Diplexers for Power Combination and Switching in High Power ECRH Systems

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***Abstract*— Electron Cyclotron Resonance Heating (ECRH) systems for next step large fusion-devices operate at a Continuous Wave (CW) power well beyond 10 MW generated by a large number of gyrotrons with typically 1 MW power per unit. The combination of the power of two (or more) gyrotrons and switching of the power between different launchers for different physics applications is an attractive feature for such systems. The combination of beams from different gyrotrons would reduce the number of transmission lines and the requirements on port space. Fast switching between two antennas synchronously with the Magneto-Hydro Dynamic (MHD) modes frequency would increase the efficiency of mode stabilization. Both, combination and switching as well as power sharing between different ports can be performed with high-power four-port diplexers using small frequency differences or small frequency-shift keying of the gyrotrons, respectively. Fast directional switches (FADIS) and beam combiners (BC) can be designed on the basis of different physical mechanisms: some selected design variants were investigated and the results are presented. Considerations on the integration of FADIS/BC's into large ECRH systems and their use in test arrangements are presented.**

***Index Terms*— Diplexers, Power combiners, Millimeter wave switches, Resonators, Plasma heating, Plasma control.**

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I. Introduction

IMPLEMENTING high power diplexers in the transmission lines of large scale Electron Cyclotron Heating (ECRH) and Current Drive (CD) systems can improve the flexibility, extend the performance, simplify the system complexity and reduce costs [1]–[4]. Combination of the power from two (or more) gyrotrons, which typically operate at 1 MW output power, reduces the number of transmission lines and launchers, as well as the required port-space for ECRH systems of large fusion devices, such as ITER. High-power fast directional switches (FADIS) and beam combiners (BC) can be composed of oversized four-port diplexers, each representing a kind of interferometer or quasi-optical resonator [5]. Selected types of diplexer designs and the related typical resonant features are presented in section II for quasi-optical and waveguide-based transmission systems together with a theoretical characterization and some experimental results. Switching and/or beam combination is obtained by either tuning the diplexer, or by tuning the frequency of one (or both) input beams by a very small amount (a few tens of MHz). A mix of both methods is possible also. The first method requires mechanical tuning of a mirror by typically half-wavelength, which can be performed on the 10 ms timescale with standard techniques. We will refer to this method as the *'slow operation mode'* to switch/combine mm-wave-beams.

The second method requires tuning of the input frequency while keeping the diplexer resonance frequency fixed. In any gyrotron, the output frequency can be tuned within a range of several tens of MHz by tuning the acceleration voltage of the electron beam. This forced frequency shift can also be used, in combination with a matched diplexer/multiplexer, to switch the combined wave beam between the output channels. In contrast to the first method, where the diplexer resonance is tuned at fixed gyrotron frequency, tuning of the gyrotron frequency can be done much faster, because no mechanical parts such as mirrors have to be moved. We shall refer to this method as *'fast operation mode'* for switching/combining mm-wave beams. The switching frequency in this case is limited only by the driving capability of the high-voltage (HV) power supply used for control of the gyrotron. In particular, controlled switching of the power from continuously operating gyrotrons between two output channels can be fast enough for synchronization with the magnetic island rotation in the tokamak plasma (5-10 kHz). In proof-of-principle experiments controlled switching up to 20 kHz was demonstrated under high power conditions [2], which would allow for a more economic use of the installed power and optimization of the efficiency for stabilization of neo-classical tearing modes (NTMs) or other MHD-modes [6]. A drawback of this method is that in general some degradation of the output power is related to the HV-modulation of the gyrotron. For a given physics application, therefore, either one of the two methods, the 'slow' and the 'fast' operation mode has to be carefully selected. Different diplexer types are discussed in Section II together with experimental results and frequency control issues of both, gyrotron and diplexer. Proposals for dedicated applications such as test facilities with 2 MW power, MHD-stabilization in ASDEX Upgrade (AUG) and Frascati Tokamak Upgrade (FTU) tokamaks, and integration in the ECRH system for ITER are discussed in section III.

II. Design and Experimental Characterization of High-Power Diplexers

A. Some representatives of the diplexer family

Frequency diplexers can be designed in various forms [1]–[5]. Here, we discuss three representative types as shown in Fig.1, with the corresponding transmission characteristics, being periodic with $\Delta f_F = c/L$. By choosing the appropriate L, the transmission characteristics can be easily matched to the application envisaged; for details see references given above.

Test systems have been built and were investigated for different high-power diplexer concepts, among them the 3 versions from Fig.1 and some other versions, which are not discussed here. Within the experimental possibilities of these mock-ups, a good agreement with theory has been obtained for all setups. A summary is given in the following, where details can be found in [2]–[5], [7]–[10].

B. Waveguide based Mach-Zehnder diplexer

The Mach-Zehnder-type diplexer shown in Fig.1(a) [4] consists of two dielectric power splitters integrated into HE_{11} waveguide with a direct connection and a delay line with a length difference *L* with respect to the direct line. This results in sinusoidal transmission characteristics. A mock-up of the interferometer of Fig.1(a) has been investigated with low power [4]. The parameters were 141 GHz, HE_{11} input in corrugated waveguide with diameter of 87 mm, Si_3N_4 splitters with refractive index of n=2.784 and 2.758, a thickness of 3.04 and 2.70 mm, and a loss tangent $\tan\delta = 1.12\cdot10^{-3}$ and $2.16\cdot10^{-3}$ respectively, standard miter bends, length of the delay line L=0.864 m. The results were in good agreement with the calculations performed for the parameters of the experiment. As expected, the measured loss (typically 10%)

