Considerations in Selection of ECH System Transmission Line Waveguide Diameter for ITER

R.A. Olstad, J.L. Doane, and C.P. Moeller
General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
olstad@fusion.gat.com

Abstract. The reference diameter for the ECH transmission lines is presently 63.5 mm. Analyses of the heat generation and removal in 63.5 mm corrugated waveguide components were reported [R.A. Olstad, et al., Proc. of IAEA TM on ECRH Physics and Technology for ITER, Kloster Seeon, Germany, 2003, http://ipp.mpg.de/tmseeon; R.A. Olstad et al., “ECH MW-level CW Transmission Line Components Suitable for ITER,” to be published in Fusion Eng. & Design (2005)]. Those analyses concluded that the temperature of all components could be kept to acceptable levels, even with operation at 2 MW cw per transmission line. Recently interest has been expressed in the community about the possible advantages of using a smaller diameter waveguide for ITER, particularly because of limited space available at both the equatorial and upper launchers. In addition to ameliorating the space constraints, there could be large cost savings for a modest diameter reduction in certain transmission line components, particularly gate valves and CVD diamond window assemblies at the entrance to the launchers.

Results of a tradeoff study on ITER waveguide diameter are reported. Diameters considered range from 45 mm to 63.5 mm; consideration is also given to the possibility of tapering down to 31.75 mm at the launchers. The most critical issue for smaller diameter components is the increased losses and increased power densities. These lead to more demanding cooling provisions and higher operating temperatures for components such as miter bends, power monitor miter bends, bellows, dc breaks, waveguide switches, and waveguide sections adjacent to miter bends. In addition, the overall transmission efficiency of the ITER transmission lines would be reduced.

1. Introduction
Over the last 20 years, General Atomics (GA) has developed high performance corrugated waveguide transmission line components for low-loss transmission of high power microwaves for electron cyclotron heating and current drive (ECH&CD) on fusion devices. GA has been focusing on developing 63.5 mm waveguide components suitable for ITER, based on the specifications available to GA beginning in year 1998. However, recently there has some discussion in the ITER community that a somewhat smaller diameter for the waveguide and related waveguide components might be desirable, at least for part of the transmission lines. This interest is driven by the desire for lower cost components, particularly for gate valves and diamond windows.

GA already has considerable experience in designing and fabricating 63.5 mm components suitable for 1-2 MW cw operation at 170 GHz. Most recently, over the last year last year, GA fabricated 2 MW cw components for FOM and CRPP for testing of the 2 MW European gyrotron and ITER remote steering upper launcher prototype being developed at FOM. The components delivered to FOM included corrugated waveguide and miter bends with arc detectors, in addition to the square corrugated copper waveguide used for remote steering. The 170 GHz, 2 MW cw components
delivered to CRPP for their 2 MW gyrotron test stand included waveguides with water cooling clamps, miter bends with arc detectors and water cooling clamps for the couplings, and a power monitor miter bend. Low power testing of the FOM components is underway, and high power short pulse testing is expected at FZK later this year. High power testing at successively longer pulse lengths and powers will be made at CRPP over the 2006-2009 time frame.

Previously, GA designed and produced a 170 GHz transmission line for Kyushu University for 500 kW cw operation on the TRIAM-1M tokamak. The Kyushu University transmission line includes 63.5 mm diameter waveguides, miter bends, power monitors, bellows, pumpout tees, waveguide switches and dc breaks, as well as tapers down to 31.75 mm to connect to a CVD transmission line window, stainless steel launcher, and dummy loads. GA has also provided 31.75 mm and 63.5 mm 170 GHz transmission line components to JAERI for 1 MW/10 s operation in their 170 GHz gyrotron testing laboratory. Similar components were also provided to NIFS for 168 GHz operation on the LHD device. GA has built numerous other transmission lines for 110 GHz, 118 GHz, and 82.6 GHz operation for GA’s DIII-D device, JAERI’s JT-60U and, in conjunction with Spinner GmbH, for TCV at Lausanne, and Tore Supra at Cadarache.

