DEVELOPMENT OF COMPACT RESONANT DIPLEXERS FOR ECRH: DESIGN; RECENT RESULTS, AND PLANS

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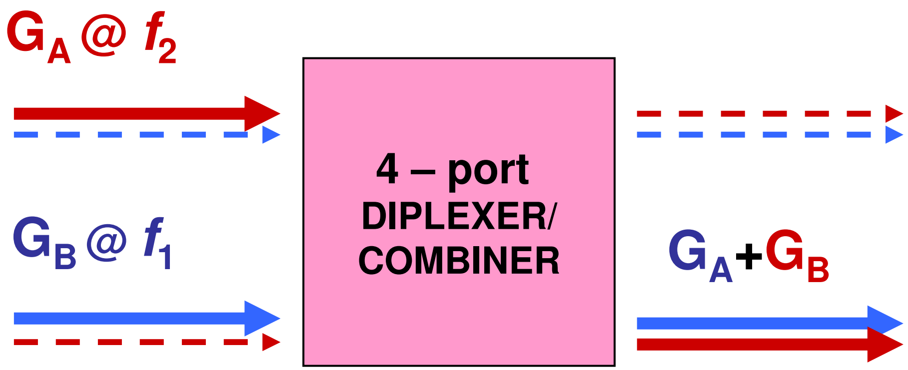
Outline

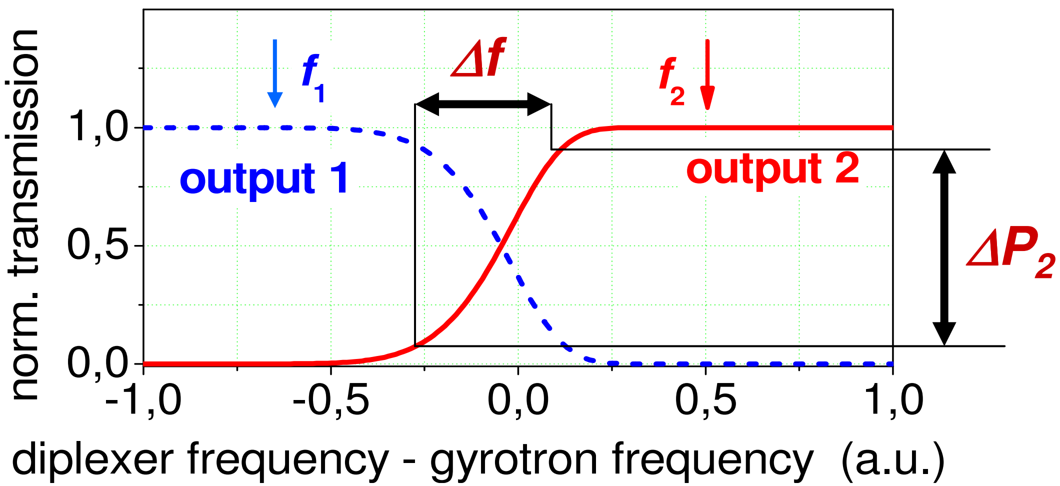
- high-power diplexers: Motivation, and principle
- Design of high-power resonant diplexers
- results from prototypes, low-power / high-power tests
- Near-term plans for applications on ASDEX Upgrade
- Present developments
- Summary, outlook

Narrow-band high-power diplexers

Principle design:



Ideal transmission function:



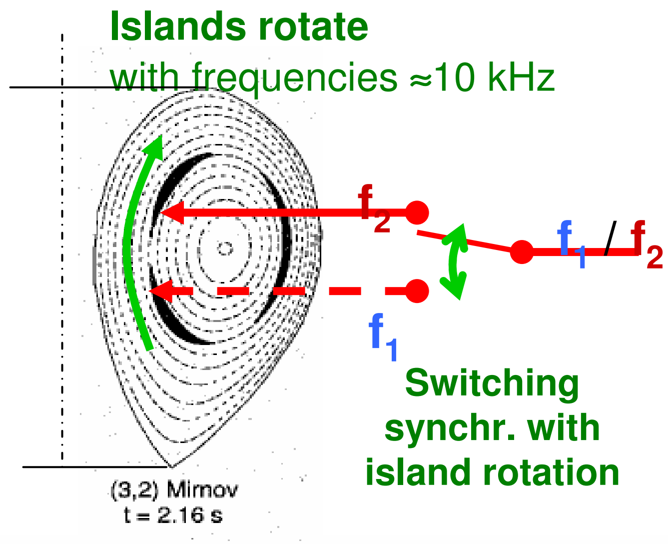
Applications of diplexers in ECRH systems

- **switching** by frequency-shift keying $f_1 - f_2$:

  $\Delta f / f \approx 10^{-4}$, with ΔU_{GA} or $\Delta U_B \approx$ kV

➔ power toggles between outputs
➔ synchronous stabilization of NTMs

slow switch by mechanical tuning of diplexer
➔ continuous operation during switching

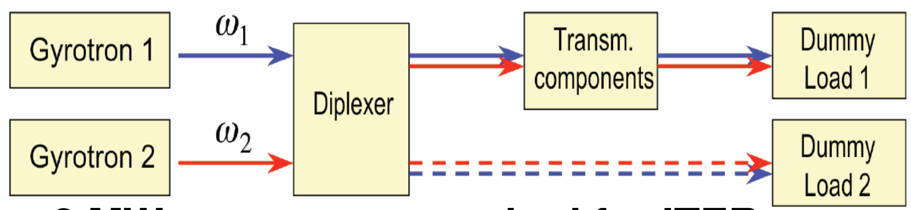


- **power combination** of two sources:

  fixed input frequencies f_1 **and** f_2

  f_1 / f_2 in push-pull:

  ➔ combined power toggles

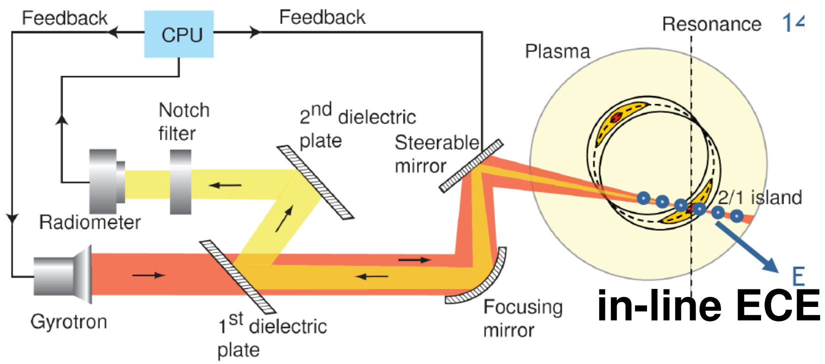


2 MW component test bed for ITER

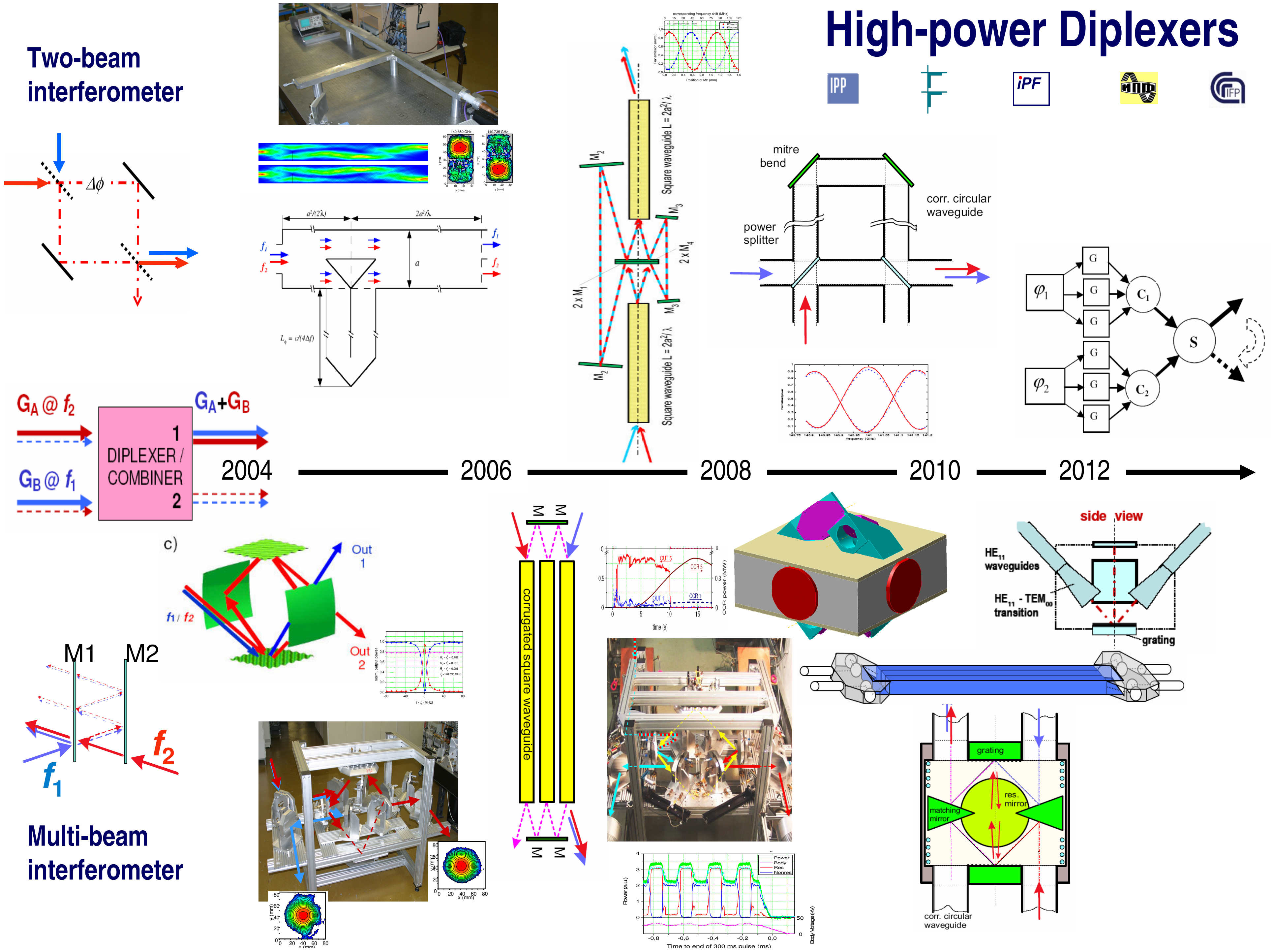
- **cw directional coupler**

  discriminates in-line ECE from ECRH

  (cf. talk by B. Hennen)

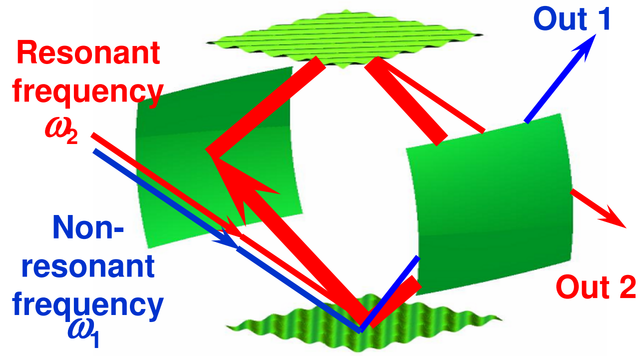


High-power Diplexers



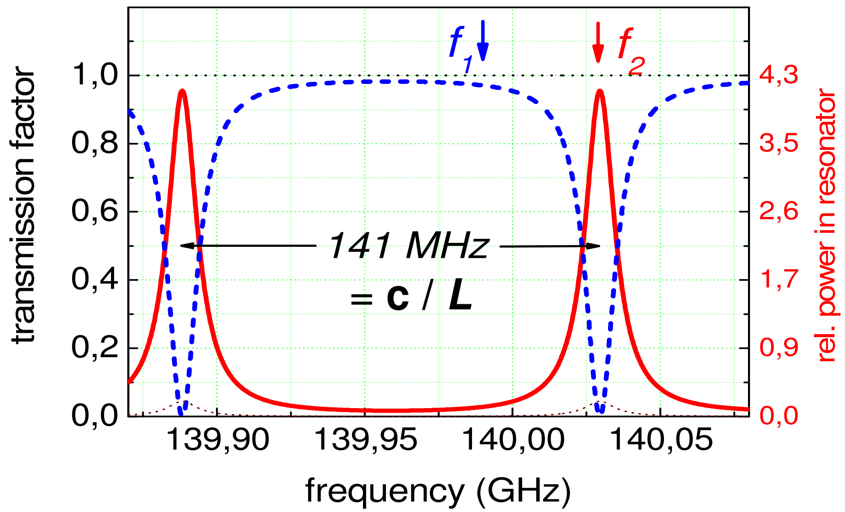
Resonant diplexer

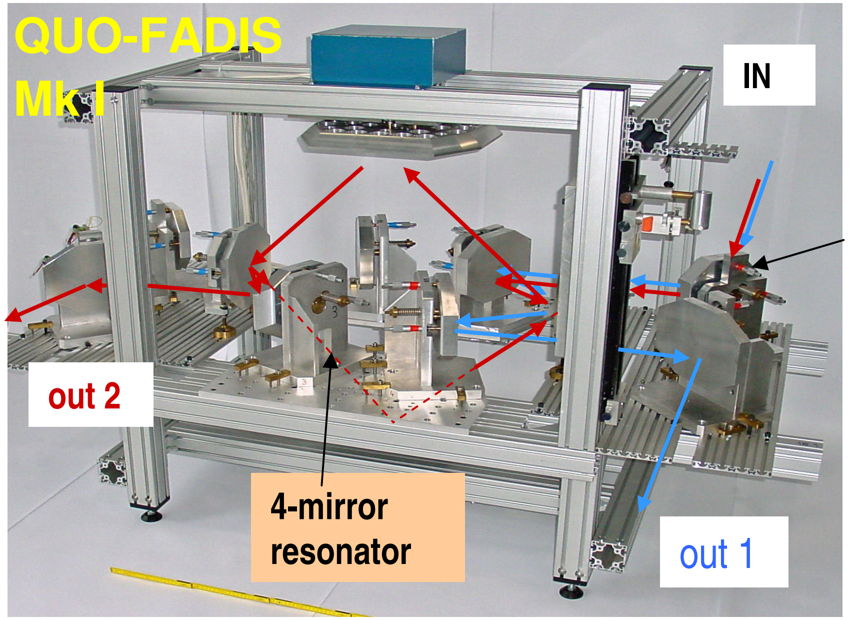
Principle:

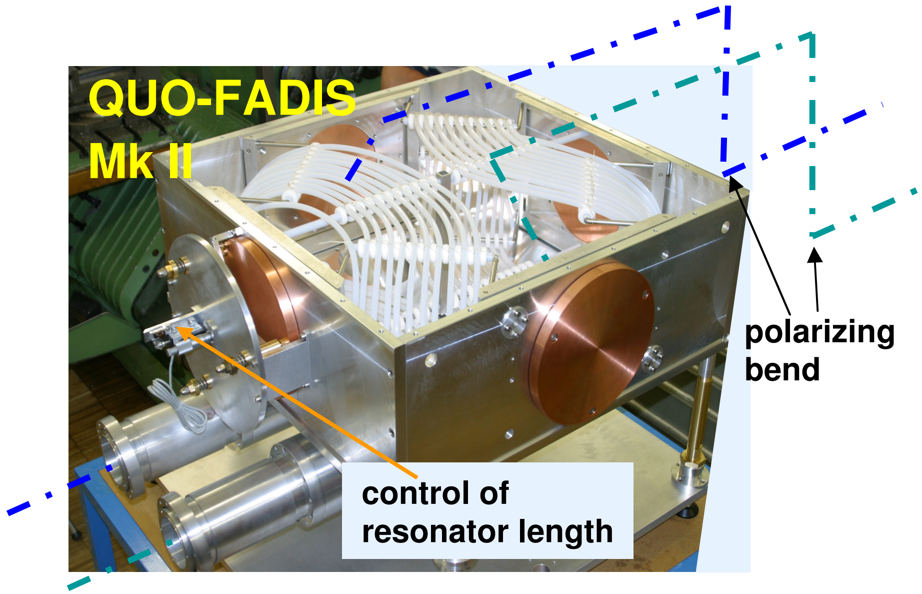


$$T_1(f) = R_0 \cdot \frac{1 + R_q - 2\sqrt{R_q} \cdot \cos(2\pi L f / c)}{1 + R_0^2 R_q - 2\sqrt{R_q} R_0 \cdot \cos(2\pi L f / c)}$$

$$T_2(f) = \frac{R_1^2 \sqrt{R_q}}{1 + R_0^2 R_q - 2\sqrt{R_q} R_0 \cdot \cos(2\pi L f / c)}$$





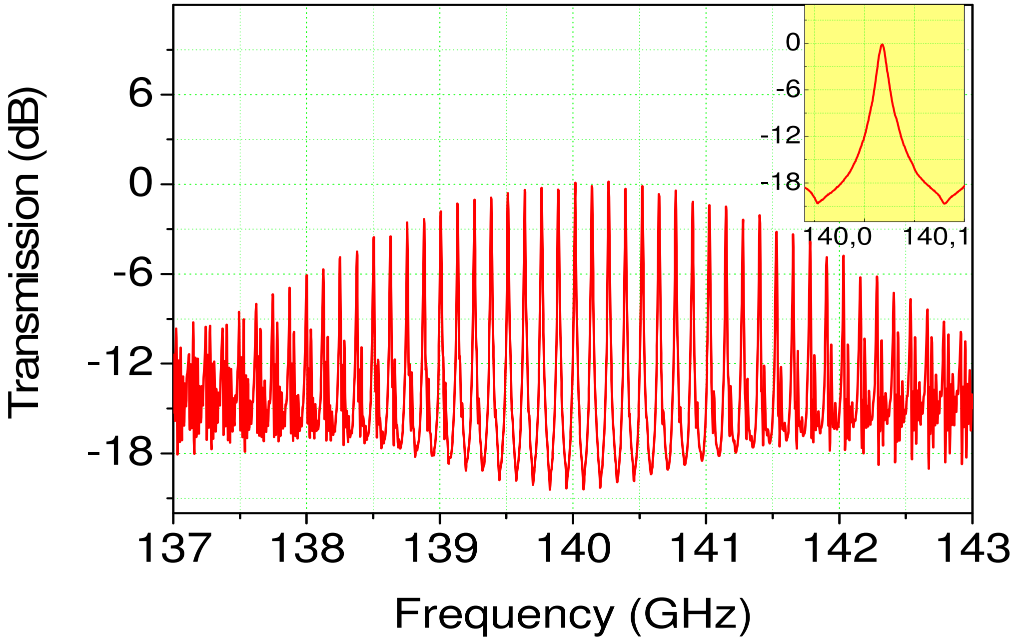


Transmission measured with matched receiver

(spurious modes are not detected)

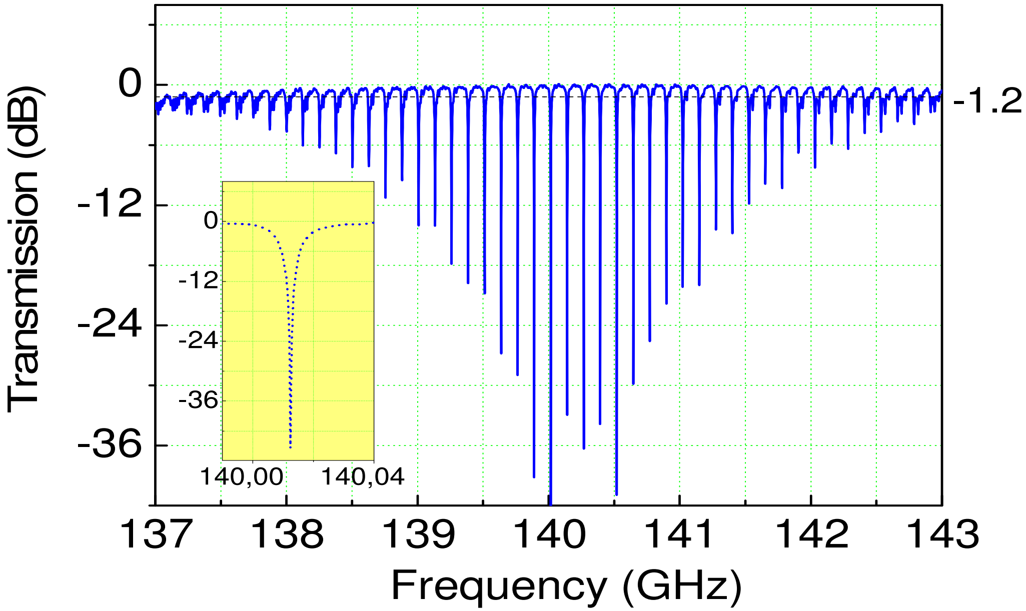
Resonant output:

- Narrow resonances,
  here typ. 10 MHz (FWHM)
- 97% -bandwidth ≈ 500 MHz,
  limited by dispersion of gratings
- Excitation of higher-order modes in the resonator for $f \neq 140$ GHz



Non-resonant output:

- Deep notches < -30 dB
- For $f \neq 140$ GHz, transmission tends to – 1.2 dB level