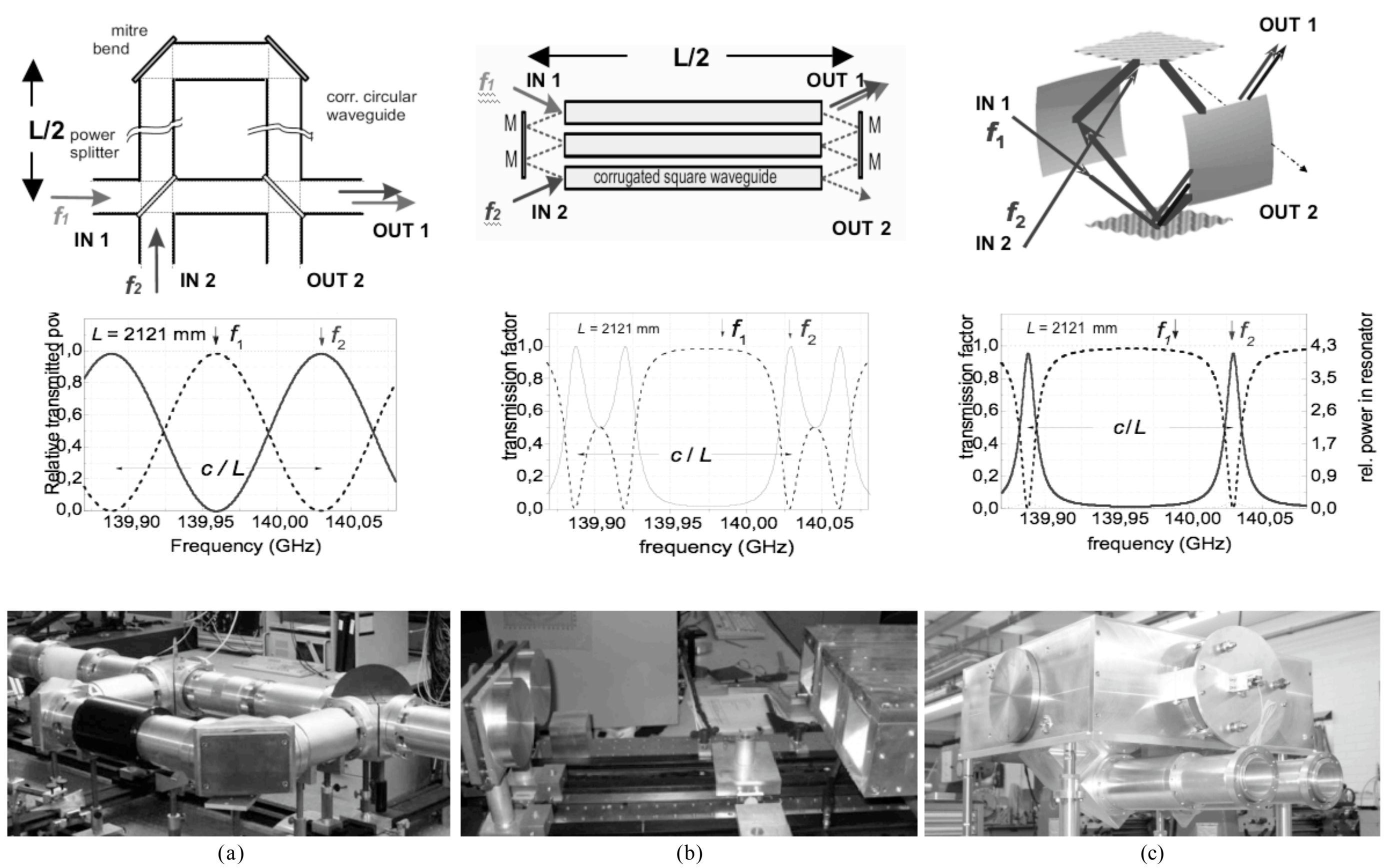

Fig. 1. Some basic designs of high-power diplexers, together with the corresponding transmission function plotted for the inputs IN1 (dashed) and IN2 (solid), and the (common) output OUT1, as well as photographs of corresponding pre-prototypes under investigation. For the other output OUT2, IN1 and IN2 have to be exchanged. In the calculation around f=140 GHz, L=2.121m was assumed. (a) Mach-Zehnder type interferometer with corrugated waveguide and dielectric beam splitters; (b) two-loop diplexer using square waveguide splitters (c) quasi-optical ring resonator (round-trip length L) with coupling gratings.

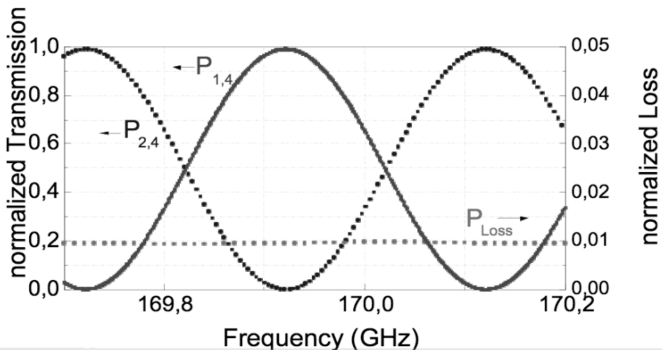

Fig. 2. Calculated power transmission from IN1 to OUT1 (solid line), OUT2 (dashed line) as well as total insertion loss of the waveguide diplexer for *D=63.5 mm, f=170 GHz, L=0.75 m, and CVD-diamond disc splitters* with d=0.87 mm.

was dominated by the strong absorption in the beam splitters. For high-power applications, CVD diamond is an appropriate material for the 3-dB splitters. The theoretical performance of a diplexer for the parameters of the ITER ECRH system was calculated. For this system, the waveguide diameter is D=63.5 mm, and the frequency f =170 GHz. Diamond disc splitters with a thickness of d=0.865 mm and a loss tangent of $\tan\delta=4\cdot10^{-5}$ were assumed. The analysis, taking into account the various loss contributions which arise in the splitters (dielectric loss and mode conversion), the miter bends (mode conversion and ohmic loss), and the waveguides (ohmic loss), yields a total transmission efficiency higher than 99%. This is shown in Fig.2, where the transmission functions for the example with L=0.75 m as well as the loss is plotted. By choosing L, the device can be easily matched to the frequency difference of two sources to be combined or to the frequency modulation characteristics of a gyrotron, the power of which is to be toggled between two launchers. Note that the operation at two frequencies is possible (e.g. 170 GHz and 136 GHz for a thickness of the CVD-diamond disc of 0.86 mm).

The strengths of this concept are the low losses and the weak sensitivity against frequency mismatch. On the other hand there is little experience with diamond beam splitters under high power conditions. However, no essential problems are expected, as the absorption is less than for conventional (resonant) vacuum windows, and no vacuum forces exist.

C. *Waveguide-based two-loop diplexer (2L-FADIS)*

The two-loop resonant diplexer of Fig.1(b) consists of two nested loops [3] formed by square corrugated waveguides with length $2a^2/\lambda$ used as 3-dB hybrids [9], and the reflectors (M). Additional mirrors provide matching of the inputs and outputs to the transmission system. The periodicity of the transmission function is determined by the overall length L/2 of the system. Special features are the steep slopes and the double-humped structure of the resonant channels, with the central minimum splitting the power from one input exactly half and half to both outputs. The free spectral range is smaller compared to single hump, resonant diplexer (see section II, subsection E). A mock-up of the two-loop diplexer was investigated using available corrugated square waveguides with a width of a=60 mm and a total length of 7.5 m [10].

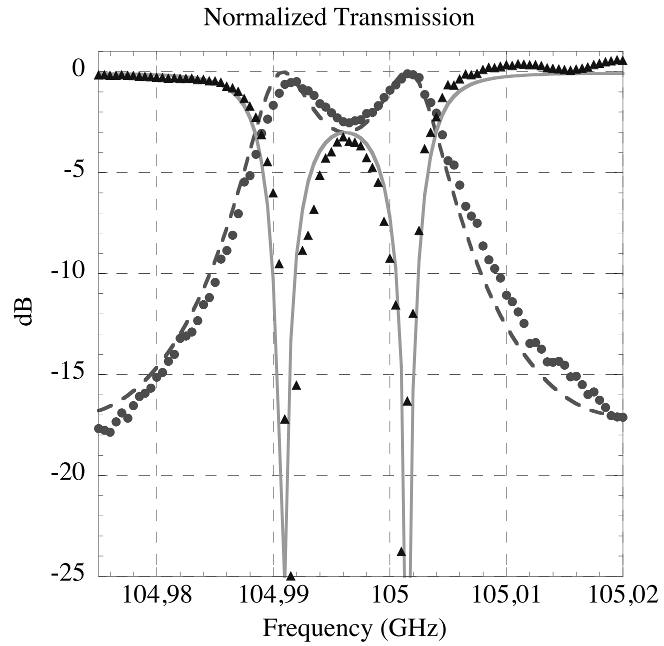

Fig. 3. Calculated (solid, dashed lines) and measured (triangles, dots) transmission functions from IN1 to OUT1 and OUT2 respectively, for the 105-GHz mock-up of the two-loop diplexer.

