Novel Vacuum Vessel & Coil System Design for the Advanced Divertor Experiment (ADX)

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Abstract—The Advanced Divertor eXperiment (ADX) [1] is a compact, high field (> 6.5 tesla), high power density tokamak, proposed by the Plasma Science and Fusion Center (PSFC) and collaborators, designed specifically to develop and test advanced divertor configurations that can accommodate the extreme plasma heat exhaust densities anticipated in next-step plasma fusion devices. ADX will also develop and test advanced technologies for Lower Hybrid Current Drive (LHCD) and Ion Cyclotron Range of Frequency (ICRF) heating, including the ability to deploy RF launch structures on the high-field-side for the first time. This potential game-changing innovation is expected to provide efficient heating and high efficiency, off-axis current drive while minimizing impurity production via plasma-launcher interactions [2, 3]. This combination of advanced divertors and innovative RF systems places unique demands on ADX’s vacuum vessel (VV), which must have an integrated design that can incorporate the required poloidal field coil set and embedded infrastructure for RF feeds to the high-field-side vacuum vessel wall.

Much of the ADX poloidal field (PF) coil system, toroidal field (TF) magnet and structural design is based on the successes of the C-Mod tokamak program, with the capability to operate at up to 8 tesla on axis – a rigid vacuum vessel providing structural support for the PF coils, and a liquid nitrogen cooled, demountable TF magnet. However, five separate axisymmetric structural shells and one inner cylinder are bolted together to form the VV in a novel configuration for ADX. This unique design accommodates the poloidal coil configurations required to produce the proposed advanced divertor shapes while at the same time providing flexibility for implementing alternative coil configurations. This paper describes ADX’s vacuum vessel, coil system design and in-vessel components.

Keywords—instrumental vacuum vessel design; high field side LH launcher; high field side ICRF antenna; advanced magnetic divertor

I. INTRODUCTION

The Advanced Divertor eXperiment (ADX) is a new compact, high field (>6.5 tesla), high power density tokamak proposed by the PSFC and collaborators, taking advantage of the high-field magnet technology and extensive infrastructure that presently supports the Alcator C-Mod facility. The initial design concept shown in Fig. 1 illustrates the arrangement of demountable Toroidal Field (TF) coil, the poloidal field (PF) coils and the Ohmic heating (OH) coils, which use the magnet technology developed for the Alcator C-Mod Tokamak. The proposed vacuum vessel (VV) design is a novel approach, composed of five separate axisymmetric structural shells and an inner cylinder wall, bolted together to form the vessel. The VV is configured to specifically evaluate advanced divertor magnetic topologies, including super-X, and X-point target long leg divertor concepts, with options for heated and liquid metal target surfaces. Additionally the VV is specifically designed to accommodate Lower Hybrid current drive launchers and RF heating antennas located on the high-field-side.

The initial design concept for ADX makes maximal use of outstanding plasma physics facility that has been assembled at the MIT PSFC for the Alcator C-Mod program – state of the art high power ICRF heating and LH current drive systems, 225 MVA pulsed power systems, and a highly experienced physics and engineering team with over 20 years of experience in the development, and operation of a cryogenically cooled, high-field, high performance Tokamak.

II. ADX VACUUM VESSEL

Fig. 2 illustrates a cross-sectional view of ADX VV. The VV is specifically designed to fulfill the poloidal coil configurations required to produce the proposed advanced divertor shapes. It also has specific ports to permit the installation of three Lower Hybrid launchers, and one two-strap ICRF antenna on the high-field-side. Two outboard, field-aligned ICRF antennas are designed to deliver 8 MW of auxiliary heating to the plasma; these have specifically designed ports to maximize performance, Fig. 3.

The vessel is constructed from Inconel 625 and like the Alcator C-Mod vessel, provides the mechanical support for the Poloidal (PF) and Ohmic heating (OH) magnets. The VV is composed of five separate shells and one inner wall cylinder which are bolted together to create the torus. The vacuum seal is achieved by welding a continuous strip of Inconel material across the bolted joints (Fig. 4). All vacuum seals can be tested prior to installation. The vacuum vessel is currently design with two oversized horizontal ports (228 mm wide) to improve in-vessel manned access for maintenance.