Power transm. efficiency, and mode purity

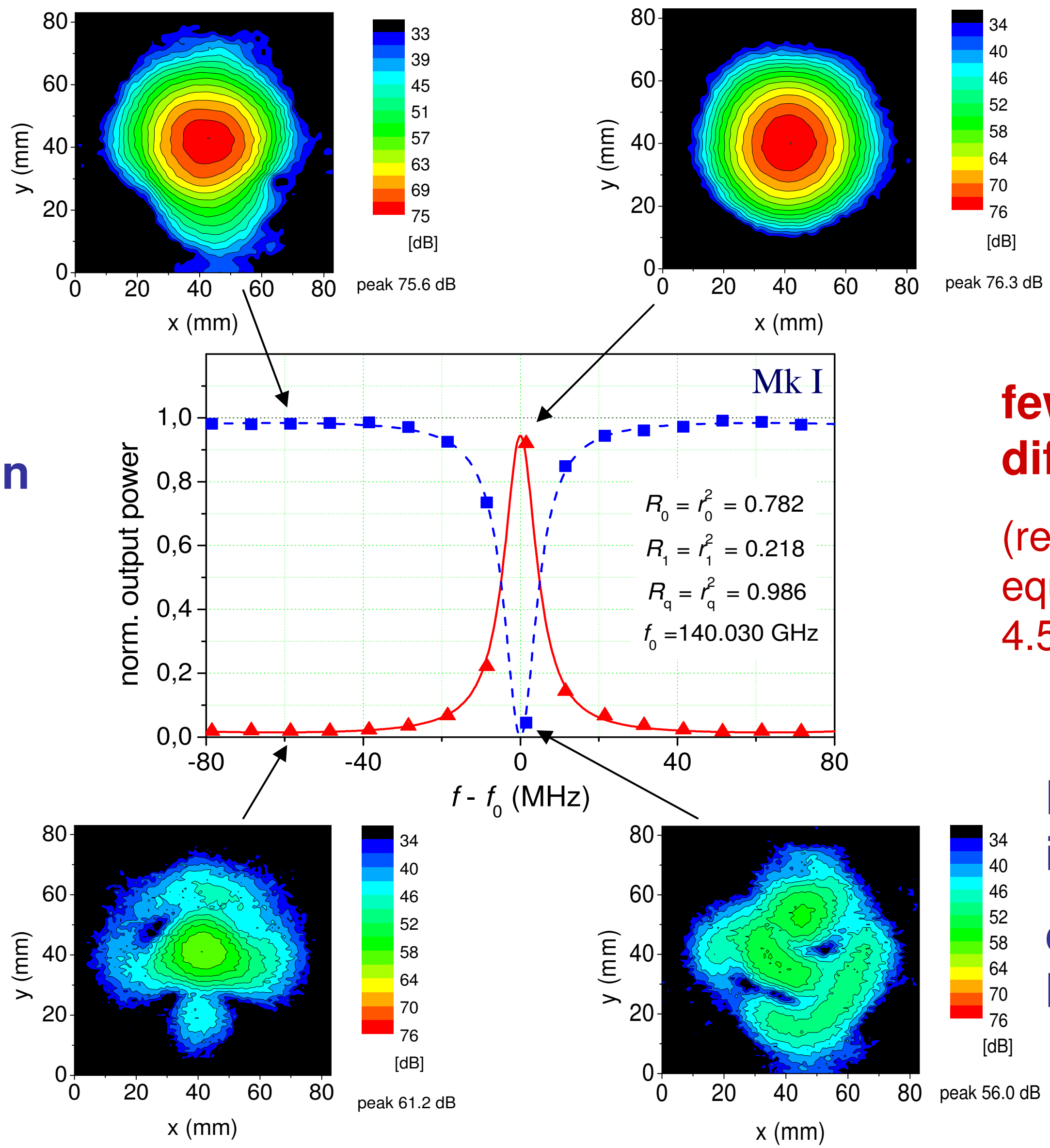
Non-resonant output 1:

TEM_{00}: 99,0 %

Resonant output 2:

TEM_{00}: 99,8 %
➔ mode-filter!

high transmission efficiency



few % ohmic, diffraction loss

(resonator is equivalent to 4.5x 4 mirrors)

Res. output 2 off resonance:

cross-talk: < 2 % mainly in TEM_{00}

Non-res. output in resonance:

cross-talk in high-order modes

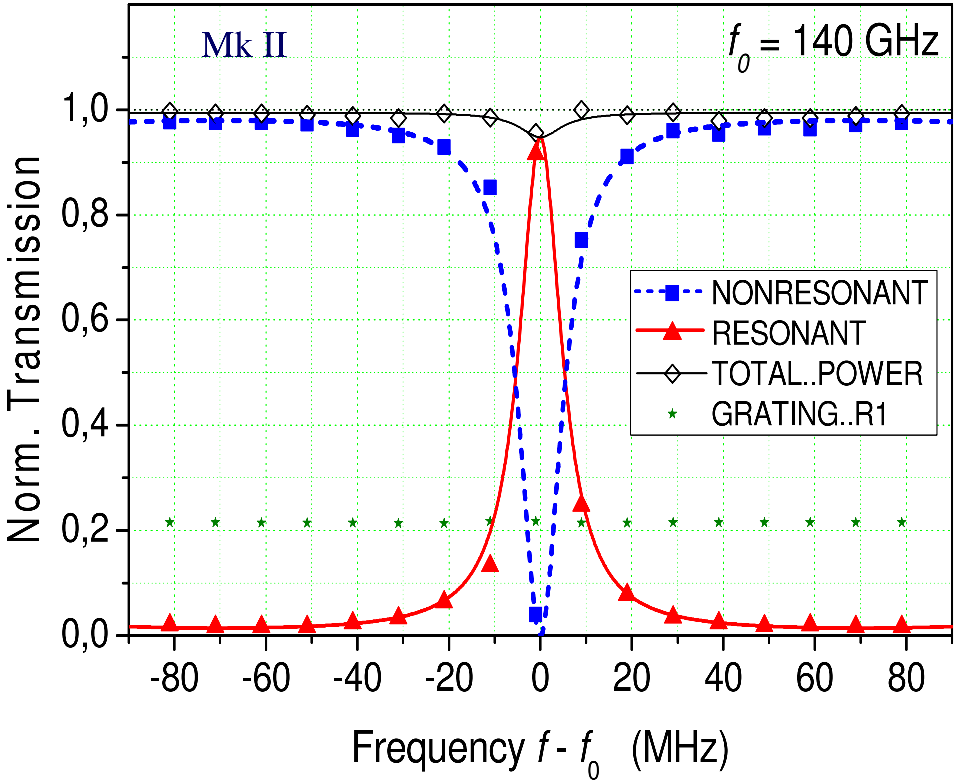
Power transmission efficiency Mk II

- 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 %

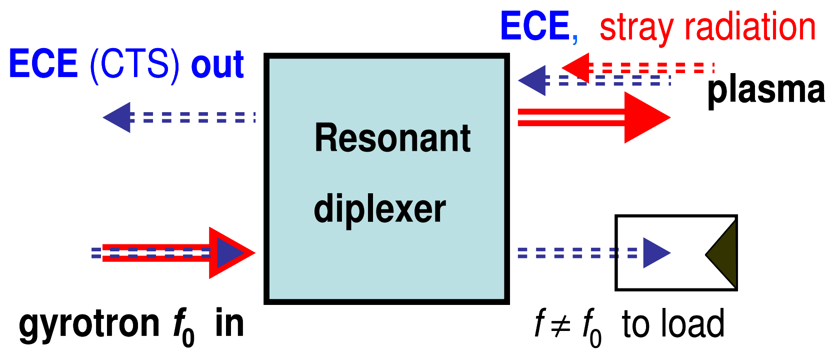
- **Insertion loss, resonant channel:**
  absorption (resonator, coupl): 4.4 %
  cross-talk (wrong modes!): 3.9 %

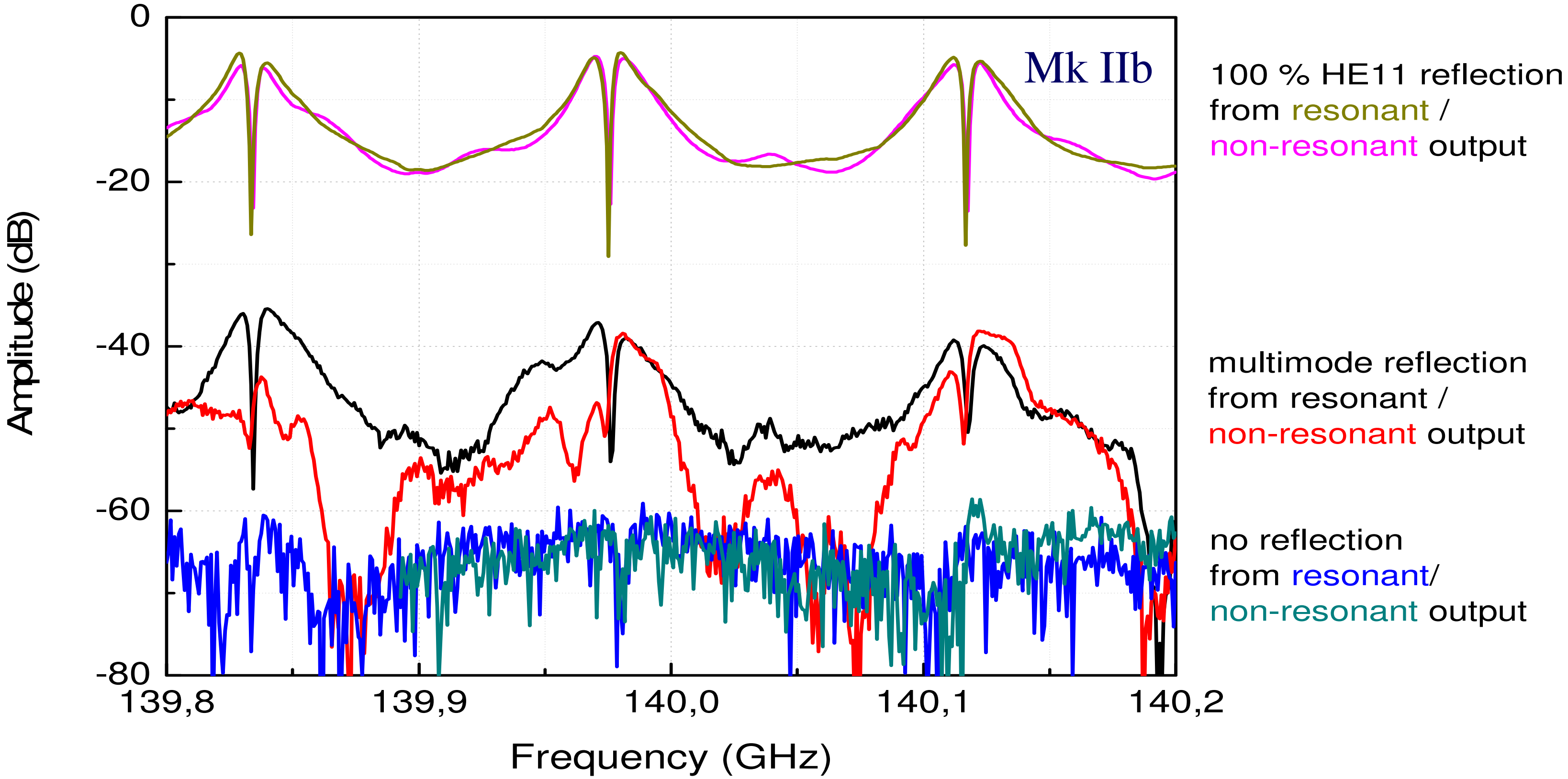
- **Average power absorption for pure HE_{11} input is 1…5 % depending on frequency.**



Port Isolation

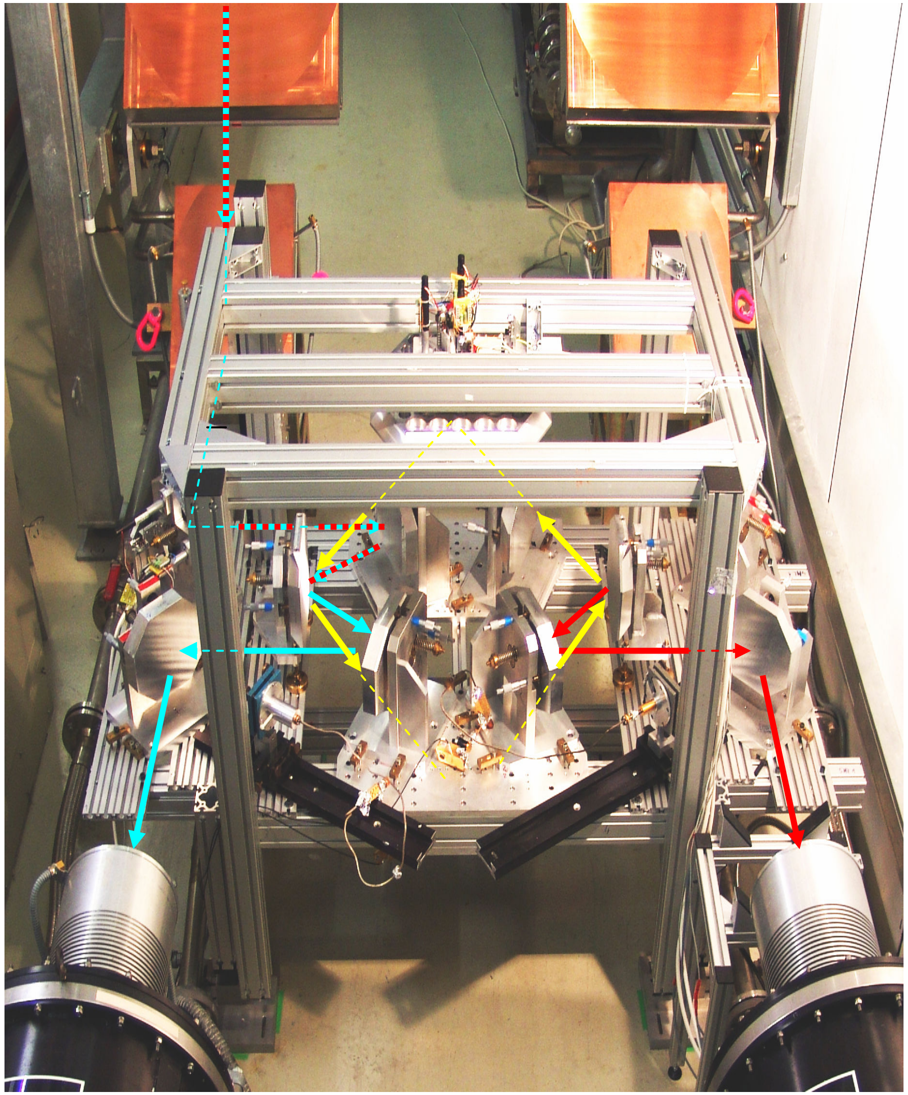
- isolation between inputs better than – 60 dB
- multi-mode reflection from outputs to input is damped by typ. 40 dB

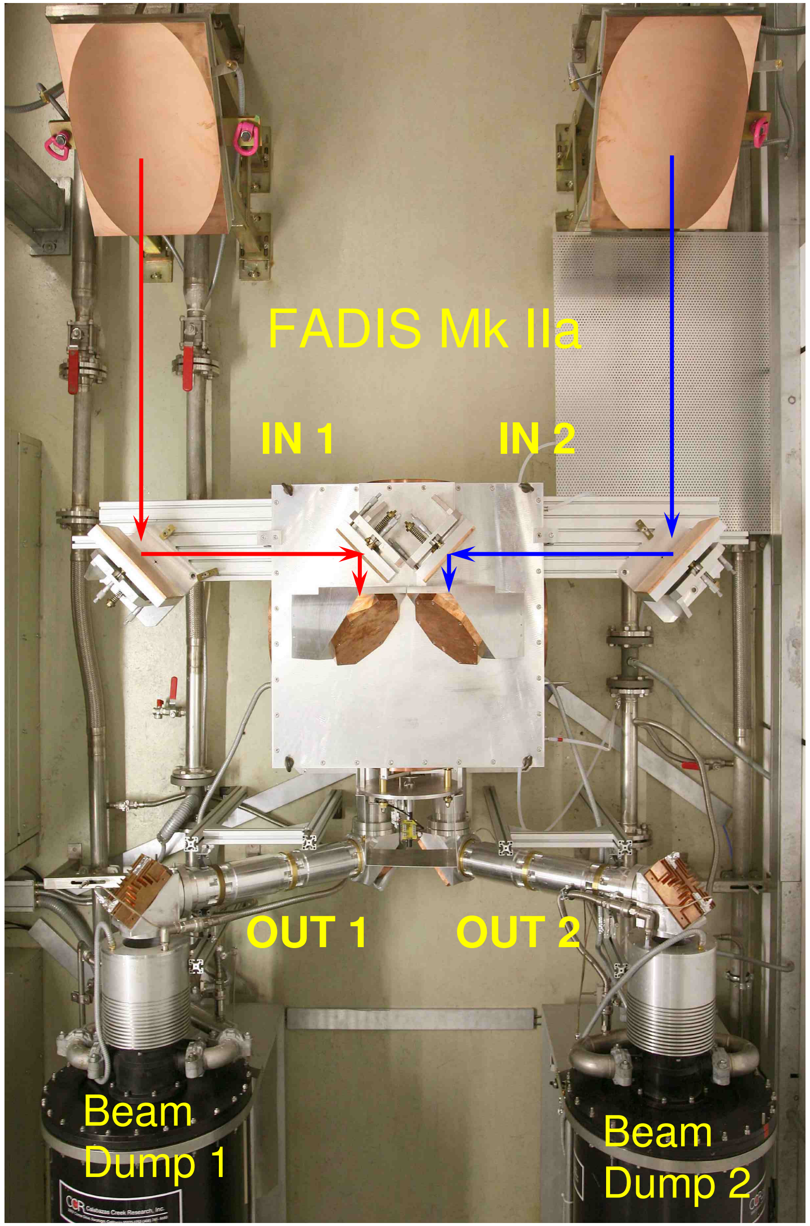




High-power test at the ECRH system of W7-X

FADIS Mk I





matching optics

waveguide section

Power Combination

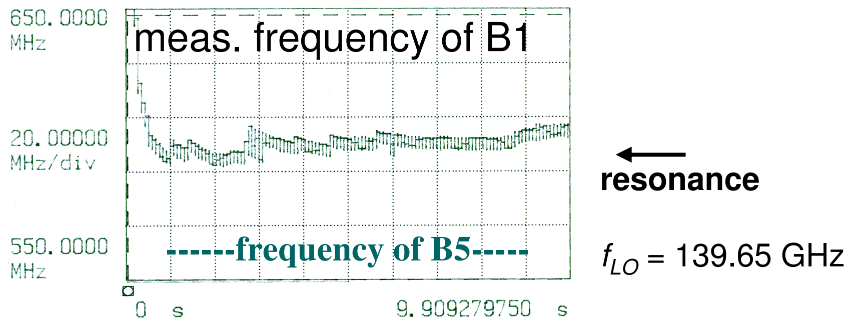
2 gyrotrons 370 / 560 kW fed into diplexer Mk I:

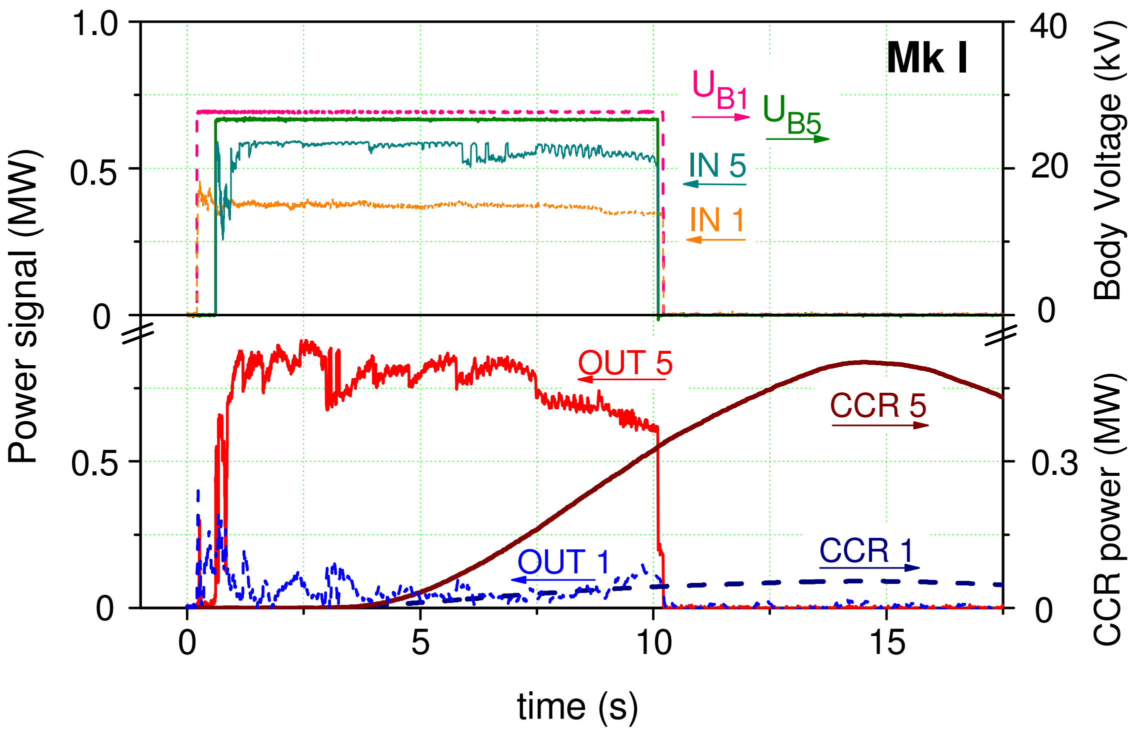
- clear demonstration of power combination

- Power ratio after 1 s:
  5.5% OUTPUT 1
  94.5 % OUTPUT 5

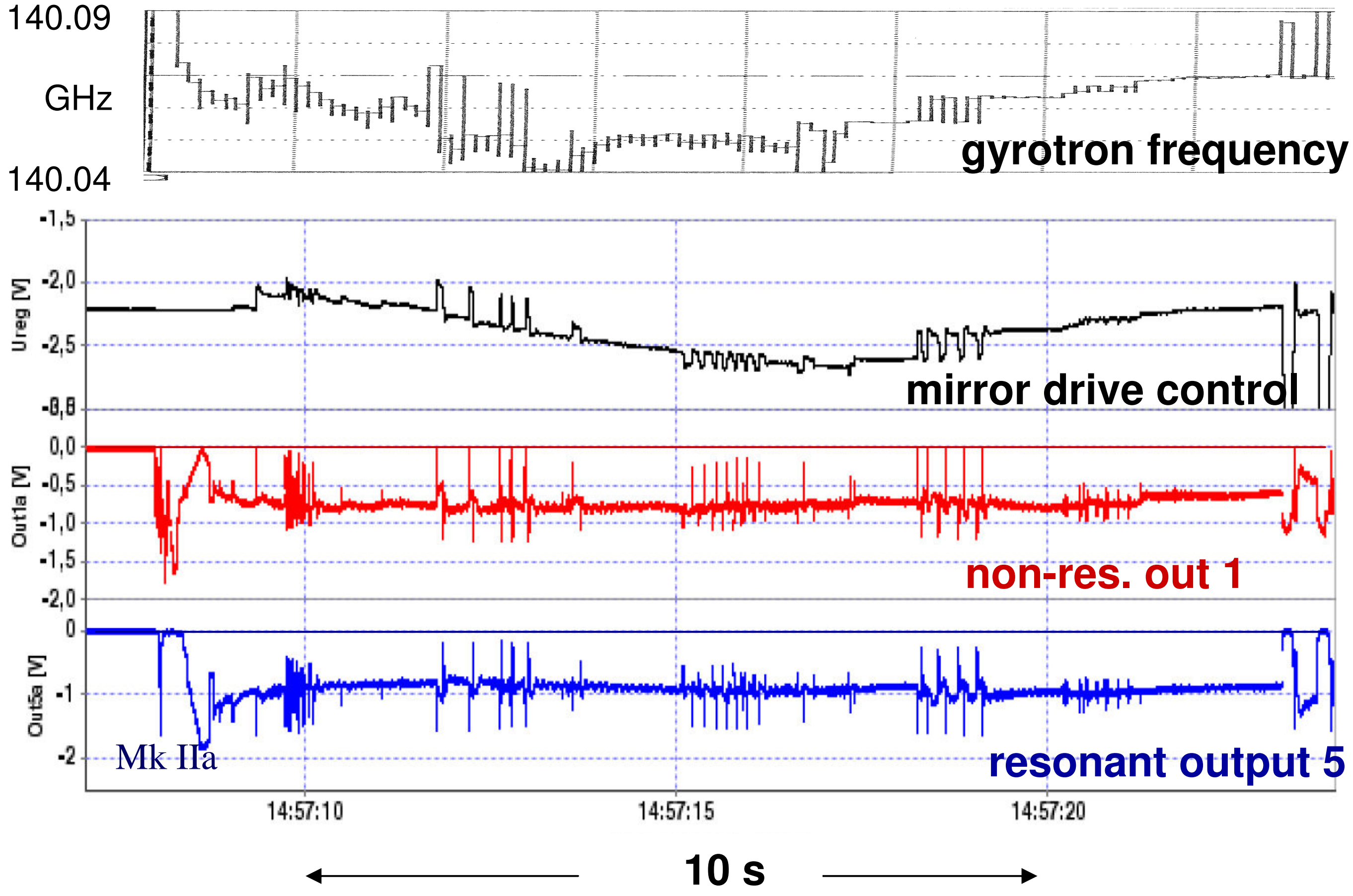
- Main problem: frequency stability of the gyrotrons

- pulse limited by uncooled Al mirrors:
  mmw-power on gratings is about 2 MW!