This allowed to set up a test system with a length of the splitting waveguides of L=2.5 m, i.e. for 105 GHz (note that the square waveguide operates as a splitter for a length of $L\approx2a^2/\lambda$). Due to experimental boundary conditions (e.g. the waveguide corrugation was optimal at 158 GHz), precise measurements of the insertion loss were not possible. However, the measured transmission characteristics agreed well with the calculation, thus providing the proof-of-principle, as shown in Fig.3.

The imaging effect, which causes the splitting of one to two beams with a definite power ratio at fractions of the length $4a^2/\lambda$, may be exploited for the realization of more compact devices, with different transmission functions. One property of the devices in which the splitting is obtained with square corrugated waveguides is the independence on the input polarization, that can be useful where required polarization is common to the output channels (see section III, subsection B).

The strength of this concept is the double hump structure, which may be interesting for asymmetric power distribution and switching, a drawback is the relatively narrow frequency band that can be used, due to the dependence of the required waveguide length on the wave frequency.

D. *Quasi-optical diplexers (QUO-FADIS)*

The resonant diplexer in Fig.1(c) is a four-mirror ring resonator [1], [2], [7], [8], consisting of two focusing mirrors and two plane phase gratings for coupling the incident beams to the resonator via the -1st diffraction order. For a compact design, the gratings are in a conical mount to form a "Magic Y" [5], i. e. the angles of incidence of input and diffracted beams are identical like in Littrow mount, but the directions differ (in the present case by 90°). Additional mirrors provide matching to the input and output beam or waveguide. The

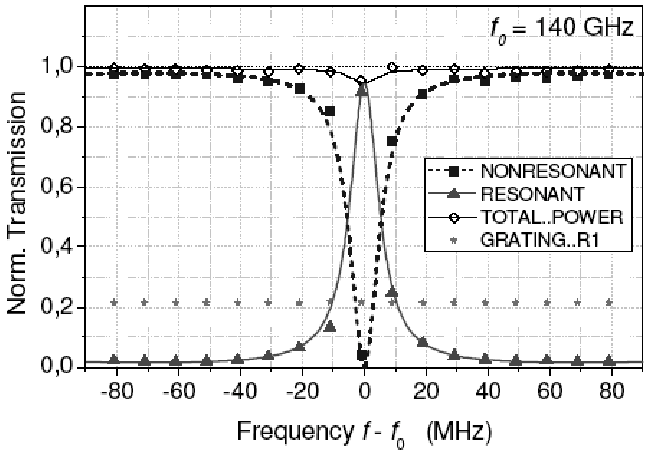

Fig. 4: Calorimetrically measured transmission function (squares, triangles) of the resonant diplexer MkII compared with calculations (dashed, solid line) assuming a round-trip resonator loss of 1.2%, from IN1 to OUT1 and OUT2 (non-resonant, resonant channel) respectively. The solid line with diamonds shows the total power. The stars give the first-order diffraction efficiency of the coupling gratings.

transmission characteristics are defined by the grating efficiency and the path length L of one round-trip in the resonator. Diplexers based on resonant cavities are characterized by a narrow resonance and a wide free spectral range between the periodic resonances as seen from Fig.1(c). We have chosen this design to explore the possibilities and investigate the performance of high-power diplexers in ECRH systems. A prototype (MkI) with a quasi-optical ring-resonator cavity was built, which was compatible with the geometry and frequency of the quasi-optical transmission system of ECRH for W7-X. After characterization of the QUO-FADIS with different low power methods [2], the diplexer was installed in the quasi-optical transmission line of the 10 MW, CW ECRH system, which is under construction for the Stellarator W7-X at IPP Greifswald [11]. First tests demonstrated the switching performance up to a switching frequency of 20 kHz, using frequency-shift keying of the 140 GHz gyrotrons. Power combination from two gyrotrons as well as first experiments on fast switching of the combined millimeter wave beam between the two outputs were successfully performed, for details see [2], [12]. The CW-dummy loads in the W7-X ECRH installation have only 1 MW capability and the experiments therefore had to be limited to a maximum combined power of < 1 MW.

Whereas the QUO-FADIS prototype was designed for compatibility with the optical transmission system operating under atmospheric pressure at W7-X, diplexers for other ECRH-systems must be compatible with waveguide transmission lines, which are either operating under atmospheric pressure (e.g. ECRH for AUG, FTU) or vacuum (e.g. ECRH for ITER). An un-cooled waveguide-based diplexer (MkII) operating at 140 GHz and at atmospheric pressure was designed based on the encouraging results obtained with the QUO-FADIS prototype and will be implemented in the AUG-system for integrated tests. The main goal is the demonstration of MHD-stabilization with enhanced efficiency. The design matches the AUG arrangement of transmission lines and waveguide dimensions and features a compact four-mirror resonator design within a rigid box providing stable alignment as well as microwave shielding as shown at the bottom of Fig.1(c). Corrugated waveguide inputs and outputs are matched to the Gaussian resonator mode by HE_{11}-TEM_{00} mode transitions. Low-power tests are in good agreement with theory. As an example, Fig.4 shows a calorimetric measurement of the transmission functions, and Table I summarizes the main data.

TABLE I
CHARACTERISTIC LOSS DATA OF THE MKII DIPLEXER

Resonant Diplexer MkII L=2.12 m, R1=0.23, HE_{11}	Absorption	Cross-talk	Total insertion loss
non-resonant channel	0.8 %	2.2 %	3.0 %
resonant channel	4.4 %	3.9 %	8.3 %

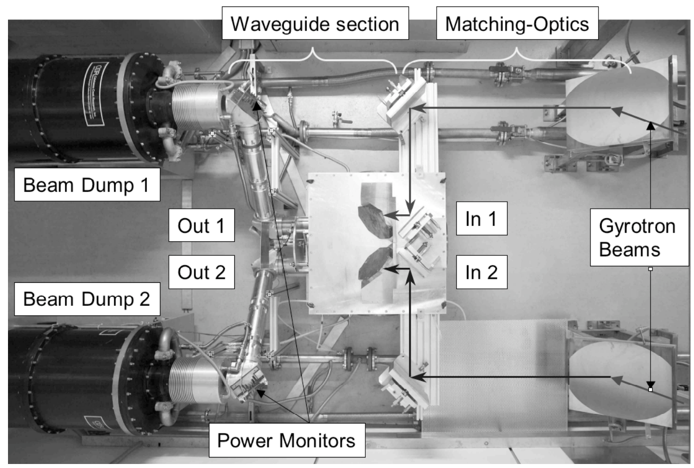

Fig.5: Photograph of the setup in the beam duct of the ECRH system for W7-X. The compact MKII diplexer is seen in the center. The arrows indicate the beam paths of both free-space beams (IN1 and IN2). The waveguide outputs (OUT1 and OUT2) with two miter bends in each arm are seen on the left side feeding the two CW-dummy loads (beam dump 1, 2).

