Additive Manufacture of RF Loads for ITER

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Abstract: The ITER fusion research facility will employ twenty-four, MW-class gyrotrons for electron cyclotron heating of the fusion plasma. Each of these gyrotron will require an RF load for commissioning and periodic maintenance and testing. These loads must dissipate approximately 1 MW of long pulse / continuous RF power with less than 0.5% of the power reflected back into the transmission line. This program is using additive manufacturing to reduce the cost and improve the performance.

Keywords: gyrotron, electron cyclotron heating, tokamak, plasma heating, RF load, waterload

INTRODUCTION

The ITER fusion research facility is currently under construction in France as the next major step toward reliable fusion power. Twenty-four gyrotrons will provide electron cyclotron heating of the fusion plasma. These gyrotrons will each generate approximately 1 MW of RF power at 170 GHz. An additional twenty-four gyrotrons are forecast for a future upgrade. Each gyrotron will require an RF load for commissioning and periodic maintenance and testing. Consequently, the loads must dissipate 1 MW for a minimum of 10 seconds. In addition, the loads must avoid reflecting more than 0.5% of the RF power back to toward the gyrotrons.

CCR began developing high power loads for gyrotrons in 1996 and began delivering 1.25 MW CW loads in 2001. These loads provided for a Gaussian mode input and used a rotating reflector at the downstream end to sweep the power around the interior. The rotating reflector accomplishes two purposes. First, it ensures that the power is evenly dissipated over the interior surfaces. Secondly, and more importantly, it eliminates arcing that invariably occurs with static loads at these power levels. This arcing is caused when constructive interference occurs at loss surfaces where excessive heating leads to outgassing. In CCR loads, the continual sweeping of the RF power moves or eliminates constructive interference before arcing can occur.

The configuration of the 1.25 MW loads allowed approximately 5% of the input power to exit back toward the gyrotron. Consequently, most customers incorporated a preload to absorb this reflected power. In 2007, CCR designed a new load that reduced this reflected power to less than 1%. A rotating launcher at the load input shields the input from reflected power. This launcher more efficiently distributed the RF power allowing operation up to 2 MW CW. One of these loads recently operated at 1.73 MW, the maximum power available.

Changing specifications for the RF load initiated another redesign in 2010. Because ITER is a nuclear facility, strict adherence to materials and assembly procedures is required. These restrictions eliminates brazes, O-rings, and ferromagnetic seals in the vacuum envelope. Also, potentially corrosive materials cannot be used in the coolant system, including anodized aluminum. CCR's 1.25 MW loads were fabricated primarily from anodized aluminum and used O-rings, and the 2 MW load used ferromagnetic seals. The design generated in 2010 replaced the rotating launcher with a revolving launcher that used a bellows to eliminate rotating joints. In addition to eliminating rotating seals, this design significantly reduced the cost. This configuration is shown in Fig. 1.

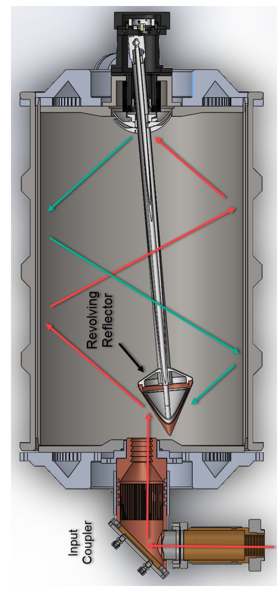

Fig. 1: Layout of 2.0 MW CW RF load for ITER. The red arrows trace RF path from transmission line, and green arrows show path toward input.

ITER restricts the vacuum envelope to copper or stainless steel. Welds are used to permanently bond components, and

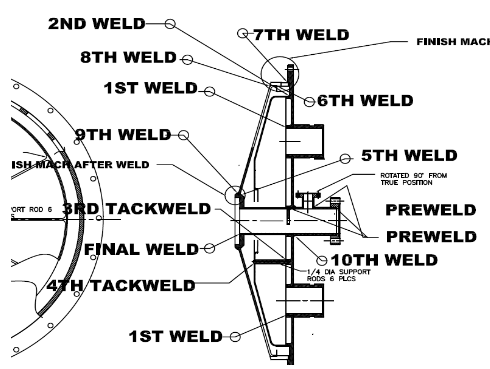

Fig. 2: End plate configuration and identification of welds

metal seals are used where components are bolted or otherwise fastened in place. The most expensive component in CCR's 2 MW loads are the coolant manifold endplates that distribute the coolant around the cylindrical load surfaces. IN 2008, CCR fabricated an ITER prototype load consisting of a copper cylinder and stainless-steel coolant manifold end plates. Fig. 2 shows the end plate design, which included sixteen machined parts and more than twenty six welds. The total fabrication and assembly cost of these plates was approximately $50K. The current program is replacing these components with Additively Manufactured (AM) components to reduce cost and improve performance.

