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A HALO RECYCLER FOR THE TANDEM MIRROR EXPERIMENT UPGRADE*

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Abstract

The halo recycler is a mechanical device on the Tandem Mirror Experiment Upgrade (TMX-U) that is designed to increase the density at the plasma edge providing enhanced shielding of the core plasma from background neutrals. Each recycler body, which consists of coaxial annular cylinders and an adjacent plenum, closely follows the magnetic flux tubes in the transition region of TMX-U. Each plenum is provided with gas feed and pressure measurement systems as well as Langmuir probes. This paper describes the design, fabrication, installation, and operation of these devices.

The recycler body is made of thin stainless steel, as is the adjacent plenum and support structure. The central plasma surface is electropolished for minimum plasma contamination. It is designed to electrically float to the plasma potential, while providing enough gas to fuel the halo. The annular gas feed regions are elliptically shaped to follow the flux tube to within an ion gyroradius (0.2 cm). The pressure measurement system included modified Shultz-Phelps gauges to measure the recycler pressures in the 10^{-3} to 10^{-5} Torr region, and Bayard-Alpert gauges to measure lower pressures. The halo recycler bodies were tested for rigidity during a magnet pulse and movement was found to be less than 0.03 cm.

During operation an infrared camera showed that the inner electropolished surfaces rose less than 5°C. This effort was, from approval to testing, completed within two months.

Introduction

A novel approach to shield the plasma core from background neutrals by increasing the density of the plasma halo was attempted on TMX-U during early 1985. A halo fueling device, known as a halo recycler, was installed in each transition region (Fig. 1) of the central cell of the machine.

Figure 1.

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The recyclers consist of coaxial plasma-shaped cylinders that conform to the field lines near the plasma. The region between the two cylinders recirculates the halo plasma that would otherwise flow out of the central cell. During physics runs the halo heating sources for the recyclers were the slot ion cyclotron resonant heating (ICRH) antenna and the central cell neutral beams.

This paper describes the reasons for locating the halo recyclers within the central cell. It also presents the design parameters and final recycler configuration. A description of the gas fueling hardware and several diagnostics is presented. Some fabrication, installation, and operation details are discussed.

Considerations Affecting the Location of the Recycler

The initial concept of halo recyclers on TMX-U is discussed in Reference 1. This concept located the recyclers in the end fan region of the machine. Because of reduced absorption of ECRH power in the plug regions, the design criteria dictated a relocation to the central cell transition region near the 10 KG point. This location would have placed each recycler inside the jaws of the plug inner cee coil between the magnetic peak and the center cell electron cyclotron resonant heating (ECRH). Initial layouts showed that this was a region of great plasma ellipticity (ratio of about 30). This would have made the recycler body difficult to fabricate and very susceptible to alignment errors. Therefore, we settled on a position further inboard, 15 cm from the slot ICRH antenna, where the flux tubes were less elliptical (ratios of about 3 to 8).

Halo Body Design Criteria

The inner and outer shrouds were to follow the magnetic flux tubes as closely as possible (Fig. 2). The tolerance was one ion gyroradius for a 60 ev deuteron (0.2 cm). The inner shroud conforms to the flux tube which maps to a 25 cm radius in the central cell because this is the limiting aperture in the machine. The outer shroud conforms to the flux tube which maps to a 34 cm radius in the central cell because the existing Slot ICRH antenna shell maps to the flux tube which is 0.5 cm larger.

The length of each body is 50 cm. This length was chosen to give a pressure differential from the front edge to the back edge of three orders of magnitude within the halo region of the recycler. This length is also several neutral mean free paths long and gives approximately a 10 to 1 aspect ratio. To insure proper performance, the halo recycler body was aligned to within 0.2 cm in all directions (x, y, z). The trailing edge of the inside shroud is 0.64 cm beyond the 25 cm flux tube. This makes the annular surface of the inner shroud a neutralizer plate for the incoming ions and electrons. The gas manifold volume at the back of the recycler is designed to the same criteria as our existing gas box. The core plasma side (Fig. 2) of the inner shroud was electropolished to reduce the vacuum outgassing and contamination of the core plasma.

Halo Recycler Gas Fueling

Figure 2.

Halo Recycler Assembly

Figure 3.

Recycler Configuration

The recycler (Fig. 3) is made of type 304L stainless steel. The inner shroud was shaped from 0.074 cm thick sheet and the outer shroud was shaped from 0.15 cm thick sheet. The radial plates of the gas manifold and the forward stiffening ring are fabricated from 0.32 cm thick plate for rigidity. The completed shrouds, before they were assembled, can be seen in Figs. 4 and 5. The outer shroud also has slots cut along the bottom edge for gas flow between the shroud annulus and the gas manifold. As seen in Figs. 3, and 5, there are 16 of these slots at 16.5 cm long and 1.0 cm wide.

The plasma flux tube cross-sections are quite closely approximated by an elliptical shape. Therefore, the fabrication of the recycler bodies was simplified by making the end openings elliptical.

Figure 5.

Figure 4.