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Fig. 1. Initial design concept for ADX. ADX is based on the High Field, Demountable Toroidal & Poloidal field magnet technology and the RF systems developed for the Alcator C-Mod Program. This design approach reuses the top and bottom domes, the top/bottom wedge plates, the draw bars and machine support legs from Alcator C-Mod Tokamak, providing the potential for a significant cost savings.

An important advantage of this design approach is the ability to fully install in-vessel components into the individual vacuum vessel shells and inner wall cylinder prior to assembling the completed vacuum vessel. This largely avoids the personnel training and safety issues associated with confined space access and entry, and allows for multiple installation/assembly operations to be performed at the same time, thus minimizing scheduling conflicts and greatly reducing assembly time. The assembly, testing and inspection process can be performed in a clean environment using Coordinate Measuring Machines (CMM) as well as standard tooling to make sure the desired installation tolerances are achieved. Fig. 5 shows the exploded view of the five shells and inner wall cylinder that form the VV. Although the vacuum vessel design and assembly appears more complicated than in a conventional tokamak system, it provides an
III. EMBEDDED MAGNETICS AND CONTROL INSTRUMENTATION

The practical operational experience that has been gained on Alcator C-Mod will be applied to ADX, leading to a number of important improvements that will be incorporated into the magnetics/control system for ADX. Similar to C-Mod, ADX will have a thick vacuum vessel, so the magnetics diagnostics must be mounted inside the vessel to provide sufficient time response.

The B-fields, fluxes, currents, and discharge duration in ADX will be similar to C-Mod. This means that the magnetic sensor set and associated analog electronics will also be similar. The ADX vacuum vessel will be designed to be baked at the same maximum temperature as C-Mod, i.e. 150 °C, allowing the same sensor materials, designs, and fabrication techniques to be employed. However, because of the segmented nature of the ADX vessel, the magnetics diagnostics will have to be installed into individual shells before the shells are bolted together. This has the most impact on instrumentation in the upper and lower divertor regions.

A basic design philosophy for the magnetics on C-Mod was to minimize in-vessel splices/connections/joints. This was driven by the premise that lead connections are prone to failure. This design philosophy resulted in long lead runs that went all the way from sensors to vacuum feedthroughs. This was feasible during the initial installation of the magnetics on C-Mod, before the tiles, divertors, antennas, cryo-pumps, and other diagnostics were installed. But it proved to be unwieldy when unanticipated, new magnetics diagnostics were added (e.g. for disruption studies), or when damaged sensors had to be replaced. In this case, it was found necessary to splice new sensors onto old leads, using both soldering and crimping.
techniques. So a new design philosophy will be employed for ADX, namely the copious use of junction boxes and/or connector strips in each of the six vessel shells. They will be permanently installed while ADX is undergoing its initial construction. The capacity of these junction boxes should exceed the anticipated number of sensors to be needed for the entire life of the machine. Large lead bundles, with appropriate arming, will be permanently run to nearby vacuum feed-throughs. Magnetics diagnostics, with relatively short leads, can then be easily installed/added/replaced at will, at virtually any location in the vessel. Such a system is being used in the EAST tokamak. Each vessel sector will have its own sensors, junction boxes, lead bundles, and vacuum feed-throughs, with no cross-connects between vessel sectors. All of this instrumentation will be installed before the vessel sectors are assembled into a closed torus. Another area of concern found through operational experience on C-Mod was that the standard, dual-connector, multi-signal vacuum feed-throughs (which initially had MIL-svals, but eventually lost their accreditation) were the most troublesome component of the magnetics system. The pin-into-socket receptors were made of materials that had insufficient springiness, and that apparently tended to build up a non-conducting oxide layer. This was particularly troublesome during disruptions. The problem was compounded by the fact that the port flanges that held the magnetics feed-throughs were inexorably intertwined with other diagnostics, and thus were often dismantled during annual shutdowns/inspections. ADX will be designed from the start to avoid these limitations – well-tested and qualified magnetics feed-throughs will be employed, physically separated from the standard diagnostic vacuum flanges, and welded directly into the vacuum vessel wall where needed to connect to junction boxes. The channels for magnetics instrumentation (Rogowski loops, flux loops) and connection leads will be machined directly into the vacuum vessel wall with removable cover plates. This will provide both a robust mechanical protection and the accurate metrology needed for this critical diagnostic set.

