GA–A23288

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This is a preprint of a paper to be presented at the 18th IEEE/NPSS Symposium on Fusion Engineering, October 25–29, 1999, in Albuquerque, New Mexico, and to be published in the *Proceedings.*

Work supported by
the U.S. Department of Energy
under Contract No. DE-AC03-99ER54463

GA PROJECT 30033
NOVEMBER 1999

Design and Analyses of Transmission Lines for the 110 GHz ECH Upgrade to 6 MW for DIII–D

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Abstract

During the summer of 1999 the installation of three new Electron Cyclotron Heating (ECH) transmission lines began as part of the 110 GHz ECH Upgrade to 6 MW project for DIII–D. An important step in the development of the transmission line design was the selection of the waveguide size. To make this selection, analyses were conducted to characterize the thermal and radio frequency (rf) loss performance of the key corrugated waveguide components under 1 MW, long pulse (10 s, 1% duty cycle) operation. Other factors that were analyzed included vacuum conductance and pumping speed, ease of installation, space considerations, and overall cost. The two candidate transmission line sizes were 2.50 in. and 1.25 in. i.d.

An overview of the design and layout of the proposed transmission lines for the DIII–D ECH upgrade project is presented. Details and results are given for the vacuum conductance analysis of the overall transmission line, the rf loss analyses and tests on corrugated waveguide and miter bends, and the thermal analyses of the mirrors in the corrugated waveguide switch and the power monitor miter bend. Finally, a discussion is presented which weighs the results of these analyses with the experience gained through the installation and operation of the existing three 1 MW ECH systems at DIII–D and concludes with the selection of 1.25 in. i.d. waveguide and components for the upgrade project.

I. INTRODUCTION

The 110 GHz ECH Upgrade to 6 MW project will double the present capability of three megawatts of ECH power to DIII–D through the addition of three new 1 MW, 110 GHz, CPI-built gyrotrons. The placement of the three new gyrotrons in DIII–D's new ECH facility requires that the power be transmitted over three new transmission lines averaging approximately 90 m in length, roughly double the length of the three existing transmission lines (Fig. 1). Power exiting the gyrotron's mirror interface unit is transferred to the torus through a transmission line consisting of internally-corrugated waveguides and, in order, a power monitor miter bend, the first of two polarizing miter bends, a waveguide switch, a phase-correcting miter bend, a vacuum isolation valve, and the second of the two polarizing miter bends. After exiting the gyrotron room, the line makes an elevation change of 7 m upward where an arc-detecting miter bend initiates a horizontal straight run of 30 m toward the exterior of the radiation shielding wall of the torus hall. A series of shorter waveguide runs connected by phase-correcting miter bends brings the line into the torus hall where power is transmitted through a vacuum pumpout tee, a waveguide taper, a DC break, a torus isolation valve, and delivered to the tokamak via a steerable launcher.

Integral to the design of the transmission line was the selection of the size of the waveguide and components. The two candidate sizes were 2.50 in. and 1.25 in. i.d.. Each size was thought to have advantages and disadvantages with respect to issues of vacuum conductance and pumping speed, thermal loading, rf loss performance, ease of installation, space considerations, and overall cost. Each of these factors was evaluated for the components of the two candidate sizes. Results of these evaluations are described in the following sections and the rationale is given for the final selection of size.

II. VACUUM CONDUCTANCE

A major factor in preventing arcing within the transmission line is maintaining an adequate vacuum pressure during operation. The vacuum conductance of the waveguides and components within the line, the quantity and integrity of the connecting seals, and the number, size and location of the pumps determines the maintainable vacuum pressure within the line and the pumping speed. The high costs of turbo-molecular pumping stations and their installation drives the need to limit the number of pumps in a line to the minimum required to meet the vacuum requirements for full-power operation.

A conductance analysis was performed on models of the candidate 1.25 in. and 2.50 in. diameter transmission lines. The results of this analysis, which assumed smooth waveguide walls and no outgassing, were combined with the findings of an earlier conductance experiment performed on 1.25 in. corrugated waveguide to estimate the time required to reach the maximum acceptable pressure for operation of 0.001 Torr using a single 250 ℓ/s turbo-molecular pump located at each end of the proposed transmission line.