In the non-resonant channel, the loss is mainly due to cross-talk (typically 2.2 %, i.e. near to theory), as well as absorption and mode conversion in the elements for coupling to the input and the output (0.8 %; about 0.4 % absorption in the matching mirrors, and 0.4 % stray radiation).

In the resonant channel, the absorption and scattering of two mirrors and two gratings with a power enhancement factor of 4.5 in the resonator results in an absorptive loss of 4.4%. If one assumes an average ohmic loss of 0.13 % per copper mirror and per reflection, the total ohmic loss sums up to 2.6 % (4 mirrors in the resonator with power enhancement [2] of 4.5, plus 2 matching mirrors). The remaining 1.8 % are absorbed in the water-filled teflon hoses at the walls. The quasi-optical diplexer is a very efficient mode filter (especially in the resonant channel), as wrong modes entering the diplexer will not excite the resonator at the resonance frequency, but are mainly transmitted through the non-resonant channel; with the mode purity of about 97% for the HE_{11} generators used, this results in a cross-talk of 3.9%. The total loss averaged over both channels is therefore 5.7%. In case of a pure HE_{11} input

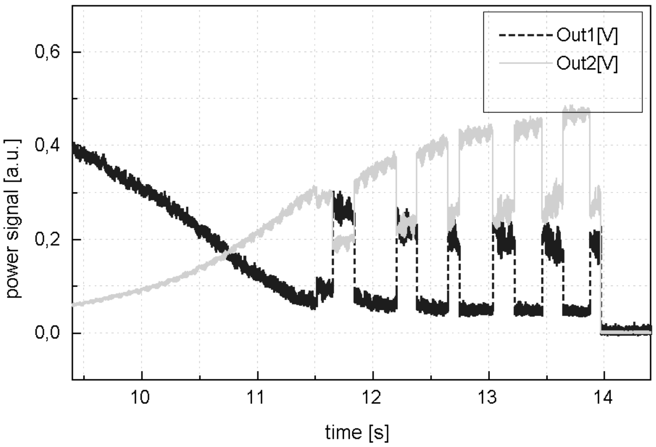

Fig. 6. Signals of the output power OUT1 and OUT2, when the diplexer is slowly tuned into resonance. Partial switching of the power occurs on spontaneous frequency jumps of the gyrotron by about 8 MHz.

mode with perfect alignment, an average insertion loss of 4% would be expected, about one half as absorptive power loss, the other half as cross-talk being transmitted to the wrong channel.

Scaling the present design towards power combination with 1 MW to each of the inputs, the ohmic loss in the mirrors sums up to 31 kW. The thermal power loading of the gratings (which have the highest loads) would be about 7.2 kW, with a power density of 370 W/cm^2. This value is still below the power density of 500 W/cm^2, which is considered as limit for the design of the mirrors in the upper launcher of ITER. The stray power to be absorbed in the box would be about 26 kW in the case of pure input mode; any additional high-order modes would also be absorbed in the box. The cross-talk from the non-resonant channel of typically 22 kW would be transferred to the resonant output as HE11 mode. Additional low-order modes at the inputs would be partly coupled to the respective non-resonant output, partly absorbed as internal stray radiation. In view of the large surface of the diplexer box, which are to be covered with appropriate absorber structures, also higher stray radiation levels in case of low input mode purity can be handled (much easier than stray radiation in un-cooled movable parts of launchers).

E. High-power measurements of the compact waveguide-based QUO-FADIS (MkII)

With the basic features determined in low power measurements, the MkII device was integrated in the quasi-optical transmission line of the 10 MW, CW ECRH system at IPP Greifswald for high power tests. The experimental arrangement is seen from top in Fig.5.

Both input and output channels of the compact QUO-FADIS are designed for standard 89.9 mm HE_{11} waveguides of the ASDEX Upgrade ECRH system. To match the geometry and the beams of the QUO-transmission line for W7-X, the HE_{11}-TEM_{00} mode transducers were omitted at the input and an optical 2-mirror beam-matching unit was adapted, as seen on the right side of Fig.5. The beams in both output channels are guided towards the dummy loads (Beam Dump 1, 2) through HE_{11} waveguides via two miter bends. The mm-wave power monitors are incorporated in the second miter bend as seen on the left side of Fig.5. One of the resonator mirrors is equipped with a tunable mounting for frequency tracking. First tests were aimed at determination of the power handling capability of the FADIS and to explore the frequency tracking capability of the feedback system for the tuning mirror.

Commissioning experiments were started with one gyrotron (B1) to explore the power and energy capability with various fixed settings of the resonance frequency. Note, that the device has no active cooling and the pulse length is thus limited by heating of the structure. The pulse length and the power were gradually increased. So far, 70-s pulses with 330 kW were obtained without problems; extension to 100 s. at this power level seems feasible. At higher input power of 550 kW, 20 sec pulse length was reliably achieved, which is close to the theoretical limit of this design. Some arcing phenomena were observed during initial operation, which disappeared after some conditioning and realignment of the RF beam coupling. Note that at this power level, the peak intensity in front of the gratings in the resonator is about 0.8 MW/cm^2, which is still below, but quite near to the 1 MW/cm^2 threshold of atmospheric air breakdown. Much higher power capability is expected for the same diplexer in case of an evacuated design (as would be the case e.g. for ITER).

Preliminary results confirm the transmission functions of the diplexer also in high-power application. An example is shown in Fig.6, where the diplexer is slowly tuned from non-resonance into resonance. Spontaneous gyrotron-frequency jumps of about 8 MHz (measured by a frequency down-converter and a time-frequency analyzer) lead to fast switching of the power between the two outputs thus demonstrating the steep slope of the resonance. Note, that this diplexer is designed for fast switching, therefore the resonance is quite narrow (cf. Fig. 4), and a relative frequency stability between diplexer and gyrotron of a few MHz is required.

