STATUS OF RESONANT DIPLexer DEVELOPMENT FOR HIGH-POWER ECRH APPLICATIONS


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Motivation

Characteristics of resonant diplexers

High-power test of Mk II in the ECRH system of W7-X

Commissioning experiments at ASDEX Upgrade

Design and test results for the compact diplexer Mk IIIb

Design of an ITER-compatible mock-up

Outlook
(One) Motivation: ECRH system for ITER

Equatorial Launcher for ECRH, ….

Upper Launchers for NTM stabilization
ECCD with synchronous power modulation

mechanical switches
2 s switching time, gyrotron off!

power upgrade at later stage?
→ power combiners!

diagnostics, control for UL

Generator 24 MW

DIPLEXER

4 – port

\[ G_A @ f_2 \]

\[ G_B @ f_1 \]

\[ G_A + G_B \]

\[ I_2 \rightarrow O_2 \]

\[ I_1 \rightarrow O_1, O_2 \]
Mach-Zehnder interferometer with dielectric splitters in HE11 waveguide

q.-optical ring resonator with grating splitters

Two-loop resonator with Talbot splitters in corr. square waveguide
Resonant diplexer

- Broad transmission (Out1)
- Narrow resonances (Out2)

- Parameters $L$, $R_1$
to match to application

- Several prototypes

Two main operation modes:
  - A (notch): dither stabilizer / f-measurement
    - power combination, in-line ECE, filter
  - B (slope): comparison of OUT1 / OUT2
    - fast switching with $\Delta f$, power divider

Kasparek et al., NF 48 (2008)
High-power test of Mk IIa at the W7-X ECRH system

Load 1
Load 2

IN 1
OUT 1
IN 2
OUT 2

directional coupler P1
directional coupler P2

feedback mirror control for tracking of gyrotron frequency

Erckmann et al. FS&T 55, 2009
Kasparek et al. FS&T 57, 2011

matching optics
Mk IIa
waveguide section
Power Combination: B1, 350 kW + D5, 360 kW

- Frequency tracker: resonance (point A) for gyrotron 1
- Frequency difference of gyrotrons approx. 30 MHz (ideal: 50 ….90 MHz)
- Power ratio in stationary phase: 89.6 % / 10.4 %
In-line ECE experiments (talk of W. Bongers)
Slow switching with mirror drive (N. Doelman)
fast switching (preparation for NTM stabilization)
various tests
Slow switching by detuning the resonator

Plasma for tests:
- ECRH L-mode, (mostly)
  \( B = 2.5 \text{ T}, \ I = 1 \text{ MA}, \ P_{\text{ECRH}} = 0.8 + 0.5 \text{ MW} \)

Slow switching:
- frequency tracker activated during first and last section of the pulse
- switching between launchers without switching off the gyrotron
Slow (mech. controlled) switching between launchers

- resonator mirror oscillates with $f = 32$ Hz
- power toggles between launchers
- deposition at $\rho_{\text{tor}} < 0.1$ and $\rho_{\text{tor}} \approx 0.35$
  confirmed from FFT of $T_e(t)$ in the plasma:
  2 maxima for $\Delta T_e$ / 2 minima for $\varphi$,
  $\Delta \varphi_{1,2} \approx 180^\circ$

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Fast (voltage-controlled) switching between launchers

frequency-shift keying, $f_{\text{mod}} = 25$ kHz, $\Delta U_B = 3.5$ kV:

- preparation experiment for synchronous NTM stabilization
- frequency tracker at B: $P(O1) \approx P(O2)$ (averaged)
- gyr. frequency modulation: $\Delta f \approx 14$ MHz for $\Delta U \approx 3.5$ kV
- switching contrast: 70 ... 80% in resonant, 50...70% in nonres. output
- power modulation additive/subtractive
Fast (voltage-controlled) switching between launchers

- \( f_{\text{mod}} = 200 \text{ Hz} \) for easy detection
- Switching contrast: 70 \( \ldots \) 80 \% res. O2
  50 \( \ldots \) 70 \% in nonres. O1
- Deposition at \( \rho_{\text{tor}} < 0.1 \) and \( \rho_{\text{tor}} \approx 0.35 \)
  confirmed from FFT of \( T_e(t) \) in the plasma

\[ \Delta U_{\text{acc}} \approx 3.5 \text{ kV} \]
\[ \Delta f \approx 14 \text{ MHz} \]
Compact all-metal ring resonator

phase reversing mirrors can be matched to

→ TEM\textsubscript{00} input
→ HE\textsubscript{11} waveguide
→ other (e.g. HE\textsubscript{1n} mixtures)

