RECENT UPGRADES AND EXTENSIONS OF THE NEW MULTI-FREQUENCY ECRH SYSTEM AT ASDEX UPGRADE

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US-EU-JPN RF Heating Technology Workshop, September 16-18, 2009, Fukuoka, Japan

OUTLINE

- Status of the ASDEX Upgrade ECRH system
- Examples of low ECRH absorption
- Installation of Sniffer Probes at ASDEX Upgrade
- EC Heating of high density plasmas (O2, X3)
- FADIS Test

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ECRH STATUS AND PLANS (1)

ECRH-1 system:

4 GYCOM gyrotrons 140 GHz, 500kW, 2s

steering of the launcher only between pulses

ECRH STATUS AND PLANS (2)

ECRH-2 system:

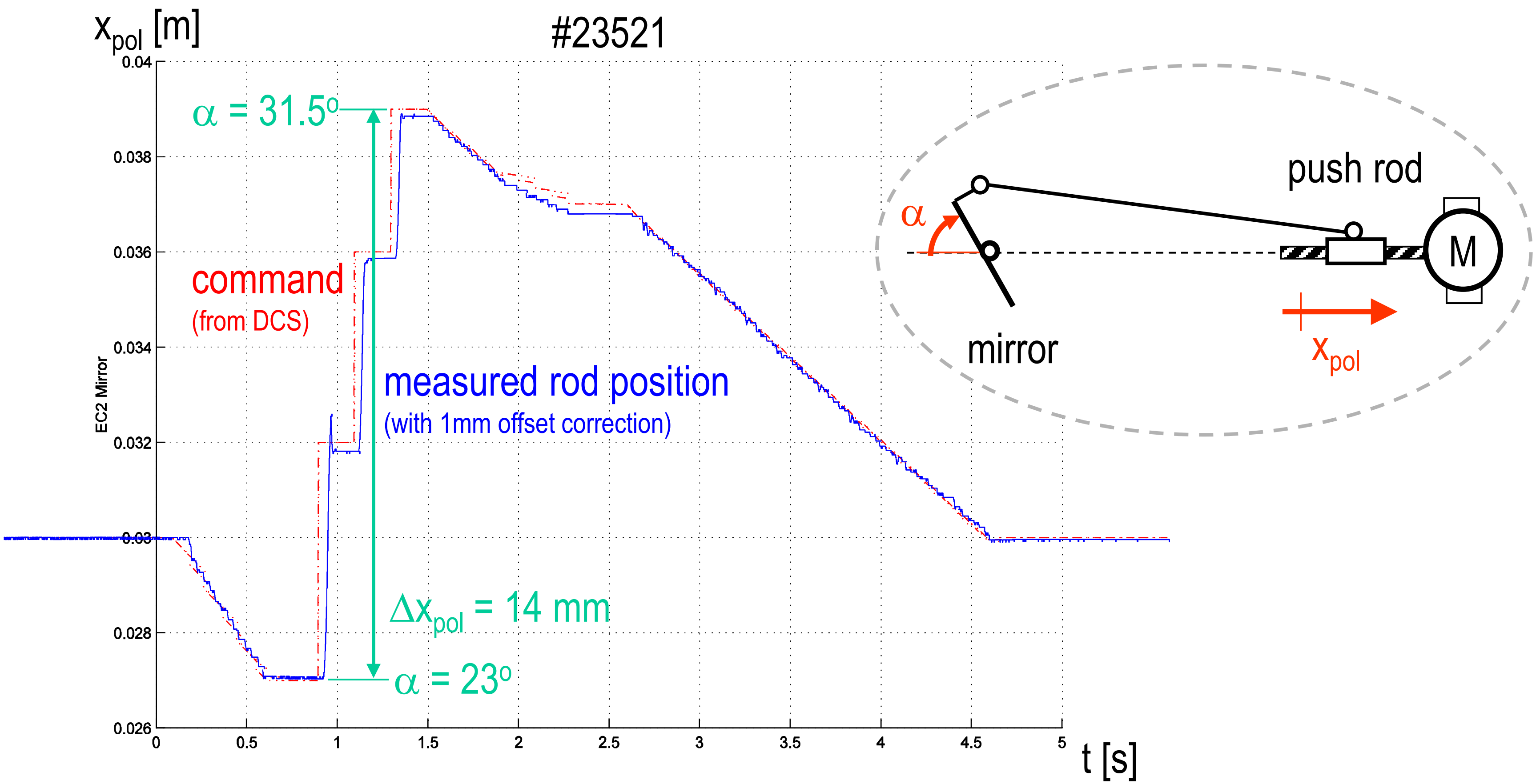
Gyrotron Odissey-2, 105/140 GHz, 910/640 kW, 10 s
vacuum leak in May 2009

next two 2f-gyrotrons (Elissey-1 and 2) delivery expected in 2009/10

4th Gyrotron possibly with 4 frequencies (105/117/127/140 GHz)