END PLATES

Manifold endplates are required on each end of the cylindrical load for coolant input and output. These plates must withstand 150 psi of static pressure and uniformly distribute the 150 gpm coolant flow around the cylinder periphery. The coolant flows between an inner cylinder forming the vacuum envelope and an outer cylinder forming the outer cooling jacket.

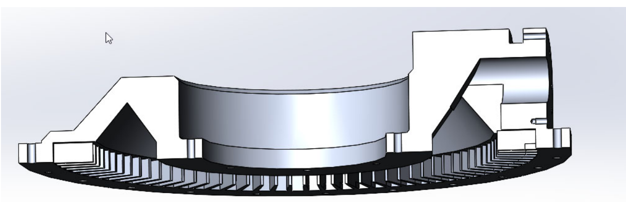

Fig. 3: Sliced model of endplate for AM fabrication

Working with our AM partner, SD3D, Inc., CCR identified Nylon-12 Carbon Fiber (CF) as an appropriate material. This was subsequently approved by the ITER operation and can be printed with filament printers. Fig. 3 shows design of a coolant endplate compatible with AM fabrication, and Fig. 4 shows a full size plate printed by SD3D. This part replaces the version shown in Fig. 2, eliminating 16 machined parts and 26 welds. It weighs approximately 27 lbs., almost 100 lbs. less that the stainless steel version.

Fig. 4: Full size, 3D-printed CF end plate

The program is now focused on replacing the stainless-steel outer cylinder forming the main coolant channel with one printed with CF. This would reduce the load weight by approximately 100 lbs.

INPUT COUPLER

The program developed a novel approach to reduce the reflected power. Fig. 5 shows the design, where the input power reflects off a miter bend mirror that focuses the power to a small aperture at the entrance to the load. This aperture is approximately 1/3 the cross-sectional area of the 2 MW load input, which exhibited less than 1% of reflected power. The Surf3d simulation of the RF path through two reflections inside the load is shown in Fig. 6.

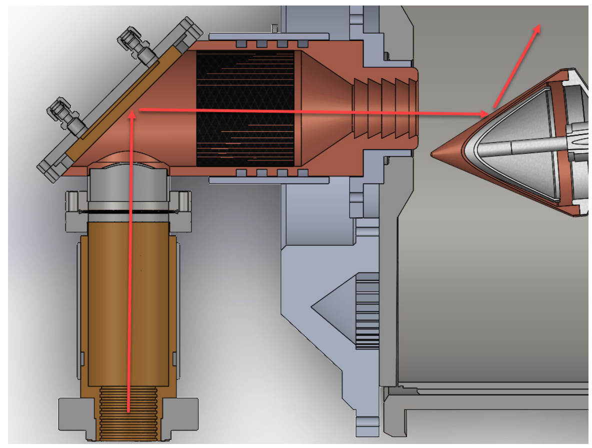

Fig. 5: Design of low reflectance input coupler. Red arrows trace RF input path.

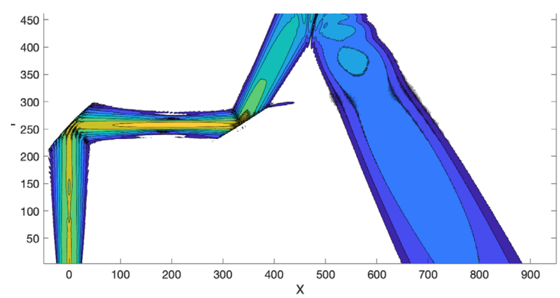

Fig. 6: Surf3d simulation of low reflectance input coupler through two reflections inside the load

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SUMMARY

CCR is applying additive manufacturing to high power RF loads for ITER. This is reducing the cost and improving performance. There is also a dramatic reduction in lead time.. The program is also investigating a novel input design estimated to reduce reflected power to less than 0.5%. Progress to date, including measure performance, will be presented.