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A STEERABLE ECRF LAUNCHER FOR ITER

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A Steerable ECRF Launcher for ITER

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A design is proposed to steer the electron cyclotron heating and current drive power for ITER using rotatable, water-cooled mirrors and low-pressure hydraulic actuators, and to accommodate changes in length of the waveguide when the temperatures of the vacuum vessel and the cryostat change using waveguide bellows. An alternative concept is also introduced that requires no moving parts within the ITER cryostat and that utilizes wave reconstruction within the waveguide to effect the steering.

1. INTRODUCTION

The Design Description Document for ITER calls for 50 MW of electron cyclotron power at a frequency of 170 GHz, upgradeable to 100 MW. ECH is well adapted to the heating and current drive applications on ITER. Taking advantage of the propagation of the wave in free space, the antennas can be located far from the plasma, which protects the mirrors from direct damage by the plasma, greatly reduces the neutron flux down the waveguides, and reduces the forces and heat fluxes on the mirrors when disruptions occur. Modeling with the Fokker-Planck codes shows that a steering range of 15° to 45° from radial is sufficient to obtain central heating as well as central or off-axis current drive over the range of toroidal fields which are planned for ITER [1]. The design of the ECH system described herein accomplishes this steering requirement in a manner consistent with the engineering requirements for ITER.

2. SYSTEM LAYOUT

The ITER ECH Launch Structure forms the in-vessel portion of the electron cyclotron heating and current drive transmission system. It consists of an array of rf waveguides that pass through both vacuum vessel and cryostat barriers and terminate in a shielding block within a midplane, radially oriented port in the ITER reactor vessel (Fig. 1). RF power exiting a waveguide first encounters a fixed inclined optic which reflects the power downward. A second optic redirects the power radially again and is rotatable ±15° about a vertical axis allowing the power to be injected at a variable toroidal angle. The power then passes through a slot in the blanket plug located on the inboard side of the ECRF port [2].

Two ports are used to inject ECH power into the tokamak. In their upgraded configuration, each port features 56 waveguides, each delivering a nominal power of 0.85 MW to the tokamak. The waveguides are arranged in an array with seven rows having eight waveguides within each row. The eight rotating mirrors within a row are steered together as a unit while each of the seven rows of mirrors are steered independently (Fig. 2).

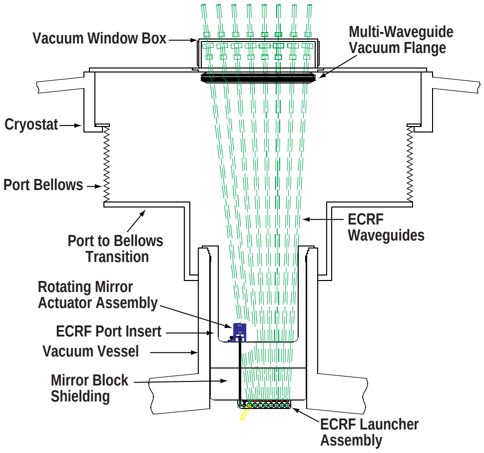

Fig. 1. Top view of proposed ITER ECRF port.

3. ROTATING MIRROR ASSEMBLY

Each rotating mirror assembly is positioned exactly beneath a fixed mirror, with the centerpoints of the reflecting surfaces of the fixed and rotating mirrors being 175 mm apart. Motion is imparted to a row of rotating mirror assemblies by a steering actuator via the steering linkage assembly. As the mirror assembly is heated by nuclear, radiant and rf Ohmic heating, it is cooled by water circulating through a circuitous path within the assembly (Fig. 3). Inlet water, with nominal temperature and pressure of 150°C and 4.0–4.6 MPa, respectively, enters the assembly at the inlet port of the coiled cooling line assembly. This assembly supplies water to the rotating base via a planar tubing coil. The water passes upward through the cylindrical wall of the base, circulates through the steering arm, then returns to the base where it is distributed to eight cooling channels which run the length of the mirror body to the mirror (Fig. 4). Within the mirror, which is composed of copper or Glidcop (a copper alloy containing a dispersion of alumina), the flow is passed through channels that run through the midplane of the mirror and are laterally spaced to equally distribute the mirror's heating load on each channel. The water is then circulated through the mirror body, through the rotating mirror base, through a second planar tubing coil, and then to the outlet port of the coiled cooling line assembly.