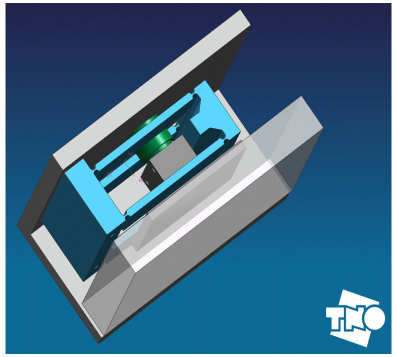




Frequency tracking of diplexer (slope of resonance)



frequency variation by 200 V - steps of body voltage



regulation to equal power output in out1 and out 5

➔ ideal for stable fast switching

Mk II typical shots: 500 kW / 20 s (max. 75 sec, limited by un-cooled mirrors)

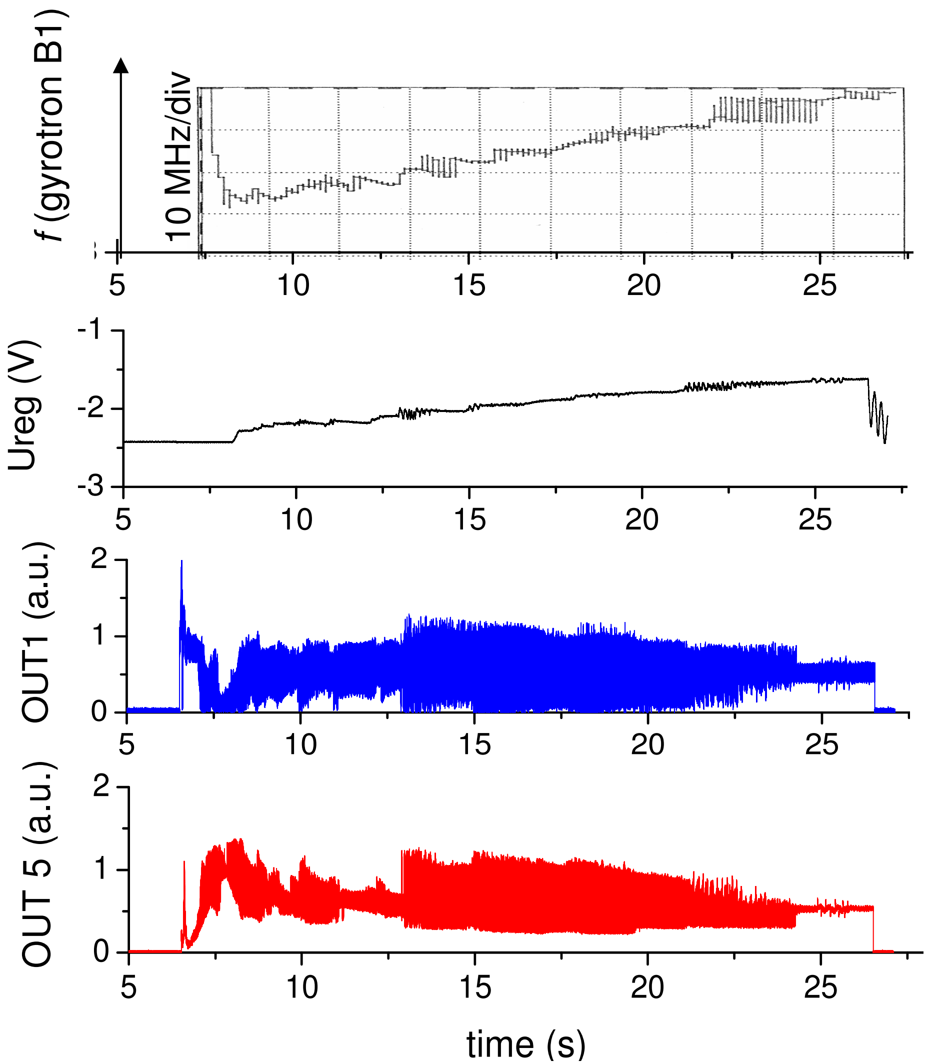
➔ long-pulse switching experiments

In preparation: tracking to peak of resonance ➔ power combination experiments

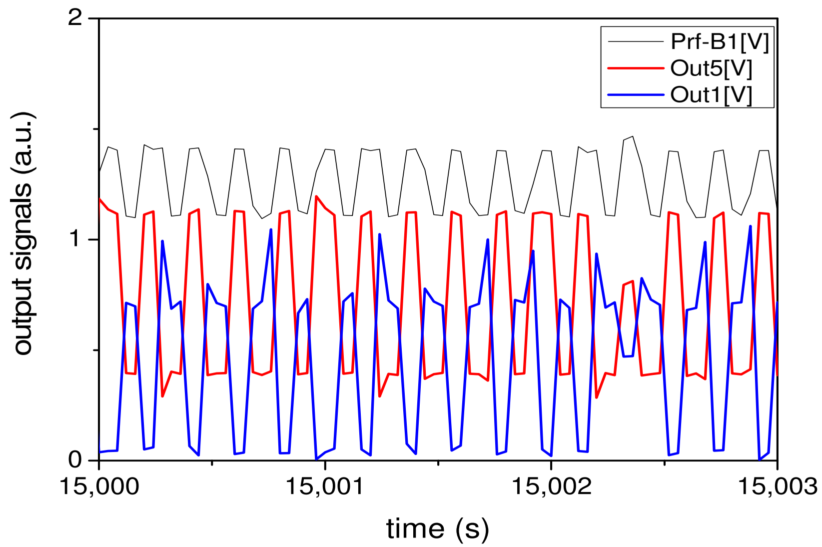
Fast switching with 5.2 kHz

ΔU_B = 4 kV…… 2 kV, 5.2 kHz square, asymetric

➔ **freq. modulation, power, and frequency varies**

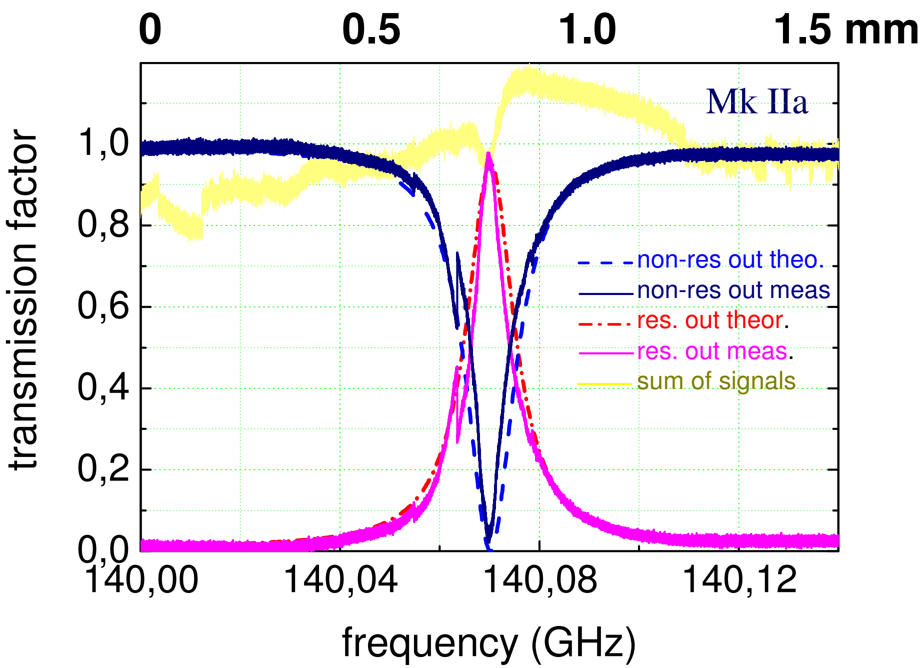


- frequency tracker follows
- frequency modulation depends on absolute frequency
- switching contrast of > 90 % only during shorter periods
- gyrotron frequency is influenced by (the phase of) reflected power within the gyrotron ?
- However: Fairly linear modulation characteristics measured e.g. on Gycom tube at FTU



Characteristics measured with high power

Transmission function recorded by continuous resonator tuning:

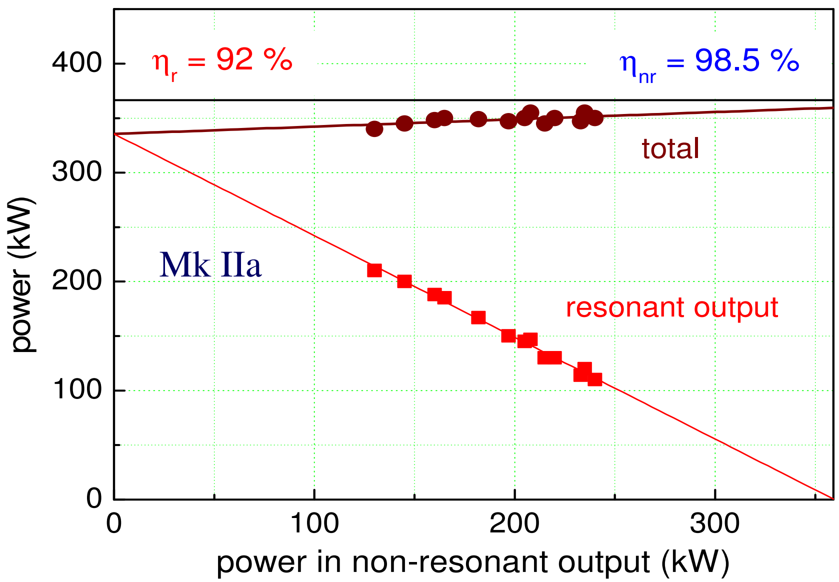


- generally good agreement;
- deviation due to frequ. jumps and drift
- normalized to sum of power signals

➔ arbitrary power splitter

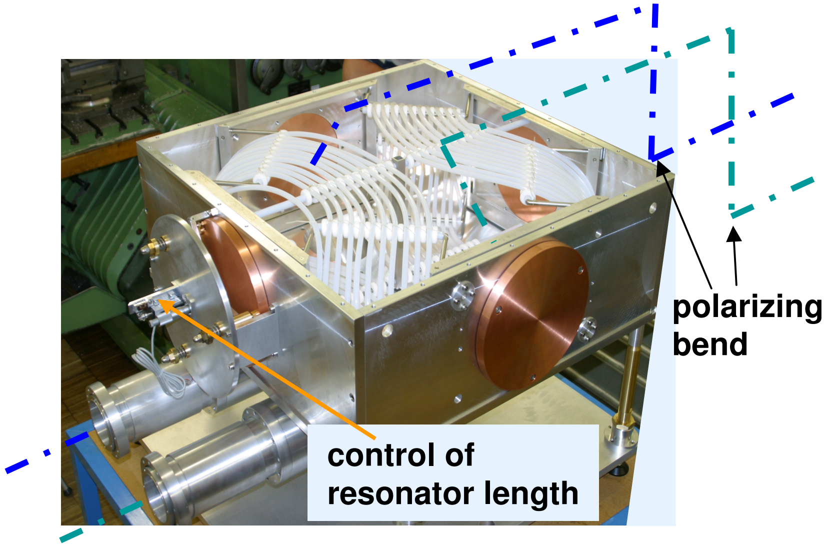
➔ slow switch

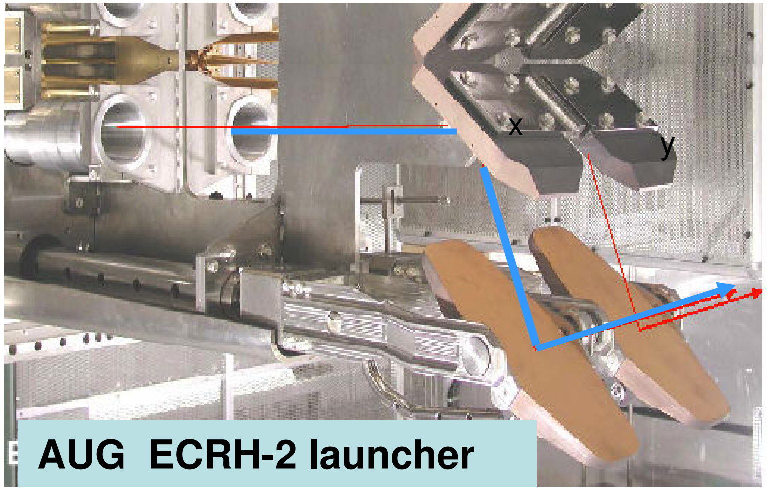
Transmission efficiency estimated by power ratio OUT1 / OUT2:



- η_{nr} taken from low-power measurement
- η_r extrapolated from ratio in outputs

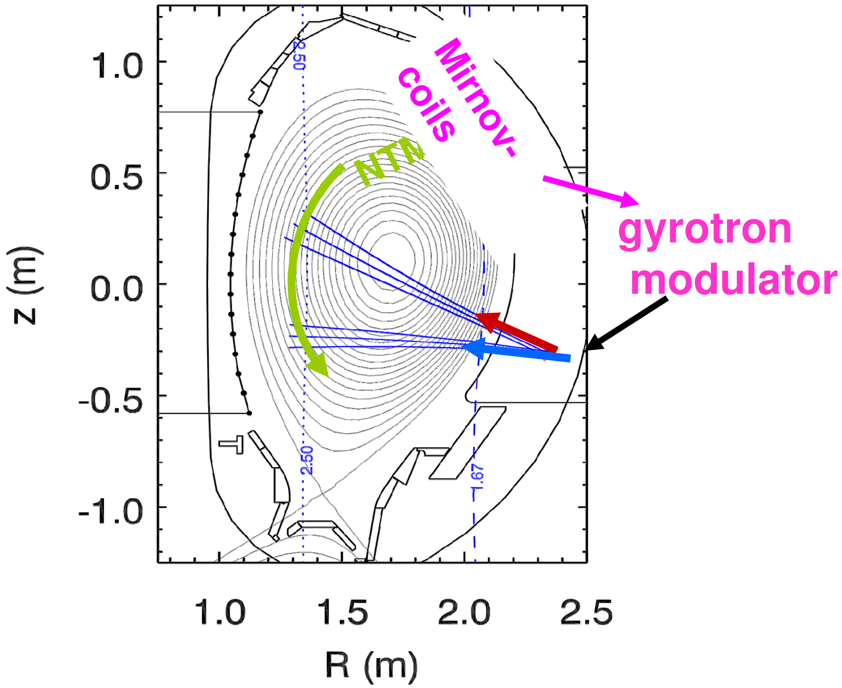
NTM experiments planned at ASDEX Upgrade





- **Synchronous NTM stabilization**
  1 beam toggles between two launchers
  ECCD position poloidally or toroidally displaced by about 180 deg with respect to NTM phase

- **independent experiments**
  (more ITER-relevant, possibly with 2 gyrotrons)
  - 1 beam for NTM stabilization
  - 1 beam for other purpose

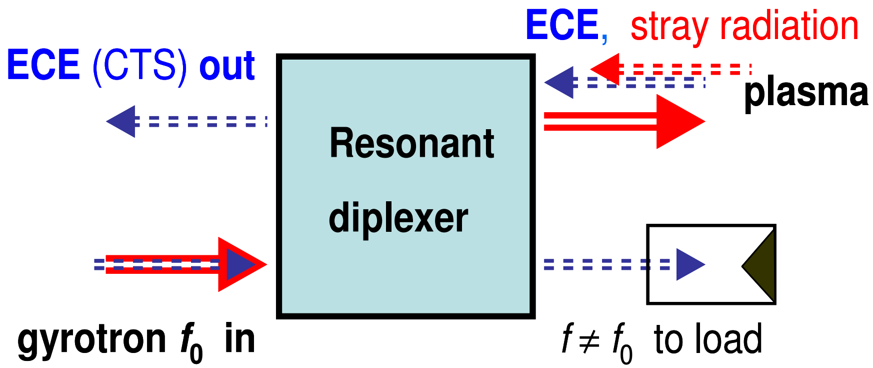


In-line ECE system for ASDEX Upgrade

In-line ECE for ASDEX Upgrade:

cf. talk by B. Hennen

Compact diplexer with cw potential



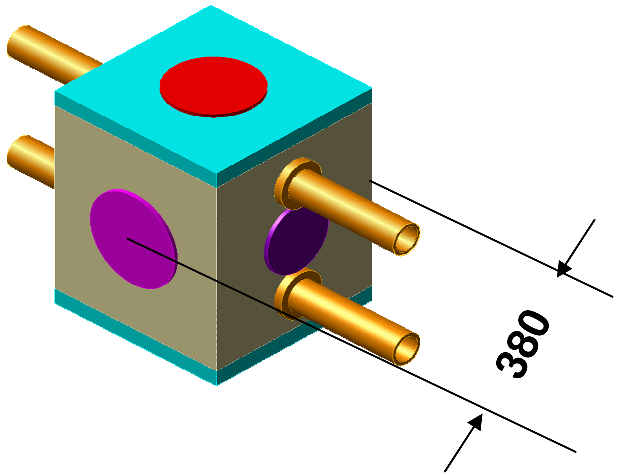
Decoupling of gyrotron from ECE

Suppression of gyrotron stray radiation in the sensitive ECE receiver

However: high stability of gyrotron / frequency tracking is required

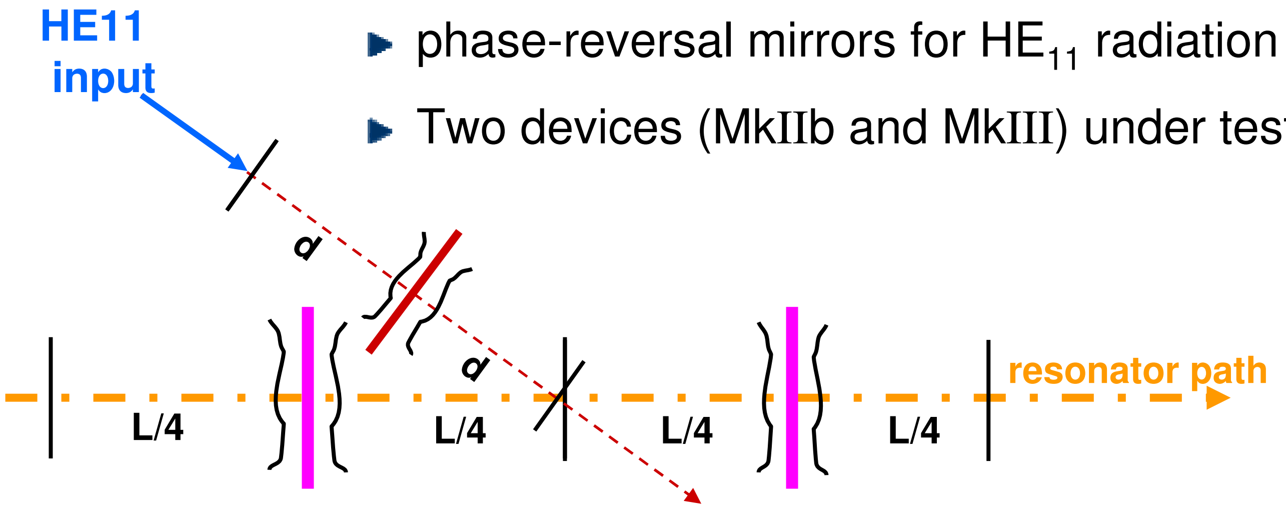
➔ additional notch-filters are needed

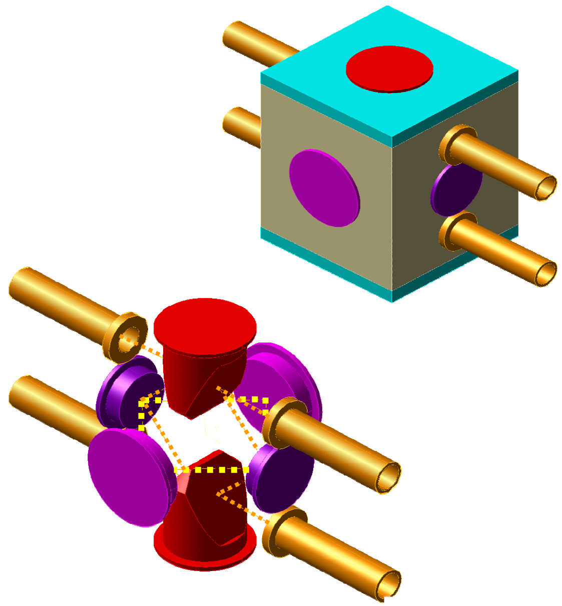
➔ for AUG: polarisation independent Mach-Zehnder Interferometer (W. Bongers)

