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ITER Ion Cyclotron Heating and Current Drive System Gas Barrier

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ITER will be utilizing ion cyclotron radio frequency heating and current drive for the plasma. This necessitates the use of two antennas, a series of transmitters and an array of coaxial transmission lines. With up to 3 MW of power being injected throughout transmission lines, they will have to be gas cooled. The transmission lines are divided into discrete sections in which cooling gas will be injected and exhausted. Each discrete section of transmission lines requires sealed gas barriers for the separation of the transmission line from the adjacent transmission line. This paper presents the design and analysis of a prototypical gas barrier that was fabricated by General Atomics for testing at the Oak Ridge National Laboratory testing facility.

Keywords: ion cyclotron, heating and current drive, gas barrier, coaxial, transmission line

1. Introduction

Two ion cyclotron antennas are being utilized to heat and drive the current of the ITER plasma. These two antennas are capable of injecting 24 MW of rf power into the plasma and are powered by 8 transmitters plus one spare. To transmit the power from the transmitters to the two antennas, water and gas cooled coaxial transmission lines, rf switches, and Hybrid Power Splitters are required to tune and match the rf power to the plasma. The transmission lines originate from the rf Building (Building 15) where the transmitters are located, route through the Assembly Building (Building 14) and enter into the Tokomak Building (Building 13) on the south side. In anticipation of the heating of the inner and outer conductors, the transmission lines are cooled by water-cooled jackets on the outer diameter of the outer conductor and the flow of inert gas between the inner and outer conductors. The flow of cooling gas requires that each of the sixteen coax lines, each approximately 150 meters in length, be separated into 4 discrete sections to allow for efficient cooling of the inner conductor. This necessitates the use of gas barriers that are compatible with the operation of RF transmission lines. One of the 4 gas barriers in each line may also serve as a secondary Tritium barrier as well.

The gas barriers as well as the transmission line are to operate to rf power levels to 6MW in the frequency range of 40 to 55 MHz. The maximum voltage standing wave ratio (VSWR) allowed is 1.05. With a 6 MW power level, the materials of all the components of the transmission line require high voltage standoff capabilities which dictate the use of ceramics or quartz for inner to outer conductor standoffs and supports as well as the gas barrier itself. The anticipated temperature range of the 300 mm diameter outer conductor of the coax is 20^o to 70^oC while the 130 mm diameter inner conductor is expected to be 20^o to 155^oC. The cooling gas for the inner conductor, either clean dry air or Nitrogen, is to have a velocity of 3 to 7 meters/second with a pressure head of 0.3 MPa absolute. These velocity and pressure parameters as well as the gas type were selected for the voltage standoff capabilities.

The qualification testing scenario for the gas barrier is 35 kV at 47.5 MHz for 3600 seconds. A maximum voltage of 40 kV will be applied for 0.1 second with a 10% duty cycle at the beginning, end, and middle of the 3600 second time duration. The cooling gas velocity will vary between 3 to 7 m/s to determine the optimal velocity for heat removal from the inner conductor.

General Atomics (GA) is pursuing the development of an ICH & CD Gas Barrier for the ITER transmission line system. GA has generated a design, and performed electric field analysis, structural pressure analysis and gas flow analysis on the design model. A prototype device has been fabricated and was delivered to Oak Ridge National Laboratory for testing. Anticipate testing to be completed by the fall of 2012.

2. Design Requirements and Operational Parameters

Based on US ITER 15101-PD00005-R00 Statement of Work document, a series of requirements were generated. Other requirements were added based on the requirements for other Ion Cyclotron Heating and Current Drive Coaxial transmission line components and the need to input and exit cooling gas into the various coaxial transmission line sections. The design requirements used in the development of the gas barrier are listed in Table 1.

In addition to the design requirements, device performance enhancements were developed for the design of the gas barrier. Gas inlet and outlet that allows for proper distribution of cooling gas has been incorporated into the design. The electric field concentrations in the areas of the inner and outer conductor supports were minimized to reduce the possibility of breakdown between the outer and inner conductors. Ease of maintenance, assembly and disassembly were also considered in the design. And finally, the gas barrier may be used as a Tritium barrier when placed adjacent to another barrier. This enhancement dictated that only materials compatible with a Tritium environment be used which were incorporated into the design.