Demonstration of fast switching at 100 Hz in the presence of slow resonator tuning on the 10-s timescale, is shown in Fig.7, top. Here, the gyrotron was modulated with a body-voltage swing of only 1 kV, leading to a relatively small power modulation of about 10%. The related frequency modulation of the gyrotron was about 8 MHz, which does not lead to complete toggling of the power from OUT1 to OUT2. A strong amplification of the input power modulation, however, is seen in Fig.7: The synchronous combination of the input-power modulation and the modulation on the slope of the diplexer resonance leads to a strong power modulation in either one of both outputs, depending on the tuning of the diplexer. The switching effect is displayed on an extended timescale in Fig.7, bottom, together with the modulated input power and the sum of the power from both output channels. The sum-signal reproduces the modulated input power. This effect might be used for NTM stabilization in ITER: Even if a diplexer is designed primarily for power combination, i.e. with a broader resonance, and the body power supplies in the

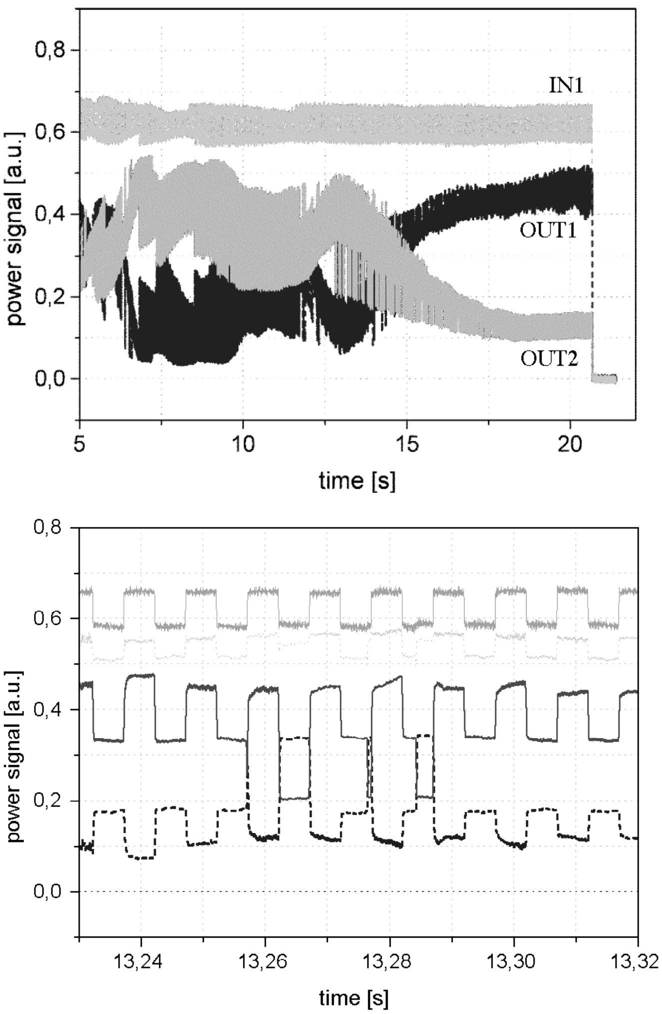

Fig. 7: Top: Input (light gray, IN1) and output power signals (black, dashed for OUT1, grey, solid for OUT2). The body voltage of the gyrotron is modulated with a square wave ΔU_{B1} = 1 kV, f_{MOD} = 100 Hz, and the resonance of the diplexer is slowly tuned with respect to the gyrotron frequency. The tuning was made manually to keep the diplexer resonance to near to the gyrotron frequency, to ensure maximum power modulation at the outputs. Towards the end of the pulse, the tuning was continuous to go out of the resonance. Bottom: Blown up detail of the pulse, showing additionally the sum of both output powers (gray, dotted).

system allow only voltage modulation of a few kV, one can obtain a 70% power modulation in one of the outputs, which can be enough for efficient NTM stabilization.

For optimum operation of the diplexers, a precisely controlled acceleration voltage of the gyrotron is a necessary prerequisite. Modern gyrotrons operate with voltage-depressed collectors to improve the efficiency. The acceleration voltage for the W7-X gyrotrons is generated by a solid state pulse step modulated (PSM) high-power cathode supply with negative polarity and a separate low-power high-voltage body supply with positive polarity, the collector being at ground potential. Cathode voltage fluctuations from the PSM are compensated by the tube-based body supply.

The acceleration voltage is controlled within ±50 V. A typical value for fast frequency tuning is about 5 MHz/kV [2] as determined for one of the W7-X TED gyrotrons. The voltage stability of the power supply is therefore more than adequate for the control of the gyrotron frequency. However, besides the acceleration voltage, other factors influence the frequency of gyrotrons as well, like output power, temperature of the cooling water (which affects the cavity dimension), reflections (internal and external) of the microwaves back into the gyrotron cavity, and others. As long as gyro-amplifiers are not available, these issues require either fast tuning of the frequency of the gyrotron via feed-back control of the acceleration voltage, or fast tuning of the diplexer relative to the free-running gyrotron. Both options are under investigation. As the frequency control of the W7-X gyrotrons via the body voltage is connected with some power loss, diplexer tuning is in development.

For long-pulse experiments on power combination and controlled fast switching without gyrotron modulation, a fast mirror control system, which is being developed by a group at TNO, Delft and FOM Rijnhuizen [13] will be implemented for fast diplexer tuning in a next step. These preliminary experiments show that a key issue for precise control of diplexers and feedback-controlled frequency tracking is power monitoring, for both input and output beams, with a high accuracy. Further work concentrates on this topic: both mm-wave power-monitors and bolometric monitors are being investigated.

III. Applications of high-power diplexers

The application of diplexers in high-power multi-channel ECRH-systems is very versatile and flexible. A clear specification of the scientific/technical goals is therefore a necessary prerequisite to select the optimum type of diplexer (see section II) and, given the type of diplexer, to design for the preferred features. In the following, we will discuss two cases, i.e. the ‘slow operation mode’, which assumes free running gyrotrons with slightly different frequency while tuning the diplexer, and, alternatively, the ‘fast operation mode’ which assumes gyrotron frequency shift keying at constant diplexer setting. Both cases were investigated with the QUO-FADIS devices.

A. Beam combination and switching by diplexer tuning (‘slow operation mode’)

If diplexers are used with free-running gyrotrons, a tuning element (movable mirror) is needed to match the transmission characteristics to relatively slow (characteristic time scale of 10 ms) variations of the gyrotron frequency. For the operation of any diplexer in an ECRH system, a remotely controllable, preferably automatic tuning of its frequency characteristics over one period of the transmission curve, i.e. $\Delta f_F = c/L$, is needed to match the gyrotron frequency and to compensate for thermal drifts. This means that one mirror in the resonator or delay line is equipped with a drive to move the mirror in normal direction over a distance of less than a wavelength. Fast and precise drive concepts for this purpose are in development [13].

