Progress in Developing the K-DEMO Device Configuration*

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Abstract — K-DEMO is being studied by South Korean researchers as a follow-on to ITER and the next step toward the construction of a commercial fusion power plant. The K-DEMO mission defines a staged approach targeting operation with an initial testing phase for plasma facing components and critical operating systems to be followed by a second phase which centers on upgrading the in-vessel components for operation at 200 to 600 MWe with a planned 70% availability.

This paper reviews the general arrangement of the K-DEMO device core, the novel configuration concept for the vertical maintenance of large in-vessel segments and describes the arrangement and maintenance of planned interfacing auxiliary systems and services – design features which impact the ability to operate with a staged mission strategy that ends with high availability operations.

Keywords—DEMO; fusion; availability

I. INTRODUCTION

The staged mission and planned 70% availability goal of K-DEMO sets a strong requirement for developing a machine design that supports operating flexibility and ease of maintenance. An earlier paper by Kim [1] provides an overview of the K-DEMO conceptual design study and defines the planned schedule and early physics scenarios that were investigated in sizing the device. A range of machine sizes has been studied (6.0-m to 6.5-m) with an emphasis on maximizing the TF magnetic field to offer engineering margin to allow for uncertainties that might be encountered in moving from ITER plasma physics operations to K-DEMO. High availability calls for the need to define large TF magnet coils that can accommodate the replacement of large plasma components defined in an arrangement that fosters ease of maintenance, access for services and is compatible with a disruption load structural support system. A number of DEMO configuration concepts have been developed and studied over the years [2-6] that hope to meet the challenge of high availability. A recent PPPL pilot plant study [7] defined an advanced tokamak (AT) configuration concept that incorporated a vertical maintenance scheme in a somewhat different arrangement – an arrangement that provides greater space on the outside of the plasma chamber for a horizontal assisted vertical maintenance scheme. Incorporating the pilot plant maintenance approach with the K-DEMO mission resulted in a design with two unique features that differentiate it from DEMO configuration designs currently being considered within the fusion community. The design offers 1) a unique vertical maintenance scheme that has the potential to meet high availability goals in an arrangement that can support some number of plasma disruptions and 2) incorporates a pair of windings within each of sixteen large TF coils sized for the machine vertical maintenance scheme.

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The current progress in developing the K-DEMO device configuration will be presented in detail in this paper along with reference changes in the machine size as reported by Kessel [8]. Very early work has started in evaluating blanket details and the effects they have on the configuration design.

II. CONFIGURATION DESIGN OVERVIEW

A. Resized device configuration

The K-DEMO device size has been updated based on a revised set of radial build dimensions established for component sizing, tolerances and space allocated to preserve gaps for clearances under operating conditions. Figure 1 list the build details out to the plasma major radius. The numbers listed are reference values that will be evaluated periodically throughout the study period and revised as required to meet changes brought on by further design and analysis details. As listed in the spreadsheet the K-DEMO device major radius was increased to 6.8-m, stemming from revisions to earlier component radial build dimensions and through updated system analysis [8].

B. Basic configuration feastures

The PPPL pilot plant vertical maintenance approach was selected because it offers the potential to improve access to plasma components and enhances integration features between the device and facility. Poloidal field (PF) equilibrium current sizing was found to favor the vertical maintenance approach for the double null plasma, when comparing PF arrangements needed for maintenance (horizontal vs. vertical). In-vessel components are subdivided into sixteen inboard shield modules, outboard blanket/shield modules and TF blanket/shield modules located beneath each of the sixteen TF coils. The expanded