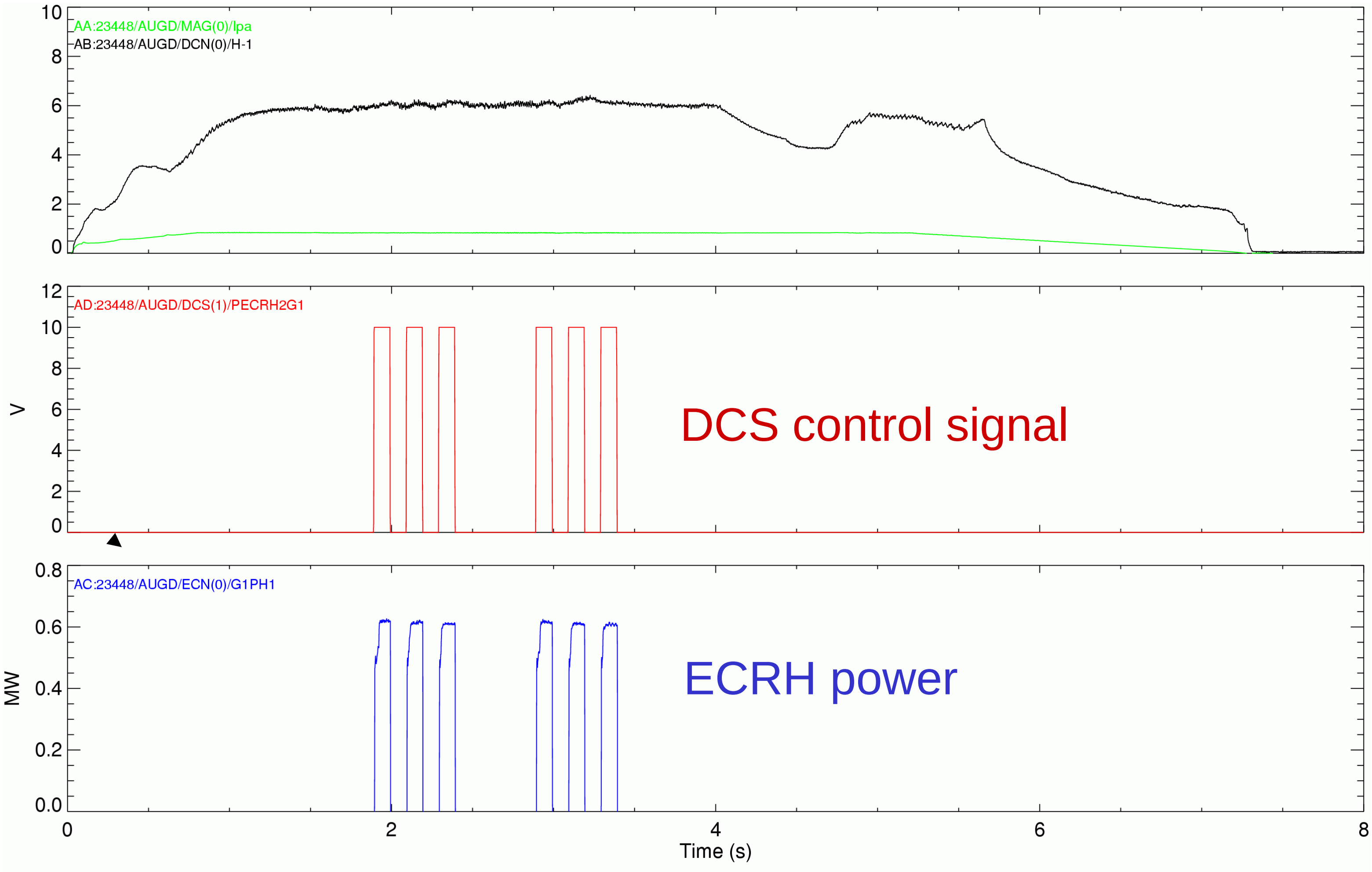
new remote control features (DCS)