Let us assume, that different gyrotrons radiate under steady state conditions at slightly different frequencies f_1 (beam 1 at input 1) and f_2 (beam 2 at input 2) respectively, where $\Delta f=f_2-f_1$ is of the order of some tens of MHz. The diplexer resonance is tuned to, say, f_1, which implies, that f_2 remains non-resonant. Beam 1 with f_1 is then switched to output 2, where it combines with beam 2, the latter operating within the free spectral range and not being affected by the diplexer. Tuning the diplexer to f_2 would lead to the reversed situation, i.e. beam combination in output 1. As a result the combined beam switches between both diplexer outputs without acting on the gyrotron frequency. The diplexer can be tuned on a time scale of some 10 ms, which is typical for motor or piezoelectric drive of a tuning mirror. This is too slow to cope with power switching in the frequency range of 1-10 kHz, which is required for MHD-stabilization in AUG, but fast enough for any application, which requires power switching in response to plasma changes on the energy confinement time scale or the current diffusion time scale. For ITER, this method would be adequate to redistribute the power between the Equatorial [14] and Upper [15] ECRH launchers to act on the power deposition profile (on-off axis heating) or the current profile by Electron Cyclotron Current Drive (ECCD). This could also be interesting for applications, where frequency variation by HV-modulation is not possible or not intended, but where the gyrotron should not be turned off during the switching process (e.g. for "hot stand-by"), or a variable splitting ratio of the power is envisaged. It is also fast enough for frequency tracking of slow frequency changes in the gyrotron, which are due to intended or accidental changes of the output power. Note, that the cavity of gyrotrons expands due to thermal loading after power switch-on with the consequence of a frequency chirp within the first second by typically 200-300 MHz, until stationary conditions are reached. An example is shown in Fig.8 (top). The asymptotic frequency depends on the output power, an example is shown in Fig.8 (bottom) for the THALES gyrotron series TH 1507.

For the W7-X ECRH system altogether 9 gyrotrons with 7 different cavities (2 repair gyrotrons) built on the same specifications were tested. The measured frequency in the first ms after turn-on of the mm-wave power is 140.3 GHz according to the design value, to allow for a 300 MHz frequency chirp at full power. We have determined a reproduction accuracy of ±30 MHz for the investigated gyrotrons. Given this accuracy, two sets of gyrotrons could be installed with frequencies, which are different by, say 70 MHz and feed them in pairs to each diplexer. Thus each gyrotron could operate at its optimum parameters, one gyrotron at the resonance frequency, the other in the non-resonant frequency band (cf. Fig.1(c) and Fig.4). Note that this difference in frequency would not affect any other part of the system, as a much higher frequency chirp has to be tolerated anyway during power switch-on. For gyrotrons operating in the hard excitation regime [16] the maximum output power is typically reached only after several tens of seconds or even later and the frequency is expected to change accordingly throughout the gyrotron pulse. A feedback-controlled tunable diplexer following the frequency of the resonant gyrotron would be able to cope with this frequency drifts.

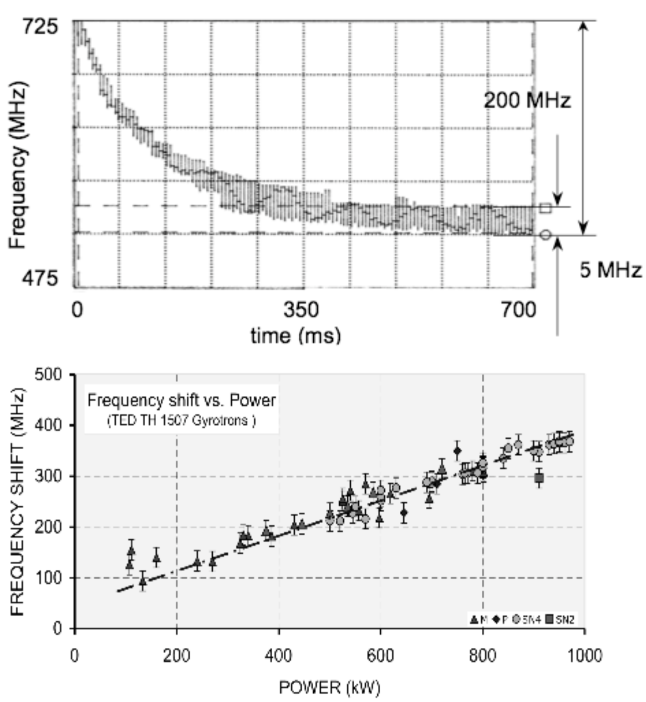

Fig.8. THALES gyrotron series TH 1507 for W7-X (140 GHz, 1 MW, CW). Top: Frequency as a function of time in the early state of an mm-wave pulse. The output power was modulated with 5 kHz resulting in a frequency modulation amplitude of about 25 MHz. Bottom: Frequency shift as a function of the mm-wave output power for several gyrotrons.

B. Beam combination and switching by frequency modulation (or ‘fast mode’)

The ‘fast’ switching is based on a small frequency-shift keying of the gyrotron between f_1 and f_2, performed by modulation of the gun anode or the beam acceleration voltage, which is related to a change of the output power. A characteristic number obtained from the TED gyrotrons for W7-X is 300 Hz/W, as seen from Fig.8, bottom. Note that for the tiny frequency shifts $f_1–f_2=\Delta f$ of some tens of MHz needed for the switching, no remarkable change of the power deposition radius in the plasma occurs. When two gyrotrons are fed into a four-port diplexer, and both gyrotrons are switched between frequencies f_1 and f_2, then the power of both gyrotrons can be combined into one of the two outputs, and switched between output 1 and 2 in rhythm with the frequency-shift keying. An application is the stabilization of neoclassical tearing modes [17], where toggling of the power between two launchers synchronous to the rotation of the magnetic islands would increase the efficiency for stabilization significantly. For this task, as mentioned in section II, the MkII resonant diplexer will be installed in the new ECRH system for ASDEX Upgrade [18]. At the output of the diplexer, polarizers are inserted in the miter bends to match the polarization to the launching conditions. A mirror drive allows the tuning of the resonator. The main application to be tested is AC-stabilization of NTMs by toggling of the power between two launchers, which aim at poloidal positions being displaced by 180° with respect to the phase of the NTMs; thus the driven EC current is always induced in the O-points yielding maximum NTM suppression [6].

At FTU, GYCOM gyrotrons are used with a frequency-to-voltage characteristic [3], which is more favorable than that of the TED gyrotrons used at W7-X. A diplexer/combiner is proposed as switch between two poloidally symmetric antennas, in order to perform high-efficiency tearing mode stabilization experiments. In this specific case, adjustment of the polarization after the diplexer is not required, since the transmission line (and launcher) geometry is such that the same polarization in the two combined lines is required. In this case, the omni-polarization characteristics of the 2L-FADIS is an advantage. Combining pairs of beams in a single line would also allow for fitting the 4 available sources into the new envisaged FTU ECRH launcher [19], [20] equipped with 2 antennas. Both a two-loop resonator version of Fig.1(b) with squared corrugated waveguides [3] and a single-loop resonator with dielectric plates as splitting media are being considered. The first, suited for any polarization, is designed for insertion in the long run of the 4 parallel transmission lines with input matching optics to convert the beams to a smaller size before entering the combiner. The second, made for short (<500 ms) pulses available at FTU and studied for use with the polarization needed for launch with the ordinary mode into the plasma, can be fitted at the positions where mitre bends are close to one another. High-power tests of a prototype, now in final design stage, are in preparation.

