Fast Switching of High-Power Millimetre Waves Between Two Launchers: Concepts, Numerical Investigations and First Experiments

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Abstract. Narrow-band frequency diplexers in connection with small frequency-shift keying of gyrotrons can be used to switch the millimetre wave power between two output channels. This technique can e.g. be used for fast beam steering for synchronous stabilization of rotating neoclassical tearing modes (NTMs) in tokamaks. Beam steering can be performed by a multi-resonant multiplexer, provided that phase-controlled sources are available. In the paper, various concepts for fast directional switches are discussed. Calculations and low-power measurements of prototypes are presented. Requirements and techniques for frequency control of the gyrotrons are discussed, and the results of preliminary frequency modulation experiments are shown. A resonant diplexer installed at the ECRH system for W7-X will be demonstrated within a year.

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INTRODUCTION

One of the most attractive features of Electron Cyclotron Resonance Heating (ECRH) and Current Drive (ECCD) systems for Tokamaks is the control of MHD-instabilities and consequent improvement of the plasma parameters. As these instabilities are well localized around resonant magnetic surfaces, narrow and well-focused ECRH-wave beams have to be directed with high accuracy to the resonant layer [1]. Especially for the case where the width of the power deposition profile exceeds the width of the island, ECCD in the O-point of the island only gives highest efficiency for NTM stabilization, which requires modulation of the launched EC power synchronously with the rotating islands.

Up to now, synchronous current drive is performed by power modulation of the gyrotron [1], with the disadvantages that (i) half of the installed power is not used, (ii) the collector of the gyrotrons can be thermally overloaded, and (iii) fast switching of MW-powers can result in severe electromagnetic interference.

An alternative for power modulation could be switching of the millimetre waves between two launchers directing the beam to poloidal or toroidal planes, which are about 180° apart from each other with respect to the phase of the NTM (see Fig. 1). Here, the power is switched synchronously with the island rotation by a fast directional switch (FADIS). This device is based on a small frequency-shift keying of the gyrotron ($\Delta f_s = f_2 - f_1 \ll f_{ce}$, i.e. some tens of MHz), and a narrow-band frequency diplexer, which directs an input beam to one of the two output channels [2]. As any diplexer can be designed as four-port device, two gyrotrons can be fed into it. If both gyrotrons are shifted between frequencies f_1 and f_2, but in opposite phase ("push-pull"), then the power of both gyrotrons is combined into one of the two outputs, and is switched between output 1 and 2 in the rhythm of the frequency-shift keying (see e.g. [3]). Thus, there is no need to increase the number of launchers. Note that besides NTM stabilization, the FADIS can be used to share the installed EC power between different types of launchers or different applications (e.g. in ITER, midplane / upper launcher), whichever is given priority during a plasma discharge.

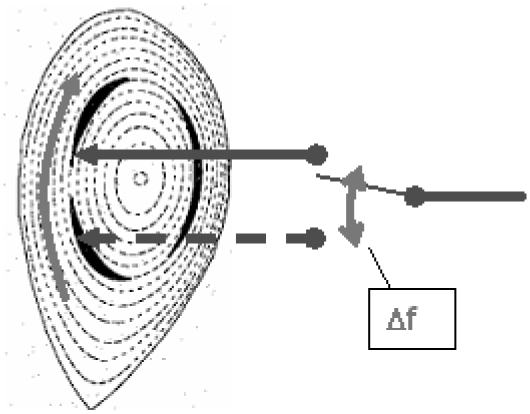

FIGURE 1. Principle for NTM stabilization using a fast directional switch: Synchronously with the rotation of the island, the ECCD beam is switched between two launchers which are about 180° apart from each other with respect to the mode phase.

The diplexer can be realized as a quasi-optical interferometer with grating splitters or 3dB-hybrids based on oversized rectangular corrugated waveguide, or, in the most compact form, as a quasi-optical cavity (ring resonator) with corrugated mirrors. The shift of the frequency in the gyrotron must be performed by modulation of the gun anode, or the beam acceleration voltage. In the paper, various concepts for fast directional switches are discussed. Calculations and low-power measurements of prototypes are presented. Requirements and techniques for frequency control of the gyrotrons are discussed, and the results of preliminary frequency modulation experiments are shown. Finally, plans for a high-power test of a resonant diplexer in the beam duct of the ECRH system for W7-X are discussed.