COMPONEN	K-DEMO COMP BUILD, Z=0	(mm)	(mm)	TOTAL (mm)
	Machine Center			0
	Solenoid Center	1490		1490
CS	ground wrap	10		
	Winding pack thk	476		
	ground wrap	10	496	1986
	Gap	10		
	Tie Plate / lead supt	114		
	OH TPT	6		
	TF TPT	9		
	Min OH/TF Gap	10		
	OH/TF deflection	10		
	Wedged coil asmbly fit up	5		
	Bucking Cyl	0	164	2150
INBD TF	Ext structure	405		
	Clearance	5		
	ground wrap	5		
	OC Winding pack thk	360		
	ground wrap	5		
	ground wrap	5		
	IC Winding pack thk	200	2850	TF inbd center
	ground wrap	5		
	Clearance	5		
	Ext structure	75	1070	3220
	TF winding tolerance	10		
	Wedged coil asmbly fit up	10		
	Trapezoidal Effect	30		
	TF TPT	10		
Thermal Insu	cold wall / thermal insul	120		
	Min VV/TI Gap	10		
	VV TPT	10	200	3420
Inboard VV	VV shell thk	40		
	Shell gap	50		
	VV shell thk	40	130	3550
	VV TPT	5		
	EM load displacement	9		
	Backbone TPT	5		
	Min VV/Backbone Gap	5		
	Thermal Shield	5		
Backbone	Backbone shield structure	100		
	Gap+TPT	5		
	Diagnostic mounting space	25	159	3709
Blanket/Shld	Manifold space	217		
	Back wall-Shield	120		
	tolerances	6		
	Breading Zone	517		
FW	FW	31	891	
	Plasma SO	100		4600
	Plasma minor radii	2100		4700
Plasma R0				6800

Fig 1. K-DEMO radial build to plasma center

TF and vacuum vessel allows sizing large vertical ports to accommodate the segmented in-vessel sector modules. Divertor components are further sub-divided and can be maintained independent of the sector module, moving them through the vertical ports. A semi-permanent inboard shield forms a strongback for supporting disruption loads, providing shielding for gaps between sectors and an alignment system for plasma components. Instead of supporting the internal blanket/shield modules from the vacuum vessel a lower base platform is included that also serves as a coolant plenum to service the FW/blanket modules. Replacement of all components would be from above, consistent with the expected initial machine vertical assembly process. Space is available to concurrently service half of the in-vessel components at any one time. The enlarged TF coils provide a very low 0.08% ripple that benefits plasma operations of a fusion reactor and allows increased space on the outside of the blankets for maintenance. The overarching design philosophy has been to expand the maintenance and service coverage of the in-vessel components from below, around the periphery of the device and from above in an effort to meet the high availability goal. The elevation view of figure 2a illustrates the basic segmentation concept defined for the internal in-vessel components to allow them to be assembled and maintained through vertical ports. Although not developed in detail, the concept being pursued strives to develop a system that supports components, moving from high to lower temperature conditions, which have toroidal and radial segmentation that allow them to be accessed and removed through vertical ports. The toroidal extent of the outboard blanket modules is sufficient to allow heating or test modules to be installed without completely splitting a module in the vertical direction; providing space for continuous blanket connections and services. Figure 2b illustrates the segmentation details of the K-DEMO device.

C. Configuration details

The general arrangement of the K-DEMO device is illustrated in the isometric view of Figure 3. Maximizing vertical access to plasma components requires enlarging the TF coils and locating PF coils farther from the plasma, restricting them to regions that do not interfere with the