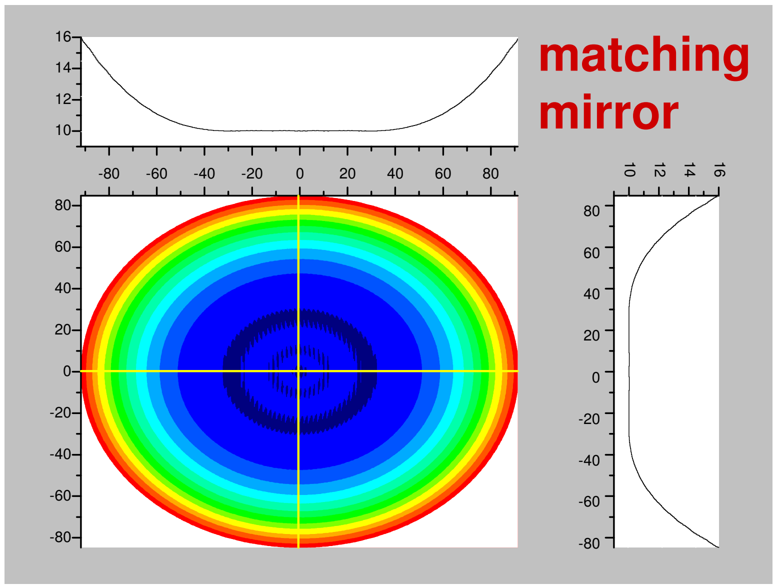


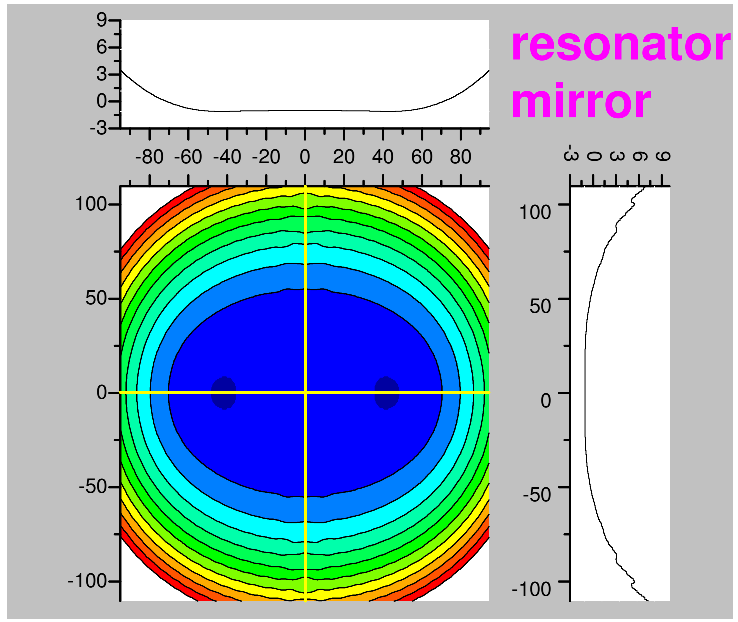
Resonant Diplexer with „HE11-Resonator“

- Direct connection of HE_{11} waveguide
- phase-reversal mirrors for HE_{11} radiation
- Two devices (MkIIb and MkIII) under test

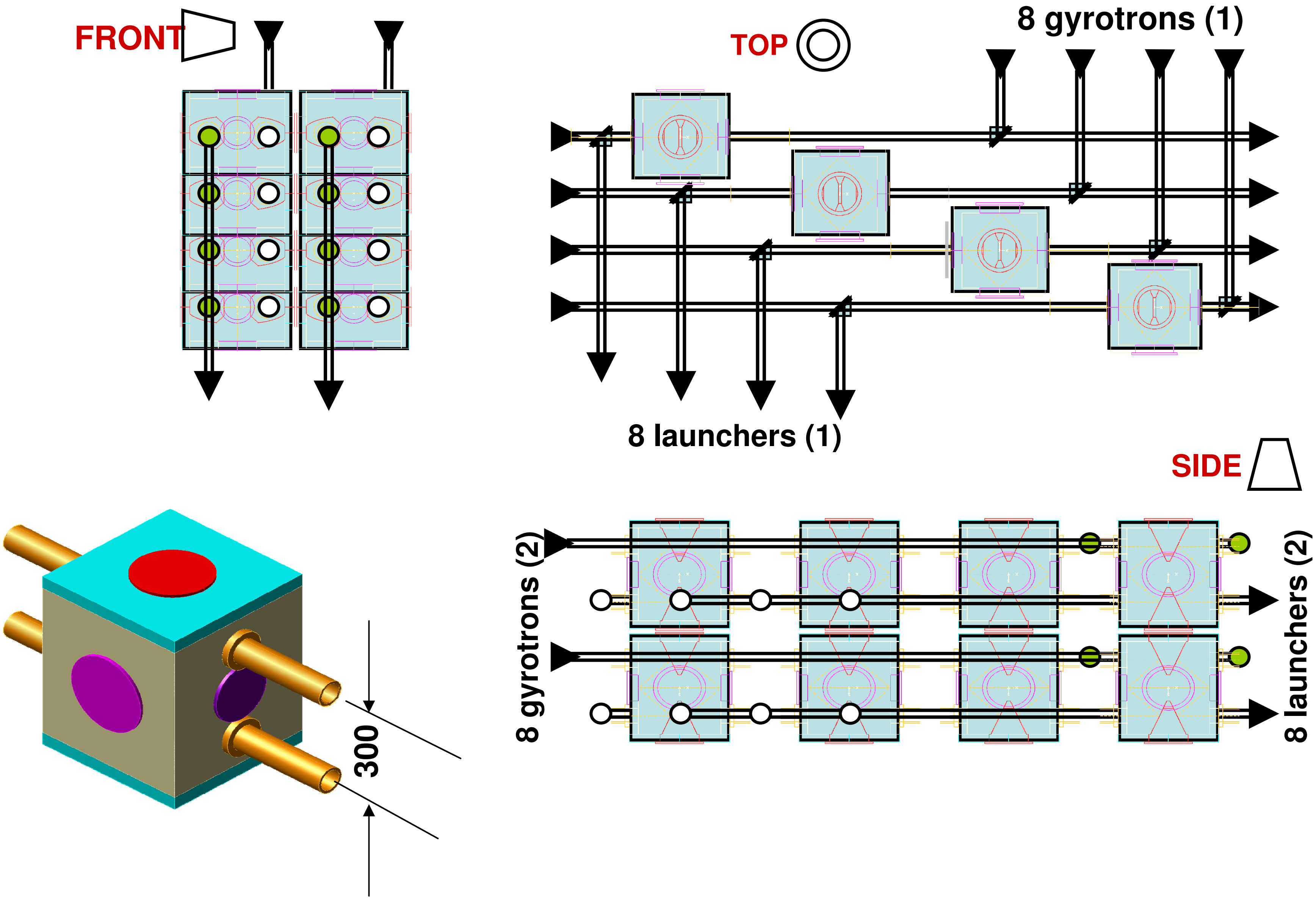






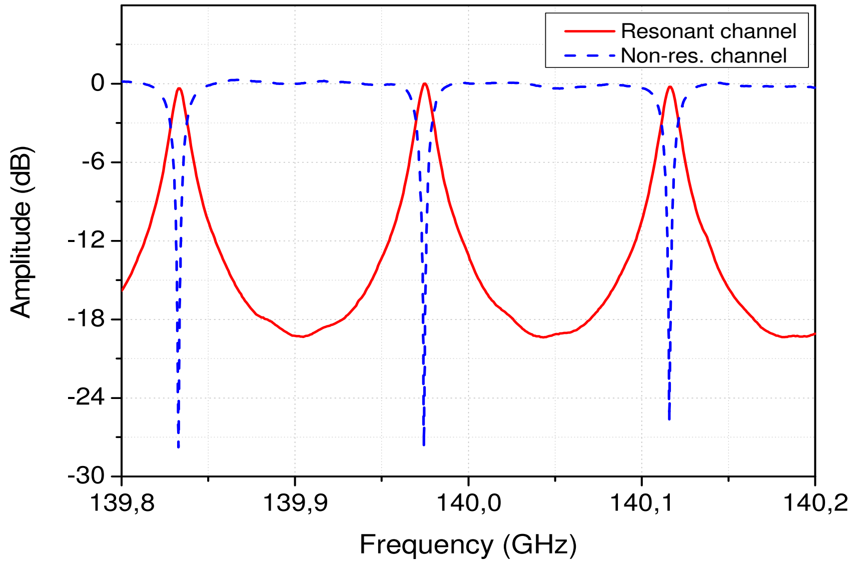


Resonant diplexers in large ECRH system



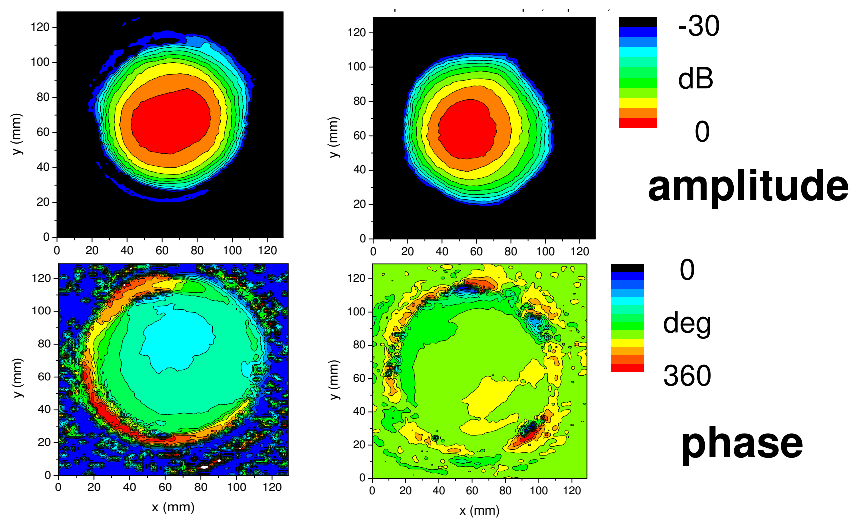
Preliminary low-power results from HE_{11}-diplexer

- Transmission functions for **non-resonant output** and **resonant output** in good agreement with calculation



- **amplitude and phase patterns show high mode purity:**
  - Non-resonant output: 95.9 %
  - Resonant output: 98.8 %
  - (Input: 97.3 %)

Nonresonant **Resonant** **output**

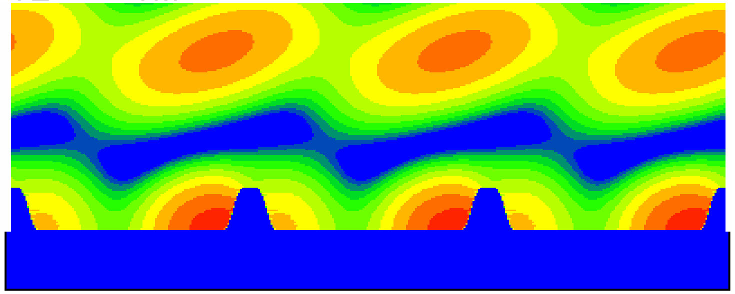


- **Insertion loss**
  non-resonant 97 %
  resonant channel : 90 %
  (larger crosstalk…)

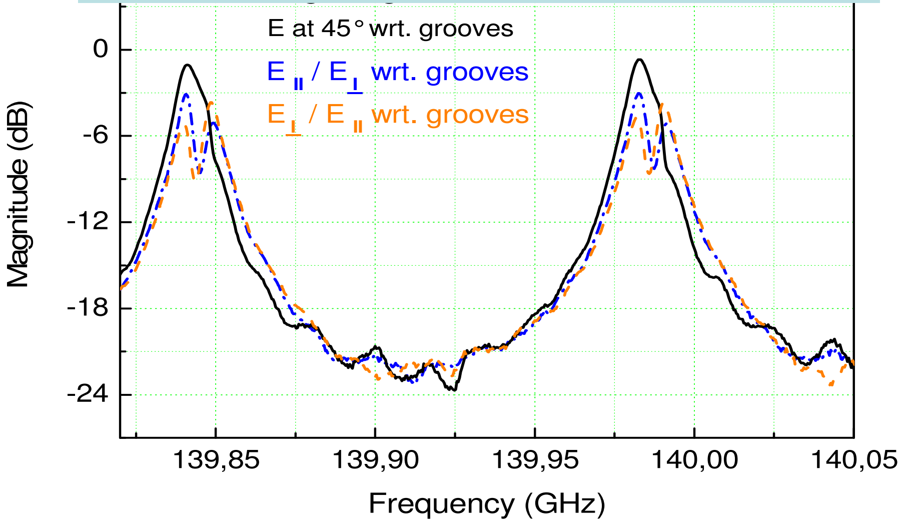
Diplexer operation with arbitrary polarisation?

grating with identical efficiency,
but different phase shift for TE and TM

$\eta_{TE} = \eta_{TM} = 0.225, \ \Delta\varphi = 0.61$



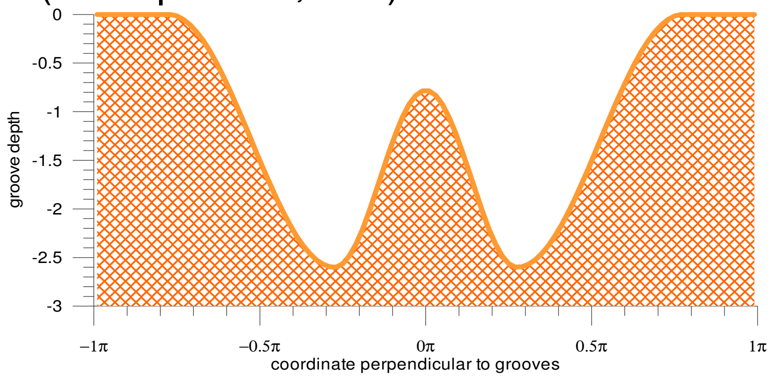
compensation of $\Delta\varphi$ by crossed grating

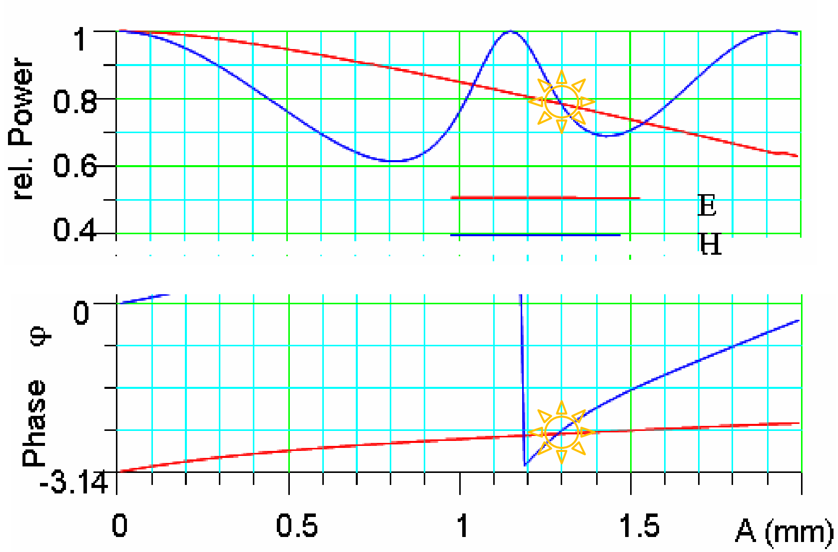


- transmission still depends on polarisation
- → mechanical error in groove profile

omni-polarisation grating

(E. Koposova, IAP)



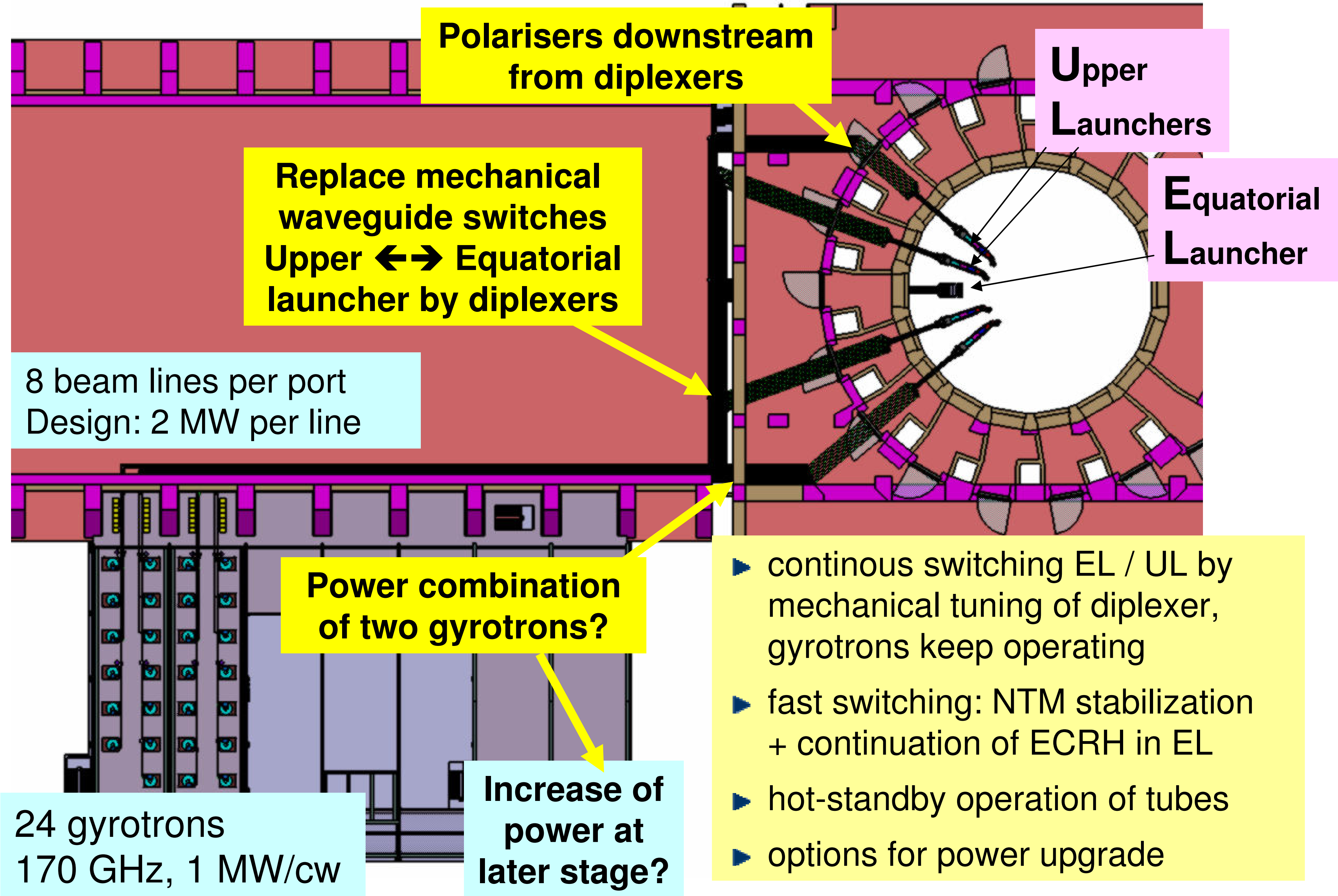


- sensitive to profile errors
- should be tested!

Summary

- High-power diplexers could strongly increase the performance and flexibility of ECRH as well as diagnostic systems.
- High-power demonstration of fast switching, slow switching, and power combination from two gyrotrons;
- frequency tracking successfully tested
- Optimization / more data on frequency-modulation of gyrotrons is needed.
- Applications at ASDEX Upgrade are in preparation: NTM stabilization with power toggling between launchers, and in-line ECE system.
- Compact designs with HE11 resonators can be directly connected to corrugated waveguides.
- Applications of diplexers in ITER ?

