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DESIGN OF THE UPGRADED TJ-II QUASI-OPTICAL TRANSMISSION LINE

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ABSTRACT

TJ-II plasma start-up and heating are made by electron cyclotron resonance waves at the second harmonic of the electron cyclotron frequency. Two quasi-optical transmission lines transmit the microwave power of the gyrotrons to the vacuum vessel. The first line launches the microwave power under fixed injection geometry, i.e. there is no possibility to change the launching angle and the wave polarization. The second line has a moveable mirror installed inside the TJ-II vessel. To get high absorption efficiency and a narrow energy deposition profile the internal mirror focuses the wave beam at plasma center.

To get more flexibility in the experiments on heating and current drive the first transmission line needs to be upgraded. The design is presented in this paper. The new launching antenna includes an internal mirror to focus the beam and to change the injection angle. Both launchers are then symmetrical. A polarizer consisting of two corrugated mirrors is used to get any wave polarization. Two mirrors with an array of coupling holes and calorimetric measurements of the energy absorbed in the barrier window allow the estimation of the microwave power launched into the TJ-II.

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INTRODUCTION

The ECRH system at TJ-II consists of two quasi-optical transmission lines, a high voltage power supply, two anode modulators, two powerful microwave tubes and their accessories. Each line transmits the microwave power delivered by a GYCOM gyroton, whose main parameters are the following: output nominal power 300 kW, maximum pulse length 1s, frequency 53.2 GHz (as corresponds to the second harmonic of the electron cyclotron frequency in TJ-II plasmas) and a gaussian purity of 96%. The gyrotrons are fed by one common high voltage solid-state power supply and are controlled by two anode modulators [1].

The first Quasi-optical Transmission Line (QTL1) was put into operation in November, 1997 and the first plasmas in TJ-II were obtained with this line. The microwave power is launched through the bottom port B3 (toroidal angle φ=25.47°) under a fixed geometry, i.e. the injection angle cannot be changed. It has 8 mirrors: one flat, six cylindrical mirrors coupled in pairs and two ellipsoidal mirrors to guide the beam. The beam waist (3.2 cm) is placed at the TJ-II window and in the plasma center the beam radius is 55 mm. The total losses are 12%: 7% are due to beam edge truncation, 4% due to the sidelobes of the gyrotron output radiation and 1% due to the absorption in the barrier window at TJ-II.

The second Quasi-optical Transmission Line (QTL2) was successfully put into operation in 1999. The microwave beam is launched through the lateral port A6 (toroidal angle φ=64.53°) and a movable mirror is placed inside the vacuum vessel. This mirror focuses the beam and the launching angle can be changed in both toroidal and poloidal directions with a flexibility of $\varphi=\pm 20°$ in the toroidal direction and $0° < \theta < 35°$ in the poloidal direction. Experiments of heating on- and off-axis and current drive (ECCD) can be carried out. There are 9 external mirrors: the first one is flat, 6 of them are cylindrical coupled in pairs and two are ellipsoidal. The losses along the line are larger than in the first line, mostly due to beam edge truncation on the mirrors: 14%. The main parameters of the mirrors of both lines are given in reference [2].

A new quasi-optical transmission line has been designed and constructed to get more flexibility in the ECRH and ECCD experiments.

As it was mentioned above, in the present QTL1 line the beam launched into the TJ-II vessel is too wide due to the long distance between the last external focusing mirror and the plasma center. To improve the launching parameters the new line has also a movable mirror inside the vacuum vessel, with the same size and curvature radii as the other one placed in sector A6 (QTL2). With this set-up, it is possible to induce currents with both antennas in co- and counter-clockwise toroidal directions. It is also possible to find a combination such that the induced current is zero along all the radial profile and a combination where the contributions of both lines add. Another important point is the wave polarization state. The gyrotron wave beam has linear polarization and the present design only allows to change the polarization plane. In the new design a pair of corrugated mirrors produces the appropriate polarization. Finally, two coupling mirrors together with calorimetric measurements allow the estimation of the power delivered to the plasma in each TJ-II shot.