C. Generation of 2 MW beams by FADIS/BC and application in a test arrangement

Gyrotrons with 1 MW power will provide a major fraction of the total power for ITER at 170 GHz in CW operation. Such gyrotrons are under development in Russia [21] and Japan [16]. In EU a more ambitious R&D program was launched aiming at 2 MW power per gyrotron [22]. All transmission and launcher components therefore have to comply with a 2 MW power handling capability and have to be qualified at this power level, before being installed. As there are no long-pulse 2 MW CW gyrotrons available at this time, we propose to combine the output beams of two ITER-gyrotrons with 1 MW each by means of a FADIS/BC. The combined beam from two gyrotrons can then be used to test transmission line components for ITER as sketched in Fig.9.

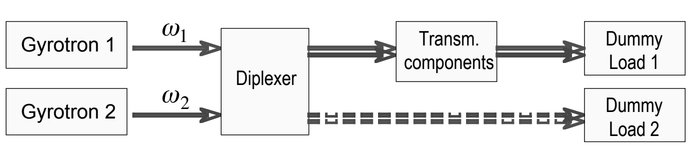

Fig.9. Principal sketch of a 2 MW test arrangement using beam combination. The 1 MW mm-wave beams from two gyrotrons are combined and transmitted through the components to be tested. A 2 MW dummy load 1 terminates the transmission line. A reference line (dashed) is connected to output 2.

A dedicated diplexer for an ITER component test facility must operate at 170 GHz, CW, and comply with the ITER-waveguide specifications. The 2 MW output of such a 4-port diplexer is fed to a transmission system, which ideally contains all ITER relevant components such as miter bends, couplers, DC-breaks, pumping units, mode-filters, waveguide switches, windows and shutters. The transmission line is terminated by a 2 MW CW dummy load [23]. The fast switching capability of a high power diplexer can be used for quantitative loss measurements of the different transmission line components under high power conditions while switching the combined beam between a reference line and the line under test. For such a test arrangement the 'slow operation mode' is well adapted and appears as the simplest approach.

D. Concepts for integration of diplexers into large ECRH systems

The diplexers discussed here differ strongly with respect to the transmission characteristics, insertion loss, cross-talk, dimensions and requirements for system integration. Therefore, the diplexer concept has to be chosen according to the concrete tasks to be performed, and to the experimental environment. A detailed discussion is beyond the scope of this paper. However, all diplexer types can be integrated into large ECRH systems. In Fig.10, solutions are sketched for the insertion in the transmission line of an ECRH system employing two sets of 8 gyrotrons to be combined and distributed to two sets of 8 launchers each. Realistic dimensions of the diplexers for a 63.5 mm waveguide system with a basic distance of 0.3 m between adjacent waveguides have been assumed. One can see that quite compact and maintainable installations are possible.

The location near the gyrotron is more suitable for switching from the line to a dummy load during testing or hot stand-by operation. This option is to replace a tripping gyrotron or to increase the available power within a very short time (see section III, subsection E).

It is worth noting that;

- some concepts are in an early stage of development: upgrades of both interferometric and resonant diplexers will be continued.

- omni-polarization performance of interferometric and resonant diplexers is planned to be realized (remember that the 2L-FADIS works at any polarization).

- as will be detailed in the next sections, in real applications of diplexers a polarizer should be inserted downstream anyway, due to the different routing of the two coupled lines and/or the different polarization requirement of the two launching conditions.

- with the installation of diplexers with tuning capability, both options for 'slow' and 'fast' beam switching/combination remain always open.

- diplexers of any kind can be composed into multiplexers.

- new methods for frequency modulation in gyrotrons without power degradation are being investigated, which appears to be feasible with triode type depressed collector gyrotrons [24].

- additional scenarios for multi-beam combining and controlled switching of the combined beam could be offered by using phase-controlled gyrotrons (if the latter ones were developed at frequencies and powers of interest).

- the reciprocity and filter characteristics of diplexers are favorable for sharing the same antenna to combine high-power ECRH launching with reception of a low-power plasma diagnostic signal (e.g. ECE [13] or with plasma fluctuation diagnostics).

Applications to ECRH systems are discussed in more details in the subsection E, taking as example the ITER ECRH System.

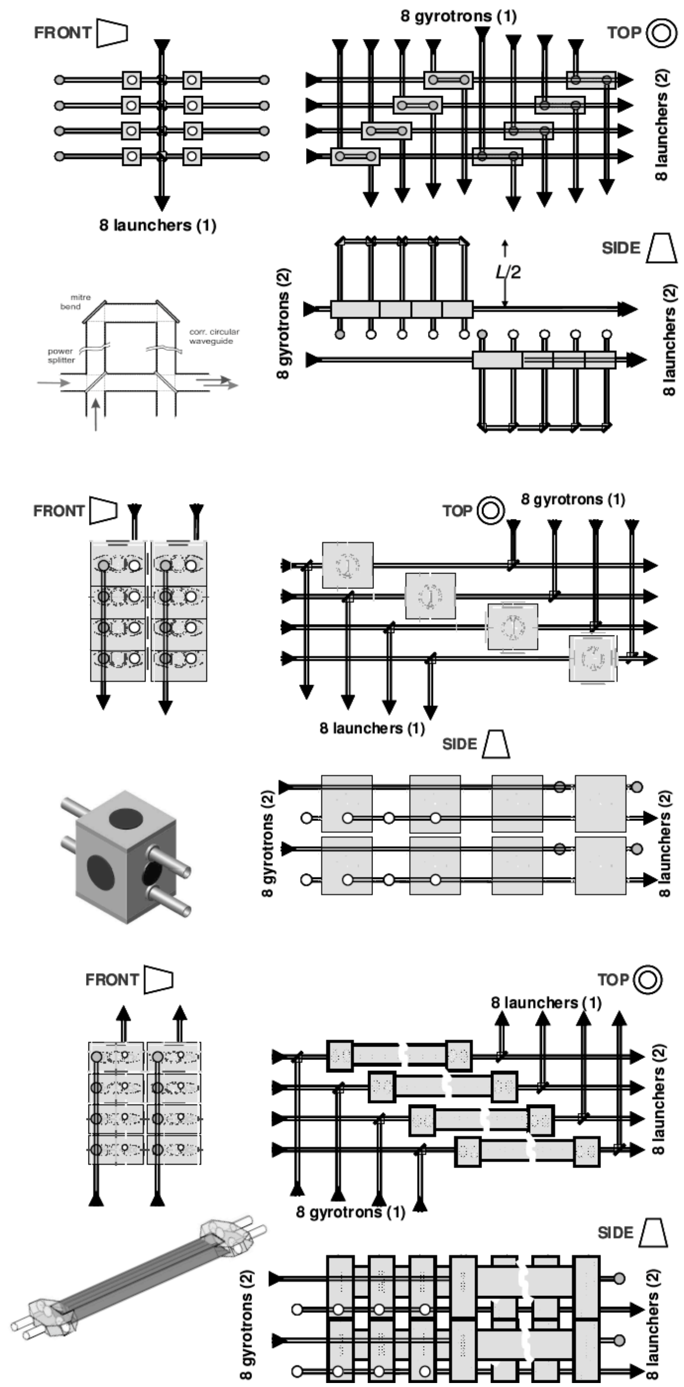

Fig.10. Examples for integration of diplexers into an ECRH system employing 2 x 8 gyrotrons and 2 x 8 launchers. Top: waveguide Mach-Zehnder interferometer, middle: quasi optical ring resonator, bottom: two-loop resonator diplexer.