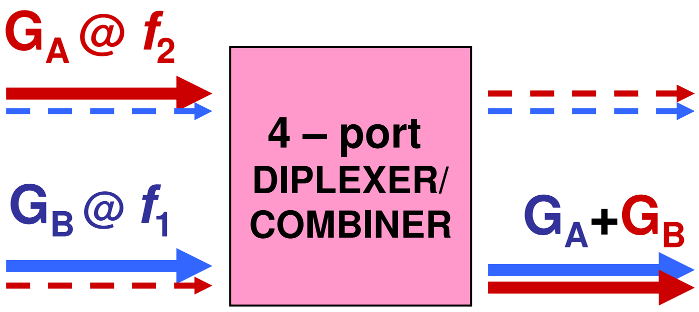
ECRH system for ITER



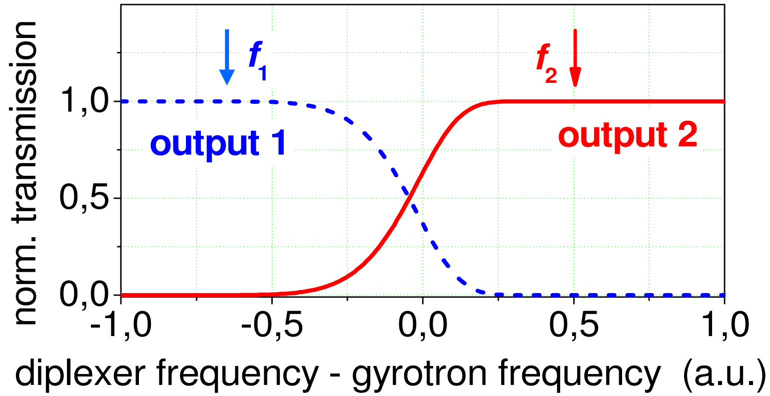
- continous switching EL / UL by mechanical tuning of diplexer, gyrotrons keep operating
- fast switching: NTM stabilization + continuation of ECRH in EL
- hot-standby operation of tubes
- options for power upgrade

Narrow-band diplexers in ECRH systems

Principle design:



Ideal transmission function:



Applications:

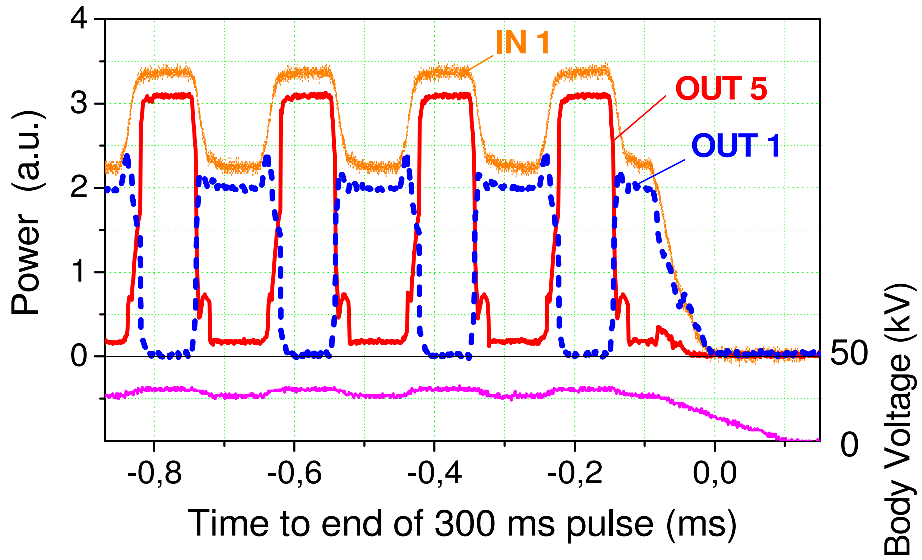
- **switching** by frequency-shift keying $f_1 – f_2$:
  $\Delta f / f \approx 10^{-4}$, with ΔU_{GA} or $\Delta U_B \approx$ kV
  ➔ power toggles between outputs
  ➔ switch has no undefined state, cw operation
- **power divider** by mechanical tuning of trans. frequency
- **power combination** of two sources:
  fixed input frequencies f_1 **and** f_2
  f_1 / f_2 in push-pull: ➔ combined power toggles
- **dir. coupler** to isolate ECRH from low-power diagnostics

Experiments with ECRH-system at W7-X

Switching (1 gyrotron ==> 2 outputs)

(P = 500 kW, f_{mod} = 5 kHz, ΔU_B = 4 KV)

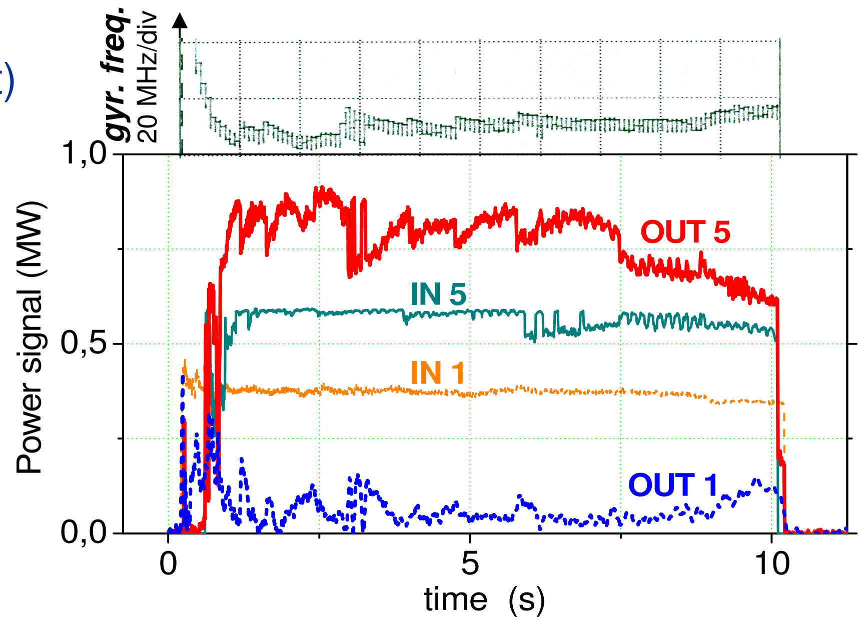
- high switching contrast
- main problem: $\Delta f \leftrightarrow \Delta P$
- improvement factor for NTM, related to power modulation: $\eta \geq 1.45$



Power combination (2 gyrotrons ==> 1 output)

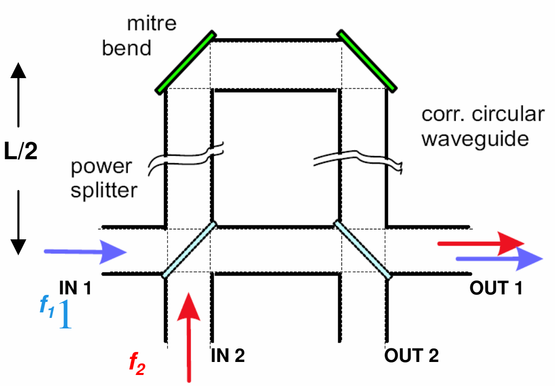
(B1, P = 370 kW, and B5, P = 560 kW, t = 10 s)

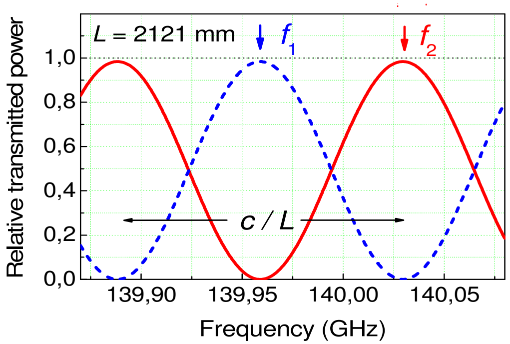
- av. power ratio after 1 s: 5.5 / 94.5
- problem: gyrotron frequency stability
- pulse ≤ 10 s due to un-cooled Al mirrors
- calibration of monitor signals with CCR loads

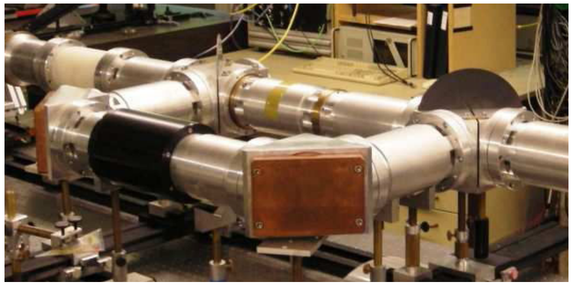


Designs for high-power diplexers

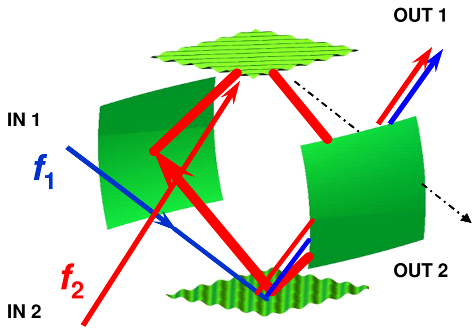
Mach-Zehnder interferometer with dielectric splitters in HE11 waveguide

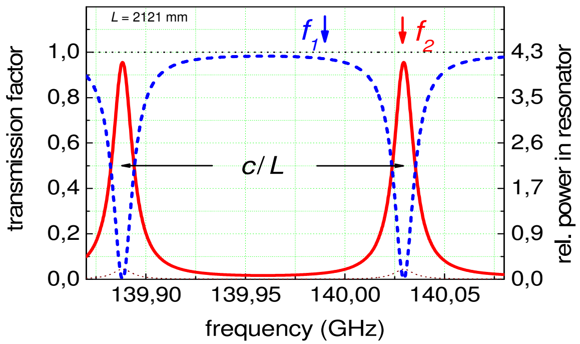


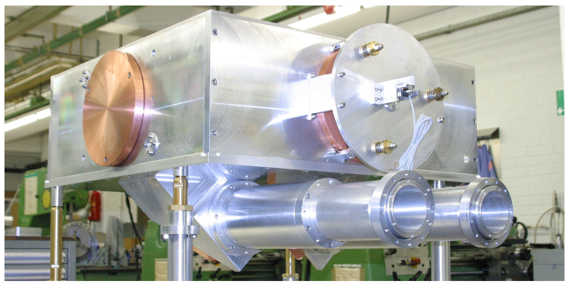




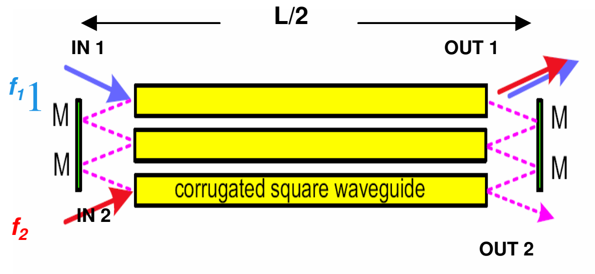
q.-optical ring resonator with grating splitters

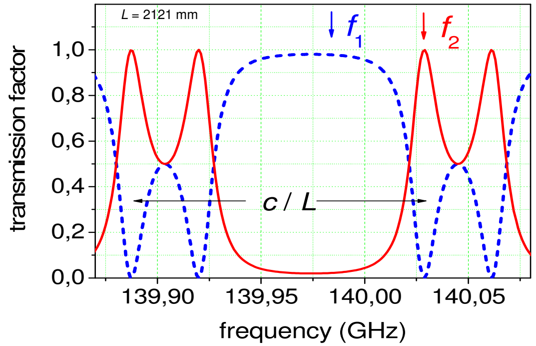


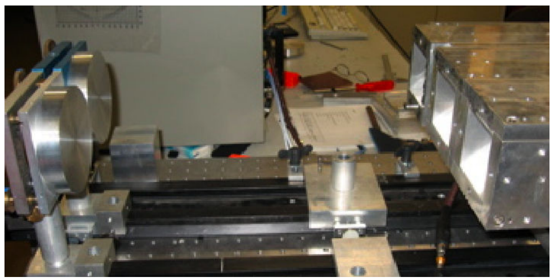




Two-loop resonator with Talbot splitters in corr. square waveguide





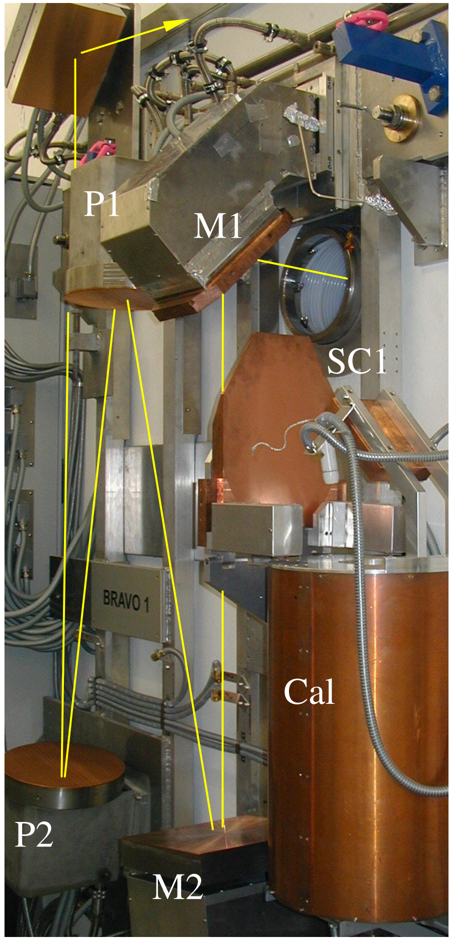


ECRH system for W7-X:

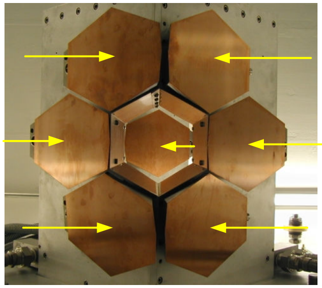
single-beam and multi-beam transmission up to the torus

Gyrotron (Thales)
900 kW / 30 min

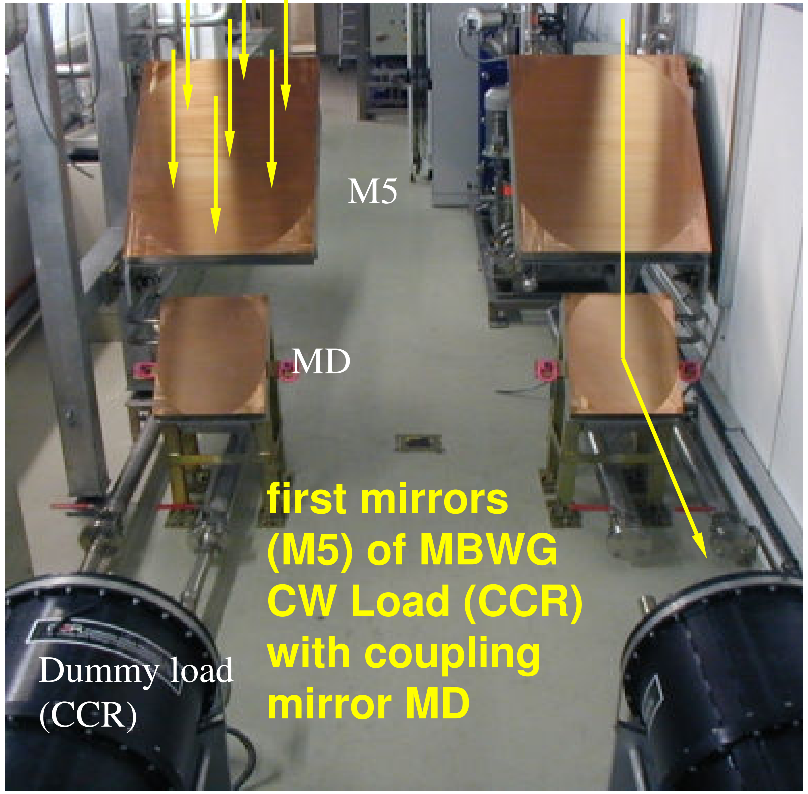
2 Prototypes
Used for experiments



Beam conditioning
(matching
+ polarisation)

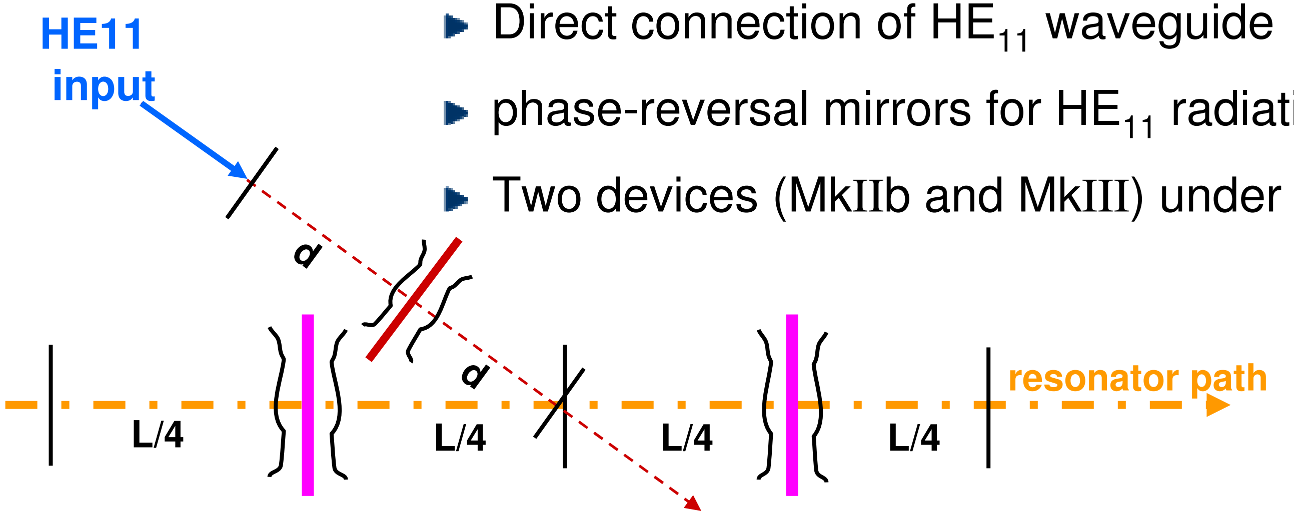


Beam
combination
(BCO)

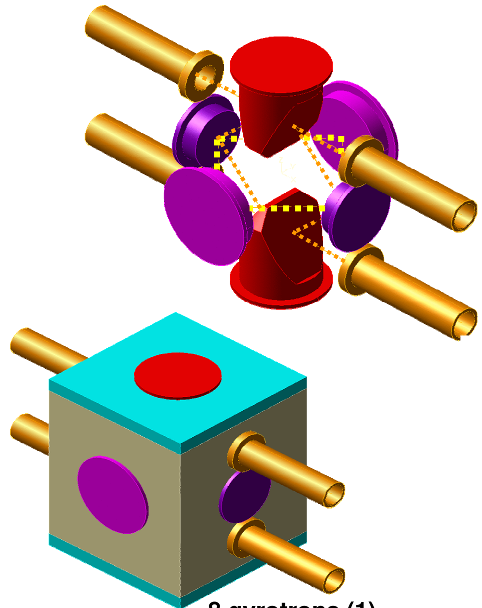


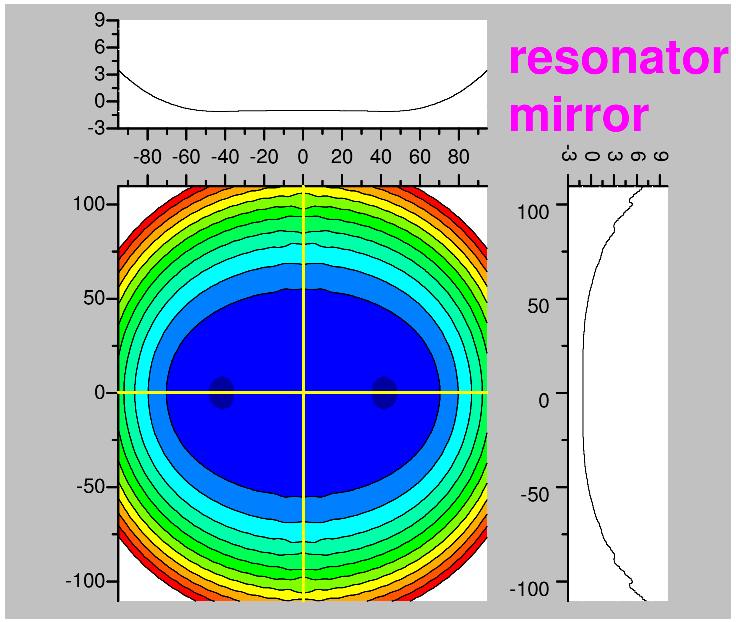
first mirrors
(M5) of MBWG
CW Load (CCR)
with coupling
mirror MD

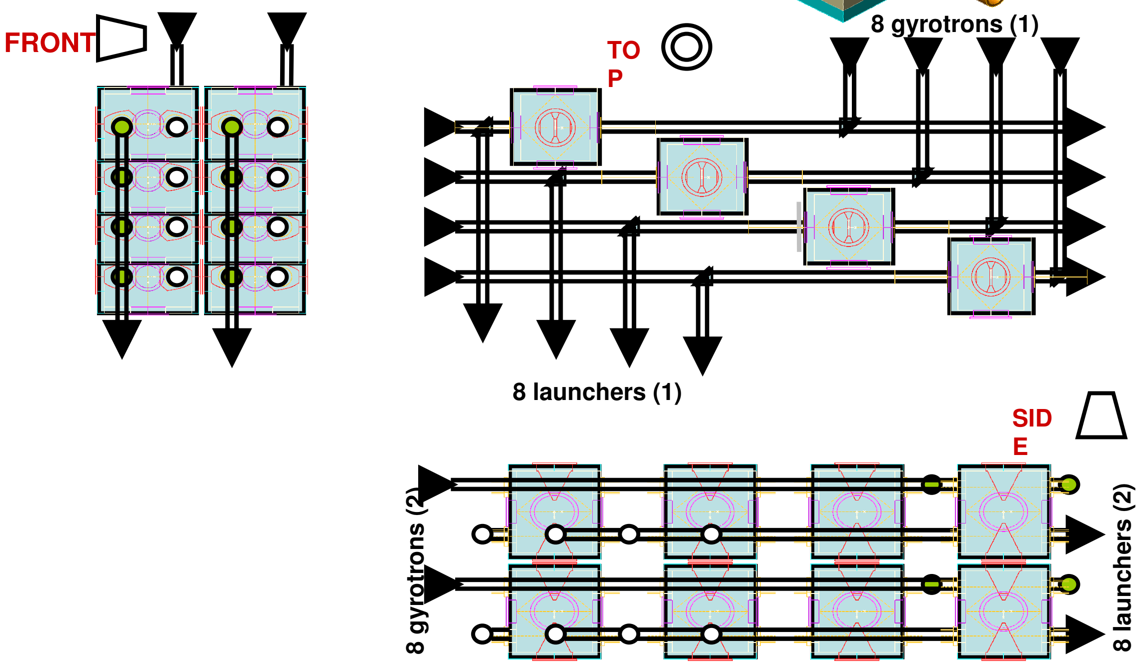
Resonant Diplexer with „HE11-Resonator“



- Direct connection of HE_{11} waveguide
- phase-reversal mirrors for HE_{11} radiation
- Two devices (MkIIb and MkIII) under test

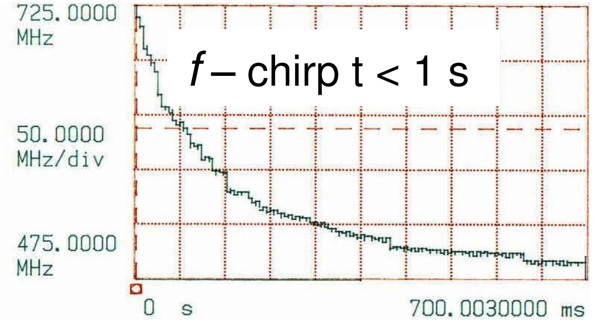




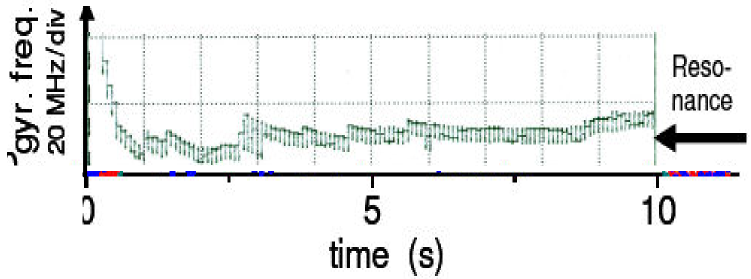


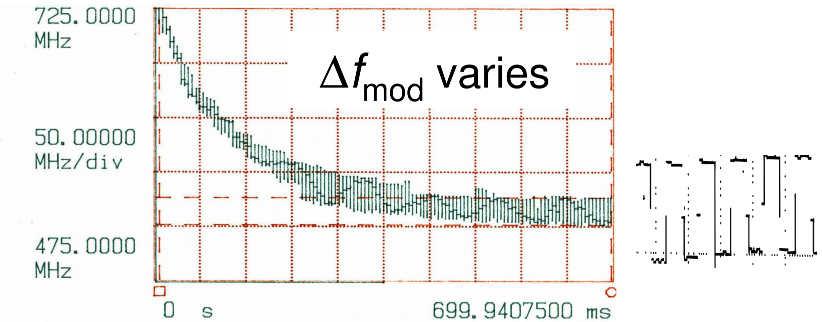
Frequency behaviour of free-running gyrotrons