→ MC III\textsubscript{b}, 140 GHz, for AUG
→ compact design for ITER?
Non-resonant channel

- $\eta_{HE11} = 0.993$ (resonator experiment)
- $\eta_{all\ modes} = 0.970$ (calorimetry, above)
- cross-talk = 0.026 (according to theory)

Resonant channel

- $\eta_{HE11} = 0.963$ (resonator / calorimetry)
- $\eta_{all\ modes} = 0.947$ (calorimetry)
- cross-talk = 0.045 (wrong modes!)
Modes have different resonances:

\[ f_{qmn} = \left[ q + \frac{1}{\pi} \left( m + \frac{1}{2} \right) \cos^{-1} g_{\perp} + \frac{1}{\pi} \left( n + \frac{1}{2} \right) \cos^{-1} g_{\parallel} \right] \cdot \frac{c}{L} \]

- Wrong modes are transmitted to non-resonant output and/or scattered and absorbed in diplexer.

**Efficient mode filtering**

Belousov et al., SMP 2003, 264

**Extreme example:**

**INPUT:** \( \eta_{HE11} \geq 47.7 \% \)

**RES. OUT:** \( \eta_{HE11} \geq 91.8 \% \)
Isolation of output port for in-line diagnostics

- isolation for HE\(_{11}\) between inputs better than – 60 dB
- multi-mode reflection from outputs to HE\(_{11}\) input is damped by typ. 40 dB
Resonator control using phase from output signal

Unambiguous control signal from simple interferometric set up

Control to operation point A, control direction for point B

Details: see talk of N. Doelman
A diplexer mock-up compatible with ITER ECRH

- vacuum-tight box made from solid Al block
- precise mounting flanges for mirrors and waveguides
- Integrated directional grating couplers for control signals
- top plate (removed) carries upper resonator mirror, absorber tubes, mirror drive.
- mock-up: solid Cu mirror without cooling. Cooling can be added easily without extra vacuum feed-throughs
- Plans: fabrication in 2012, tests starting end 2012 at IPF and JAEA

\[ f = 170 \text{ GHz, } \]
\[ \text{HE}_{11} \ 63.5 \text{ mm, } \]
\[ \text{waveguide distance 300 mm;} \]
Resonant diplexers have many applications in ECRH systems: “Slow” and “fast” switching between launchers, arbitrary power distribution, Power combination, dir. coupler for In-line ECE, mode filter….

High-power test of Mk II functionality at ECRH system of W7-X.

At ASDEX Upgrade: commissioning experiments on fast switching successful; experiments on NTM stabilization in preparation.

Compact diplexer Mk IIIb for direct integration into HE\textsubscript{11} lines shows high performance.

Development of an evacuated 170 GHz diplexer mock-up underway……
Resonant diplexers in large ECRH system

8 gyrotrons (1)
8 launchers (1)

8 gyrotrons (2)
8 launchers (2)

300
Power transmission efficiency, and mode purity

Non-resonant output 1:

TEM$_{00}$: 97.3 %

Power transmission efficiency > 99 %

Resonant output 2:

Version with grating $R_1 = 0.14$

(Inline ECE: $R_1 = 0.3$)

HE$_{11}$: 97.6 % ➔ mode-filter!

6.7 % ohmic, diffraction loss

(for $R_1 = 0.14$, the resonator is equivalent to line with 28 mirrors)

Non-res. output in resonance:

cross-talk in high-order modes

$\eta_{HE11} \geq 29\%$ !!
Pulse start:
continuous power on Launcher L1 (non-resonant output O1, mirror drive at fixed position)

after 500 ms:
start of modulation, drive to B (slope) for optimum switching contrast

Launcher L3 (resonant output O1) can be used for NTM stabilization

Launcher L1 (remaining power) is used for central heating
Continuous shift of resonator mirror, $+30$ Hz mod.
Gyrotron frequency measurements (Gycom, Elisey-2)