POLOIDAL MIRROR MOVEMENT CONTROLLED BY DCS

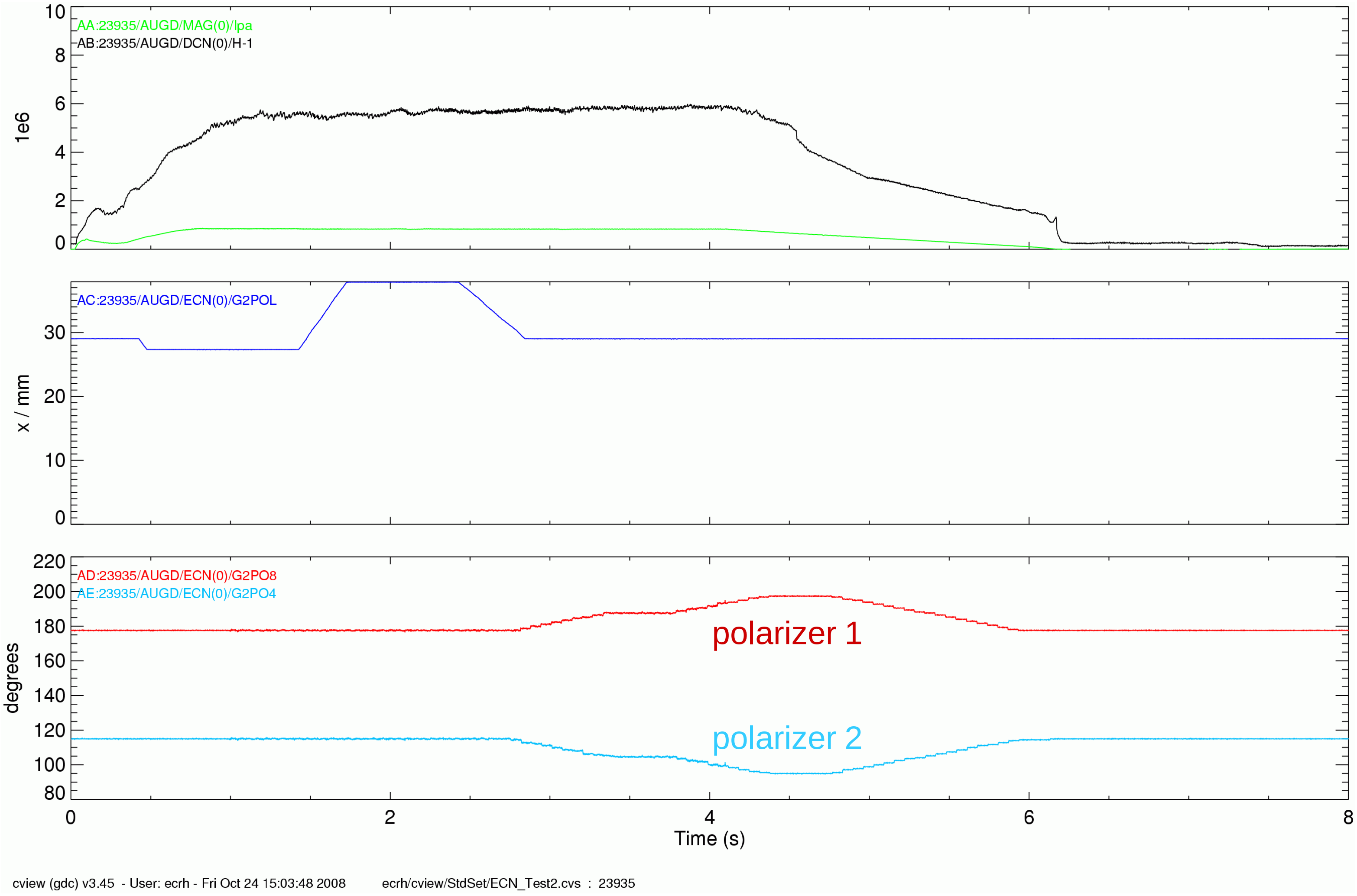


- Push rod position x_{pol} controllable with DP waveform
- Clipped to stay within geometrical limits defined by ECRH
- Range ± 1 cm around the initial mirror position