CHARACTERISATION OF A WAVEGUIDE DIPLEXER

The diplexer presented in this chapter is based on the Mach-Zehnder type of the two-beam interferometer [3] and consists of two 3-dB hybrids and a delay line in between. The device employs corrugated rectangular waveguides which show image multiplication ("Talbot-effect") and thus can be used to design the 3-dB splitters [4]. A sketch is shown in Fig. 2. The power is fed from a square corrugated waveguide ($HE_{1,1}$ mode) into the main rectangular diplexer waveguide with width a (and height b). According to the propagation constants of the excited waveguide modes, the amplitude distribution at the entrance is split into two identical patterns after a length of $a^2/(2\lambda)$. At this position, a mitre bend in the waveguide directs one part into a folded delay line made from corrugated square waveguide, and again couples this part back into the rectangular waveguide. Depending on the relative phases of the two identical patterns, a recombination of the patterns occurs after a length of $2a^2/\lambda$. In the ideal case, the output power toggles between the two output waveguides according to

$$P_1(f) \;=\; P_0 \cdot \sin^2\left(\frac{\pi \cdot L_\phi f}{c}\right), \qquad P_2(f) \;=\; P_0 \cdot \cos^2\left(\frac{\pi \cdot L_\phi f}{c}\right) \tag{1}$$

Therefore, for the application as a FADIS, the gyrotron has to be frequency shifted by

$$\Delta f_S \;=\; \frac{c}{2 \cdot L_\phi} \tag{2}$$

which can be adjusted by the length of the delay line. Calculations using a mode-matching technique and optimization routines have been performed showing that for highly oversized waveguides optimum results are obtained for input and output waveguides with a width of $a/2$. Detailed calculations (ohmic loss and loss in the mitre bends of the delay line was neglected) have been performed for a diplexer at f = 140 GHz, a = 60 mm, b = 30 mm, and L_ϕ = 1680 mm. Figure 3 shows the results. According to the mode analysis at the exit, the maximum output power in $HE_{1,1}$ mode is more than 99%. An experimental device was built and investigated, showing a very good qualitative agreement with the calculations. An example is shown in Fig. 3b, where amplitude and phase distribution at the output are plotted for the frequency, where the maximum power is coupled to the lower exit. Quantitatively, the measurements show higher loss: at maximum, 96% of the input

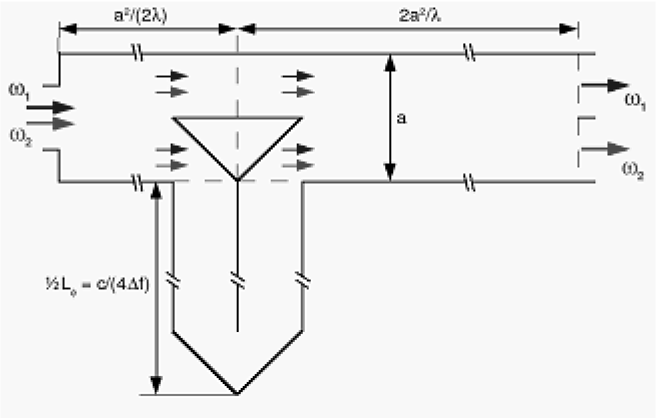

FIGURE 2. Principle for NTM stabilization using a fast directional switch: Synchronously with the rotation of the island, the ECCD beam is switched between to launchers which are about 180° apart from each other with respect to the mode phase.

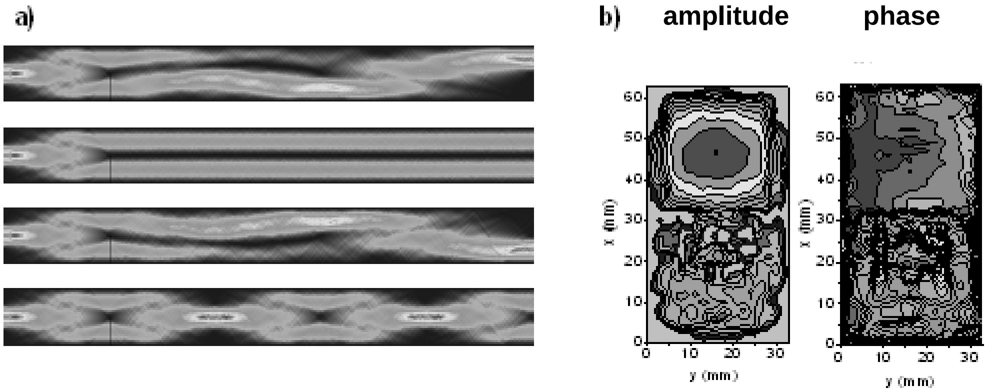

FIGURE 3. a) Calculated amplitude distributions for the waveguide diplexer for a frequency of 140.65 GHz, 140.693 GHz, 140.735, and 140.778 GHz, which corresponds to a phase shift in the delay line (marked as black tick in the plots) of 90°, 180 °, 270° and 360°, respectively. b) Measured amplitude and phase distribution at the exit for 140.65 GHz. Dynamic range shown is 30 dB with 3dB/colour step and 20°/step, respectively.

