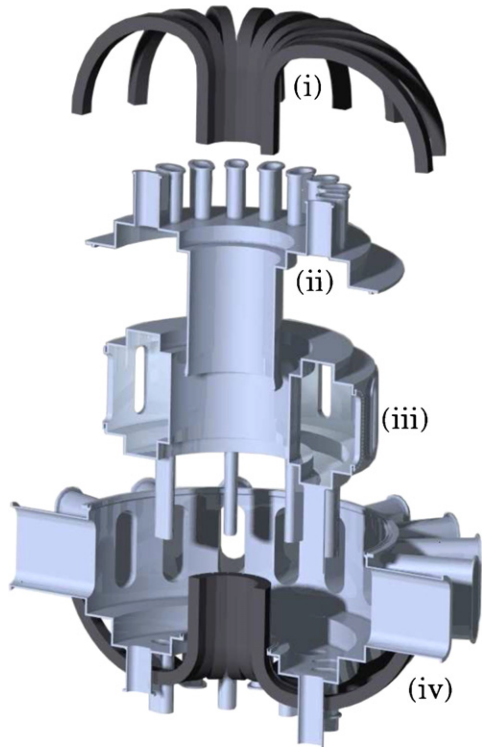

Fig. 1. The demountable toroidal field (TF) magnets proposed for Vulcan [4] allow for vertical disassembly of the Vulcan core components. With the (i) TF magnets demounted, the (ii) top of the secondary VV can be removed, allowing the (iii) primary VV to be removed vertically in one piece for ex situ maintenance or replacement, as well as access to (iv) the secondary VV.

2.1. Material choices

The high-temperature operation of Vulcan, combined with the need to withstand $\vec{J} \times \vec{B}$ disruption forces (see Section 3), imposes significant constraints on the choice of structural materials. The secondary VV and other structural components are water-cooled at or below 373 K, and standard vacuum-grade stainless steels are expected to be sufficient. For the primary VV, however, structural materials that maintain favorable mechanical properties, such as strength, fracture toughness, and material creep, up to 1000 K are required for the primary VV to be robust against disruption-induced mechanical stresses that are expected to be more frequent in an experimental device like Vulcan than a commercial reactor. Neutron activation of structural materials is not expected to influence material choice due to the significantly lower thermal reactivity and 2.45 MeV neutron flux in Vulcan compared to a deuterium-tritium burning reactor [4].

Because the activation concern is greatly mitigated in Vulcan, many high-performance nickel alloys (*e.g.* Inconel 718/625/623/X-750, Hastelloy) and molybdenum-based alloys (*e.g.* TZM) may be considered for Vulcan that are considered unsuitable for reactors. In addition, relatively new materials like oxide-dispersion strengthened (ODS) steels and vanadium alloys have operating ranges approaching 1000 K, although further development of fabrication and joining techniques will be required before they can be used in the construction of vacuum vessels. Reviews of structural materials for fusion applications may be found in [5,6].

Inconel X-750, an austenitic precipitate-hardened nickel-chrome alloy, has been chosen for the initial analysis of the primary VV and support structure due to its high tensile strength and creep resistance at temperatures above 1000 K. Inconel X-750 has been widely tested in high-temperature industrial and military application, such as nuclear power plants, gas turbines, and jet engines,