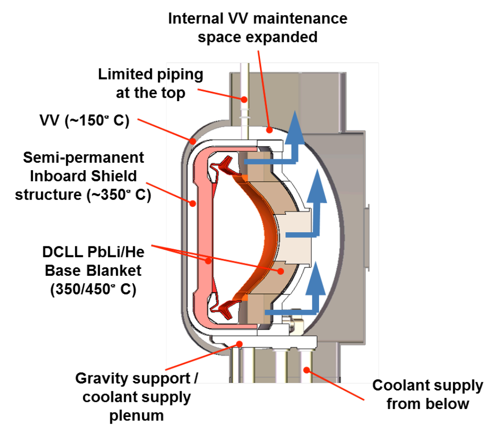


Fig 2a. In-vessel segmentation scheme

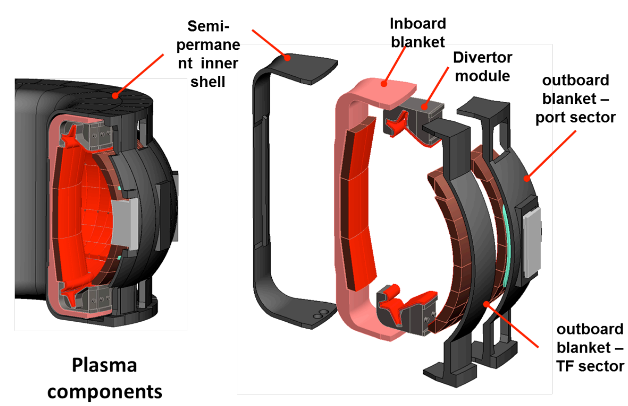


Fig 2b. K-DEMO divertor / blanket module arrangement

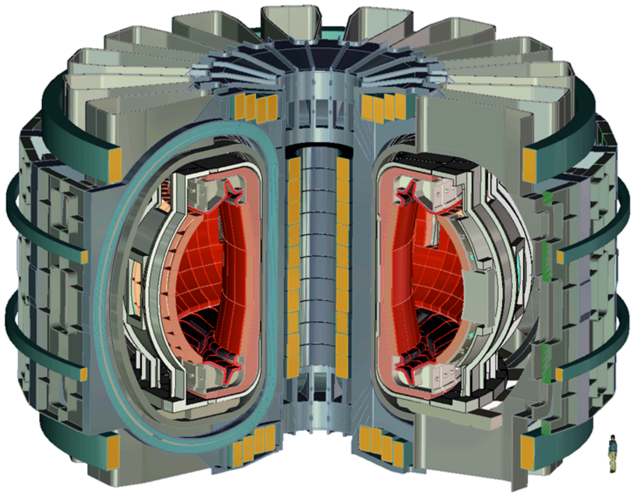
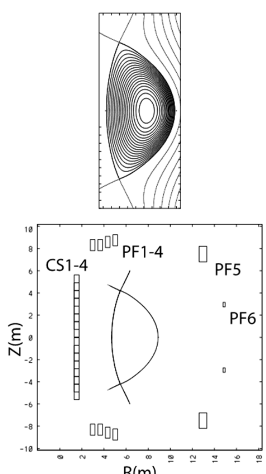


Fig 3. K-DEMO isometric view

vertical access ports or smaller planned horizontal ports. Past power plant design studies have investigated similar PF coil arrangements with successful results. To validate earlier studies an equilibrium calculation was made looking at the PF solutions for the Phase II operation of K-DEMO. Figure 4 shows the results of the analysis illustrating coil locations and currents for the Phase II flat top condition.

Vertical maintenance allows the development of a large structural shell to be formed at the outer region of the TF returrn legs to support the TF against out-of-plane magnetic loads. Access space is provided on the shell for horizontal ports sized for heating systems and maintenance access to assist in-vessel vertical maintenance activities. The inner portion of the TF coil case was designed to follow an ITER style support system; analytical details of the TF will be discussed later in Section III.

MA	ψ = -100 Wb Pre-mag	Ip = 12 MA, β_N=3.0, li(1) = 0.7, ψ = 100 Wb	Ip = 14 MA, β_N=4.2, li(1) = 0.7, ψ = 100 Wb
CS1	7.68	-3.11	-1.55
CS2	7.68	-3.11	-1.55
CS3	9.65	-3.25	-2.25
CS4	9.65	-3.25	-2.25
PF1	2.323	4.506	5.715
PF2	3.171	6.235	7.909
PF3	3.475	6.169	7.897
PF4	3.663	5.286	6.914
PF5	0.021	-13.70	-15.95
PF6	0.184	0.135	-0.223