ROUTE THROUGH THE EXPERIMENTAL HALL AND BEAM PARAMETERS

The distance that the microwave beam covers is around 11 m. The route is almost the same as the actual path for QTL1 with the suitable change to be able to launch the microwave power through the lateral port B3 (φ=25.47°). Both lines launch the beam at two toroidal symmetrical positions. A top view of both lines with their internal mirrors in respect to the TJ-II stellarator is shown in figure 1.

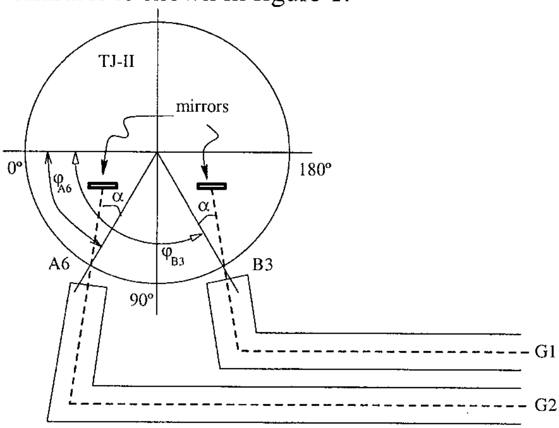


Figure 1. Schematic top view of the position of the lines in the torus hall

8 ellipsoidal mirrors and 2 grooved plane reflectors transmit the power from the gyrotron to the vacuum vessel. The beam is focused by the internal mirror at plasma center with a beam waist of 9.5 mm, the same as in QTL2. The beam diameter at the barrier window is 100 mm. The material of the mirrors is aluminum, except of the internal one, which is made of stainless steel. The mirrors are fixed on mounts, which allow the alignment of the mirror orientation in two planes with micrometers. A side view of the new line can be seen in figure 2.

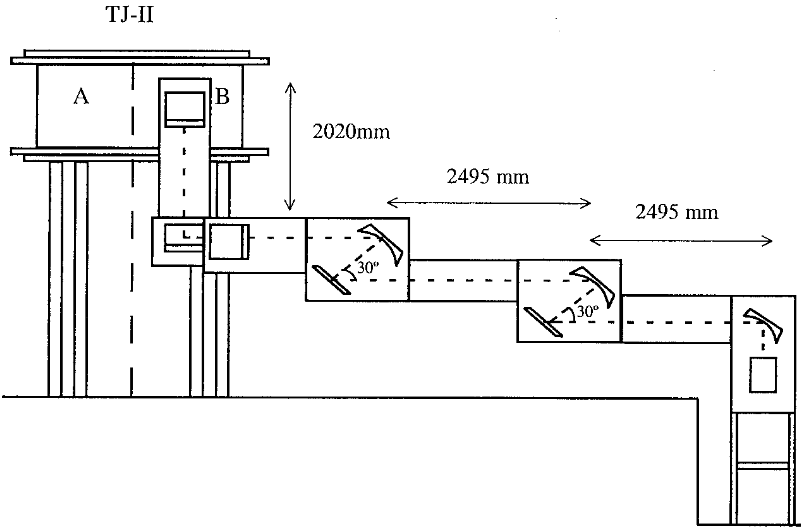


Figure 2. Side view of the new transmission line.

The gyrotron output radiation is Gaussian-like with a purity of 96%, but it is astigmatic, i.e. the wave beam cross-section is elliptical. With the first two matching mirrors this astigmatism is corrected. The distance between mirrors, the beam waists position and the beam size on the mirrors are shown in table 1. The gyrotron window is the reference and the distance between the window and the first mirror is 700 mm. The beam waists in vertical and horizontal planes are not located at the window: as table 1 shows, in vertical plane the waist is w_o=18.14 mm placed 12.3 mm inside the gyrotron, and in horizontal plane w_o=23.15 mm placed 179.6 mm outside the gyrotron. After the second mirror the beam cross-section is circular.