The shrouds were formed on solid wood forms that were milled to the correct contours on an NC mill. The forming and welding proved to be a very delicate operations. In fact, the first recycler made was not acceptable because the welding caused the shrouds to

warp considerably. To reduce warping, the shrouds and end plates were joined with very light welds. The welding was also done by skipping around, allowing the material to cool between weld passes. A stiffening ring was added to the front edge to control warping at this critical point.

Five holes with 7 cm rotatable conflat flanges were also added to the gas manifold and outer shroud for gas fueling, pressure gauge assemblies, as well as a Langmuir probe. The completed recycler body assembly is shown Fig. 6.

Figure 6.

Diagnostics and Fueling

Two pressure gauges, one three-tipped Langmuir probe, and one voltage and current monitor were installed on each halo recycler to monitor its performance and to help adjust the gas fueling (Fig. 7). Two programmable gas valves were installed on the gas manifold of each recycler to provide deuterium gas fueling (Fig. 2).

Halo Recycler Diagnostics

Figure 7.

The pressure gauge assemblies (Fig. 8) consisted of one modified Shultz-Phelps gauge and one Bayard-Alpert Fast Ion Gauge (FIG). Each was electrically isolated from the halo recycler by a ceramic break. The Shultz-Phelps gauges monitor the pressure from 10^{-3} Torr to 10^{-5} Torr, the expected operating range of the recycler. The Bayard-Alpert gauges monitor the lower pressures prior to each shot. The ceramic insulator breaks required external shields on them to protect them from titanium gettering inside TMX-U.

The Shultz-Phelps gauges were modified to operate in the magnetic field by replacing the regular filaments with special tungsten filaments. The new filament withstands the Lorentz forces generated by the magnetic field. The orientation of this gauge was along the magnetic field (horizontal in Fig. 8) so that the field passes normally through the gauges collector plates. The machine field then has less affect on the gauge operation.

Figure 8.

The Bayard-Alpert ion gauges were oriented perpendicular to the machine magnetic field (vertical in Fig. 8); this insures ion propagation to the collector grid and thereby enables proper gauge operation. Two baffles were spot welded inside the ceramic break to neutralize plasma ions from the recycler cavity, thus reducing their effect on gauge accuracy.

The three-tipped Langmuir probe assembly (Fig. 9) protruded through the halo recycler gas manifold into the halo region between the inner and outer shrouds. Three tips were required to uniformly monitor the electron temperature and density in the neutralizer region. This assembly was also electrically isolated from the recycler by a shielded ceramic break.

A high current electrical conductor was attached to the body of each recycler to allow us to monitor the voltage or current. The insulation on this conductor was protected from the machine gettering by copper silphon tubing that was isolated from the recycler by a small ceramic break.

The two gas valve assemblies (Fig. 10) were attached to the back of the recycler gas manifold

Figure 9.

(Fig. 2) with stainless conflat flanges. Because the gas valves are sensitive to high heat loads, the 1-inch diameter tube was added to place them away from the pumping neutral beam paths (Fig. 2). These valves are the same type of piezo-electric valve used elsewhere on TMX-U. These valves were also electrically isolated from the recycler. Placing the valves at the small radius section of the elliptical manifold provides the most uniform fueling from the two valves.

Resulting Changes to Other TMX-U Systems

The installation of the halo recyclers required several changes to the TMX-U machine configuration. The plasma limiting surfaces that had previously protruded several inches inside of the Slot ICRH antenna had to be enlarged to a 34.5 cm flux tube. The six getter wires inside the Slot antenna were also removed to clear this flux tube. The west central cell gas box was rebuilt with correspondingly larger limiters. The 2 x 170° ICRH antenna was completely removed from the vessel because the antenna element and Faraday shield radii were too small.

Installation and Operation

The halo recycler bodies were supported by steatite insulators to hold off 3kV from ground. A value of 4 kV/cm along an insulator was used to specify the insulator length. We slotted the support brackets to provide for alignment during installation. The alignment tolerance was to place each recycler within 0.2 cm of the specified location. The alignment was performed by placing 0.025 cm diameter steel wire cross-hairs on the front and back openings of each recycler. These cross-hairs were then aligned to a surveyor's transit, which was aligned to the machine's axis. The final alignment was set within 0.08 cm for each recycler.

During initial operation of the recyclers, several machine magnet shots were taken to check the movement that might occur due to eddy currents that would

Gas Valve Assembly

Figure 10.

develop on the recycler bodies. The movement, as viewed with the machine surveyor's transit, was less than 0.03 cm.

An infrared camera was also set-up to view the recycler movement and heating during plasma shots. The recyclers were viewed through an infrared transparent window at the machine vacuum wall. There was no perceptible movement and the heating was no greater than 5°C on the inner surface of the inner electropolished shroud.

TMX-U experiments operated for several months with these recyclers. Because we were unable to couple substantial amounts of ICRH power in these experiments, the plasma physics results were similar to those achieved previously. It is suspected that the ICRH Slot antenna did not function properly without limiters which keep plasma away from the antenna feeds. The halo recycler results were encouraging in that they demonstrated that such a device, located so near the plasma, did not cause serious wall reflux problems.

Acknowledgement

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References

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