* 100 Wb flux state is scaled based on ARIES-ACT1, double swing

Fig 4. PF coil solution for K-DEMO Phase II high current, high beta flat top condition

With the introduction of a base machine support system and a separate semi-permanent structure to support and align the blanket modules it is expected that a lighter weight vacuum shell can be formed on the inboard side, somewhat offsetting the increase in the radial dimension emanating from the added semi-permanent blanket support/alignment system. While the upper vacuum vessel vertical port is used for plasma component maintenance the lower vertical port will contain the support legs for the plasma core base structure and piping services. A vacuum boundary with a sliding interface to the cryostat lower section will be established – an arrangement developed for the PPPL AT pilot plant.

Design studies have been initiated to look at blanket designs and service details that play a major role in developing a successfully integrated device configuration. Solid and liquid blankets will be evaluated with design details from ITER and studies from within the fusion community used to underpin the effort. The cost of tritium is expensive so reaching tritium breading ratios (TBR) much greater than 1 will be required.   Of equal importance is developing the integrated details of the blanket system to include local piping, support systems and the interface to plasma control components (magnetic loops and passive plates). Figure 5 shows in-progress development of solid breeding blanket concepts with a breakdown of some of the components. The selected candidate blanket design will be made based on technology considerations, the ability to meet TBR requirements, expected system reliability and ease of maintenance.

III.   MAGNET DESIGN AND ANALYSIS DETAILS

A. TF design

Incorporating a pair of windings within each TF coil was initiated to reduce pressure drop problems that occur with large coils and to reduce costs. The pressure issue could be

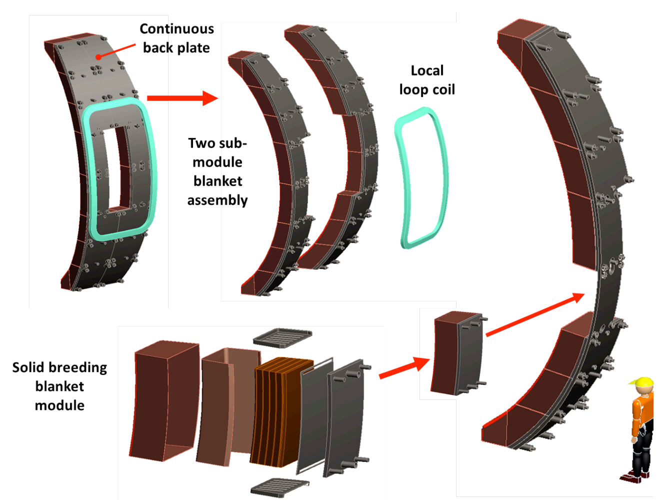


Fig 5. Solid breading blanket design

solved by inserting a larger cooling spiral so the main merit is the reduction of CICC (cable-in-conduit conductor) length. Making a very long CICC is somewhat limited by engineering problems and incorporating a two winding scheme (a graded coil approach) helps solve this problem. The main cost of CICC is the superconductor (CS) strand cost. The cost of OFHC copper strands is almost insignificant. Based on initial calculations the anticipated cost reduction for K-DEMO two-winding design is approximately $1.7 B. There are also expected significant cost reductions in cabling, tube cost, jacketing and coil manufacturing. Figure 6 shows the basic TF winding arrangement of the 16 Tesla peak field magnet.

