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In-situ characterization of spurious modes in HE_{11} transmission lines with a 5-port coupler

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Abstract. Real-time in-situ measurement of spurious modes in HE_{11} transmission lines is becoming an important topic for the design of next-generation ECRH installations (e.g. ITER), because the acceptable tolerances for the alignment of the waveguides and coupling optics are small for oversized waveguides. Also, the effects of spurious modes (ohmic heating, wrong beam parameters at the launcher) become increasingly critical. We present a method for in-situ characterization of 4 dominant spurious modes by using a 5-port coupler, which is integrated into a miter bend. The coupler signals can be directly transformed into the mode spectrum by a matrix multiplication. A general formalism for obtaining the coefficients of the transformation matrix is presented along with a method for optimizing the coupler positions in order to obtain the maximum dynamic range for the diagnostics.

1 Introduction

Misalignments or deformations of oversized HE_{11} waveguides excite unwanted spurious modes, which can lead to localized heating, arcing and antenna beam deformation in high power ECRH installations [1]. Therefore, there is a growing interest in in-situ diagnostic methods (and ideally real-time correction mechanisms) for the mode purity such systems.

Since we have highly oversized waveguides and can assume balanced hybrid modes, we use the system of linear polarized (LP)-modes [2], where the HE_{11} mode is denoted LP_{01}.

An exact characterization of the mode spectrum in a waveguide requires the knowledge of the complex field amplitudes for the entire cross-section and a mode analysis. By considering the main types of alignment errors, however, we can identify 4 dominant spurious modes [3]: The even and odd LP_{11} modes are excited by a tilt or an offset of the beam coupled from the gyrotron to the waveguide input. The rotational symmetric LP_{02} and LP_{03} modes result from a wrong spot size of the input beam or a non-planar phase front at the waveguide input. Together with the LP_{01}-mode we get a system of 5 modes. The waveguide fields resulting from these misalignments are illustrated in Fig. 1. Here we see the typical beat patterns which show up due to the different phase constants of the main mode and the spurious mode.

Under the assumption, that no other modes are present in the waveguide, we can calculate the mode spectrum from the field amplitudes at 5 locations of the cross section, if these are chosen properly. To make the detection independent from the position of the coupler along the waveguide axis, we need the phase information of the coupler signals as well.

Section 2 describes a prototype, which was investigated experimentally to verify the principal behavior. Section 3 describes a general formalism for calculating the mode spectrum from the coupler signals. A further optimization of the coupler positions is presented in section 4.

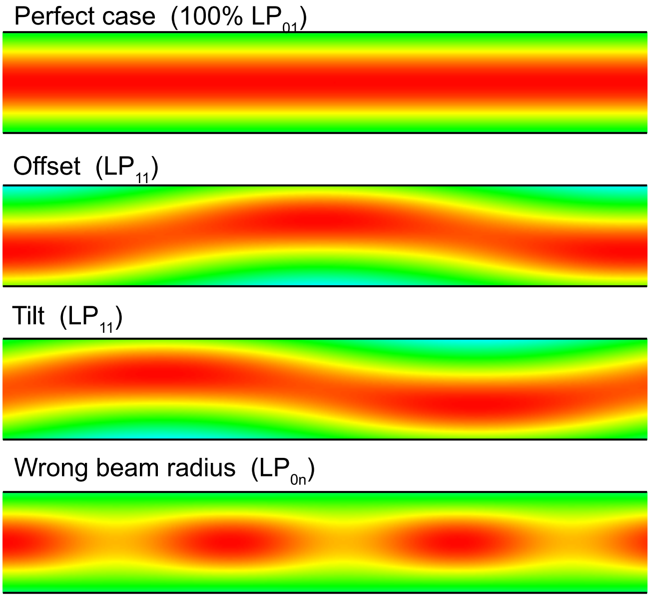

Fig. 1. Typical types of misalignments and the resulting field distributions and dominant spurious modes

2 Prototype 5-Port Coupler

For obtaining the field values at the waveguide cross-section we integrate leaky-wave antennas into the mirror of a miter-bend, which are connected to fundamental mode waveguides below the surface. The use of leaky-wave antennas instead of single-hole couplers has the advantage that they are less sensitive to very high order modes (stray radiation) and that one can distinguish between forward and reflected modes. In addition, the field is averaged over a larger area, which results in an additional attenuation of higher-order modes, which would disturb the analysis. The Brillouin angle of the fundamental waveguide is matched to the 45° angle of the incident beam on the 90° miter bend.