The general configuration of the ITER transmission lines is shown in Fig. 1. The details of the layout are not yet available to GA, but it is reasonably clear that the ex-vessel transmission lines will include rf conditioning units (including matching optics, polarizer pair, switch, and gate valve), 1-2 MW cw dummy loads, dc breaks, corrugated aluminum waveguide, power monitor miter bends, miter bends, expansion section/bellows, waveguide switches, pumpouts, gate valves and rupture disk sections [1]. It is not clear if the ex-vessel transmission lines also include stainless steel corrugated waveguide close to the torus. It is also still ambiguous as to whether the transmission lines need to be suitable for 1 or 2 MW operation. ITER documents specify 1 MW cw operation, yet the EU is developing 2 MW gyrotrons and expects the transmission line components to be suitable for 2 MW operation.

2. Considerations in Reducing the ITER Waveguide Diameter
The potential advantages of reducing the ITER waveguide diameter appear to be the following:

- Reduction in diameter to 60 mm would enable the use of less expensive CVD diamond disks in the barrier windows at the torus. This is based on the present pricing and size availability of CVD disks by various suppliers. See Ref. [2] presented at this meeting for a discussion of the advantages of waveguide diameter reduction to 60 mm.
- Reduction in diameter to 60 mm would enable the use of a standard-size VAT gate valve as part of the tritium boundary between the primary and secondary vacuum isolation system.
- Further reduction in diameter, e.g. to 45 mm or 31.75 mm, at least near the torus, would reduce the congestion at the launchers and enable the use of even smaller, less expensive torus windows and gate valves. 31.75 mm would probably only be practical for 1 MW transmission and not for 2 MW transmission.
- An appreciable reduction in diameter would enable the use of smaller, less expensive components.

The disadvantages in reducing the ITER waveguide diameter appear to be the following:

- A reduction in waveguide diameter to 60 mm or 45 mm would require redesign of components already designed for 63.5 mm waveguide.
• A smaller diameter would increase the losses in the various components and result in higher component temperatures for long pulse/cw operation. Some components may require extensive redesign to keep them within a safe operating temperature range. The effect of a reduction from 63.5 mm to 60 mm would be fairly small since this would amount to only a 5% reduction in diameter. Using the equations in this paper, the resultant loss in the waveguide increases about 18.5% (loss inversely proportional to diameter cubed); mode conversion loss in miter bends increases about 9% (loss inversely proportional to diameter to 3/2 power); net increase in loss in a 100 m transmission line with 8 miter bends is about 10%.
• A smaller diameter would reduce the transmission line efficiency.
• An appreciable reduction in diameter would necessitate cooling all of the waveguide, thereby increasing the associated hardware, installation and maintenance costs.
• Tapers in the transmission lines would be required if smaller diameter waveguide is used only near the torus.

The relevant loss and temperature calculations for the various components are given below.

3. Waveguide Cooling Considerations
The calculated ohmic losses in dB/m for various standard diameter waveguides propagating HE_{11} are shown in Fig. 2. The 31.75 mm waveguide is a “100-180 GHz” waveguide in use at JAERI for ECH, the 63.5 mm waveguide is a waveguide used at JAERI and Kyushu University for 170 GHZ experiments, and the 88.9 mm waveguide is an “80-180 GHz” waveguide used at NIFS for ECH. The assumed corrugation depths are 0.50 mm, 0.45 mm, 0.45 mm, and 0.55 mm, respectively for the 31.75, 44.45, 63.5 and 88.9 mm diameters. These losses were calculated using a space harmonic analysis to determine the tangential magnetic fields across all surfaces of the corrugations and then integrating the square of these tangential magnetic fields across all surfaces of the corrugations. The resulting calculated ohmic losses for 1 MW transmission at 170 GHz are:
• 32 watts/m in 63.5 mm waveguide
• 89 watts/m in 45 mm waveguide
• 251 watts/m in 31.75 mm waveguide.