ECRH POWER CONTROLLED BY DCS



ECRH POLARIZATION SCAN DURING PULSE



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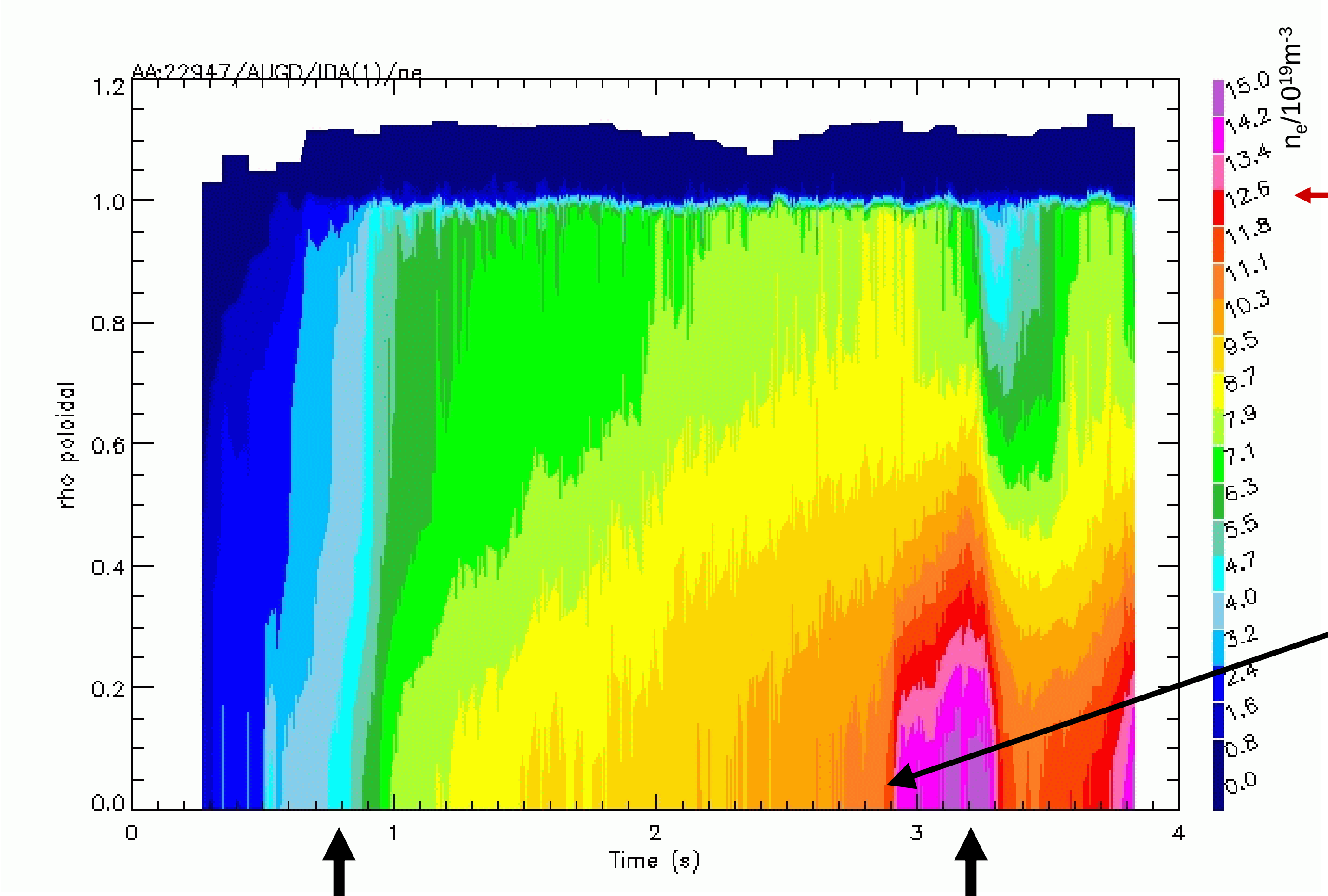
EXAMPLES FOR LOW ECRH ABSORPTION

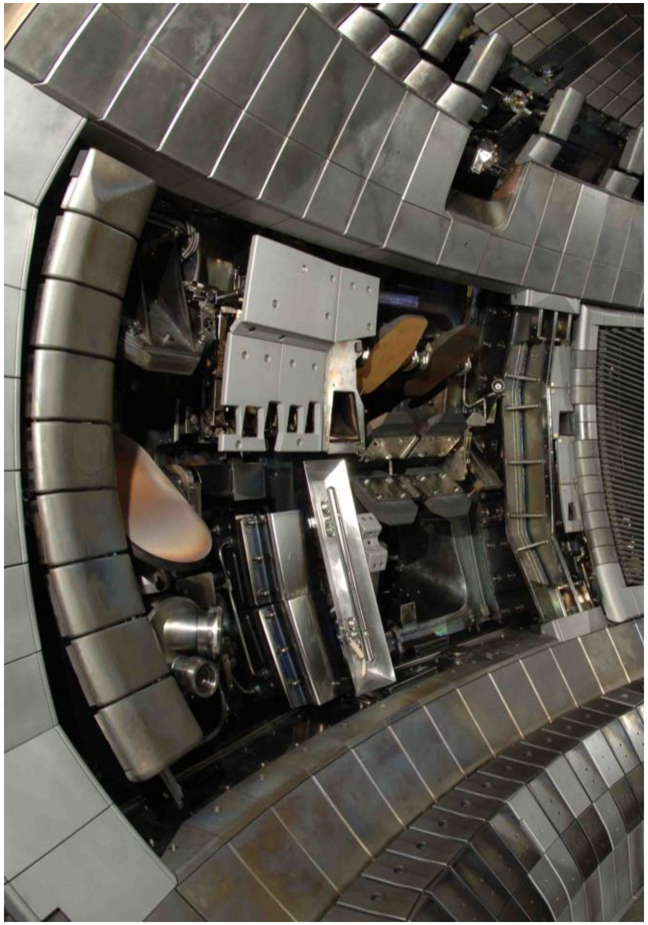
- CTS experiments
- ECRH breakdown assist
- ECRH cutoff