Nr.	Distance between mirrors	w_{0in}	Distance w_{0in}-mirror	w_{mirror}	w_{0out}	Distance w_{0out}-mirror
1	700.0	18.14 23.15	712.3 520.4	72.7 46.5	48.0 18.0	-1461.7 -431.1
2	400.0	48.0 18.0	1861.7 831.1	84.5	59.8	1992.3
3	3188.4	59.8	1196.1	69.7	59.8	-1193.5
4	800.0	59.8	1993.5	84.6	59.8	1993.5
5	3188.4	59.8	1194.9	69.7	59.8	-1192.4
6	800.0	59.8	1992.4	84.5	59.8	1992.4
7	3988.4	59.8	1996.0	84.6	83.9	519.6
8	1249.0	83.9	729.4	85.3	27.6	1242.6
9	2020.0	27.6	777.4	57.6	30.1	823.2
10	1535.0	30.1	711.8	52.0	9.5	272.0
P	272.0	**9.5**				

Table 1. Distances between mirrors, beam waists position and beam size on the mirrors. All the dimensions are in mm. The distances are positive in the propagation direction.

MIRROR PARAMETERS

The first two matching mirrors transform the astigmatic gaussian beam from the gyrotron into a symmetric Gaussian beam. This is important, on the one hand because the beam is axisymmetric through the rest of the line and, on the other hand, if the gyrotron has to be changed, the same beam parameters can be achieved by changing only these two mirrors.

The first mirror is hyperbolic and the second one ellipsoidal. The main parameters of the mirrors are summarized in the following table (table 2).

Mirror	1° Hyperbolic	2° Ellipsoidal
Focal distance in incidence plane	-1904.4	714.7
Focal distance in perpendicular plane	1075.2	1626.1
Mirror size in the incidence plane	411.0	478.0
Mirror size in perpendicular plane	186.0	338.0

Table 2. Parameters of the first two mirrors. Dimensions in mm.

The surfaces can be calculated for astigmatic beams with the following equation [3]:

$$Z=h_{20}x^2+h_{02}y^2+h_{12}xy^2+h_{03}x^3$$

Where:

$$h_{20}=\frac{1}{4\cdot\cos\theta}\cdot\left(\frac{1}{r_{xi}}-\frac{1}{r_{xo}}\right)$$

$$h_{02}=\frac{\cos\theta}{4}\cdot\left(\frac{1}{r_{yi}}-\frac{1}{r_{yo}}\right)$$

$$h_{12}=-\frac{\tan\theta}{4}\cdot\left(\frac{1}{r_{xi}^2}-\frac{1}{r_{xo}^2}\right)+\frac{\tan\theta}{8}\cdot\left(\frac{1}{r_{xi}}-\frac{1}{r_{xo}}\right)\cdot\left(\frac{1}{r_{yi}}-\frac{1}{r_{yo}}\right)$$

$$h_{03}=-\frac{\cos\theta\cdot sin\theta}{8}\cdot\left(\frac{1}{r_{yi}^2}-\frac{1}{r_{yo}^2}\right)$$

where θ is the incidence angle. When h_{12} y h_{03} are equal to zero, the surface is toroidal. The coordinates are chosen such, that x corresponds to the incidence plane and y to the perpendicular plane.

For mirrors 1 and 2 the coefficients are summarized in the following table (table 3):

Coefficient	Mirror 1	Mirror 2
h_{20}	-1.85×10^{-4}	2.17×10^{-4}
h_{02}	1.64×10^{-4}	2.47×10^{-4}
h_{12}	0	0
h_{30}	-7.85×10^{-8}	-7.85×10^{-8}

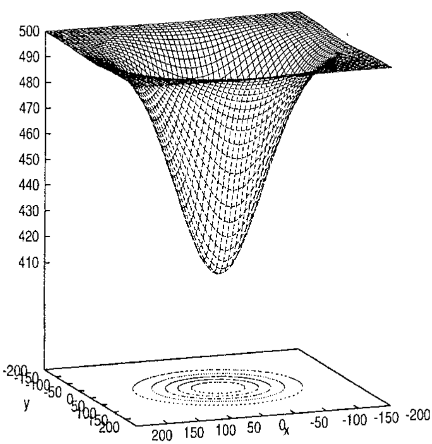
Table 3. Mirror surface coefficients for mirrors 1 and 2

The probable distortion of the beam [3] has been calculated with a numerical code and it is proved that the distortion is minimum. The numerical code is based on the Huygens-Kirchoff integral and calculates the field from the currents generated in the mirror [4]. Some high order modes appear, the power of each one is presented in table 4.