The analysis estimated the conductances of the 1.25 in. and 2.50 in. transmission lines to be 0.0275 ℓ/s and 0.220 ℓ/s, respectively. It was also concluded that, although the transmission line contains numerous different components, the predominant factor in the line's overall conductance is the waveguide diameter. Since the conductance of a tube varies as the cube of its diameter, the conductance of a 2.50 in. diameter line is eight times greater than that of a 1.25 in. line of the same length.

*Work supported by U.S. Department of Energy under Contract No. DE-AC03-99ER54463.

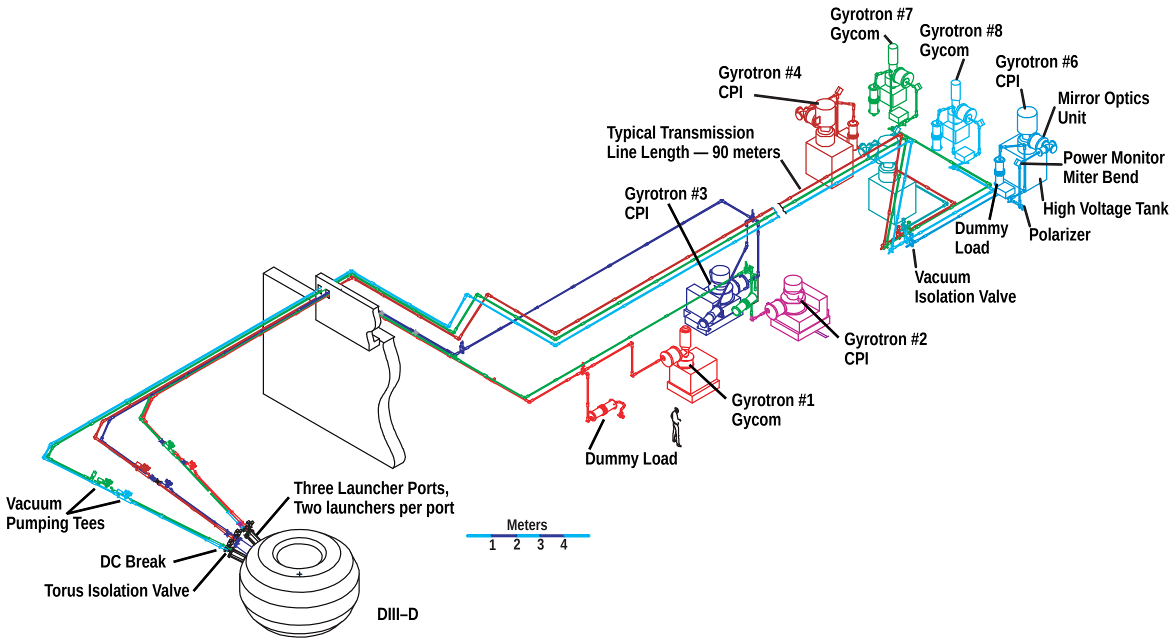

Fig. 1. DIII–D 110 GHz ECH transmission systems.

The experimental test results provided an empirical benchmark of the effects of corrugated inner walls and outgassing on the pumping speed of the proposed waveguide runs. The test measured the time required to reach a vacuum level of 0.001 Torr in a 30.5 m long, 1.25 in. corrugated waveguide section with two integrated miter bends. Pumping was provided by a 330 ℓ/s turbo-molecular pump located at one end of the section while the transmission line pressure was measured at the opposite end. Applying these test results to the new transmission lines and adjusting for the differences in length and pump size, the pumping time required to reach the maximum operating pressure of 0.001 Torr was estimated to be approximately 6 hrs for 1.25 in. waveguide system and approximately 3 hrs for a 2.50 in. system.