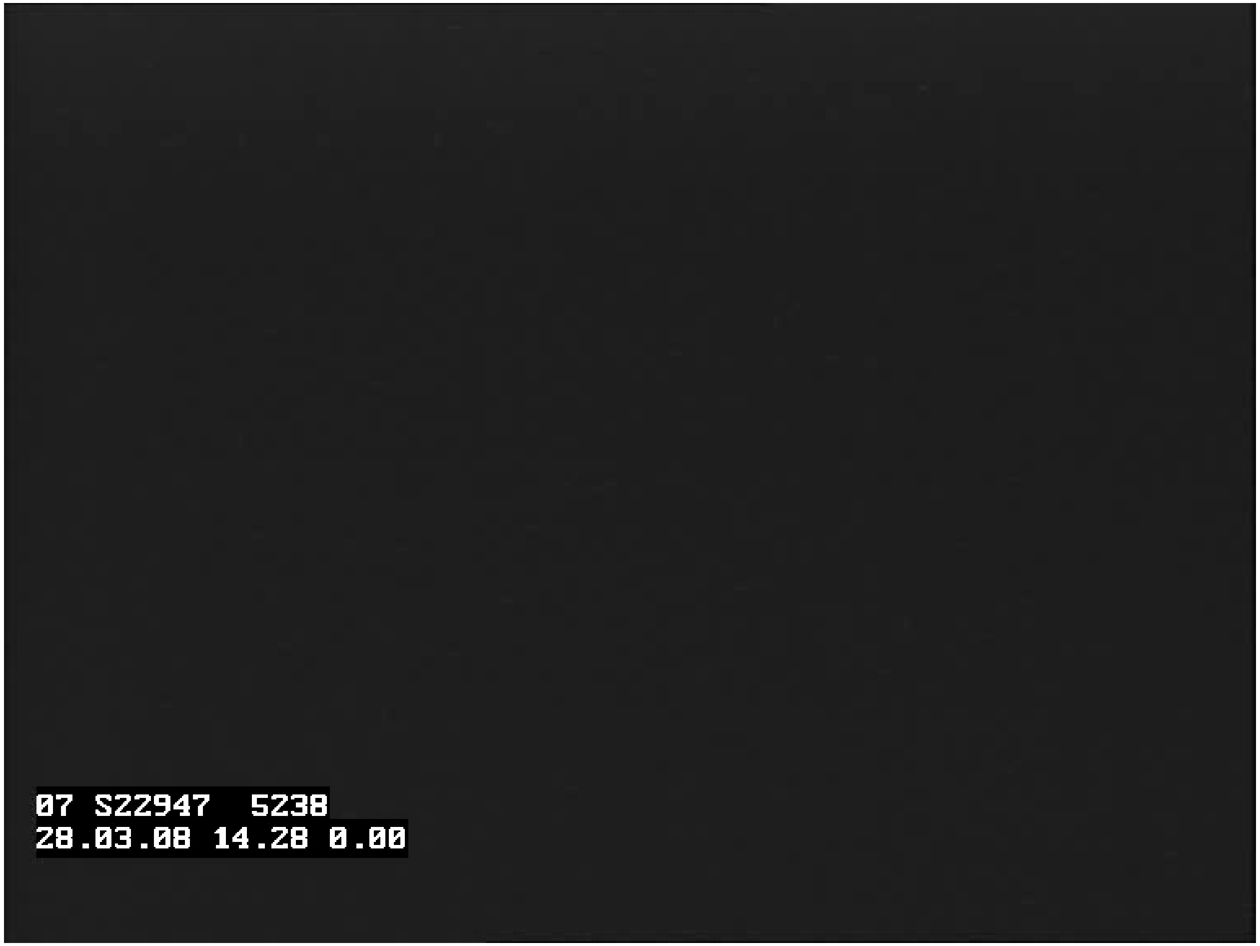
EXAMPLES FOR LOW ECRH ABSORPTION (1)

CUTOFF **Example: #22947, B_t=-2.5T, I_p=1.2MA, central heating**



EXAMPLES FOR LOW ECRH ABSORPTION (2)