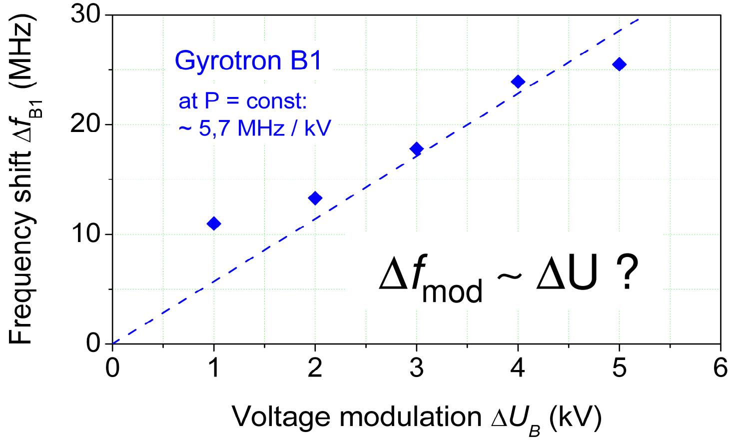
(An amplifier with sufficient power – the ideal solution – is not viable in next years)

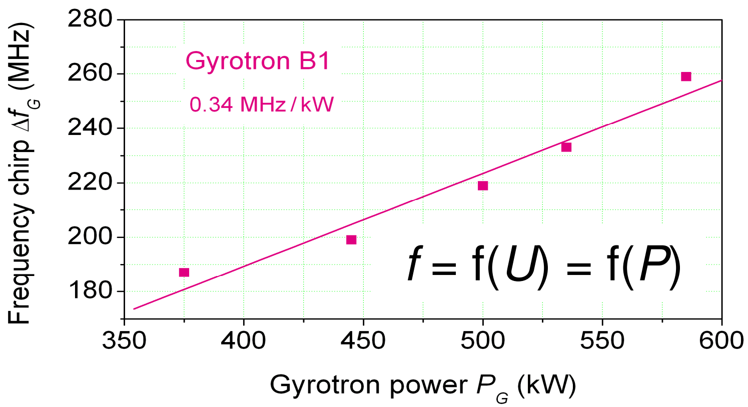


spontaneous frequency jumps









➔ **optimization of gyrotron tuneability**

➔ **tuning / tracking of diplexer**

Main motivation: Synchronous NTM stabilization

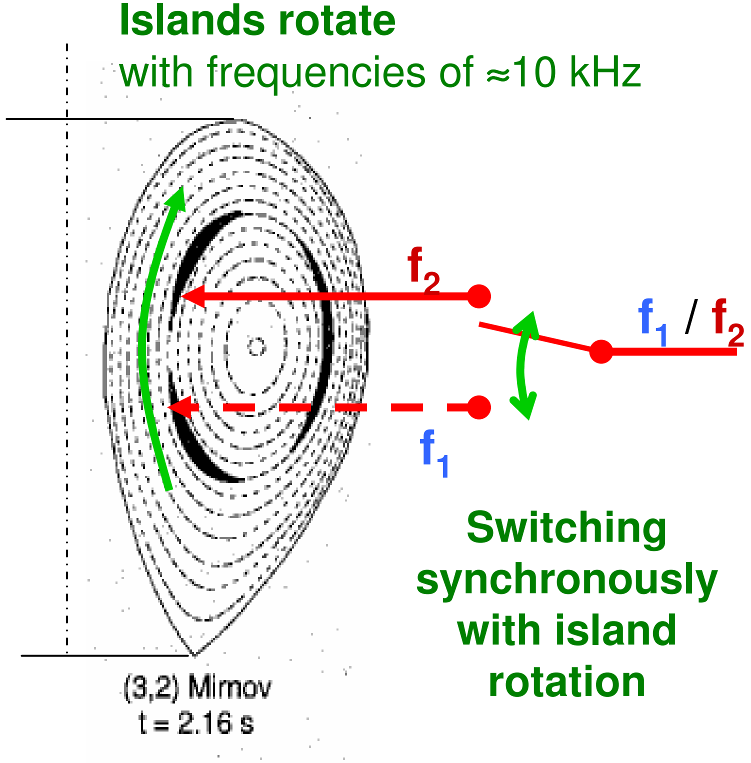
Optimum NTM stabilization:

EC current drive in the O-point of the islands
(at least results similar to non-modulated ECCD)

==> **power modulation** of gyrotron,
synchronized with the island rotation
e.g. M. Maraschek et al., PRL 98, 025005 (2007)…

Disadvantages:

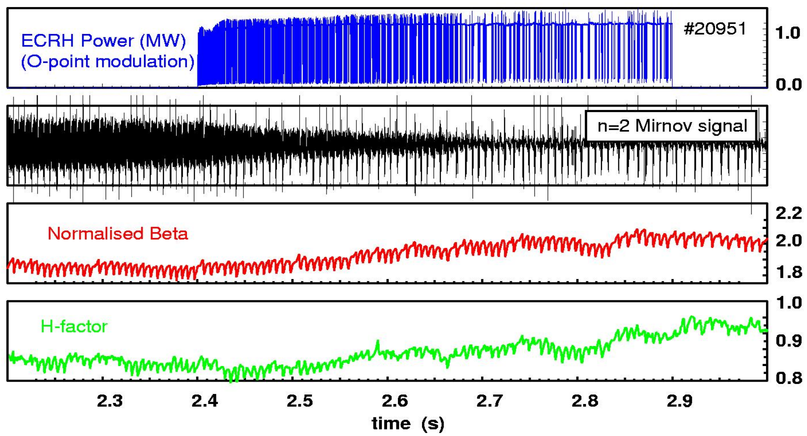
- installed gyrotron power is partly wasted,
- possible EMC problems
- overload of gyrotron collector



Alternative: FAst DIrectional Switch

Switch CW power between 2 launchers, at positions where island phase differs by about 180° (toroidally or poloidally)

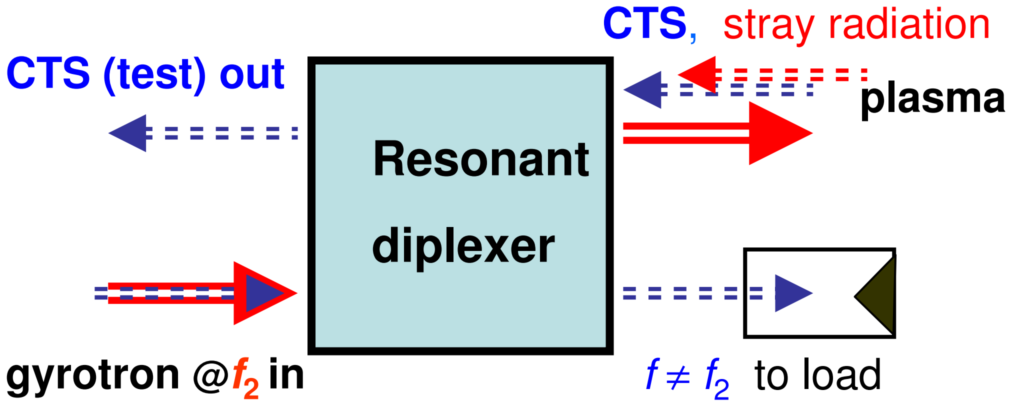
➔ **stabilizing power is increased by ≤ 2**



Collective Thomson scattering using gyrotrons

Collective Thomson scattering

projects on TEXTOR, LHD, ASDEX Upgrade (Risø), ITER….

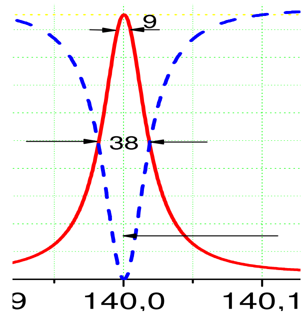


Benefits from resonant diplexer:

Gyrotron frequency filter:

- main frequency transmitted
- spurious frequencies are absorbed in the load.

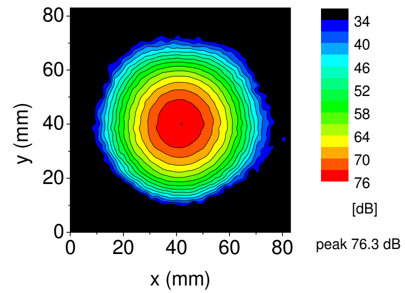
➔ dynamic range of the detection system is improved.



Spatial filtering:

- beam quality of the probing beam is increased,

➔ improved spatial resolution of scattering system



Decoupling of source from receiver:

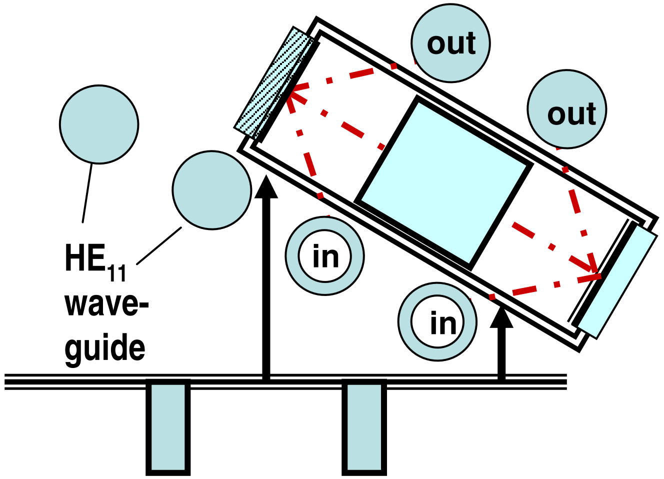
➔ simple backscattering experiment without extra antenna

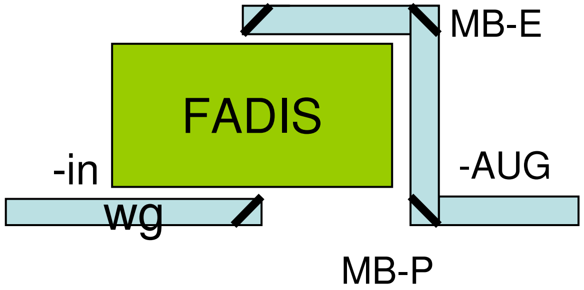
➔ useful for the commissioning and test of a CTS experiment

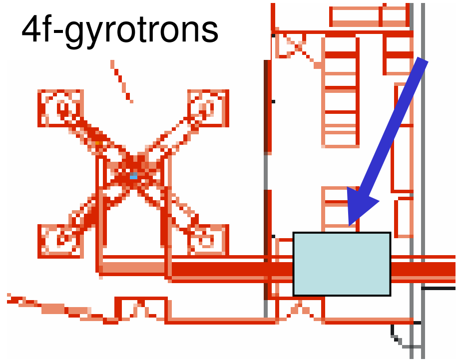
Load available for calibration

use mechanical tuning of resonator mirror

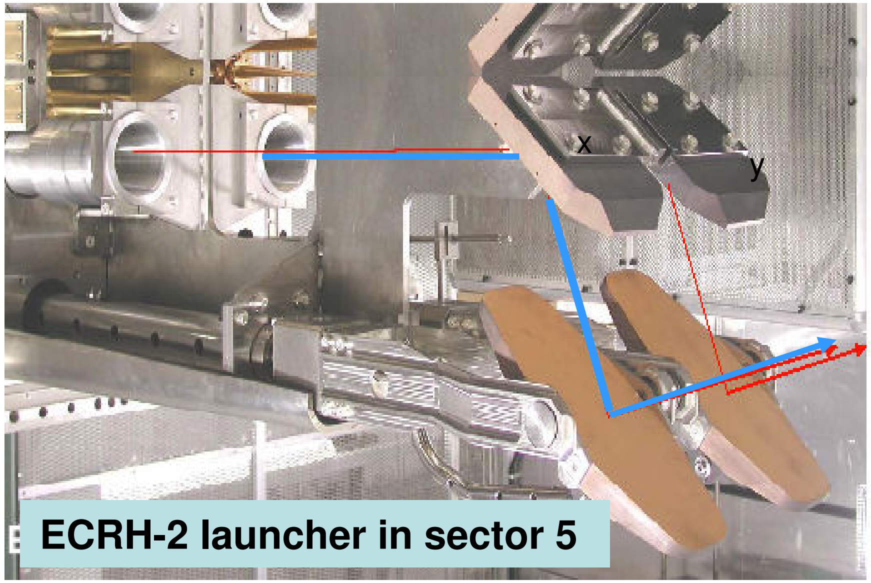
Integration into ECRH-2 of ASDEX Upgrade







new 105 -140 GHz ECRH system

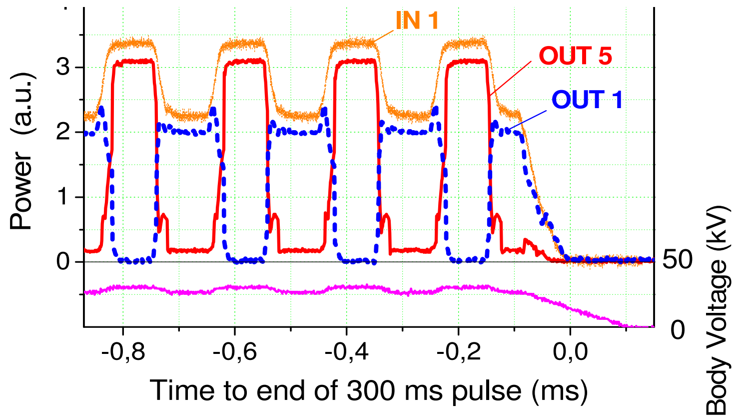


ECRH-2 launcher in sector 5

- connection to any adjacent waveguides
- operation planned from autumn 2010
- connected to lower launchers sector 5

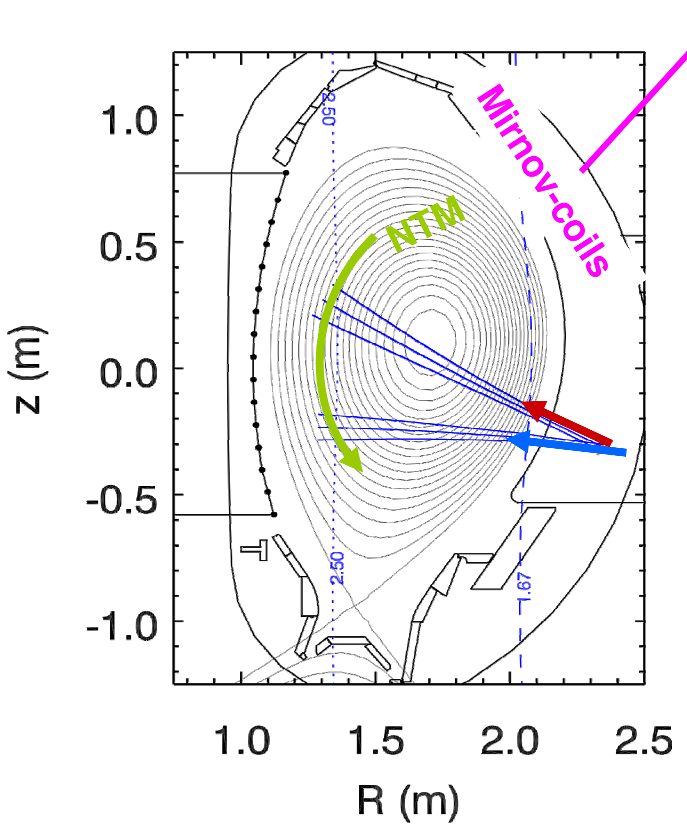
Experiments planned at ASDEX Upgrade

- **Synchronous NTM stabilization**
  1 beam toggles between two launchers
  ECCD position poloidally or toroidally displaced by about 180 deg with respect to NTM phase



- **independent experiments**
  (more ITER-relevant, possibly with 2 gyrotrons)
  - 1 beam for NTM stabilization
  - 1 beam for other purpose

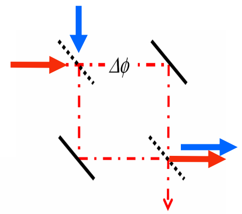
- **applications for plasma diagnostics**
  - in-line ECE (IPP - FOM)
  - collective Thomson scattering (IPP - Risø)
    (needs only one line / launcher)



Mach-Zehnder diplexer in HE_{11} waveguide

two 3-dB hybrids (gratings / square waveguides / dielectric sheets)

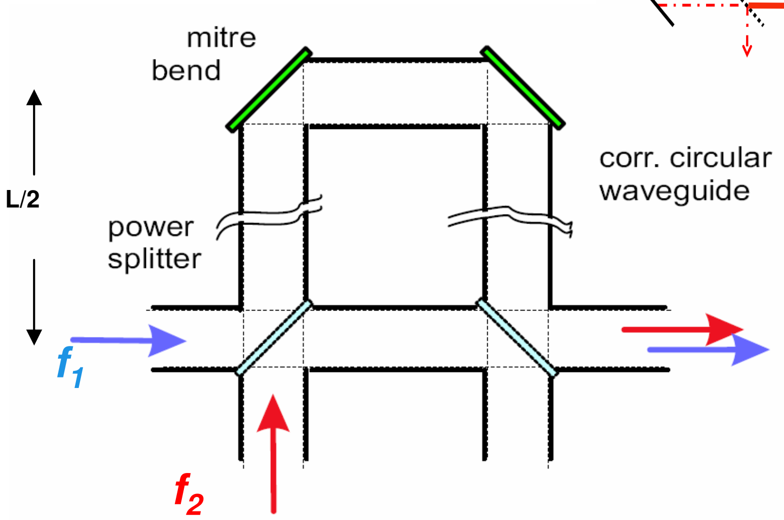
+ delay line (HE_{11} waveguide / beam waveguide)



Transmission characteristics:

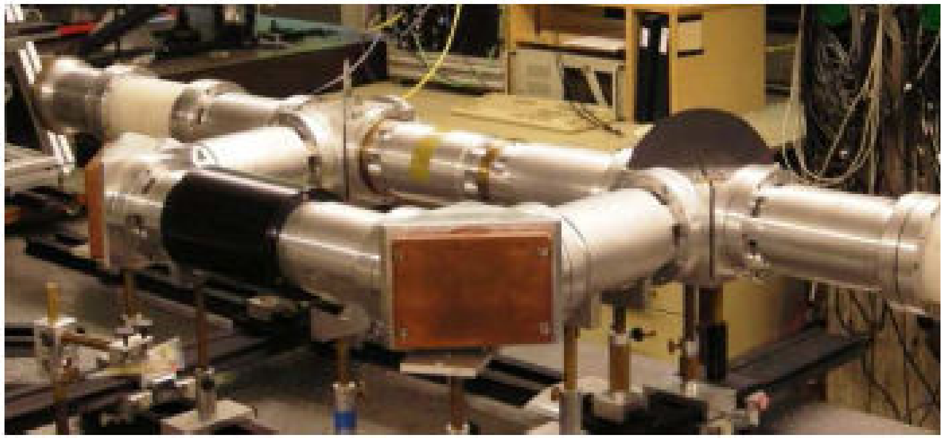
$$P_{1,4} = R^2 + T^2 + 2RT \cdot \cos\left(\frac{2\pi f L_{eff}}{c}\right)$$

$$P_{2,4} = 2RT - 2RT \cdot \cos\left(\frac{2\pi f L_{eff}}{c}\right)$$



Design of mock-up:

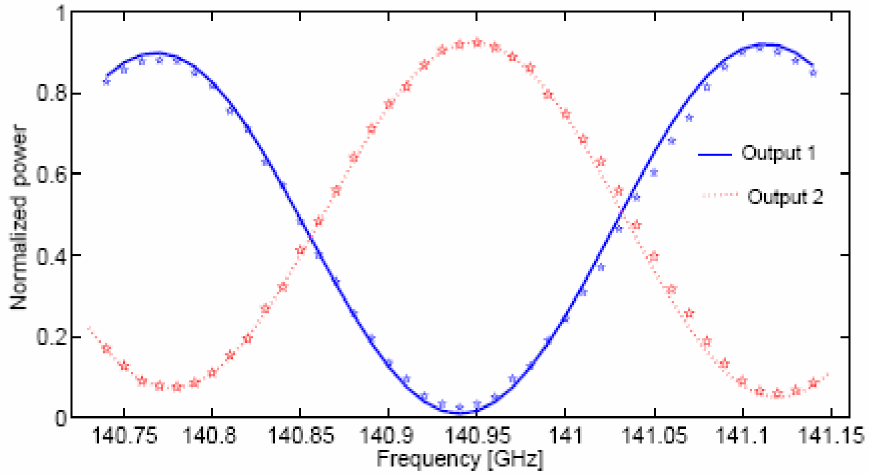
- 87 mm HE11 waveguides
- Delay line L = 0.87 m
- Cu mitre bends
- Si_3N_4 splitters (d ≈ 3mm, high loss!)