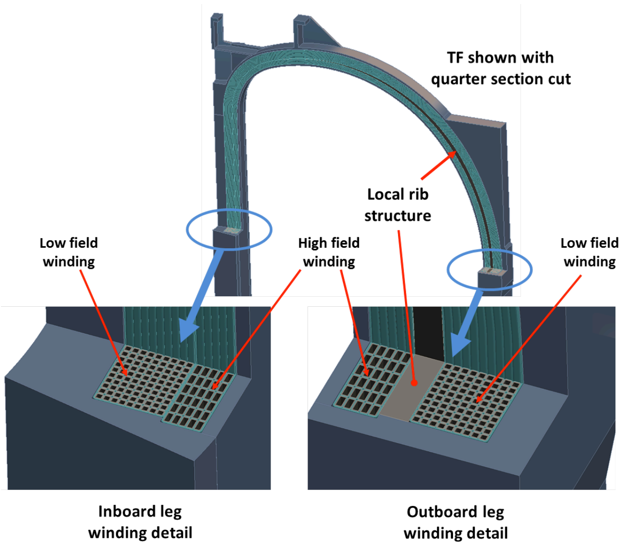


Fig 6. Illustration of two-winding TF design

The physical dimensions of the high current density Nb_3Sn CICC cabling schemes are presented in Fig. 7. The conductor size and strand details were altered from the earlier reported study [1] to increase quench energy and stability margins. Further winding analysis will be carried in the next phase of the design study. Progress is being made in defining the winding turn cross-over details, helium feed-through design, magnet intercoil joint scheme, lead supports and the lead routing through the cryostat. Some details are highlighted in Figure 8.

B. Analysis

An FEA analysis of the TF windings, case and inter coil structure is in works but the results were not completed to be presented in this paper. Based on analysis of the smaller PPPL AT pilot plant, a similar configuration design, stress levels in the TF were within design alowables. However, given the larger size of the K-DEMO TF coil a potential concern is raised dealing with the load split between the inboard and outboard legs of the magnets. If the TF design lacks stiffness in the support structure of the back leg more of the TF vertical load will be carried by the inboard leg which may require more structural material to support the

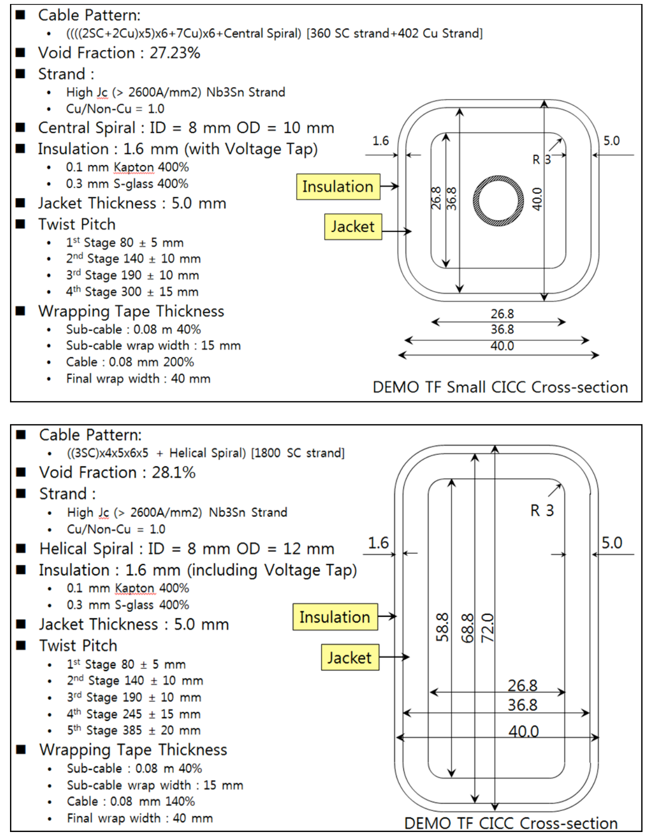


Fig 7. Small and large CICC winding parameters

winding than initially planned. Any material increase would result in an increase in the machine size. The two winding scheme in itself is more efficient in current capacity and reduces the overall winding pack area in the TF inboard leg when compared to a single winding pack design; however, an analysis is needed to determine if the space that has been