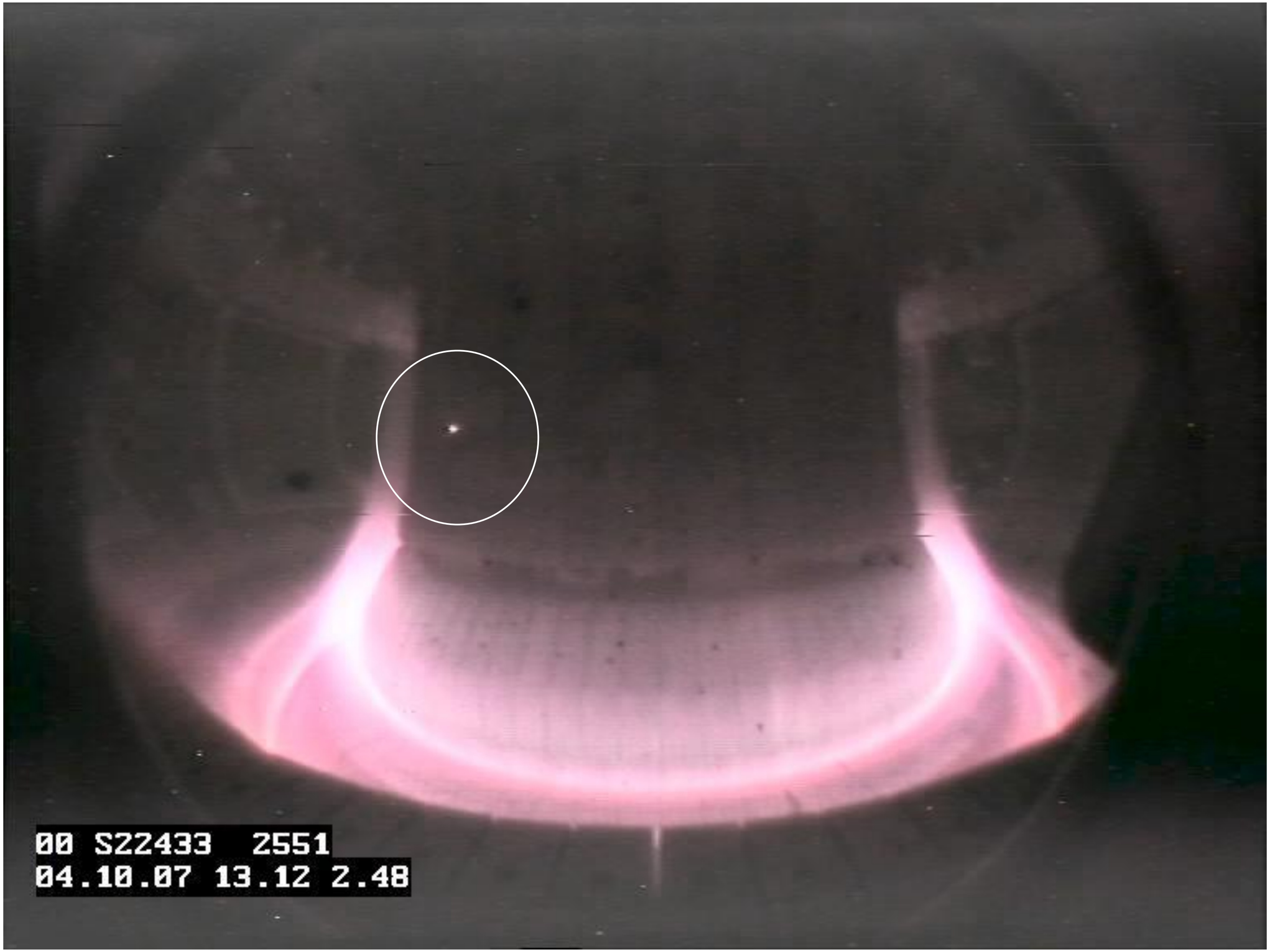


EXAMPLES FOR LOW ECRH ABSORPTION

- CTS experiments
- ECRH breakdown assist
- ECRH cutoff
- Wrong polarizer setting