III. RF LOSS PERFORMANCE

Corrugated waveguide of 2.50 in. i.d. has a far greater sensitivity to axial curvature than does 1.25 in. waveguide, producing greater mode conversion losses for a given level of curvature. Measurements of this phenomenon were made on a straight, 10 m long run of 1.25 in. waveguide. At 110 GHz, mode conversion loss was first measured with the section straight, then with a center support raised 10 cm above its aligned position. There was no measurable difference in loss. Although the same experiment was not done using 2.50 in. waveguide, calculations estimated that a mode conversion loss of 1% or more would be induced in a 10 m long run if its center were raised only 2 cm.

Since long waveguide runs are supported by numerous supports along their length, the likelihood of generating mode conversion losses from small, periodic misalignments is probably greater than from a large, single misalignment. A computer code was written to calculate the mode conversion loss in a transmission line supported periodically. This code calculates the mode conversion due to random misalignment of the supports as well as the curvature due to gravity sag between supports. In a 50 m run of 2.50 in. waveguide, the mode conversion loss at 110 GHz is less than 1% when the rms misalignment is 2 mm, when the support spacing is 3.5 m or more, but was found to increase significantly as the support spacing decreased. (The "peak-to-peak" misalignment is approximately three times the rms misalignment). For support spacing equal to the standard 2 m long waveguides, the misalignment would have to be reduced to less than 1.3 mm for the mode conversion to be less than 5% for a 50 m run.

For a 50 m run of 1.25 in. waveguide, the mode conversion at 110 GHz due to 2 mm rms misalignment was calculated to be less than 1% regardless of the support spacing. This tolerance of misalignment by 1.25 in. waveguide has a major impact on cost of installation and maintainability of alignment that will be addressed later.

Mode conversion losses are also induced in miter bends. These losses are a function of the size of the miter bend and the frequency of the transmission. Calculations of the mode conversion in the two sizes of miter bends at 110 GHz estimated a loss of approximately 0.5% in the 2.50 in. miter and approximately 1% in the 1.25 in. miter. Since there are eleven miter bends in each of the new transmission lines, mode conversion losses in miter bends would total approximately 5.5% and 11% for 2.50 in. and 1.25 in. lines, respectively.

Another source of mode conversion loss is misalignment of the waveguide at the output of the mirror optics unit (MOU). It is at this location that the free space beam passing through the MOU must be coupled into the waveguide. Errors in beam offset, tilt, and diameter size cause mode conversion. Analyses of these misalignment types have shown that 2.50 in. waveguide is more sensitive to tilt errors and less sensitive to offset errors than 1.25 in. waveguide. Experience with the existing three DIII–D gyrotrons has shown that offset misalignments are significantly easier to measure and correct than tilt misalignments. Since loss due to beam diameter size error varies as the square of the percentage of the diameter error, it is believed that neither waveguide size holds a distinct advantage over the other in this misalignment type.

Ohmic wall loss is inherent to all waveguide-type transmission lines. A computer code was developed that calculates the ohmic loss in a waveguide as a function of its corrugation geometry and the frequency of the rf transmission. Analyses using this code estimated that the ohmic losses in 2.50 in. waveguide are approximately one-sixth as high as in 1.25 in. waveguide. For the lengths of the proposed transmission lines, ohmic losses were estimated to be approximately 4% for 1.25 in. waveguide and approximately 0.7% for 2.50 in. waveguide.

IV. THERMAL LOADING

The mirrors in miter bends, polarizers, and waveguide switches are subjected to thermal loading as a result of resistive losses at their reflective surfaces. The magnitude of the power density of these losses is greater in 1.25 in. components than in their 2.50 in. counterparts. Thermal analyses were performed on the mirrors of the most critically loaded components to determine their peak temperatures during 1 MW, 10 s, 10 min operation cycles.