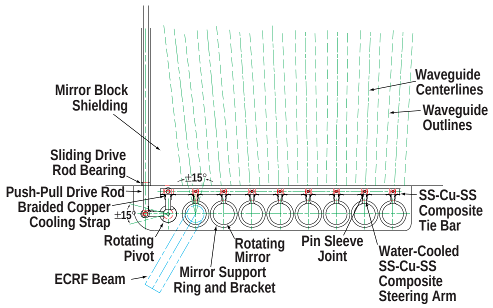

Fig. 2. Top view of proposed ECRF launcher platform.

Analyses were conducted to determine the optimal geometry of the cooling system of the rotating mirror assembly. A thermal-hydraulic analysis determined the optimal cooling flow parameters to achieve adequate mirror cooling with equal thermal loading on each cooling channel, while minimizing the pressure drop across the mirror, body, and coiled cooling line assemblies and maximizing the spring flexibility of the coiled cooling lines. The specifications and predicted performance for the cooling system of the rotating mirror assembly are listed in Table 1. The planar, Archimedean coil configuration of the coiled cooling line assembly, with 4 mm diameter by 0.20 mm wall thickness stainless steel tubing, was calculated to require a torque of only 0.36 N-m per coil (0.72 N-m per assembly) to produce an angular displacement of 15°.

A frictionless rotatable pivot, based on the Bendix Flexural Pivot, is incorporated in the base of the mirror assembly and facilitates motion through the required ±15° rotation. This pivot consists of two concentric metal bushings which are interconnected by three radially-oriented, thin, flat, metal springs (Fig. 5). Results of a structural analysis determining the appropriate geometry of the pivot's flat plate springs are listed in Table 2.

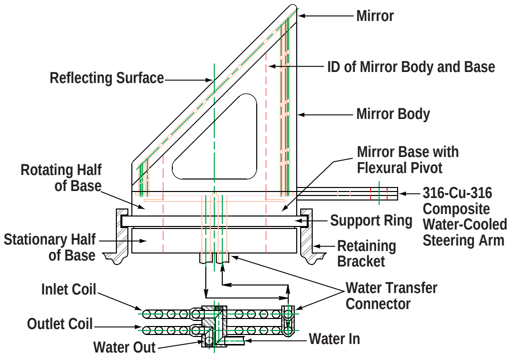

Fig. 3. Flow path through the rotating mirror assembly.

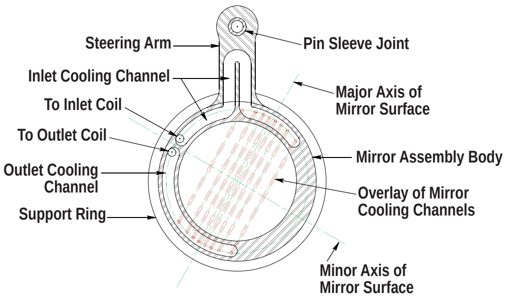

Fig. 4. Top view of rotating base and water cooled steering arm with overlay showing the location and orientation of the mirror cooling channels.

4. STEERING ACTUATOR AND LINKAGE ASSEMBLIES

The proposed actuation concept utilizes low pressure, hydraulic power to expand and contract sealed metal bellows that are fixed on opposing sides of a moving actuator plate (Fig. 6). The position of the actuator plate is sensed by a linear position sensor. Displacement feedback is sent to a controller which coordinates the flow of hydraulic fluid, a radiation-resistant aromatic siloxane, to and from the actuator through electronic servo valves. Motion is transferred from the actuator plate to the drive rod plate, which is attached to the outboard end of the drive rod, through the drive frame. Surrounding each hydraulic bellows is a larger-diameter containment bellows. In the event of a leak in the hydraulic bellows, the escaping hydraulic fluid would be contained within the containment bellows. Detection of a leak is facilitated by the circulation of an inert gas through the containment bellows to a gas analyzer located outside the reactor area.

The steering linkage assembly transfers the linear motion of the actuator's drive plate into rotation of the rotating mirrors of the ECRF launcher assembly. Motion is transferred from the actuator to the rotating mirrors through a series of structural linkages connected by low-friction, anti-galling, pin sleeve joints. The linkages are cooled either by direct water circulation or by conduction through cooling straps.