E. Options for applications and integration in the ECRH system for ITER

The baseline design of the ITER ECRH system [25] will employ 24 gyrotrons operating at 170 GHz; a power upgrade is presently being discussed. The gyrotrons are connected via evacuated corrugated HE_{11} waveguides to 4 upper launchers (UL, MHD stabilization) and one equatorial launcher (EL; 24 beams, central heating and current drive). A central unit with mechanical waveguide switches connects the gyrotrons either to the ULs or the EL.

For the application of diplexers in this system, several options exist, as diplexers can be used:

a) as switches near to the gyrotrons, between transmission line and loads allowing gyrotrons in hot stand-by.

b) for power combination from two 1-MW gyrotrons on a common transmission line to reduce the number of waveguides. Note that the different launching conditions for the EL and the UL require different polarizations, i.e. present diplexers should be installed between the gyrotrons and the polarizers.

c) to replace the mechanical waveguide switches in the present baseline design.

Option c) is most attractive, because

- Firstly, this allows switching of the power from the EL to the UL by tuning of the diplexer in the same way as with mechanical switches, but without the need to switch off the gyrotrons during the switching process. Note, that the power goes either way, but not to unknown or unwanted places. Furthermore power sharing with arbitrary fractions between the UL and EL is possible, which is excluded with mechanical switches.

- Secondly, efficient AC-stabilization of NTMs is possible as soon as a mode occurs: The gun anode or body voltage of the gyrotrons is modulated with the mode frequency, and the diplexers are tracked such that the corresponding frequency modulation results in a maximum power modulation at the outputs for the ULs, synchronous to the rotation of the island. There is no waste of installed power at the modulated operation, as the asynchronous power is still available at the EL and can be used to continue the task as before the onset of the NTMs.

- Thirdly, as the transmission lines are designed for a power of 2 MW and two gyrotrons could be fed into the inputs, the use of diplexers is desirable also from the point of view of a later power upgrade, which can be realized by either increasing the number of 1 MW gyrotrons or increasing the power per gyrotron, or both. In either case the use of diplexers would allow to double the power without the need to allocate additional port space and to increase the number of the transmission lines between diplexer and torus ports. Let us consider 3 cases:

Case 1

Let us assume, that the FADIS/BC's replace the mechanical waveguide switches. We can then define two sections of the transmission system, one 'upstream' from the diplexers and one 'downstream': The upstream section contains all transmission components in the direction towards the gyrotrons, such as beam matching optics, miter bends, mode filters, pumping sections etc. The downstream section contains all waveguide components in the direction towards the launchers, such as the polarizer, miter bends, the barrier windows, pumping sections, mode filters, shutters etc. The location of the FADIS/BC in the transmission line can be optimized to avoid additional components and to make the upstream section simple and 'low cost' as compared to the downstream section. The upstream section would operate at 1 MW per line, whereas the downstream section would operate at 2 MW per line with 12 diplexers in the BC-mode. Only 12 downstream waveguides are then needed to feed the equatorial port and additional 12 downstream waveguides for the upper ports. Note that in the present baseline design twice as much waveguides are planned in the downstream section to the EL and the UL's, respectively. Furthermore, only half of the port space would be used. The reduced complexity and number of the transmission lines and the related cost savings have to be estimated in detail taking into account that 24 mechanical switches are replaced by 12 diplexers. The arrangement is sketched in Fig.11 and some key numbers are given at the bottom of the figure, 1st line.

Case 2

Let us now consider an optional doubling of the installed ECRH power assuming 1 MW gyrotrons as generators. 48 transmission lines are needed then in the upstream section, feeding altogether 24 diplexers with two inputs each, which are operated in the BC-mode. 48 waveguides are needed in the downstream section to feed the equatorial (24, 2 MW each) and upper ports (24, 2 MW each), respectively. This is the number of waveguides and the port space, which are allocated to ECRH already in the baseline design for 24 MW power. The additional investment as compared to the baseline design is the replacement of the 24 mechanical switches by 24 diplexers and the installation of additional 24 upstream waveguide sections. This scenario is also summarized at the bottom of Fig.11.

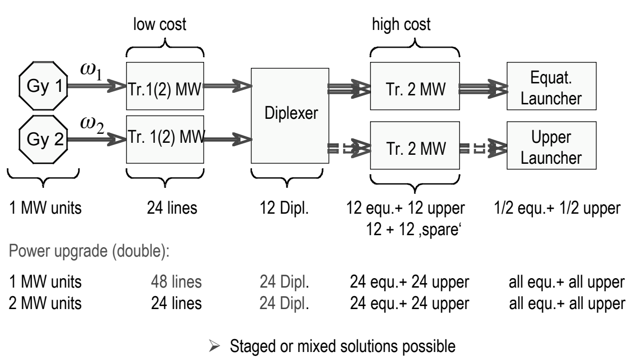

Fig.11. Principal sketch of a possible integration of diplexers into the ITER ECRH transmission line. Case 1: 24 units with 1 MW each. Case 2: 48 units with 1 MW each. Case 3: 24 units with 2 MW each.

Case 3

An optimistic approach for the power doubling would assume gyrotrons with 2 MW output power. In this case the diplexers will be operated in the switching mode and only one input is fed at each diplexer. Power combination is not an option, since waveguides and launchers are designed 2 MW/line only. Fast and slow switching between different launchers remains, however, a viable and attractive application. The upstream section of the transmission line would then transmit 2 MW/line and 24 lines are needed. The downstream section remains the same as in case 2. This scenario is summarized also at the bottom of Fig.11.

It is worth noting, that the use of diplexers allows any approach, which is staged in time, as well as mixed solutions with gyrotrons of different source power, once the condition is observed, that no transmission line section exceeds a maximum power loading of 2 MW.

IV. Conclusion

High-power diplexers are attractive transmission-line components, which can strongly increase the performance and flexibility of multi-MW ECRH systems. Combination of the power from individual sources and sharing of the power between different types of launchers or different applications depending on the experimental priority becomes feasible.

The results obtained up to now in the development of several prototypes including the high-power demonstration (~1 MW) of fast switching (~10 kHz) and power combination from two gyrotrons confirm the applicability of these devices. In near future, further high-power tests as well as demonstration experiments on ASDEX Upgrade and FTU are planned. A study shows that diplexers with the required performance can be integrated into large ECRH systems to simplify the transmission system and launchers and to allow more efficient plasma stabilization and gyrotron operation. The results motivate their development until maturity, especially in view to applications in ITER and other next step devices.

Further research is aimed to study other multiplexing schemes and arrays of phase-controlled gyrotrons. Gyrotron developers are encouraged to continue the development of frequency or even phase controlled gyrotrons, the availability of which would further extend the application palette of high-power diplexers.

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