The unique array of tightly-spaced, small-diameter holes on its reflecting surface and the deep, wide, tapered lens-slot on its back side make the mirror of the 110 GHz power monitor miter bend the most susceptible of all the actively-cooled transmission line components to thermally-induced fatigue failure (Fig. 2). This mirror was analyzed using the finite element code ANSYS. The resistive loss on the mirror's surface was estimated to be 0.15% distributed over an elliptical area according to the following power distribution:

$$Q''(r) = q''_o \, J_o(2.405\, r/a) \, J_o(2.405\, r/b) \ \mathrm{W/cm^2} \qquad (1)$$

where:

q''_o = heat flux at center of mirror at 20°C = 497 W/cm^2 for 1 MW

r = distance from center of mirror, cm

a = major radius = 2.25 cm

b = minor radius = 1.6 cm

The water flow rate through the mirror was assumed to be 2 gpm; radiant cooling was also modeled. For 1 MW power transmission and a conservatively-assumed duty cycle of 10 s pulses with a 10 min repetition rate, the peak temperature was

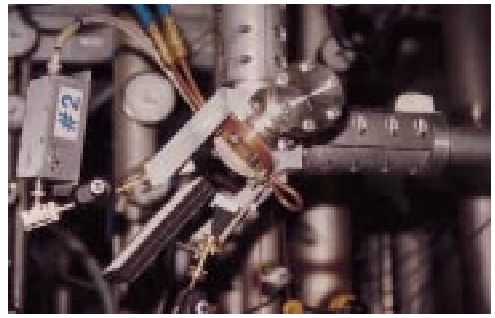

Fig. 2. 1.25 in. power monitor miter bend with water-cooled, GlidCop mirror.

determined to be 351°C with no thermal ratcheting. A similar analysis performed on a 2.50 in. power monitor miter bend mirror with 1 MW power transmission and the same duty cycle yielded a peak temperature of 146°C. These results suggest that either size component could be used for 1 MW, 10 s, 1% duty cycle with the restriction that the 1.25 in. mirror be made of GlidCop, a dispersion-strengthened alloy of copper and alumina particles. The lower peak temperatures in the 2.50 in. mirror would allow it to be made of half-hard, oxygen-free, high-conductivity copper.

The mirror of the 1.25 in. waveguide switch is cooled indirectly through contact conduction to an actively-cooled base plate. This mirror was similarly analyzed using ANSYS with the conservative assumption of only radiant cooling. Results yielded a maximum temperature for a 1 MW, 10 s, 10 min duty cycle of 398°C, consisting of a ratcheted bulk temperature of 297°C and a peak temperature rise during the pulse of 101°C.

A 1 dimensional thermal analysis was done to estimate the effects of the contact-conduction cooling of the actively-cooled base plate on the ratcheted bulk temperature of the mirror for the same duty cycle. The cooling path modeled included the contact-resistive interfaces of the mirror to the switch slider in which it is bolted, and the slider to the cooled base plate to which it is forced by means of an 80 psi pneumatic actuator. This analysis estimated that the contact-conductance cooling resulted in a ratcheted bulk temperature of the mirror of only 65°C. Combining this result with the peak temperature rise of 101°C of the mirror during the pulse determined by the ANSYS analysis yields an overall peak mirror temperature of 166°C, a significant decrease from the case with radiant cooling only.

V. INSTALLATION CONSIDERATIONS

The rf loss analyses reported earlier concluded that, for 50 m long straight runs of 1.25 in. waveguide, the mode conversion loss can be kept below 1% for misalignment of 2 mm rms regardless of the support spacing. This converts to a peak-to-peak maximum misalignment of approximately 6 mm. Similar loss performance can be achieved with 2.50 in. waveguide as long as the support spacing is 3.5 m or greater. Through experience installing the transmission lines for

DIII–D's first three 1 MW ECH systems it was found that an alignment criteria of better than 2 mm rms can be achieved without undue cost or effort. A laser sighting tool was designed that can be inserted into the open end of a miter bend assembly located at the end of a straight run. The beam is aligned to land on a target attached to the waveguide or miter bend assembly at the opposite end of the straight run being surveyed. Once the end points of the straight run are established, the target is attached to each intermediate waveguide clamp within the run and all clamps are then aligned. It is estimated that rms misalignment can be held under 1 mm rms using this technique.