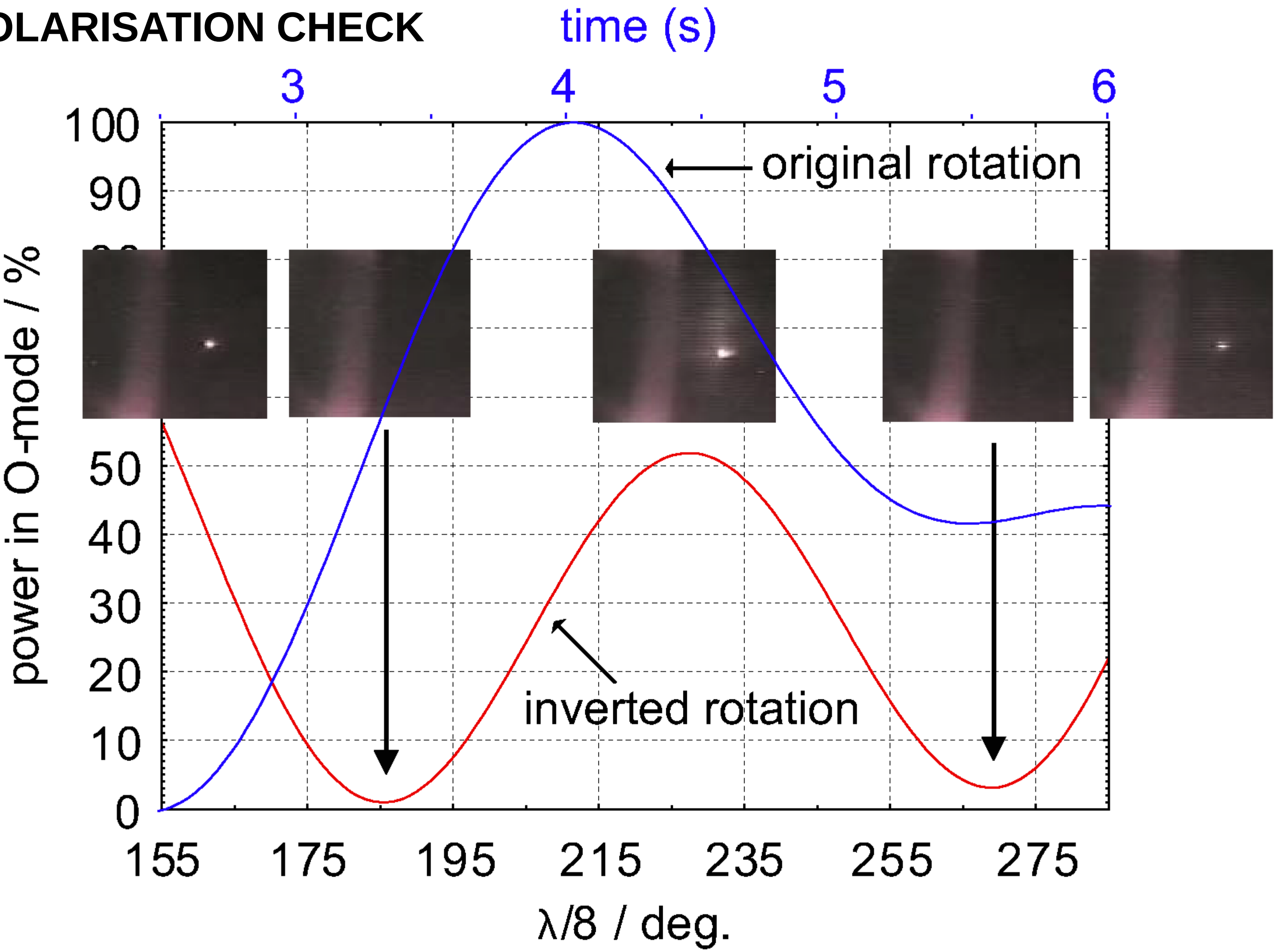
EXAMPLES FOR LOW ECRH ABSORPTION (3)