HE_{11} wg. diplexer: experimental results / outlook

Measurements on mock-up:

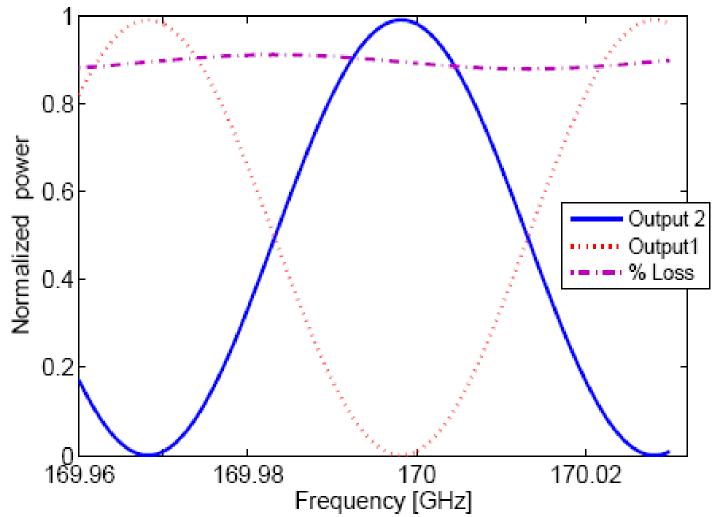
- power transmission as calculated (loss is dominated by Si_3N_4 splitters!)
- good agreement of measurement and calculation proves a good coherence of the fields, i.e. high mode purity



Calculation including losses

(170 GHz, HE_{11} ø 63.5, diamond d=0.87mm)

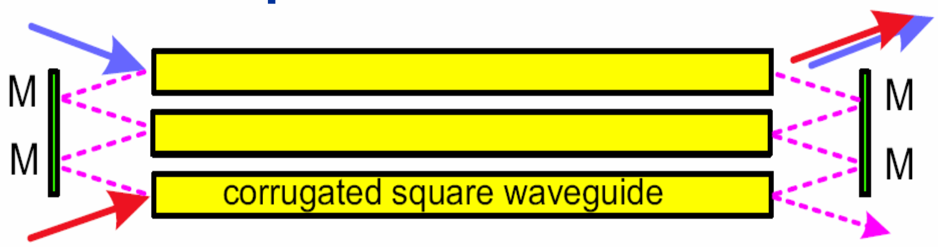
- Total transmission **loss < 1%**
- Useful bandwidth > 3 GHz
- High contrast (Max:Min)
- operation at a second frequency possible (e.g. 170 GHz and 136 GHz)



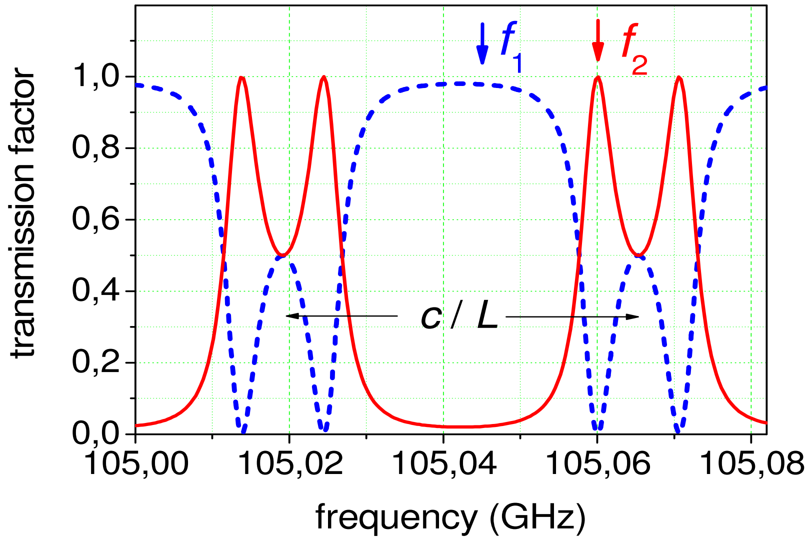
HE_{11} waveguide diplexers with diamond splitters promise high performance

Two-loop resonator with square waveguides

Principle:

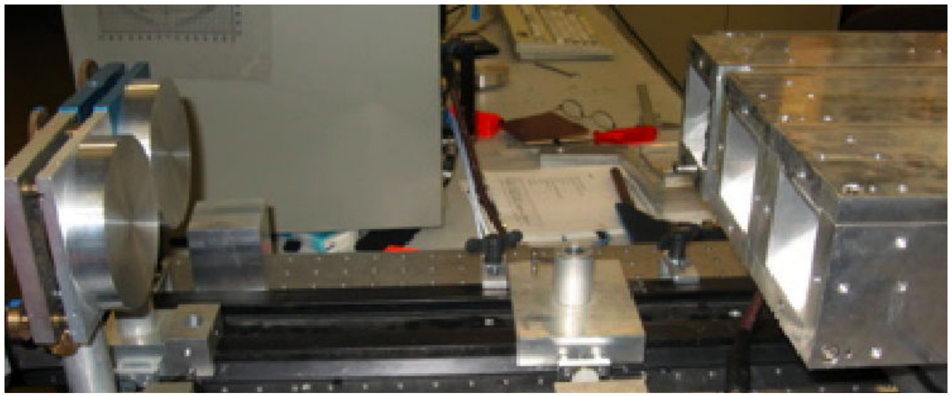


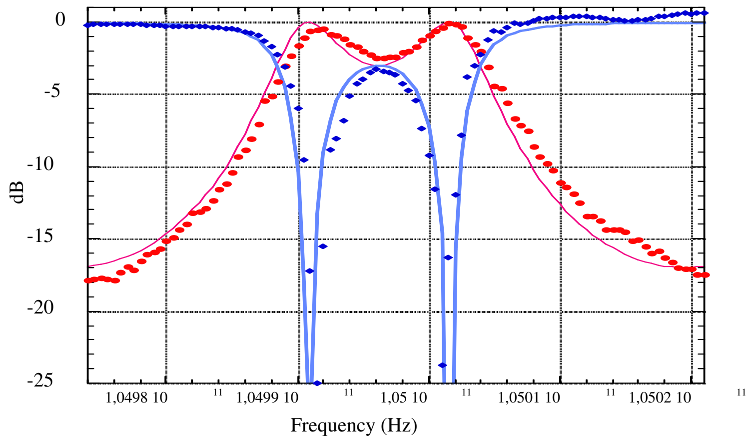
- very steep transmission function possible:



Measurements on mock-up (105 GHz):

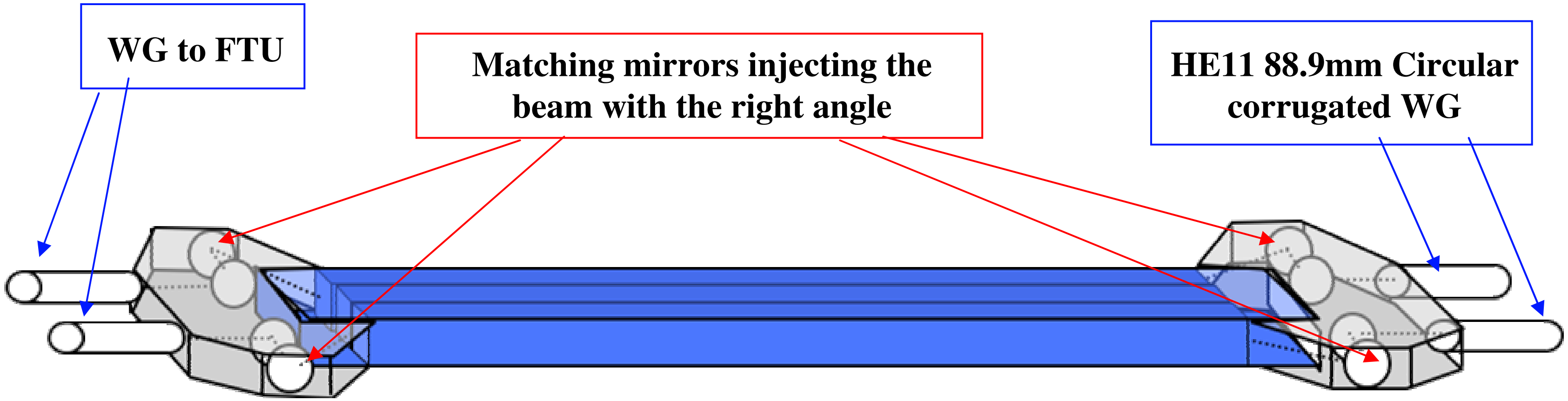
- agreement of measurement and calculation confirm principle
- absolute power transmission measurements to be done in protoype

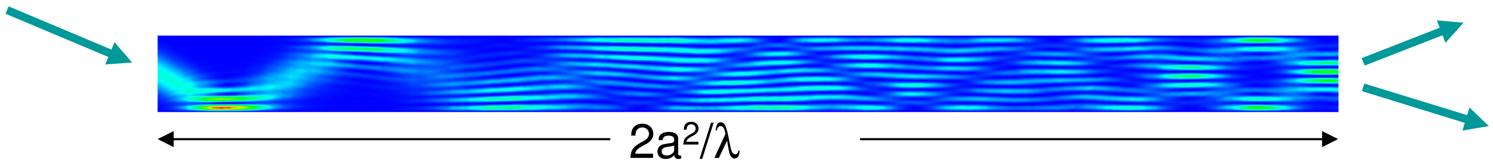




Compact two-loop resonator for HE_{11} input

- Integrated resonator and matching optics for HE11 waveguide
- parallel inputs and outputs allow easy integration
- Independent on polarization
- At present optimization of input- and output fields
- experiments on FTU on power combination and NTM mode suppression planned



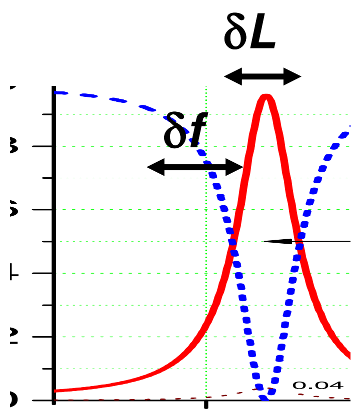


Frequency control / frequency tracking

frequency control of gyrotron:

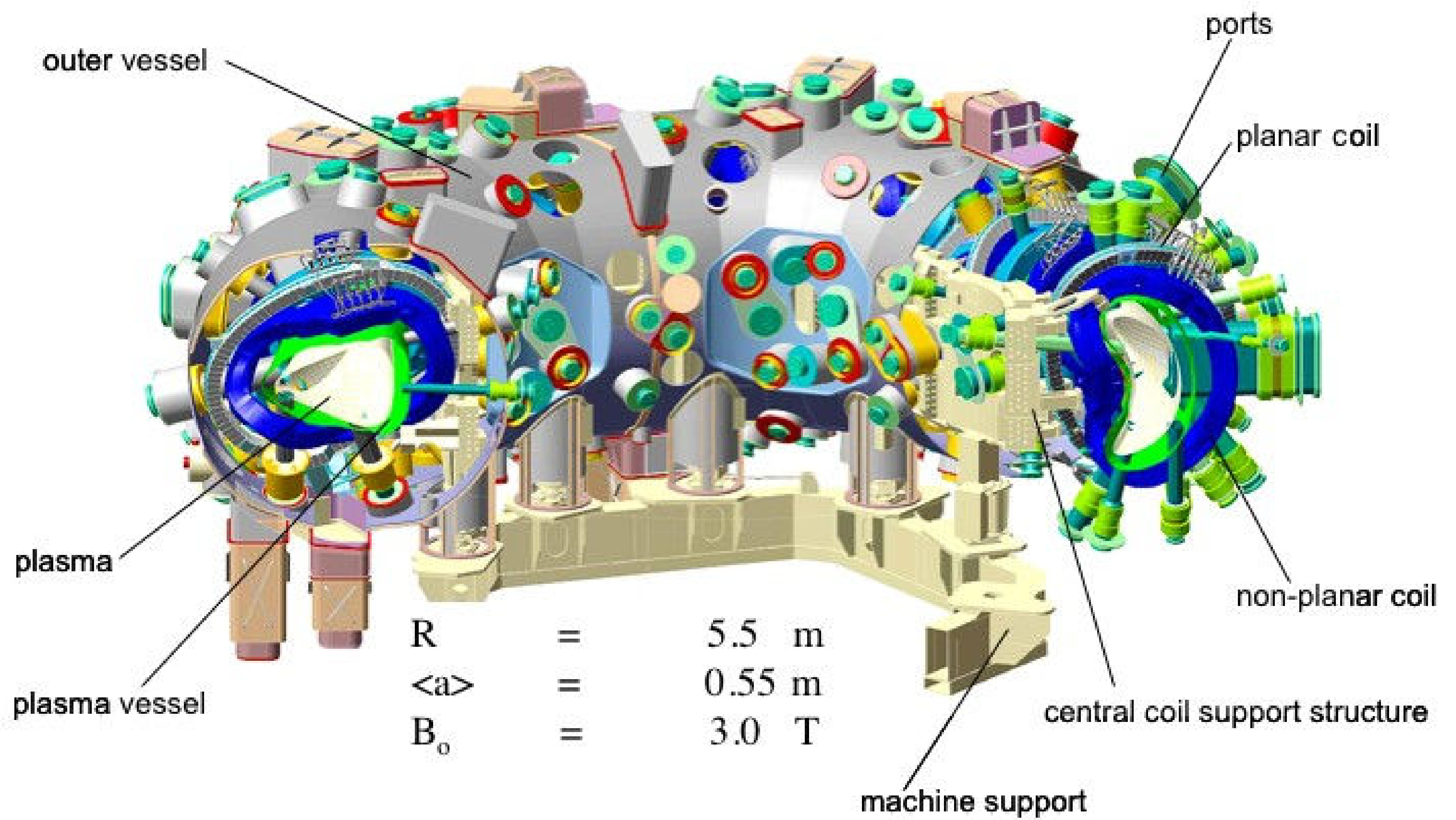
- variation of the power: ……….must be avoided!
- control of cavity cooling water ($\Delta f \approx$ 2...3 MHz/°C): …very slow, but helpful
- control of $U_{gun\text{-}anode}$ or U_{body}: ….should be limited to ΔU needed for fast switching
- but calculations at IAP for JP triode gyrotron: modulation of $U_{gun\text{-}anode}$ and U_{body} →strong frequency-shift keying without power modulation! …. should be checked!
- Injection locking / feedback? …. theor. predicted, but feasible?? check!

frequency control / tracking of diplexer:

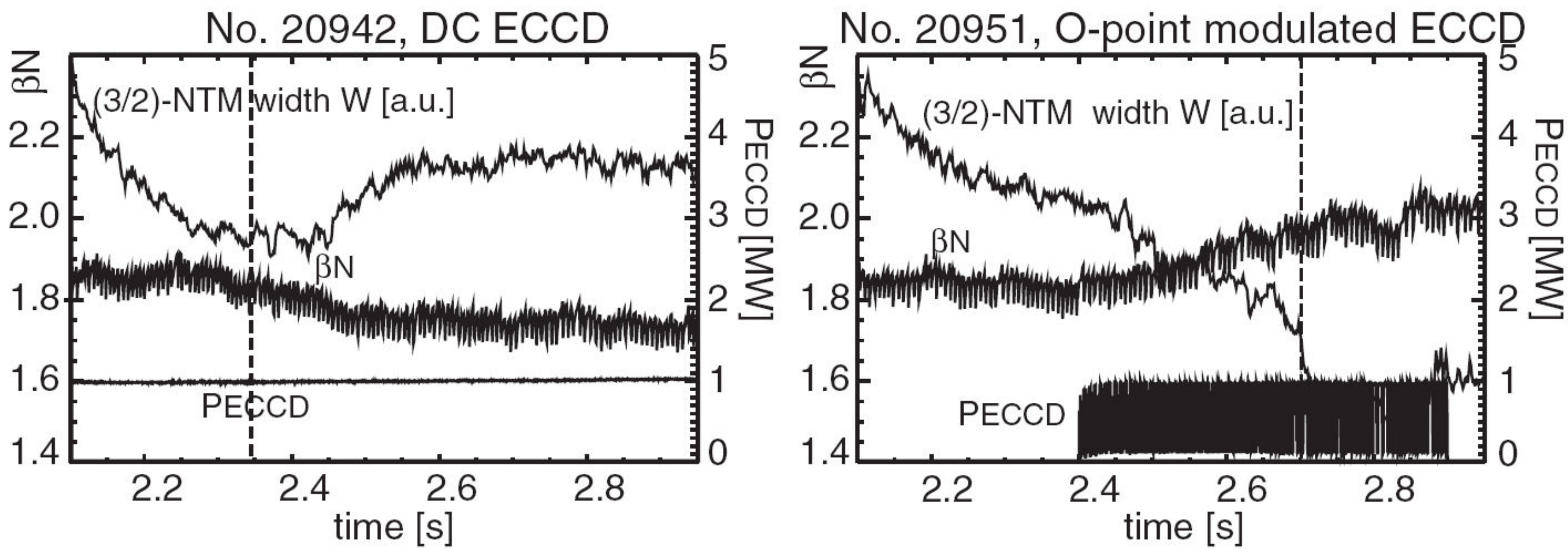


- motorized tuning of delay line / resonator length is necessary
- movement of one mirror by $\approx \lambda/2$, typically < 1.5 mm
- drives: motor, piezo drives, voice coil (N.J. Doelman et al.,TNO)
- control by small modulation of resonator length (mechanical) or gyrotron (voltage) and phase-synchronous detection of power in resonant channel (development)

The stellarator Wendelstein 7-X



ECRH: 140 GHz, 10 x 1 MW, CW
+ option: 70 GHz, 2 x < 1 MW

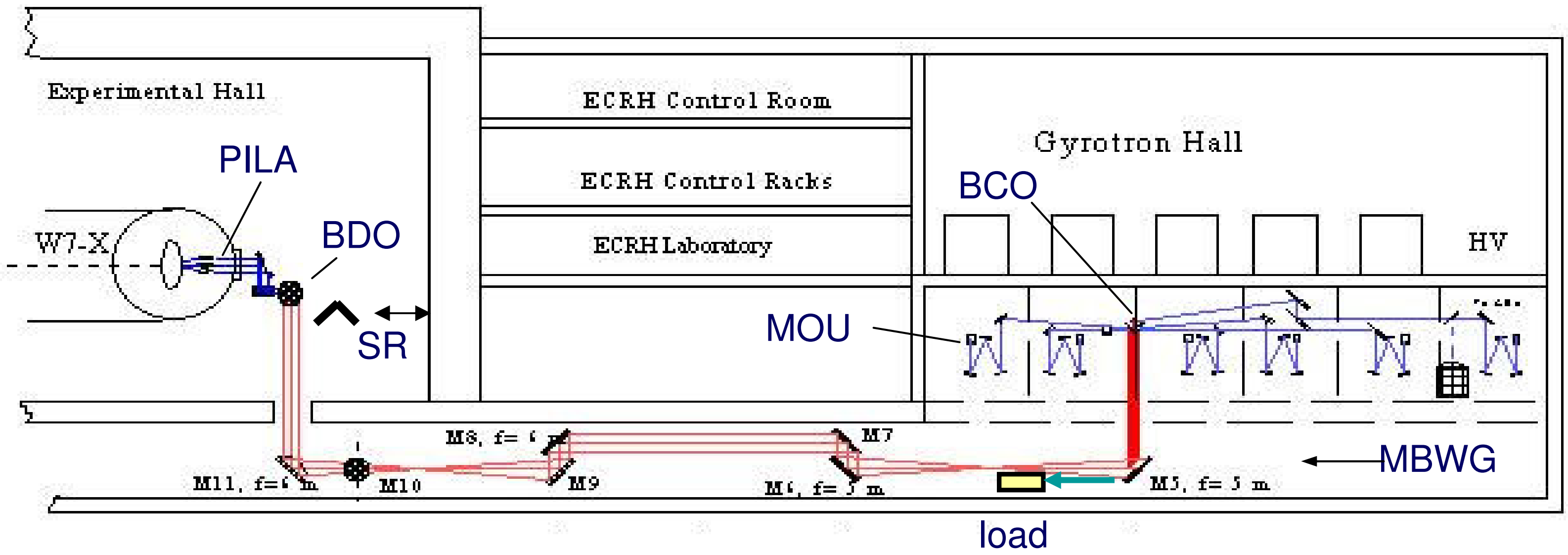


PRL **98,** 025005 (2007)

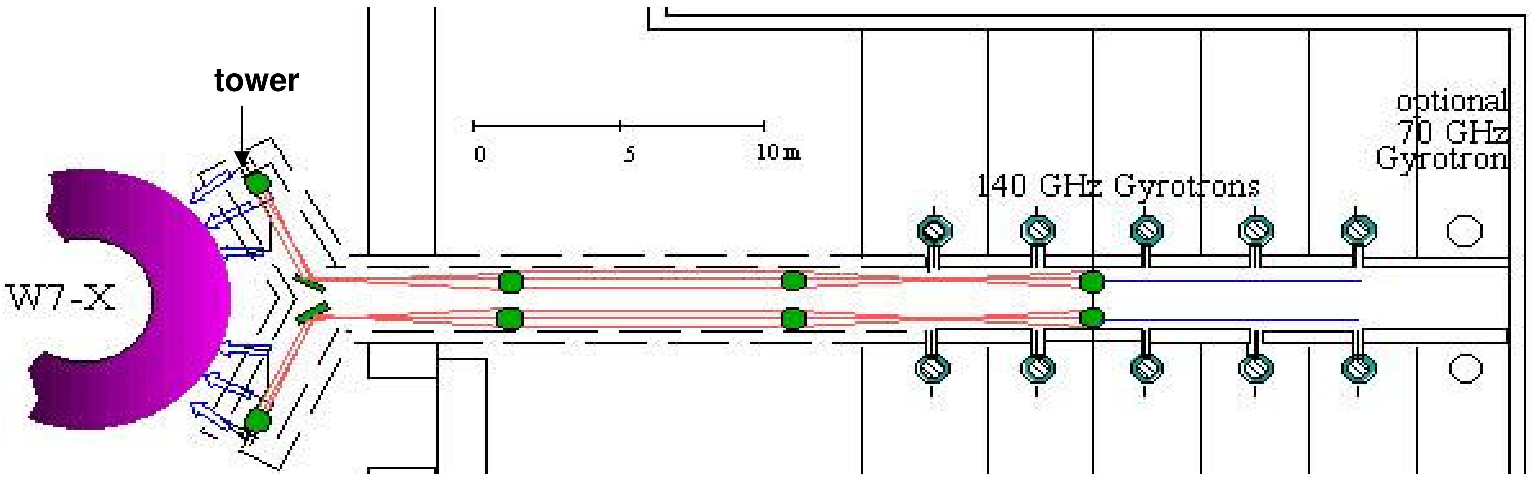
FIG. 4. Comparison between two nearly identical discharges with unmodulated (a) and modulated (b) broad ECCD deposition. Only the B_t ramp has been slightly adapted to match the resonance condition between ECCD and the mode. The vertical dashed lines indicate the time when the resonance is reached and the minimum island size $W_{\min}$ is taken.