The size and expense of the support systems for the transmission line components were assessed. The small size and weight of 1.25 in. waveguide and components allows the use of lightweight, Unistrut-type channels and thinner-section plates in the support structures of virtually all components. The weight of 2.50 in. components, however, can be up to four times greater than of their 1.25 in. counterparts. It was concluded that components such as the pneumatically-actuated vacuum isolation valves would require significantly more complex and robust support structures for their 2.50 in. versions than for their 1.25 in. versions.

The greater sizes of the 2.50 in. components were found to be critical issues in locations of fixed space limitations. One such location was at the site of the ECH waveguide penetration through the radiation shielding wall of the torus hall. Use of 2.50 in. waveguide would have required significant and costly expansion of the existing penetration in this structure. A second critical region was in the new gyrotron room where an 18 in. raised floor would not allow placement of three 2.50 in. waveguide runs under the floor without interference with cable trays and water and CO_2 lines.

VI. COST COMPARISONS

An analysis was performed to estimate the cost differences for the fabrication and assembly of 2.50 in. transmission line components versus 1.25 in. components. Wherever possible historical cost data from previous 2.50 in. and 1.25 in. component projects was recalled. The analysis estimated that the cost of the components alone to outfit the three proposed transmission lines for the 2.50 in. size would be 28% greater than for the 1.25 in. size. One significant factor in this differential was the cost for 2.50 in. waveguide bellows, a component that is not required for 1.25 in. transmission lines because of their greater inherent flexibility and lower susceptibility to mode conversion loss due to line bowing. The production of miter bends also made up a large amount of the total differential because the larger material section sizes for the 2.50 in. component greatly affect the costs of raw materials and machining. It should be noted that the quoted cost differential does not include the additional higher costs of transmission line supports for the 2.50 in. waveguide and components.

VII. CONCLUSION

Analyses were conducted to evaluate the characteristics of 2.50 in. and 1.25 in. transmission line components in key performance areas for the purpose of selecting a size for use in the three new 1 MW ECH systems for the 110 GHz ECH Upgrade to 6 MW project for DIII–D. The performance areas included vacuum conductance, rf mode conversion loss due to alignment quality, ohmic wall loss, thermal loading, installation considerations, and cost.

The vacuum conductance analysis determined that the 2.50 in. line has a conductance eight times greater than the 1.25 in. line. Furthermore, the time required to pump the 2.50 in. system to its operating pressure threshold of 0.001 Torr was calculated to be half of that required for the 1.25 in. system. However, even with its inferior conductance, the pumping speed of the 1.25 in. system was sufficient to achieve the threshold operating pressure in a reasonable time, 6 hrs, with no additional intermediate pumping station being required.

The rf loss analyses showed that the relative insensitivity to waveguide misalignment of the 1.25 in. system could have significant advantages over the 2.50 in. system in minimizing mode conversion losses. Although the desired alignment quality was achievable with either system, it was thought that this quality level could be attained with less effort and cost with the 1.25 in. system.

Assessments of the ohmic wall losses in the waveguides and the mode conversion losses in the miter bends determined the 2.50 in. system to have non-trivial advantages. For the proposed transmission lines, these losses could total 6% for the 2.50 in. version and 15% for the 1.25 in. version. Alignment of the waveguide at the output of the MOU, however, was considered to be easier with the 1.25 in. system due to its lower sensitivity to beam tilt errors.

The critical 2.50 in. components were found to be exposed to lower peak thermal loadings than their 1.25 in. counterparts. Still, however, the peak temperatures derived for the 1.25 in. components were within the safe working limits for GlidCop, the dispersion-strengthened alloy of copper and alumina particles, for 1 MW, 10 s, 1% duty cycle operation.

The assessment of component size, support systems, and the space limitations at specific locations within the DIII–D facility yielded a distinct advantage to the 1.25 in. system. Although a rigorous assessment of the installation costs of the two systems was never performed, the component fabrication and assembly costs for the three 2.50 in. systems were estimated to be 28% greater than for the 1.25 in. systems.

In the end, the 1.25 in. system was selected over the 2.50 in. system on the basis of space limitations unique to the DIII–D facility, ease of installation and alignment, and overall cost, and its acceptable performance in rf losses, vacuum conductance and peak thermal loading.