This heat can be removed if necessary to keep the waveguide temperature at safe levels by one of various techniques: forced air cooling, water cooling tubes, water cooling jackets, or water cooling clamps, as provided by GA to CRPP for the European 2 MW gyrotron test stand. An example of such a cooling clamp is shown in Fig. 3, although the type shown in the photo is clamped to the waveguide coupling rather than to the waveguide directly. The cooling clamp design has two cooling channels and a thermal interface pad between waveguide and clamp to provide good heat transfer. More information on cooling clamp design and performance is given in Ref. [3]. The performance of the clamp was modeled by calculating the temperature rise midway between two cooling clamps separated by length 2L. The temperature rise during cw operation at this location is given by \[ \Delta T' = q' L^2/2 k \]
where \( q' \) is the power absorbed per unit length, \( k \) is the thermal conductivity of the waveguide material, and \( A \) is the waveguide cross-sectional area. For 6061-T6 aluminum, the thermal conductivity is 1.67 W/cm-K near room temperature, and it is insensitive to temperature. The calculated temperature increases for different cooling clamp spacing for various waveguide sizes are as follows:

For 80 cm between clamps
• \( \Delta T = 12^\circ \text{C} \) for 63.5 mm waveguide at 1 MW (25°C at 2 MW)
• \( \Delta T = 45^\circ \text{C} \) for 45 mm waveguide at 1 MW (90°C at 2 MW)
• \( \Delta T = 170^\circ \text{C} \) for 31.75 mm waveguide at 1 MW (340°C at 2 MW).

For 40 cm between clamps
• \( \Delta T = 3^\circ \text{C} \) for 63.5 mm waveguide at 1 MW (6°C at 2 MW)
• \( \Delta T = 11^\circ \text{C} \) for 45 mm waveguide at 1 MW (22°C at 2 MW)
• \( \Delta T = 42^\circ \text{C} \) for 31.75 mm waveguide at 1 MW (84°C at 2 MW).
4. Ohmic Losses and Cooling of Miter Bend Mirrors

The fractional ohmic loss at a mirror in a miter bend is given by [4]:

\[ \text{Ohmic loss} = 4 \left( \frac{R_s}{Z_0} \right) \cos 45^\circ \] (H - plane polarization),
\[ \text{Ohmic loss} = 4 \left( \frac{R_s}{Z_0} \right) \cos 45^\circ \] (E - plane polarization)

where \( R_s \) is the surface resistance, which is proportional to the square root of the bulk resistivity and also the square root of the frequency. \( Z_0 \) is 377 Ohms, the impedance of free space. The worst-case polarization is the E-plane polarization, when the electric field is in the plane of the bend. At 170 GHz for ideal copper, \( 4 \frac{R_s}{Z_0} \) is about 0.0011 at room temperature. In practice, surface roughness effects increase the loss by around 20%. The ohmic loss for the E-plane polarization is therefore about 0.19%, or 1900 W for 1 MW incident (3800 W for 2 MW incident). The mirror cooling design has been upgraded to remove this power level for cw operation by directing the water cooling channel toward the center of the mirror where the peak heat load is greatest (Fig. 4). With this optimized cooling of the mirror, the estimated maximum temperature increases of the mirror surface for cw operation for the various waveguide diameters, assuming a water flow rate of 0.13 l/s, are:

- 33 °C for 63.5 mm waveguide at 1 MW (66°C at 2 MW)
- 66°C for 45 mm waveguide at 1 MW (>132°C at 2 MW)
- >135°C for 31.75 mm waveguide at 1 MW (>270°C at 2 MW).

More precise calculations would require finite element analyses to account for the increase in copper resistivity with increasing temperature. A prudent maximum temperature increase of a copper mirror is about 200°C. Based on the above estimates, it is apparent that miter bend mirrors in 63.5 mm or 45 mm waveguide will work at 1-2 MW, but heating in 31.75 mm miter bends is unacceptably high at 2 MW. Regular miter bends in 31.75 mm would be acceptable at 1 MW transmission, but power monitor miter bends, which have a relatively thin layer of copper at the mirror surface in the region of the coupling holes, would not be suitable for 1 MW cw operation.
This analysis is also applicable to polarizer miter bends. The ohmic loss in grooved mirrors can be a factor of 2 greater than for flat mirrors, with the magnitude of increase depending on the polarization. This would make it undesirable to use polarizer miters in 31.75 mm waveguide even at 1 MW, unless the incident polarization range is restricted to keep losses within acceptable limits.