IV. ADX Coil System

The current TF coil design for ADX is made from Copper C107 and consists of 120 turns with each turn made up of four separate conductor plates, see Fig. 6. The innermost plates, making up the TF core, are wedge shaped and are bonded together to form a strong cylindrical structure that must react the local in-plane and out-of-plane electromagnetic loads internally. Although not yet analyzed at this point in the design to support the stresses, the TF core copper plates can be reinforced with 216 Stainless Steel plates. This unique design solution was developed for C-Mod. As in the C-Mod design the OH magnets are to be wound on the TF core, but will be free to move vertically in relation to the TF core. The OH magnets are secured (keyed) to the VV central cylinder. This approach creates a compact and efficient design. Twenty upper horizontal arms, 20 lower horizontal arms, and 20 vertical legs, each made up of six copper plates, form the rest of the TF magnet. The coil has a total of 480 joints with each joint composed of four felt metal pads for a total of 1920 contact pads, Fig. 7. In this regard the ADX TF coil is identical to the successful Alcator C-Mod TF coil. The demountable TF coil for ADX, provides the flexibility to make changes to the Tokamak vacuum vessel, Poloidal coil arrangement, and internal vessel components in a timely manner. Experience with the operation of C-Mod, shows that a complete disassembly and reassembly can be performed within 10 months.

The TF coil, the poloidal field magnets and the support structure for ADX is inertial cooled with liquid nitrogen and
will operate at approximately -190 °C. Heaters attached to the outer walls of the VV allow for baking to a temperature of 150 °C and to control the operating temperature as desire, typically 35 °C.

All 20 PF coils are symmetrically arranged about the mid-plane of the vessel into upper and lower sets. The coils are secured to the VV with additional structural components and some of the coils are trapped in the pockets of the vessel once bolted. Preliminary analysis indicates the stresses on the coils and vessel to be within allowables [5]. However, this initial analysis work is limited since it did not incorporate a complete range of plasma equilibria and fault conditions. A full set of analysis will need to be performed in the future.

Current is supplied to the PF coils through coaxial current leads that extend in radially through the cylinder. The coax current leads are identical to the C-Mod PF coils current leads.

V. RF SYSTEMS

The MIT PSFC team has recently developed an advanced Field Aligned (FA) ICRF four strap antenna that has demonstrated superior performance compared to conventional antenna [3]. The FA ICRF antennas were designed and fabricated at PSFC. The proposed FA ICRF antennas for ADX make use of the development work done in Alcator C-Mod with the additional benefit of ADX having specifically designed ports to best optimize the RF coax feeds and strap connections. In addition, in its present design, ADX will have one high-field-side (HFS) ICRF antenna for the purposes of testing. The vacuum vessel design could also incorporate multiple HFC ICRF antennas as a potential upgrade, taking full advantage of the anticipated benefits of HFS launch. The coaxial feed-throughs are installed on special ports located on the upper shell of the vessel. The RF coaxial feed-throughs connect to a vertical strip-line along the inner wall of the vessel that connects to an end-fed-center-ground strap mounted on the inner wall of the vessel, Fig. 8.

ADX is also specifically designed to accommodate the installation of LH launcher on the HFS. The present design calls for the installation of three HFS LH launchers, which will be fed through a set of ports on the upper shell of the vessel, see Fig. 8. The LH is fed by four WR187 wave guides through the upper ports and down the inside of the vessel wall that connect to a 4 x 8 array coupler. The couplers are design to be demountable for maintenance, and future upgrades. As shown in Fig. 8, more room is available to increase the number of LH couplers as a future upgrade.

VI. SUMMARY

ADX is a new and exciting tokamak designed to address key issues: advanced divertors, advanced RF systems, core plasma, pedestal, boundary layer and plasma wall interaction physics. Taking from the knowledge learned from C-Mod, a novel segmented vacuum vessel has been designed. This design accommodates the poloidal coil configurations required for the advanced divertor shapes while at the same time providing flexibility for implementing alternative coil configurations. It provides ideal port configuration for the ICRF antenna and ports permitting the installation of HFS LHCD and ICRF antenna.

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REFERENCES