Mode	Power
TEM_{00}	0.9882
$TEM_{01}{}^{cross}$ (Mirror 1)	0.0010
TEM_{01}	0.0021
$TEM_{10}{}^{cross}$ (Mirror 2)	0.0033
TEM_{10}	0.0002
TEM_{21}	0.0043

Table 4. High orders mode analysis.

In figure 3 the field radiated from the first mirror and in figure 4 the radiated field from the gyrotron and after the second mirror are shown.



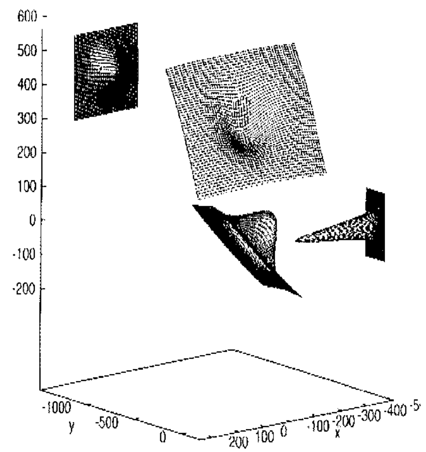


Figure 3 and 4. Field radiated from the first mirror and field radiated from the gyrotron and after the second mirror. The dimensions are given in mm.

The calculations show that the mirrors can be fabricated with a toroidal surface because the beam distortion is almost the same as with a more complicated surface and the mechanisation is easier.

Mirrors 3 and 4 are flat and are used as polarizers. The rest of the mirrors are ellipsoidal and their parameters are summarized in table 5.

MIRROR	4	6	7	8	9	10
Focal distance	1994.2	1994.2	3521.6	1304.9	533.8	222.8
Size in incidence plane	342	342	570	482	325	190
Size in perpendicular plane	339	339	338	341	230	170

Table 5. Mirror main parameters. Dimensions in mm.

The position of mirror 10 inside the vacuum vessel can be seen in figure 5. This mirror focuses the beam at plasma center with a beam waist of 9.5 mm along a distance of 272 mm. It is movable in poloidal and toroidal directions. Having this flexibility it is possible to heat the plasma on- and off-axis at different toroidal angles. This new launching geometry is also capable of inducing localized currents [5,6].

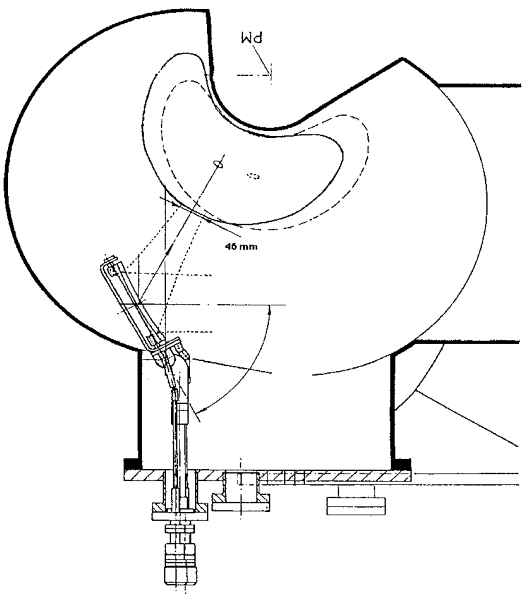


Figure 5. Position of the last mirror inside the vacuum vessel.

All the mirrors are made of aluminum except the internal one, which is made of stainless steel in order to avoid impurities inside the vessel.

In general, to heat the plasmas by EC waves at the second harmonic an elliptical polarization is required. As the output radiation of the gyrotron has a linear polarization it is necessary to incorporate polarizers to choose the optimal polarization.

Two corrugated mirrors, an elliptical polarizer and a twister are set in positions 3 and 5. The first one gets the required elliptical polarization and the second one rotates the polarization plane [7]. To avoid arcing at high-power level, the corrugations have a sinusoidal shape (table 6). The groove shape is very important to determinate the polarizers performance.

Polarizer	Amplitude	Period
Elliptical polarizer (3)	0.738	3.381
Twister (5)	1.065	3.381

Table 6. Groove shape. Dimensions in mm.