Similarly, this analysis applies to waveguide switches, which use a copper mirror to deflect the beam 90° when in the diverted position. In the present mirror cooling design, the water is not directed quite as close to the mirror surface, so control of the incident polarization may be needed to limit the ohmic losses at the mirror surface if the switch is to operate 2 MW cw in the diverted position. The critical issue is how many thermal cycles the copper mirror must survive before failure due to thermal fatigue. Calculations show that a 63.5-mm switch mirror can handle 2 MW for up to 5000 cycles for arbitrary polarization, but can handle 2 MW for up to 10,000 cycles for circular polarization. This is based on an analysis of low cycle fatigue of OFHC copper at high temperature as a function of the plastic strain per cycle (see Fig. 6 in Ref. [7]). For 2 MW CW in the E-plane polarization, the calculated temperature rise at the center of the switch mirror reaches close to 300 °C. This calculation assumes turbulent flow in the cooling channels, and includes the temperature rise from the cooling channels to the mirror surface, as well as the effect of the increase in copper resistivity with temperature. With an average thermal expansion for copper of 17.7 parts per million per degree C from 20 to 300°C, the expansion at the mirror center is about 0.5%, with corresponding approximate 5000 cycles to failure for high conductivity copper. Similarly, with 2 MW in circular polarization, the temperature rise at the mirror center is approximately 210 °C, with a resultant expansion of about 0.35% and 10,000 cycles to failure.

5. Mode Conversion Losses at Miter Bends
The fractional mode conversion loss in an ideal miter bend propagating HE_{11} is given by [5]: mode conversion loss = 0.55 (λ/D)^3/2. About half of this mode conversion is into higher order modes close to cutoff, and an approximately equal amount of these modes are in the forward direction and reverse direction in the waveguide. As a result, the estimated conversion into higher order modes is as follows:

- 0.065% in each direction for 63.5 mm waveguide (1300 W at 2 MW)
- 0.11% in each direction for 45 mm waveguide (2100 W at 2 MW)
- 0.18% in each direction for 31.75 mm waveguide (1800 W at 1 MW).

Based on experiments at GA, rough estimates for damping lengths of these higher order modes are 1.6 m, 1.1 m, and 0.8 m for 63.5 mm, 45 mm, and 31.75 mm waveguide, respectively. The resulting temperature increase of waveguide sections under miter bend couplings cooled using water cooling clamps are:

- +20°C for 63.5 mm waveguide at 2 MW
- +50°C for 45 mm waveguide at 2 MW
- +55°C for 31.75 mm waveguide at 1 MW.

These temperature increases are acceptable for the 63.5 mm and 45 mm waveguide for up to 2 MW operation, but only marginally acceptable for 31.75 mm waveguide at 1 MW. More detailed information is given in Ref. [3] for the case of 63.5 mm waveguide.
6. Cooling Considerations for dc Breaks
To handle 1-2 MW cw power in the dc break (Fig. 5), the G-11 plastic insulators used in our present design will be changed to alumina (94% pure). The fractional power radiated from a gap of width $g$ in waveguide of diameter $D$ propagating HE$_{11}$ with a wavelength $\lambda$ is given by [5]: 

$$\text{fractional radiated power} = 0.55 \left(\frac{g\lambda}{D^2}\right)^{3/2}.$$ 

A 2.5-mm gap is sufficient to hold off 5 kV. The radiated power from such a gap is:

- 0.002% for 63.5 mm waveguide (40 W at 2 MW)
- 0.0056% for 45 mm waveguide (112 W at 2 MW)
- 0.016% for 31.75 mm (160 W at 1 MW, 320 W at 2 MW).