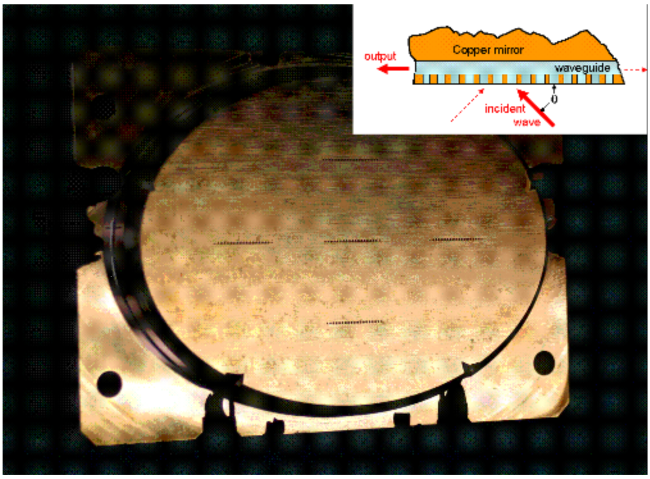

Fig. 2. Prototype of a 5 port coupler

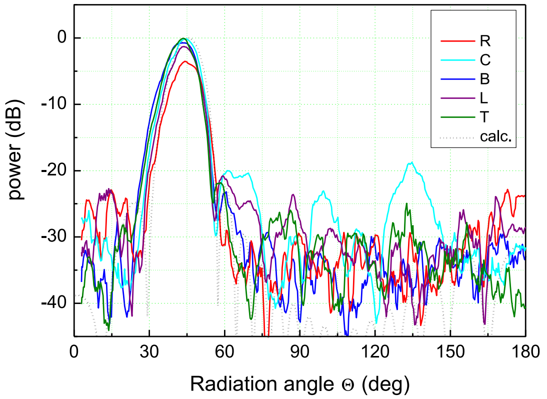

Fig. 3. Measured and calculated radiation patterns of the couplers.

The fabrication by electroforming avoids any contact problems within the coupler waveguides; this makes the design robust with respect to heating in high-power applications. Moreover, a second layer of channels for water cooling for CW operation can be easily embedded into the copper mirror. Fig. 2 shows the prototype.

The measured and calculated antenna diagrams of the coupler channels are shown in Fig. 3. One can see that the maximum sensitivity is at an angle of 45°, which corresponds to the propagation direction of the modes to be detected since the coupler is integrated into a 90° miter bend. The differences in sensitivity (especially for the right channel) can be compensated numerically by the signal processing together with the phase differences.

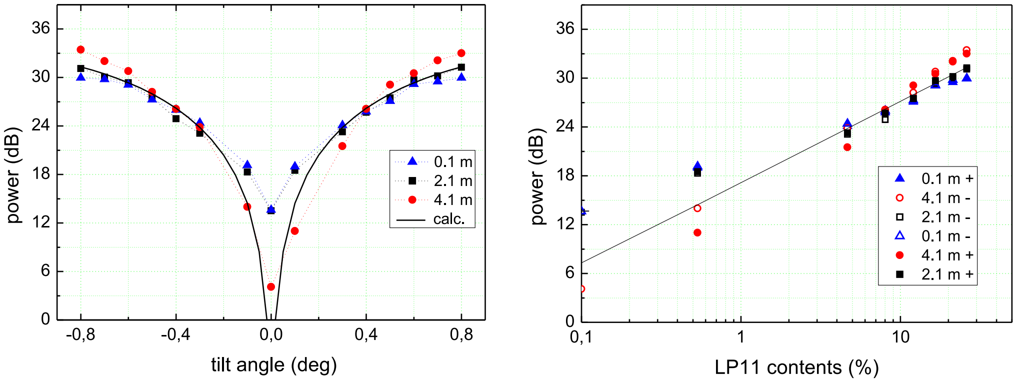

Fig. 4. Difference signal as a function of the tilt angle (left) and as a function of the LP_{11} content (right). Measurements were done at 0.1 m, 2.1 m and 4.1 m. The solid line is the calculation.

Numerous measurements where done with the prototype coupler and different mode mixtures at different positions.

As an example, LP_{01}-LP_{11} mixtures generated by a waveguide tilt, are shown. In this case, the LP_{11} content can be obtained from the difference signal of e.g. the left and right coupler such that the contributions of the symmetric LP_{01}-mode cancel each other. Thus, the amplitude of the difference signal will be independent from the location of the coupler in the beat pattern (cf. Fig. 1).