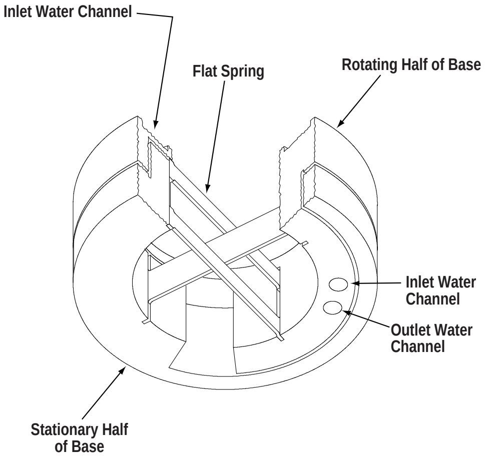

Fig. 5. Details of the rotating base of the rotating mirror assembly.

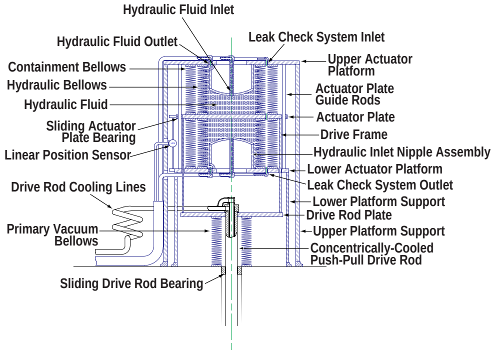

Fig. 6. Cross-sectional view of steering actuator assembly.

Table 1. Specifications and predicted performance for the cooling system of the rotating mirror assembly

Design: Geometry	
Feed line tubing, outside diameter	4 mm
Feed line tubing, wall thickness	0.20 mm
Feed line tubing, coil type	Archimedean spiral
Feed line tubing, coil pitch	6 mm (1.5 x tube o.d.)
Mirror, number of water channels	eight
Mirror, diameter of water channels	1.3 mm
Mirror, spacing of channels from mirror centerline (two at each distance)	1.68 mm (lst channel); 5.20 mm (2nd channel); 9.29 mm (3rd channel); 15.40 mm (4th channel)
Analysis: Predicted Performance	
Inlet water temperature (assumed)	150°C
Outlet water temperature	200˚C
Water temperature rise	50˚C
Water flow rate	3.2×10^{-5} m^3/s
Water flow velocity in mirror	3.1 m/s
Convection heat transfer coefficient in mirror	35.9 kW/m^2-K
Inlet water pressure (assumed)	4.6 MPa
Water pressure drop across mirror assembly	0.38 MPa
Maximum steady bulk mirror metal temperature	255˚C

Table 2. Performance Specifications for proposed Bendix-type flexural pivot for rotating mirror assembly

Design: Dimensions	
Outside diameter	80 mm
Overall axial length	30 mm (25 mm within spring region)
Length of flat springs	50 mm
Width of flat springs	one at 11 mm, two at 5.5 mm
Thickness of flat springs	0.84 mm
Assumed elastic modulus of springs*	200 GPa (for type AISI 420 steel)
Analysis: Predicted Performance	
Maximum torque at 15˚ rotation	1.13 N-m (10 lbf-in.)
Safe uniform lateral buckling load	1,260 N (283 lbf) at 0˚ rotation
Safe uniform axial buckling load	218 N (49 lbf) at 0˚ rotation
Safety factor for buckling	2
***Alternative Spring Materials**	Alloy A-286 (stainless steel) Alloy 718 (nickel alloy) Machinable tungsten alloys

5. SLIDING WAVEGUIDE JOINT

Radial motion between the vacuum vessel and the cryostat is accommodated in the waveguide by a sliding joint by which the waveguide length can change. This is accomplished by incorporating a tube of larger diameter onto the end of one of the waveguides into which the adjacent waveguide is inserted. The minimum overlap length is 1.5 times the outside diameter of the waveguide to maintain the necessary radial and axial alignment of the waveguides to minimize RF-mode conversion. A gap of 0.13 mm between the Nitronic 60 sleeve section and the inserted waveguide assures free fit at all temperatures and reduces the risk of binding or galling under vacuum conditions. A vacuum bellows surrounds the sliding joint to maintain vacuum integrity between the primary and secondary vacuums. Calculations indicate that the mode conversion losses anticipated with this design are approximately 1%, with this mode-converted power being propagated to the plasma rather than being dissipated locally in the waveguide.

6. REMOTE STEERING DESIGN

In order to avoid the potential problems associated with wear, seizing and galling of sliding parts, flexible coolant ducts, and large mechanical disruption forces within the ECRF port, an alternative steering concept was developed which employs no moving parts inside the cryostat. This concept uses reconstruction of the wave front at the exit aperture of the waveguide of a wave traveling at the desired angle to effect steering [3].

ACKNOWLEDGMENTS

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