The temperature rise in 94% pure alumina ceramic rings due to the absorption of the power radiated from the gap is described in Ref. [3] for the 63.5 mm waveguide diameter case. Those results showed that the alumina ceramic rings would be about 10°C hotter than the adjacent aluminum for HE$_{11}$ power of 2 MW. Scaling these results to smaller waveguide diameter gives a ceramic temperature increase of about 40°C for 45 mm waveguide at 2 MW, and about 80°C for 31.75 mm waveguide at 1 MW and 160°C at 2 MW. The aluminum waveguide segments on each side of the ceramic can be cooled with built-in cooling channels, or water-cooling clamps can be used as described previously.

From these results, no direct cooling of the ceramic is required for 63.5 mm or 45 mm dc breaks at 1-2 MW, but ceramic cooling would be required for 31.75 mm waveguide, even at 1 MW. These results assume that HE$_{11}$ is propagating through the waveguide. If higher order modes are present, such as would occur if the dc break is near a miter bend or the gyrotron output is misaligned when it is injected into the waveguide, leakage through the gap in the dc break would be larger than assumed.

7. Considerations on Bellows Cooling
Figure 6 shows a 63.5 mm bellows suitable for up to 2 MW cw operation. The thin-walled aluminum flexible sections under the special couplings can be kept at acceptable temperature for 2 MW operation by adding a water cooling clamp in the central stiff region, as well as on the couplings. The heat deposition in 45-mm diameter bellows is 3 times as large as for 63.5 mm diameter bellows, and the 30% smaller cross section of the thin-walled flexible sections reduces the thermal conduction. These factors make it inadvisable to use the present bellows design at 45 mm or smaller, even for 1 MW cw operation. Smaller bellows, however, could be made using an alternative design in which corrugated sliding sections are used to accommodate expansion and contraction in the transmission line.

8. RF Breakdown Considerations
The risk of rf breakdown increases as waveguide diameter decreases since the rf electric field for any mode (or a fixed sum of modes) at a given total power varies inversely as the waveguide diameter. The greatest risk of breakdown occurs from higher order modes generated at miter bends or generated due to poor alignment of the waveguide. If these higher order modes reach miter bends, high levels of modes close to cutoff can be generated, and these modes can have high fields at the waveguide wall which can lead to breakdown. It is difficult to predict, however, what the electric field strength of these modes would be and whether or not breakdown would be likely to occur.

9. Discussion and Conclusions
From the analyses in this paper, it can be concluded that 63.5 mm waveguide is a prudent diameter to use for all of the transmission lines for ITER from the standpoint of rf losses in components and the ability to cool them to safe operating temperatures. If congestion problems at the ECH ports, diamond disk cost considerations for the torus windows, and/or gate valve cost considerations make it important to use smaller diameter waveguide close to the torus, it would be relatively straightforward to redesign components for 60 mm waveguide. This 5% reduction in diameter would not have a substantial effect on component heating. As an alternative, it may be possible to persuade CVD diamond disk vendors to make somewhat larger disks without substantial price increase so they could be used in 63.5 mm clear aperture windows. Similarly it may be possible to persuade VAT to produce a model with a somewhat larger opening than for the standard CF63 valve and to incorporate a corrugated insert in the paddle.
Further reduction to 45 mm could be accommodated for limited types of components near the launchers, i.e. waveguides, regular miter bends, and dc breaks for up to 2 MW cw operation. Polarizers in 45-mm diameter might require operation in a restricted polarization range. Reduction to 45 mm would only make sense if CVD windows could handle the higher power density and smaller gate valves were available to reduce congestion.

A reduction to 31.75 mm could be accommodated only for straight waveguide and regular miter bends for a 1 MW system. Again, this would only make sense if the CVD windows could handle 1 MW cw and if standard CF 40 gate valves are modified to incorporate corrugated inserts.

As a last point, it should be noted that the performance of all transmission line components, at whatever diameter(s) are chosen for ITER, should first be demonstrated at full design power under cw conditions before the components are built and installed on ITER. One option for such testing is described in Ref. [6] presented at this meeting.

References
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