Fig. 4 (left) shows the difference signal as a function of the tilt angle. Fig. 4 (right) shows the difference signal as a function of the calculated LP_{11} content at different positions.

The measurements were done at different positions (i.e. with different phase shifts of the modes) by inserting straight waveguide sections between the input and the coupler. The principal results are independent from the coupler position. Differences from the theoretical behavior can be explained by the mechanical inaccuracies of the angle adjustment. Also the HE_{11} mode, which was available in the laboratory, was non-perfect.

All measurements clearly confirm the predicted behavior of the coupler. By doing a better compensation of the sensitivity differences of the channels and a more precise compensation of the phase shifts between the channels, the accuracry can be further improved.

3 Calculation of the mode powers from the coupler signals

In the general case, the number of modes, which can be detected, is equal to the number of couplers, if the coupler positions are chosen properly. Assuming a mode mixture, which consists only of the modes LP_{01}, LP_{02}, LP_{11e}, and LP_{11o}, it is possible to unambiguously obtain the mode powers from the coupler signals L, R, T, B and C. In addition, the relative phases of the modes have no influence on the calculation, which means that the results are independent from the actual position of the coupler in the transmission line. This is done by multiplying the coupler signals, which are assumed (e.g. adjusted with phase shifters) to have identical phases, with real weighting factors (e.g. adjusted by attenuators) and summing them up. The sums are then proportional to the mode amplitudes. By defining a vector **A**, whose coefficients are the mode amplitudes, the general formula is:

$$\mathbf{A} = (M) \begin{pmatrix} L \\ R \\ T \\ B \\ C \end{pmatrix} \tag{1}$$

where L, R, T, B and C are the complex signals from the couplers. In order to find the coefficients of the transformation matrix (M) we assume a pure mode (denoted 1) with the power of 1. For obtaining the amplitude of this mode from the coupler signals L_1, R_1, T_1, B_1 and C_1, and suppressing this mode in the other output channels, the matrix (M) must fulfill the condition:

$$(M) \begin{pmatrix} L_1 \\ R_1 \\ T_1 \\ B_1 \\ C_1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

By multiplying (2) with $(M)^{-1}$ we obtain:

$$(M)^{-1} = \begin{pmatrix} L_1 & X & X & X & X \\ R_1 & X & X & X & X \\ T_1 & X & X & X & X \\ B_1 & X & X & X & X \\ C_1 & X & X & X & X \end{pmatrix} \tag{3}$$

where X denotes the not yet known coefficients. By writing the analogous expressions for the other modes (denoted $2-5$), we finally get the complete inverse matrix of (M):

$$(M)^{-1} = \begin{pmatrix} L_1 & L_2 & L_3 & L_4 & L_5 \\ R_1 & R_2 & R_3 & R_4 & R_5 \\ T_1 & T_2 & T_3 & T_4 & T_5 \\ B_1 & B_2 & B_3 & B_4 & B_5 \\ C_1 & C_2 & C_3 & C_4 & C_5 \end{pmatrix} \tag{4}$$

To extract 5 mode amplitudes from the 5 coupler signals, the coupler positions must be chosen such, that the the matrix $(M)^{-1}$, which consists of the sampled mode fields, is non-singular. Additional criteria for a further optimization of the coupler positions are described in section 4.