power is found at the upper or lower exit, and the mode analysis yields an $HE_{1,1}$ mode purity of 80 %. This discrepancy can be explained by the loss of the standard mitre bends in the delay line (about 1% per bend) and some imperfections in manufacturing of this prototype. Another 1 % loss is expected from the input coupling [5], as a circular corrugated $HE_{1,1}$ waveguide (diam. 32 mm) was used.

Note that this waveguide diplexer can be seen as an example for several possible variants of diplexers based on the imaging properties of corrugated rectangular waveguides. In the present diplexer, the input section can be made $L = 2a^2/\lambda$ long to get two inputs, which allows simultaneous combining and switching of two sources into one output channel. Instead of the spatial Talbot effect, the angular Talbot effect can be used for the 3-dB hybrids (*cf.* [6]). Some quasi-optical variants have been described in [7]. Also, a resonator-type diplexer is under development [8].

DESIGN AND TEST OF A QUASI-OPTICAL FADIS

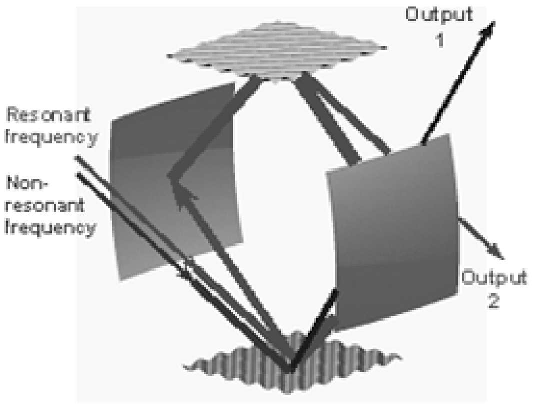

FIGURE 4. Principle of the compact quasi-optical diplexer employing a ring resonator with gratings as input and output couplers.

A compact design for a diplexer/FADIS can be obtained by an open quasi-optical arrangement of two reflecting diffraction gratings integrated into a quasi-optical ring resonator with a high Q-factor. A principle sketch is given in Fig. 4. An incident wave beam at frequency f_1, which is detuned from the resonance frequency f_2 of the ring resonator, is reflected by the grating in the specular direction. If the incident RF beam is tuned to the resonant frequency, the ring resonator will be 'loaded' and the second grating emits the beam into another well-defined direction. Transmission to output 1 and 2 is given by [9]:

$$T_1(f) \approx 1 - \frac{1}{1 + 4R_0/R_1{}^2 \cdot \sin^2(\pi L f/c)}, \qquad T_2(f) \approx \frac{(1 - A/R_1)^2}{1 + 4R_0/R_1{}^2 \cdot \sin^2(\pi L f/c)} \tag{3}$$

where R_0 and R_1 are the efficiencies of the grating in 0^{th} and -1^{st} order, L is the round-trip length of the resonator and $2A$ the loss (ohmic and diffractive) for one round-trip. With these parameters, the diplexer can be adapted to the FADIS application. This type of diplexer has been investigated in detail for high-power multi-cannel transmission [10]. Low-power tests have been performed with results in agreement with theory [11], as shown in Fig. 5. At present, a prototype diplexer for 140 GHz/1 MW is built, and preparations are ongoing to test it in the transmission system of the ECRH installation at the stellarator W7-X in Greifswald [12]. This diplexer consists of a ring resonator with $L = 2.4$ m, matching mirrors for the incident beam from the gyrotron and the output beams, which will be coupled into calorimetric loads. The efficiency of the gratings is $R_0 = 0.755$ and $R_1 = 0.245$, respectively, and the round trip loss is estimated to be 2.8 %, yielding an unloaded Q-factor of $Q_0 = 250000$ and a loaded one of $Q_{\mathrm{load}} = 12000$. At 1 MW input power, the maximum electric field corresponds to an energy-flux density of 0.77 MW/cm^2, which is below the 1 MW/cm^2 threshold of atmospheric air breakdown.