- Fast frequency chirp due to voltage rise at start (20 MHz/div)
- Thermal chirp < 50 MHz
- Stable frequency for t > 2 s
- 50-Hz modulation (25 MHz/div)
- Modulation with 1 kHz, \( \Delta U_B = 2.8 \text{ kV} \):
  - \( \sim 17 \text{ MHz frequency shift} \)

\( \rightarrow \text{Good conditions for diplexer operation} \)
Frequency behaviour of free-running gyrotrons

- Optimization of gyrotron tuneability
- Tuning of diplexer with movable mirror

\[ f = f(U) = f(P) \]

\[ \Delta f_{\text{mod}} \sim \Delta U \]
Mirror control activated for $t > 1200$ ms
- Prerequisite for stable switching experiments
- Arbitrary power distribution between outputs
Narrow-band diplexers in ECRH systems

► **switching** by shifting the transmission curve
  ➔ power is arbitrarily distributed between outputs
  ➔ switch has no undefined state, cw operation

► **switching** by frequency-shift keying of gyrotron:
  \[ \Delta f / f \approx 10^{-4}, \text{ with } \Delta U_{GA} \text{ or } \Delta U_B \approx \text{kV} \]
  ➔ power toggles between outputs

► **power combination** of two sources:
  fixed input frequencies \( f_1 \) and \( f_2 \)
  \( f_1 / f_2 \) in push-pull: ➔ combined power toggles

► **discrimination** of ECRH and ECE
Overview on resonant diplexers

Mock-up Mk I, TEM\textsubscript{00} resonator, for gaussian beams.
$L = 2.4\ m\ c/L = 125\ MHz$

Mk II a, TEM\textsubscript{00} resonator.
Transitions HE\textsubscript{11} to TEM\textsubscript{00}
$L = 2.1\ m,\ c/L = 141\ MHz$

Compact Mk III b, HE\textsubscript{11} resonator
direct HE\textsubscript{11} in / out
$L = 0.9\ m,\ c/L = 331\ MHz$

V. Erckmann et al.
FS&T 55, 23-30, 2009
ECE (broad spectrum) and ECRH (“single” frequency) share same antenna:

→ **Decoupling by diplexer**

(W. Bongers, this conference)
Continuous control of power sharing EL / UL

- efficient NTM stabilization with few kV modulation; asynchronous power left for ECRH in EL
- option for power upgrade by feeding 2nd gyrotron
- high mode purity / low stray radiation level in UL

Development of evacuated, water-cooled diplexer ??

Replace mech. switches by diplexers !

Bruschi et al., IEEE-PS 2010
Erckmann et al., IAEA-TM ECRH 2009
• Transmission functions for non-resonant output and resonant output in good agreement with calculation

• Insertion loss, non-resonant ch.: absorption (mainly coupling): 0.8 % cross-talk (about theory): typ. 2.2 %

• Insertion loss, resonant channel: absorption (resonator, coupl): 4.4 % cross-talk (wrong modes!): 3.9 %

• Average power absorption for pure HE$_{11}$ input is 1…5 % depending on frequency.
Frequency tracking with controlled resonator mirror

- Gyrotron: frequency chirp for $t < 1\,\text{s}$, spontaneous $f$-jumps $\sim 10\,\text{MHz}$

- Mirror drive with feed-back control to track resonator frequency

- **Gyrotron frequency to coincide with**
  - **A:** 70-Hz dither stabilizer
    - power combination
  - **B:** comparison of $\text{OUT1} / \text{OUT2}$
    - fast switching, power divider

\[ f_{\text{GYR}} [\text{GHz}] \]

\[ p_{\text{RF}} [\text{a.u.}] \]

\[ 1.5\,\text{mm} \]

\[ \frac{c}{L} = 141\,\text{MHz} \]
Compact Diplexer for HE$_{11}$ (or TEM$_{00}$):

- compatible with AUG – ECRH
- integration into ITER system?

Power combination: input at $f_1$ and $f_2$

Fast switching along slope by $\Delta f$-keying
ECRH system for Wendelstein7-X:
single-beam and multi-beam transmission up to the torus

Gyrotron (Thales)
900 kW / 30 min
M, S1, S3, S4

Beam conditioning
(matching + polarisation)

Dummy load (CCR)

first mirrors (M5) of MBWG CW Load (CCR) with coupling mirror MD

Beam combination (BCO)