Table 1. Design Requirements and Operational Parameters

Up to 3 MW power capability
35 to 65 MHz, 50 Ω impedance, maximum VSWR 1.05
305 mm od
Compatible with Mega Industries End Flange 708095-701
Gas velocity 3-7 m/s
Gas pressure 0.3 MPa delta
Gas maximum temperature 110°C
Inner conductor temperature 20°C to 155°C
Outer conductor temperature 20 °C to 70°C
Maximum delta T between outer and inner conductors 70°C
Outer conductor water cooling
Maximum water inlet pressure: 0.8 MPa
Minimum water outlet pressure: 0.2 MPa
Maximum water delta T: 30°C
Minimum water delta P: 0.4 MPa
Ceramic or quartz insulator
Outer conductor to meet ASME B31.3 paragraphs 304.1.2(a)
All welds to meet ASME B31.3 -2004, paragraph 304.3.3 weld size

3. Description and Design

A model of the gas barrier is shown in figures 1, and 2. Photographs of the assembly with a bypass "U" connection pipe are shown in figures 3, 4 and 5. The barrier consists of a 305 mm diameter outer conductor, a 130 mm diameter inner conductor, an outer conductor gas plenum, 19 mm diameter copper outer conductor cooling tubes, quartz support pins and barrier cone, ethylene propylene diene monomer (EPDM) gasket and o-rings, and ITER standard 305 mm diameter coaxial transmission line mating flanges.

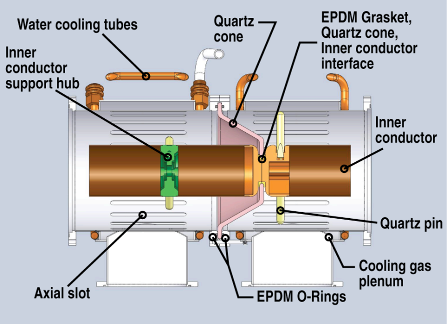

Fig. 1. Gas barrier model (internal view)

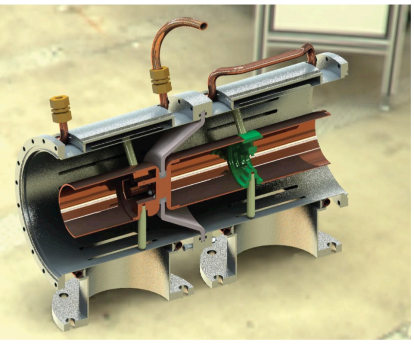

Fig. 2. Gas barrier (Iso view)

The welded outer conductor assembly is made of Aluminum 3003 rolled plate for ease of construction and has 6.4 to 13 mm wide axial slots to allow for proper gas distribution into the inner to outer conductor plenum. The 349 mm diameter gas plenum allows for the cooling gas injection or exit, and distribution of the gas around the circumference of the outer conductor via axial slots. Copper cooling tubes are secured with thermally conductive epoxy to the outer diameter of the outer conductor. The cooling water in the copper tubes is to absorb the RF resistive heat deposited in the outer conductor as well as the heat transferred from the inner conductor to the outer conductor via the injected gas.

Fig. 3. Gas barrier assembly

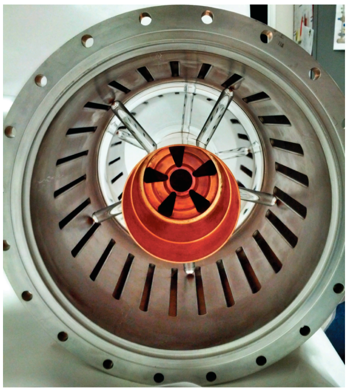

Fig. 4. Gas barrier assembly (end view, interior)

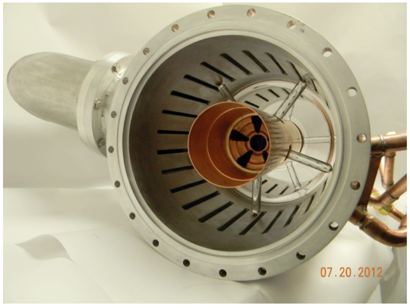

Fig. 5. Gas barrier assembly (end view)

The welded outer conductor assembly is made of Aluminum 3003 rolled plate for ease of construction and has 6.4 to 13 mm wide axial slots to allow for proper gas distribution into the inner to outer conductor plenum.

The 349 mm diameter gas plenum allows for the cooling gas injection or exit, and distribution of the gas around the circumference of the outer conductor via axial slots. Copper cooling tubes are secured with thermally conductive epoxy to the outer diameter of the outer conductor. The cooling water in the copper tubes is to absorb the rf resistive heat deposited in the outer conductor as well as the heat transferred from the inner conductor to the outer conductor via the injected gas.

Fused quartz pins support and position the OFE Copper inner conductor in relation to the outer conductor. The 19 mm diameter pins are recessed into sockets in the inner conductor. Wave springs located in the bottom of the sockets allow for a constant load on the pins and the proper positioning of inner conductor.