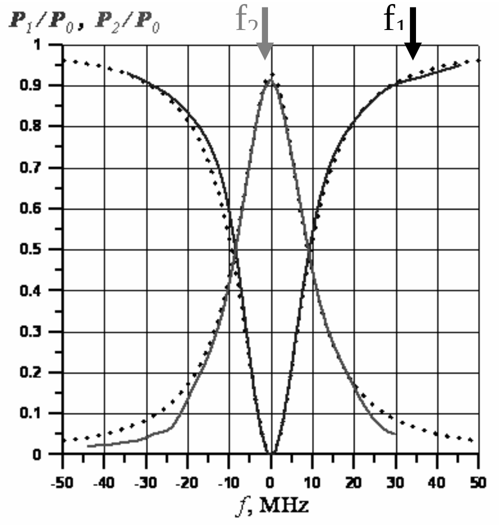

FIGURE 5: Results from a 34 GHz diplexer. Experimental (solid) and theoretical (dashed) curves illustrating RF power distribution between output channels. Frequencies f_1 and f_2 could be used for the FADIS.

The expected transmission curve is similar to the one in Fig. 5, therefore the typical frequency chirp of the W7-X gyrotrons during switch-on of about 300 MHz is by far sufficient to measure the transmission characteristics. For the FADIS application, a good contrast is reached for $\Delta f_s > 30$ MHz.

OPTIONS FOR GYROTRON FREQUENCY CONTROL

The frequency control of the gyrotrons can be performed using various techniques. In any case, a HV modulator with appropriate bandwidth and voltage swing has to be applied (see e.g. [13]). A very precise frequency control can be realized by phase locking of the gyrotron to a frequency synthesizer [14, 15]. This scheme is most convenient for a triode-type gyrotron, where the control voltage coming from the phase-locked loop is applied to the gun anode. The method was verified by an experiment with a 13 GHz gyrotron, the spectral bandwidth of which was reduced by a factor of 20 with this phase locking.

Present-day high-power gyrotrons, which usually are of the diode type, can only be controlled via the acceleration voltage of the electron beam. For this case, the variation of the frequency is always connected with a variation (usually reduction!) of the output power. Therefore, operation regimes of the gyrotron have to be used where on the one hand the frequency – voltage characteristic is as steep as possible and on the other hand the necessary frequency shift Δf_s for a good channel contrast in the diplexer is as small as possible.

Measurements of the frequency characteristics of the THALES gyrotrons for W7-X and on the GYCOM gyrotrons installed at FTU have been started. Although preliminary, some results are remarkable:
In the GYCOM tube, a clear modulation characteristic is found with a slope of about 10 MHz / kV. A modulation experiment with $U_{\mathrm{mod}} = 2$ kV and 500 Hz confirms this value. This modulation characteristic could result in a good contrast for the FADIS application without too much power loss in the second channel.

In the W7-X gyrotron, the frequency drift after thermalization of the cavity (> 1 s) was less than 5 MHz / 160 sec. This high stability might allow to reduce the requirements concerning frequency control of the gyrotron; at least the matching of the diplexer characteristics to the frequency of the gyrotron could be done by moving one of the resonator mirrors. The output frequency showed spontaneous switching between two frequency levels (mostly 3.4 MHz apart, but larger separations have been observed for other gyrotron parameters), which also could be triggered by a modulation of the acceleration voltage by 1 kV. These frequency levels are probably produced by modulation of the gain due to reflection of stray radiation in the gyrotron back into the cavity with the appropriate rotation direction. Step-like variation of the frequency was often observed in gyrotrons with tiny reflections of the cavity mode from the output window ("long-line effect") and was also described theoretically [16]. Possibly, this effect could be used in the design of stable FADIS operation with negligible power loss.

CONCLUSIONS

A fast directional switch based on diplexers together with frequency-shift keying of gyrotrons can strongly increase the performance of ECRH systems: For synchronous suppression of NTM modes, the available power in principle can be doubled, and generally, the flexibility of any system can be enhanced. An additional feature is the combination of two sources into one transmission line.

The development of diplexers is underway, various concepts are under investigation. High-power tests are scheduled for the beginning of next year, and the application of the FADIS on FTU is in discussion. Although concepts for frequency control of gyrotrons are available, more investigations are needed. Especially the development of a phase-locked frequency control would allow stable FADIS operation, but would give a much broader range of applications. Provided that several gyrotrons can be controlled from a common master oscillator, phased array applications would become possible [10]. In principle, this would allow to replace launchers with mechanical beam steering by electronically controlled scanning of millimetre wave beams.

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