ECRH – System at the Stellarator W7-X

Vertical cross-section



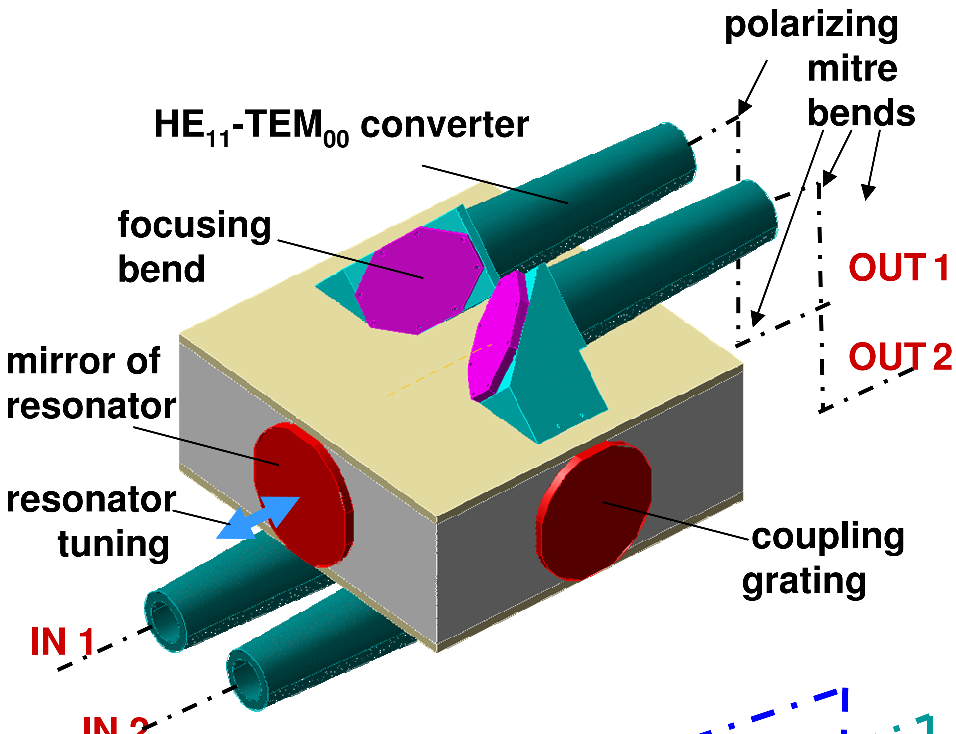
top view

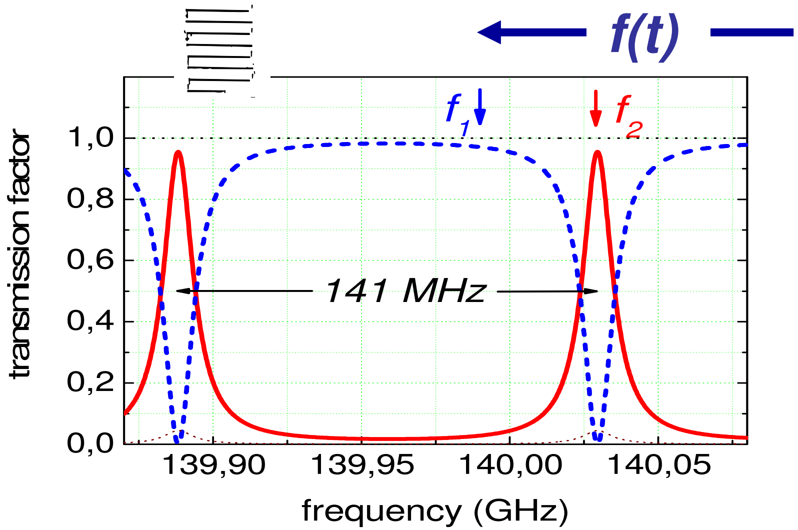


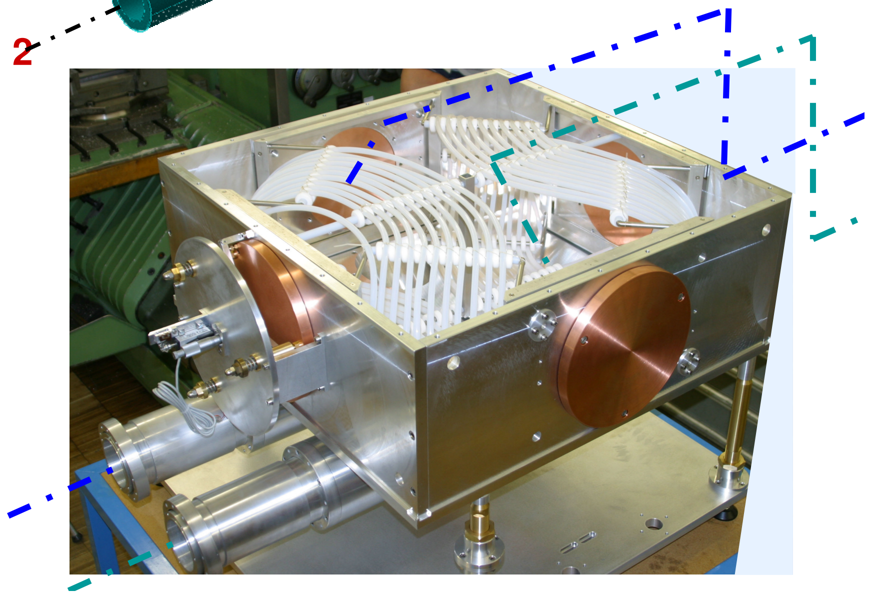
Quasi-optical diplexer Mk II

compact, closed q.o. diplexer:

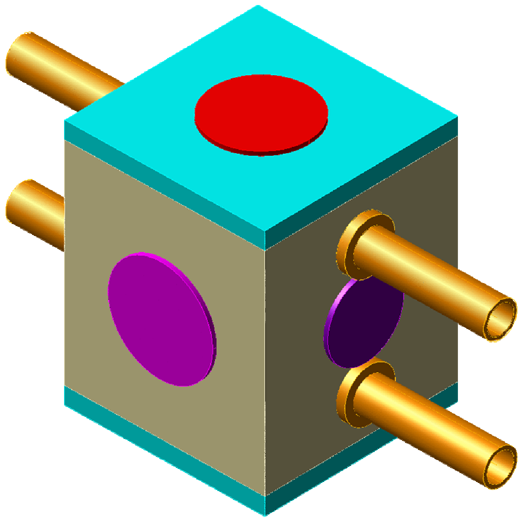
- compatible with **HE_{11} waveguide, Ø 87 mm**
- **HE_{11} – TEM_{00} – converters**
- **Cu mirrors,** uncooled, **>> 10 s operation**
- Teflon hose **absorber** for stray radiation
- **2 mitre bends at each output:**
  - coaxial input and output
  - integrated **polarizers** (λ/8 and λ/4)
- **control of resonator length ± 1 mm**
  - simple (IPF) / voice-coil (TNO/FOM)

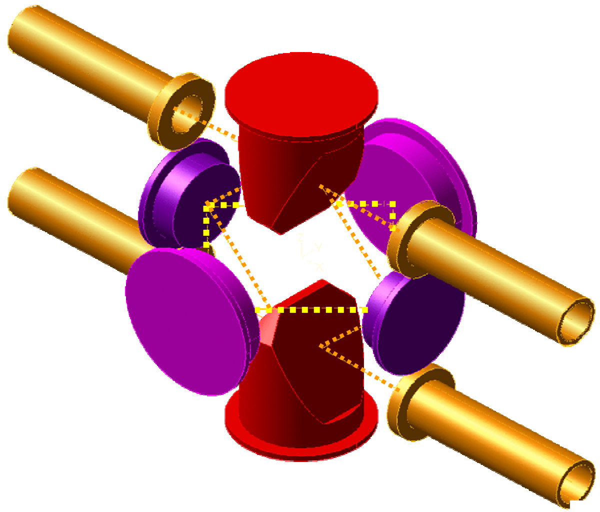






Compact resonant diplexer with HE_{11} input

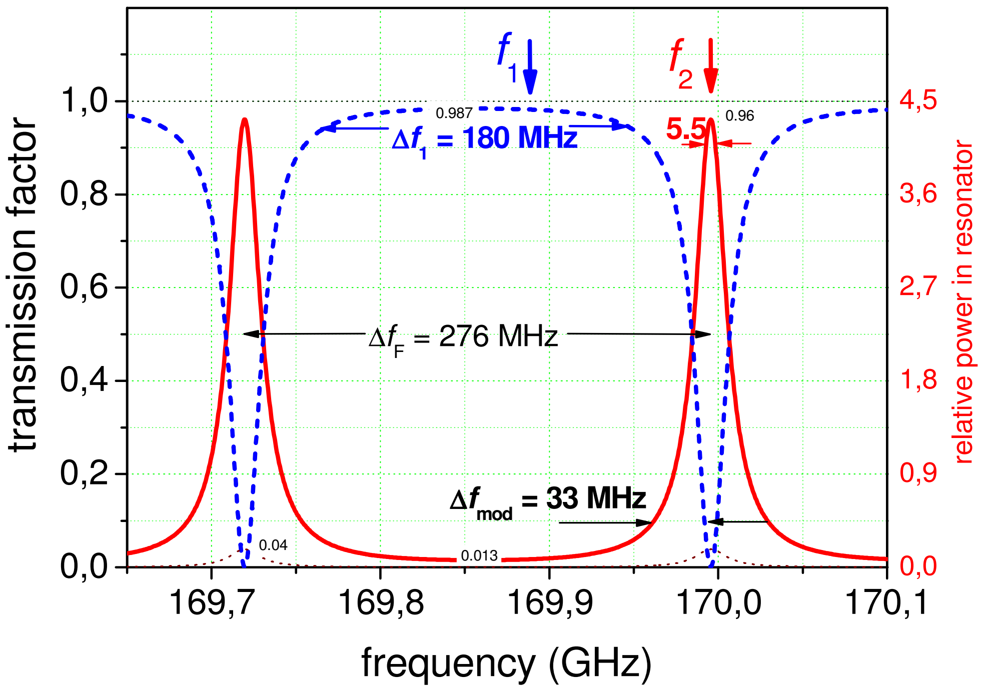




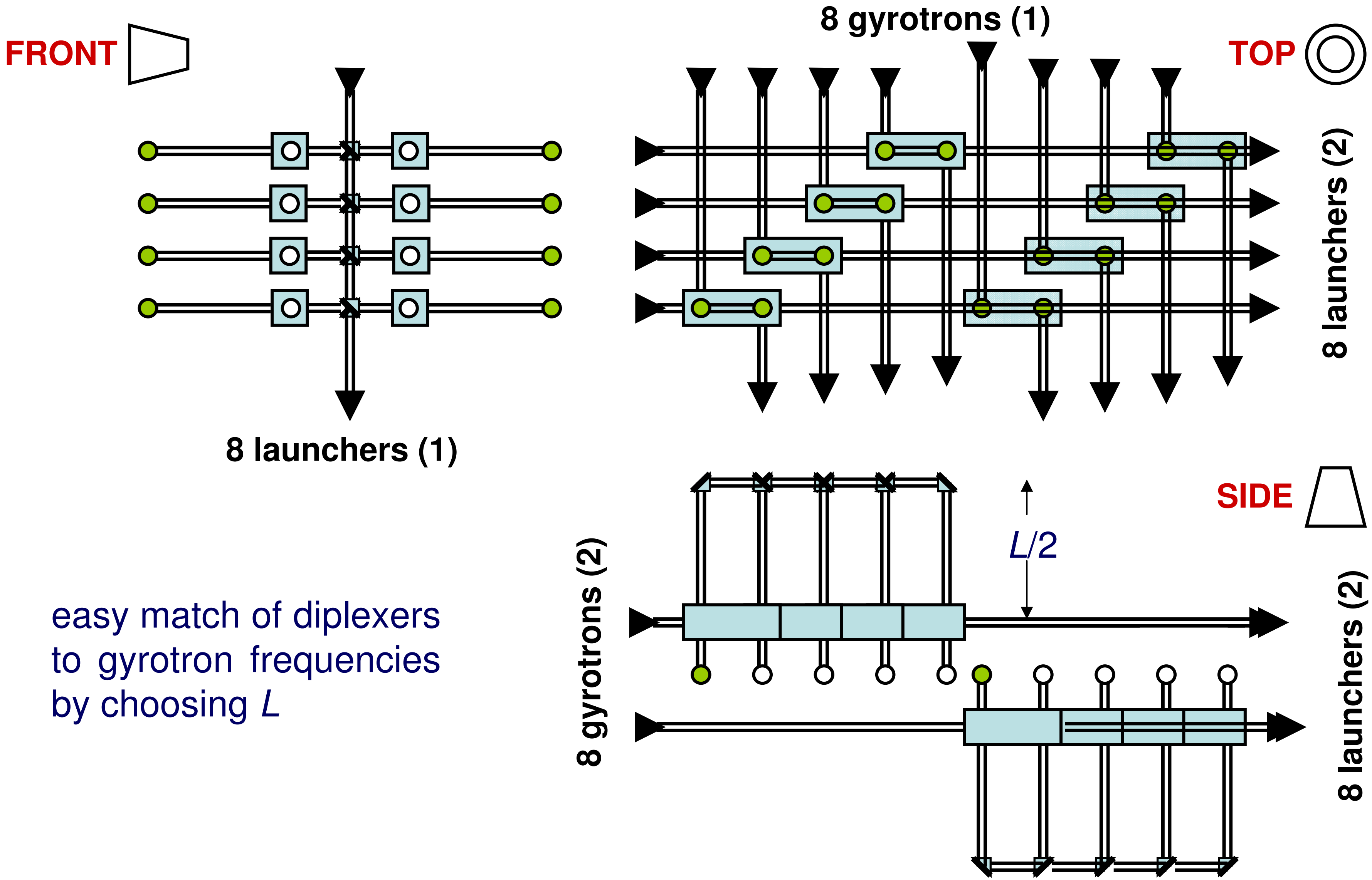
Example:
distance of inputs:
d = 300 mm
resonator length:
L = 1075 mm

Design options:

- **TEM_{00} resonator (as usual),**
  HE_{11} -TEM_{00} converters at in / output
- **HE_{11} resonator**
  (**HE11** input and phase reversing mirrors)
- uptapers / free-space propagation
  to reduce thermal load on mirrors
  (ø 63.5 mm: 6 MW/m² → 3 MW/m²)



wg. Mach-Zehnder diplexers in large ECRH system

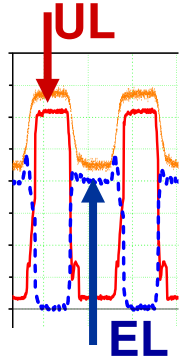


easy match of diplexers
to gyrotron frequencies
by choosing L

Applications of diplexers in ITER ECRH system

Replacement of waveguide switches by adjustable diplexers:

- **arbitrary distribution / switching of the power between EL and UL** by mechanical re-tuning of the diplexer (no significant power loss; gyrotrons keep operating during switching)
- **efficient AC-stabilization of NTMs** as soon as a mode occurs: voltage of synchronous modulation starts, $\Delta U \approx$ few kV diplexers are tracked such that Δf results in max ΔP at the outputs for ULs, asynchronous power is still available at the EL for independent tasks

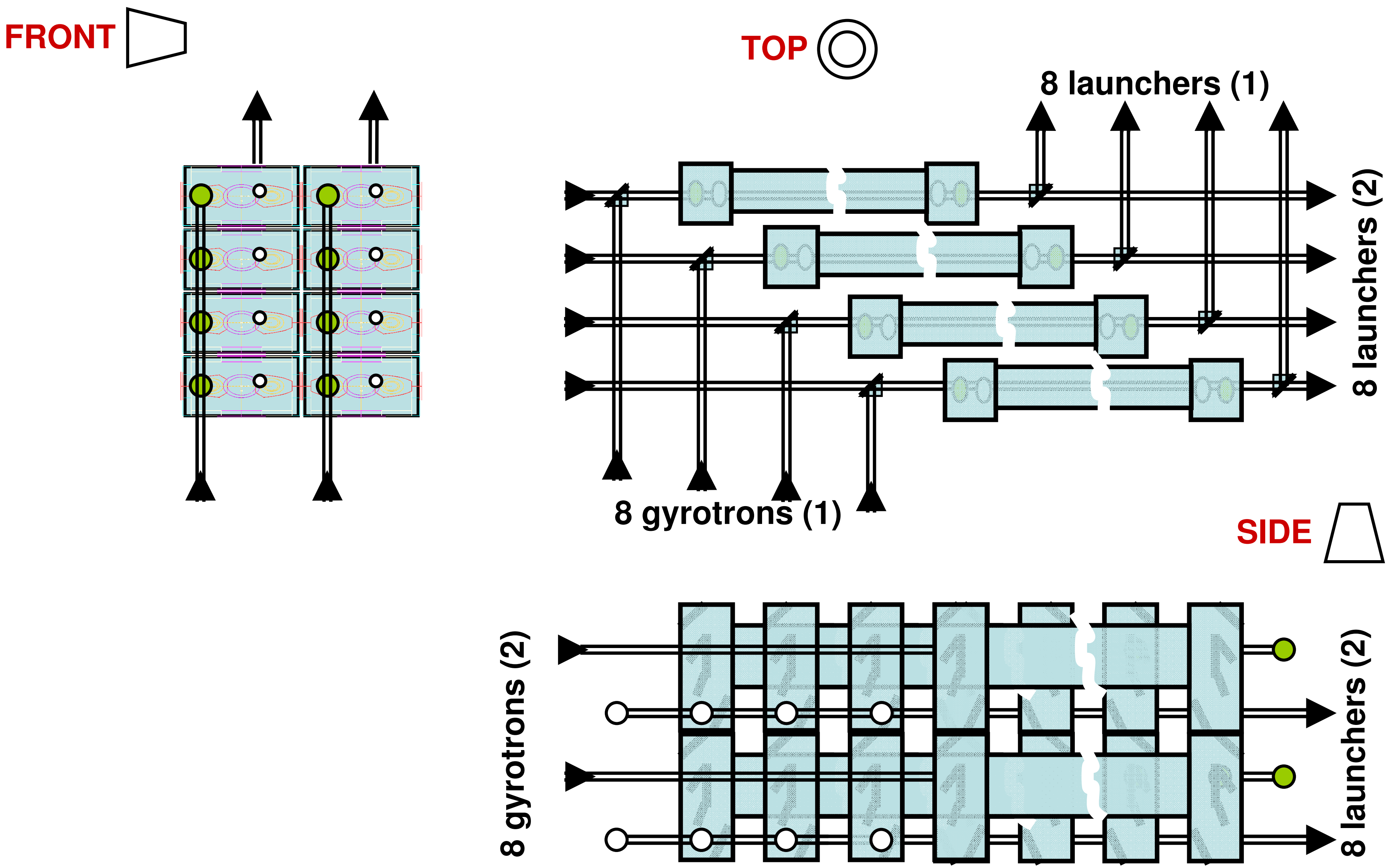


- if (at a later stage) more gyrotrons are added: feed into the second inputs. **efficient AC-stabilization of NTMs** with diplexer as fast switch and combiner both gyrotrons are modulated with Δf_S, diplexer is tracked that $f_{A,O} = f_2$.

Insertion of diplexers near to the gyrotrons:

- between launchers and loads, allowing **gyrotrons in hot stand-by**
- **power combination from two 1-MW gyrotrons** on a common transmission line in case of a power upgrade at a later stage.

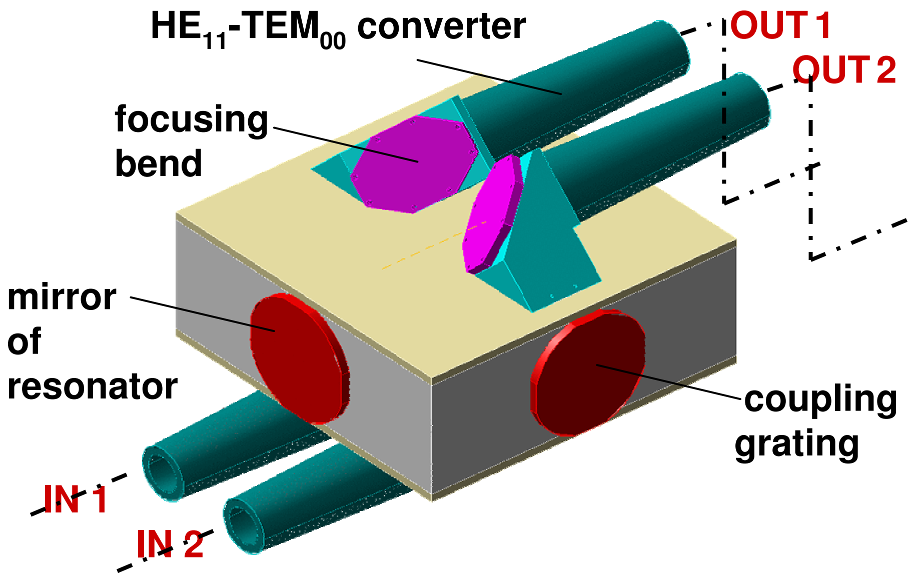
Two-loop diplexers in large ECRH system



Compact quasi-optical diplexer for ECRH on ASDEX Upgrade

Design and construction of a compact, closed q.o. diplexer

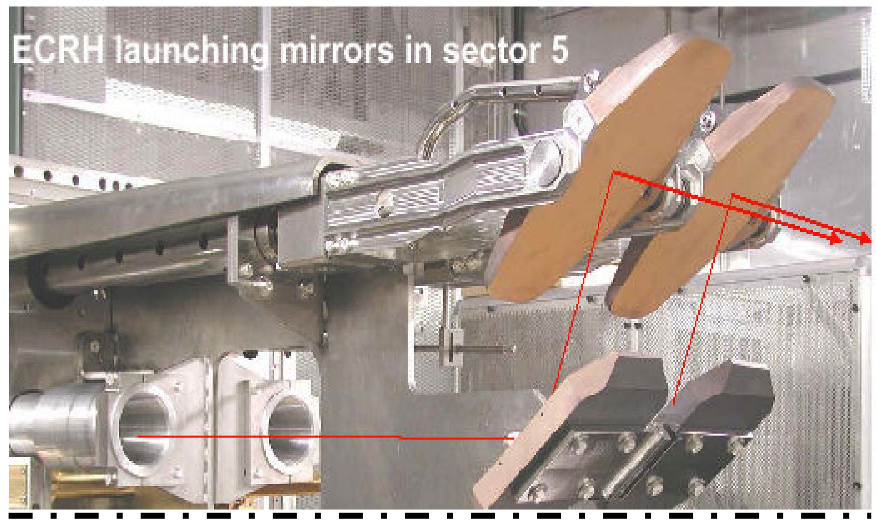
- compatible with ECRH on ASDEX Upgrade:
- connection for HE_{11} waveguide, Ø 87 mm
- HE_{11} – TEM_{00} – converters at in- and outputs
- control of resonator length



Application in the new ECRH system on ASDEX Upgrade

- low-power test (possibly high-power test at W7-X)
- Integration in the ECRH system
- Experiments planned:
  - synchronous NTM stabilization using the symmetric launchers
  - in-line ECE

(Sat, 10:00 H25 W.A. Bongers, FOM, et al.,)



Comparison of various diplexers

Frequency: 170 GHz,

(equivalent input waveguides D = 63.5 mm / a = 60mm

Type of diplexer	**Length** incl. coupling	**Insertion loss** averaged for output 1, 2	**thermal load** max., 0.5E+0.5H for 1 MW input	**Remarks**
q.o ring resonator	**1 – 5 m** (depends on coupling)	**5.3 %**	**> 630 W/cm²** **(gain 3.9)**	needs waist size w_0 > 25 mm
two-loop wg. resonator	**5 m**	**9.5 %**	**300 W/cm² ?**	Loss mainly in sq. waveguide
Square w.guide spatial Talbot	**34 m**	**8.0 %**	**162 W/cm²**	Length due to *a* = 120 mm!!
Square w.guide angular Talbot	**10 m**	**6.1 %**	**162 W/cm²**	

note: q.o. two-beam interferometers not investigated up to now