Like the pins, the barrier cone is made of fused quartz and has a cone shape to optimize the breakdown resistance of the barrier. To optimize the breakdown resistance of the cone, the angle of inclination of the cone is to match the Brewster angle of the material [2], [3]. The Brewster angle (B) for quartz was calculated to be 56^0 (n = tan(B) where n = index of refraction for material). Sellmeir equation for index of refraction for 3+ meter wavelength was used to further refine the Brewster angle.

> Sellmeir Equation: $n^2(\lambda) = 1 + B_1 \lambda^2/(\lambda^2-C_1) + B_2 \lambda^2/(\lambda^2-C_2) + B_3 \lambda^2/(\lambda^2-C_3)$
>
> B_1, B_2, B_3, C_1, C_2 and C_3 are constants specifically for Quartz .

With this equation, the Brewster angle is 60^0 and was chosen for design of the cone angle.

Fused SiO or quartz material is used for its dielectric properties and minimal impact on the electric field. Quartz's dielectric constant is 3.75 at 1 MHz. It was determined empirically that a 2.5 cm long quartz pin could support 45 kv [4]. The corresponding maximum electric field concentration capability (E_p) was 2.12 MV/m ($E_p = V_{peak}/r \ln(b/a)$ where "r" and "a" are the radius of the inner conductor and "b" is the radius of the outer conductor).

To seal one side of the barrier from the other, EPDM o-rings and gasket are used. The o-rings are the typical coaxial transmission line 317 mm diameter, 1.5 mm cross section o-rings which are to be used throughout the coaxial transmission. A custom inner conductor/quartz cone gasket was designed to seal the inner conductor/quartz cone interface. The inner conductor is two pieces, which bolt together at the inner diameter of the cone. The two inner conductor pieces compress the EPDM gasket against the quartz creating the seal between the two sides of the barrier assembly. Since the gasket is a flexible material, the inner conductors would not be fully supported. This necessitated the use of the quartz pins and hub arrangement to support and position the inner conductor.

EPDM material, specifically Royalene, was selected for the gasket and o-ring material because of it survivability in a tritium environment [4,5,6] and operational temperature limits. Note that if the operational temperature limit is increased above 155°C, an alternative EPDM material such as Royaltherm which has a service temperature up to 190°C, should be investigated. Testing of Royaltherm in a tritium environment has not been completed.

4. Analysis

A series of analyses were performed to verify the integrity of critical design features of the barrier. An electric field analysis of the inner conductor/quartz interface was performed to insure the electric field concentrations were not excessive. Several versions of the geometry of the inner conductor in the area of the quartz material were analyzed. The geometry in figure 6 shows the optimal configuration to position the highest electric field concentration, furthest from the quartz material. For simplicity of the analysis, the 60^0 cone portion of the quartz was not included in the analysis. To obtain the maximum electric field concentration on the inner conductor radius adjacent to the quartz (E_p), the ratio of the peak field derived from the analysis shown in figure 6 (1.14) to the nominal field (0.7) is multiplied by the peak electric field value corresponding to a 3 MW power level (0.32 MW/m). This results in a maximum field concentration of (1.14/0.7) 0.32 MW/m = 0.52 MW/m. This field concentration, when compared with the maximum electric field concentration capability (E_p) for quartz, 2.12 MV/m, has a safety factor of 4.

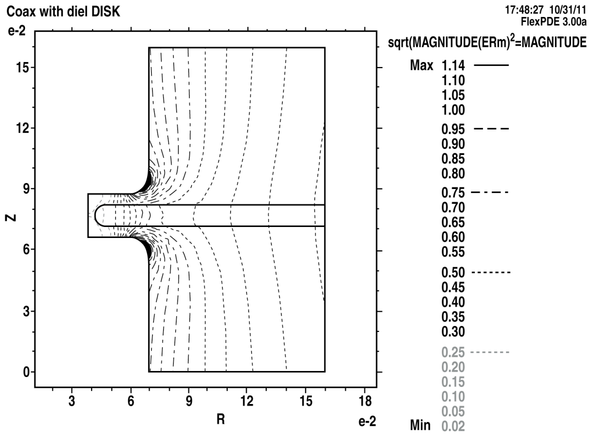

Fig. 6. Gas barrier electric field contours

The quartz cone will be subjected up to 0.3 MPa pressure differential when various sections of the coaxial transmission will be evacuated prior to injection of the cooling gas. An analysis of the quartz cone with a pressure of 3.2 kgf/cm^2 was analyzed to verify that the cone has enough of a safety margin when under pressure. As seen in figure 7, the maximum stress the quartz experiences is 86 kgf/cm^2 in the area of the cone to outer diameter flat ring transition. With the maximum tensile strength of quartz being 500 kgf/cm^2, the safety factor of the quartz design is 5.8.