POWER MEASUREMENTS

It is very important to know the power delivered into the plasma in each discharge. To estimate the power two mirrors with an integrated directional coupler have been designed. One mirror is installed at the beginning of the line to measure the output power from the gyrotron. The other mirror is the 9^{th}, i.e. the nearest mirror to the vacuum vessel, which is used to measure the power at the end of the line. Thus, the transmission losses can be estimated. In figure 6 a schematic drawing of the structure can be seen.

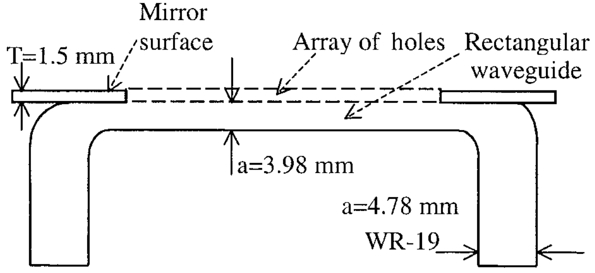


Figure 6. Schematic drawing of the mirror with coupling holes

A small amount of the microwave power impinging on the mirror is coupled into a rectangular waveguide. The width of the rectangular waveguide is chosen so that the propagation constant is equal to the wave vector for the incidence angle [8]. With a taper the dimension is increased till the standard WR-19. To improve the radiation pattern, i.e. to get low side lobes and a narrow antenna beam, the diameter of the holes is varying to produce a truncated Gaussian taper of the coupling efficiency.

Owing to the symmetric design the device works as bi-directional coupler, i.e. it is also possible to detect and measure the reflected radiation. Once calibrated, the power during each shot can be measured.

Calorimetric measurements with a cylindrical water load will be also carried out. With a movable mirror placed after the second mirror the beam is diverted to the load. In figure 7 the position of the load and the movable mirror can be seen.

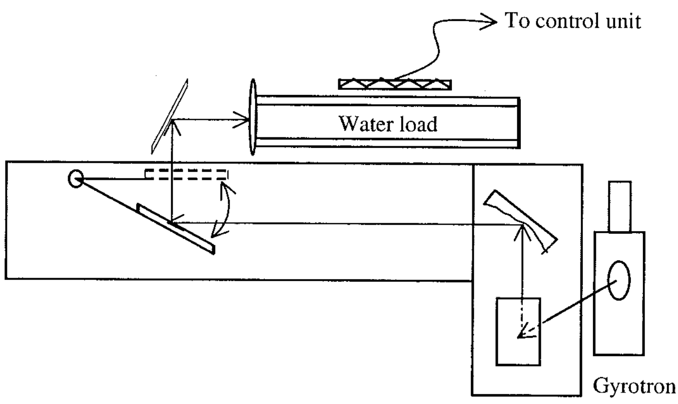


Figure 7. Cylindrical water load and movable mirror to carry out calorimetric measurements between shots.

The load is 2 m long and its internal diameter is 80 mm. The beam waist diameter at the aperture is 26.3 mm. The maximum pulse length is 100 ms.

POWER LOSSES

The main sources of transmission losses have been calculated and are estimated to be 8%. In table 7 the different losses are summarized. One can see, that the largest contribution is ohmic losses followed by diffraction due to the beam truncation on the mirrors.

Losses	%
Beam truncation	1.7 %
Ohmic losses	2.5 %
Mode conversion	1.2%
Cross polarization	1.25%
Absorption at barrier window	1%

Table 7. Losses along the transmission line in %.

CONCLUSIONS

The design of a new quasi-optical transmission line for TJ-II ECRH system has been presented in this paper. The main requirements to achieve more flexibility in the ECRH and ECCD experiments are accomplished. Both antennas, in QTL2 and in the new QTL1, are positioned at two toroidally symmetric positions.

The first two mirrors correct the astigmatic beam radiated from the gyrotron. The rest of the line transmits a Gaussian beam with a circular cross-section. The internal mirror focuses the beam and its movement allows on- and off-axis heating, as well as ECCD experiments with both lines. The appropriate wave polarization can be obtained with corrugated polarizers. The power delivered to the vacuum vessel and the reflected power are measured with two coupling mirrors, one placed next to the gyrotron and the other placed next to the stellarator.

The total losses along the line are quite reasonable: about 8% and the beam distortion is negligible.

The line is to be put into operation in 2001.

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