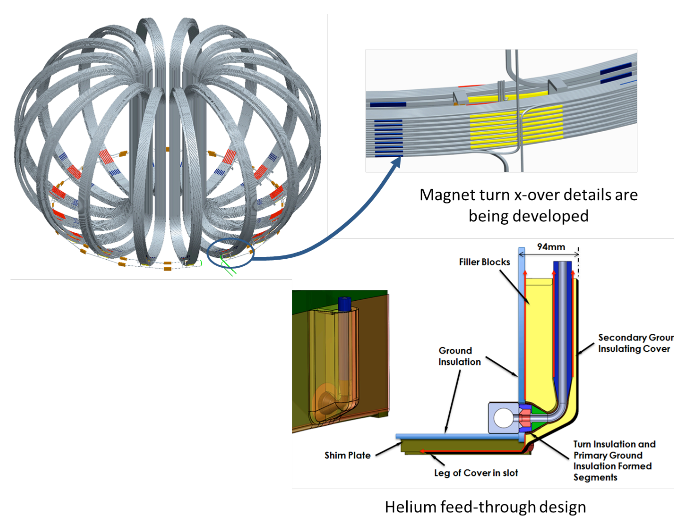
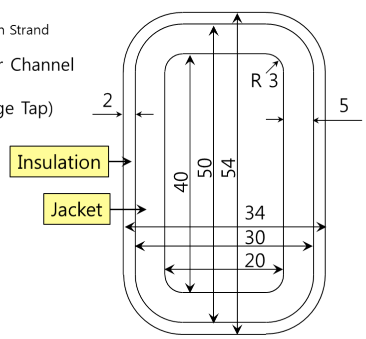


Fig 8. TF design features currently being developed

allocated for the TF winding and case is sufficient.

A preliminary analysis of the PF magnets has been run with the results showing a smeared stresses in the central solenoid (CS) at 76 MPa. Based on the CS cross section (shown in Figure 9) the jacket stress would be 2.6 times higher or 200 MPa. ITER allows 450 MPa implying that the jacket could be thinned to provide more cable space, or allow a reduction in the build space allocated to the CS. The rounded corner rectangular conductor can have high stress concentration factors, but assuming the number of cycles is low enough then fatigue will not be a concern. Evaluating the stress conditions for the PF ring coils resulted in stress levels below allowable requirements, with the largest stress (332 MPa) found in the large outer PF coil located outside the vertical ports.

- Cable Pattern: (2SC+1Cu)x3x4x4x6 [576 SC Strand + 288 Cu Strand]
- Void Fraction : 35.85%
- Strand :
  - ITER Type (Jc ~ 1000A/mm2) Nb3Sn Strand
  - Cu/Non-Cu = 1.0
- NO COOLING SPIRAL → Corner Channel
- Jacket Thickness : 5 mm
- Insulation : 2.0 mm (with Voltage Tap)
  - 0.1 mm Kapton 400%
  - 0.4 mm S-glass 400%
- Twist Pitch
  - 1st Stage 20 ± 5 mm
  - 2nd Stage 45 ± 10 mm
  - 3rd Stage 85 ± 10 mm
  - 4th Stage 150 ± 15 mm
  - 5th Stage 355 ± 20 mm
- Wrapping Tape Thickness
  - Sub-cable : 0.08 mm 40%
  - Sub-cable wrap width : 15 mm
  - Cable : 0.5 mm 60%
  - Final wrap width : 7 mm



DEMO CS CICC Cross-section

Fig 9. CS CICC Parameters

IV. SUMMARY

The conceptual design of K-DEMO continues to evolve and analysis details are underway looking at the key component areas that underpin the design. The device size has increased somewhat from the design reported in earlier reports with greater margin provided in the TF windings and expansion of the operating space for both stages of machine operation. Future work will involve expanding the design and analysis details of the TF system, blanket system and performing a preliminary analytical assessment of the semi-permanent inboard shield/strongback in its ability to support the plasma core components against disruption loads.

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