As with the quartz cone, the barrier's gas plenum and weld joints will be subjected to a 0.3 MPa pressure differential. A pressure analysis was performed and all weld joints and wall thicknesses were sized to meet or exceed the requirements of ASME B31.3-2004.

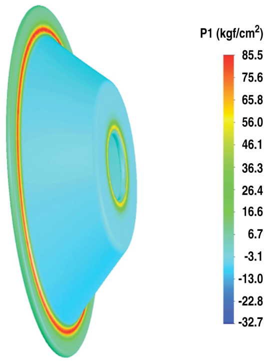

Fig. 7. Quartz cone, stress distribution

To determine proper outer conductor slot dimensions and to verify proper flow distribution of the cooling gas, a gas flow velocity analysis was performed with the 2 specified gas velocity inputs, 3 m/s and 7 m/s. Velocity profiles were modeled at 3 axial locations for the 2 gas velocity inputs. The slot dimensions were adjusted to provide a somewhat uniform velocity profiles at the three axial locations and the two velocity inputs. Two profiles are shown in figures 8 and 9 for the 3 m/s and 7 m/s input velocities. The axial location of the profiles is 20 cm from the center of the quartz cone/inner conductor interface. For the 3 m/s velocity input case, velocity ranges from 1 to 4 m/s in the inner to outer conductor plenum. For the 7 m/s velocity input case, the velocity ranges from 1 to 8.5 m/s in the inner to outer conductor plenum. The velocities profiles shown in figures 8 and 9 are typical for all the 3 axial locations in the barrier assembly. The velocity profiles become more uniform further down the adjacent coaxial transmission line piece. The uniform profiles indicate that cooling gas is somewhat evenly distributed around the inner and outer conductor plenum. The intent of the even distribution is to allow the cooling gas to absorb more uniformly the heat generated from the inner conductor and either transfer the heat to the cooled outer conductor or remove it from the transmission line section via the exit gas barrier assembly.

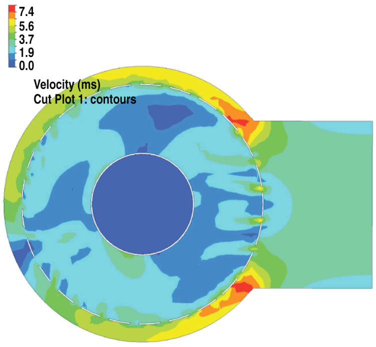

Fig. 8. Gas Velocity Profiles, 3 m/s Input

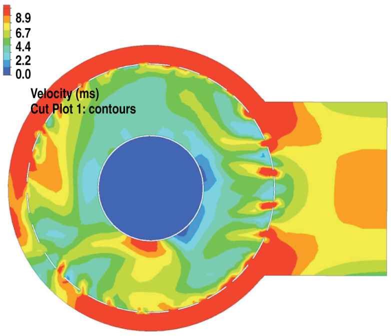

Fig. 9. Gas Velocity Profiles, 7 m/s Input

4. Conclusion

At this point in time, it is believed that all known design requirements have been met or exceeded in regards to barrier and stand-off materials, compatible sealing material (tritium compatible), serviceability, weld configuration and sizes, and flange configurations. Additional features were incorporated to allow cooling gas injection and removal as well as cooling gas disbursement. Further analyses are recommended to insure material service temperature maximums are not exceeded. Testing of the barrier at ORNL will provide verification of the assembly and determine its capabilities.

Acknowledgments

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References

[1] R. Rathi, et al., IEEE/NPSS 24th Symposium on Fusion Engineering (2011).

[2] L.Heikinheimo, et al., "Dielectric Window for Reactor Like ICRF Vacuum Transmission Line," Fusion Engineering and Design 55 (2001) 419-436.

[3] RC Walton, et al., "A Continuous Wave RF Vacuum Window", JET, September 1999.

[4] S.W. Ferguson, et al., "RF High Voltage Performance of RF Transmission Line Components on the DIII-D Fast Wave Current Drive (FWCD) System," 16th IEEE/NPSS Symposium on Fusion Energy (SOFE), Champaign, IL, 1995, pp. 837-839.

[5] E. Clark, et al., "Effects of One Week Tritium Exposure on EPDM Elastomer," SRNLST1-2008-00524, 7 June 2007.

[6] W.A. Swansiger, et al., "Tritium, Deuterium, and Helim Permeation Through EPDM O-Rings", Fusion Technology **21**, March 1992.

[7] C.L. Talcott, et al, "Three Tritium Systems Test Assembly Off-Loop Experiments", 0-7803-1412-3$04.00C1994IEEE, October 14, 1993.