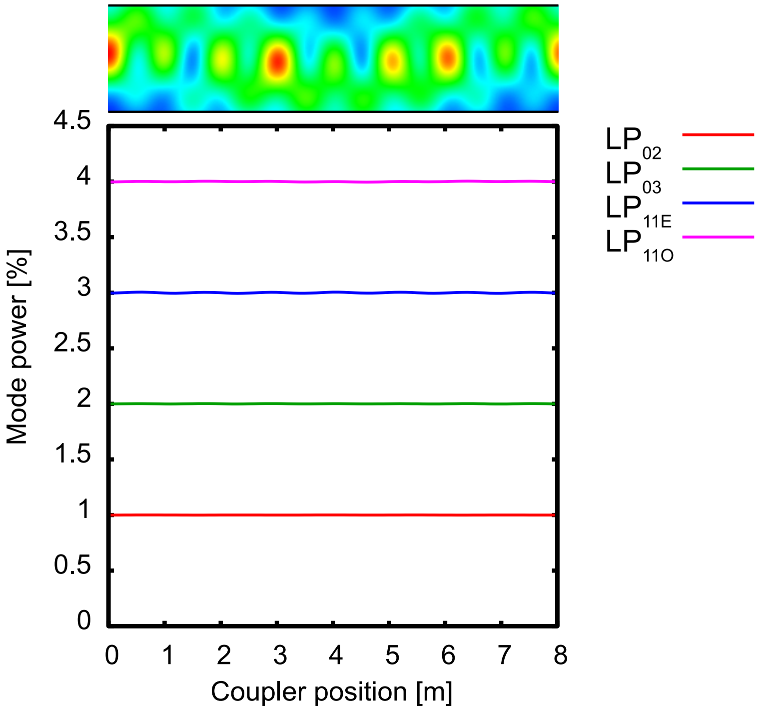

Fig. 5. Field pattern and detected mode powers of a mode mixture (90 % LP_{01}, 1 % LP_{02}, 2 % LP_{03}, 3 % LP_{11e}, 4% LP_{11o}

To test the algorithm, a synthetic mode mixture was generated and the total field was calculated at several positions of the waveguide. Fig. 5 shows the field distribution in the waveguide and the calculated mode powers. In spite of the irregular interference pattern in the waveguide, one can see that the contents of spurious modes can accurately be detected at all positions.

One principal problem of this method is the sensitivity to other modes, which might propagate in addition to the considered ones. In this case the signals for the mode amplitudes are disturbed and the levels are no longer independent from the position of the couplers. A partial compensation is achieved by using leaky wave antennas, which (i) have the highest sensitivity for Brioullin angles close to zero and (ii) integrate the field over a larger area, which suppresses the finer field distributions of higher-order modes.

For a realization of this technique, mixers will be inserted directly after the couplers with a LO frequency generated by a single side band up-converter from the gyrotron frequency. The calibration of the system (i.e. compensation of phase shifts and different attenuations) will then be done at frequency in the MHz or kHz range.

4 Optimum Coupler positions

While the theoretical calculation works independent from the coupler positions (as long as the matrix inversion in 3 can be done), noise will limit the dynamic range of the spurious mode detection in practice. In order to achieve a maximum dynamic range, we choose the coupler positions such, that the largest absolute value of the transformation matrix (i.e. the largest amplification factor) becomes as small as possible. Variable parameters are the radial positions r_{lr} and r_{tb} of the left-right and top-bottom couplers, respectively. The calculation was done for 140 GHz and a waveguide diameter of 87 mm. The result is shown in Fig. 6. The optimized radial coupler positions are at 0.63 R and 0.33 R, where R is the radius of the waveguide.

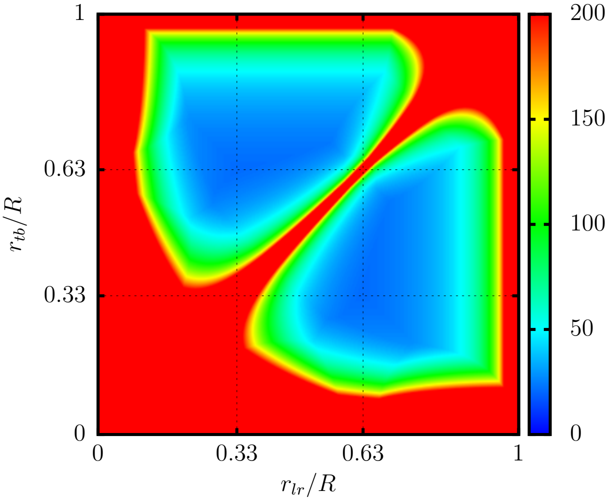

Fig. 6. Maximum amplification factor for obtaining the mode powers as a function of the radial coupler positions.

5 Conclusion

The present work shows that a 5-port coupler integrated into a miter bend is a valuable tool for mode analysis and alignment in LP_{01} transmission lines. Depending on the signal analysis, the power of the main mode and several higher-order modes can be measured. The device is especially sensitive to the modes, which are excited when the line is fed with a beam with diameter mismatch, angular misalignment or transversal offset. Proof-of-principle measurements clearly confirm the calculations.

The present design using short line arrays for the couplers reduces the interference from very high-order modes, and allows the discrimination of forward and backward modes.

A general formalism was developed to calculate the weighting factors for detecting the mode amplitudes independently of the coupler position within the transmission line. The positions of the holes must be chosen such, that the matrix of the sampled field amplitudes is non-singular. A further optimization was performed, which results in high signal levels from the couplers to improve the robustness against noise.

Work for an optimized coupler with additional cooling channels is underway.

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