wrong polarizer setting

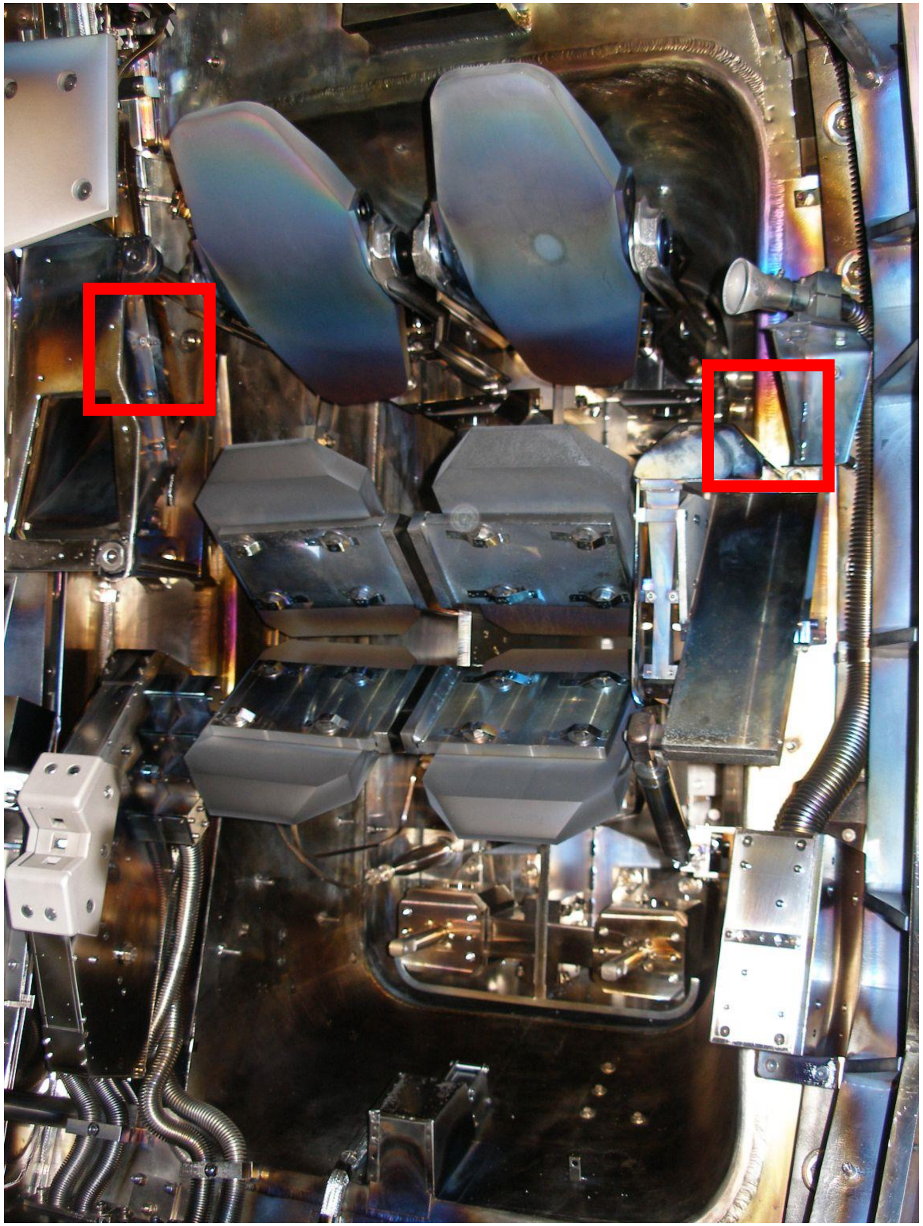


EXAMPLES FOR LOW ECRH ABSORPTION (4)

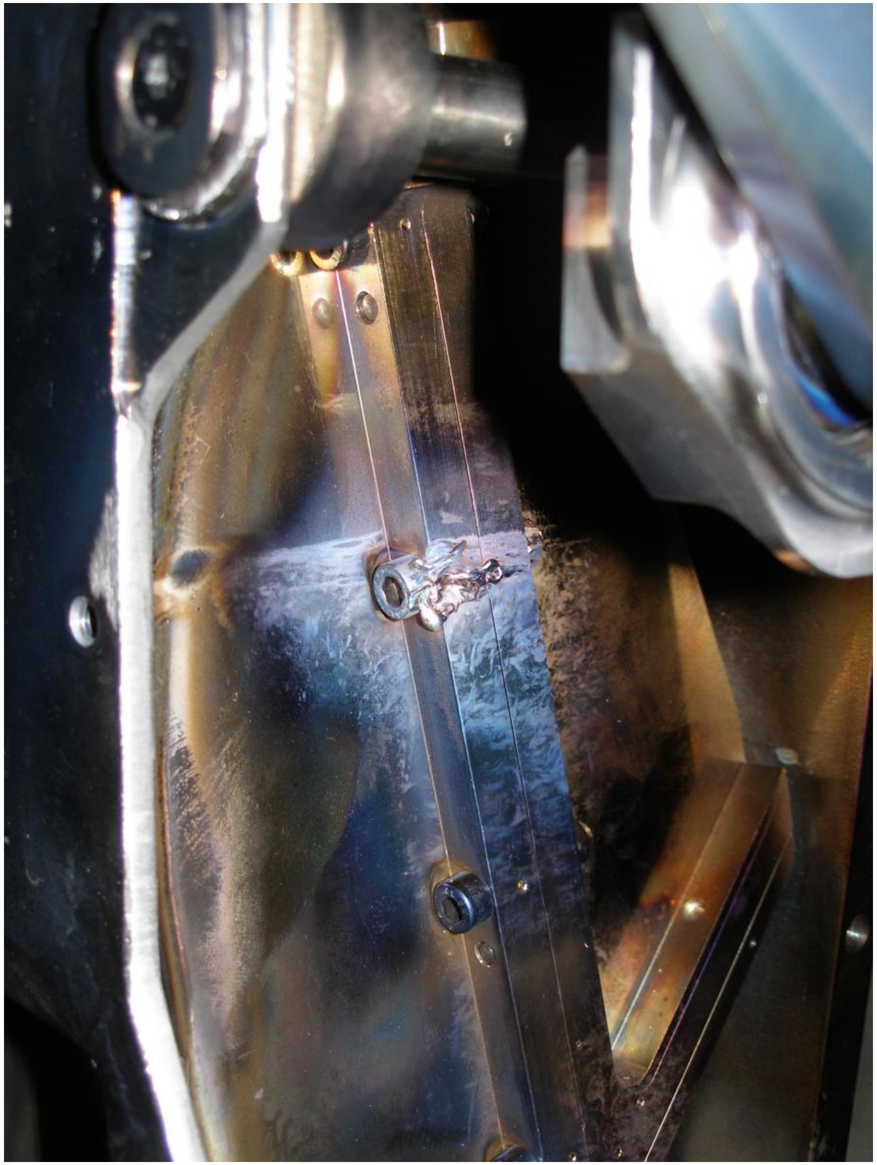
POLARISATION CHECK



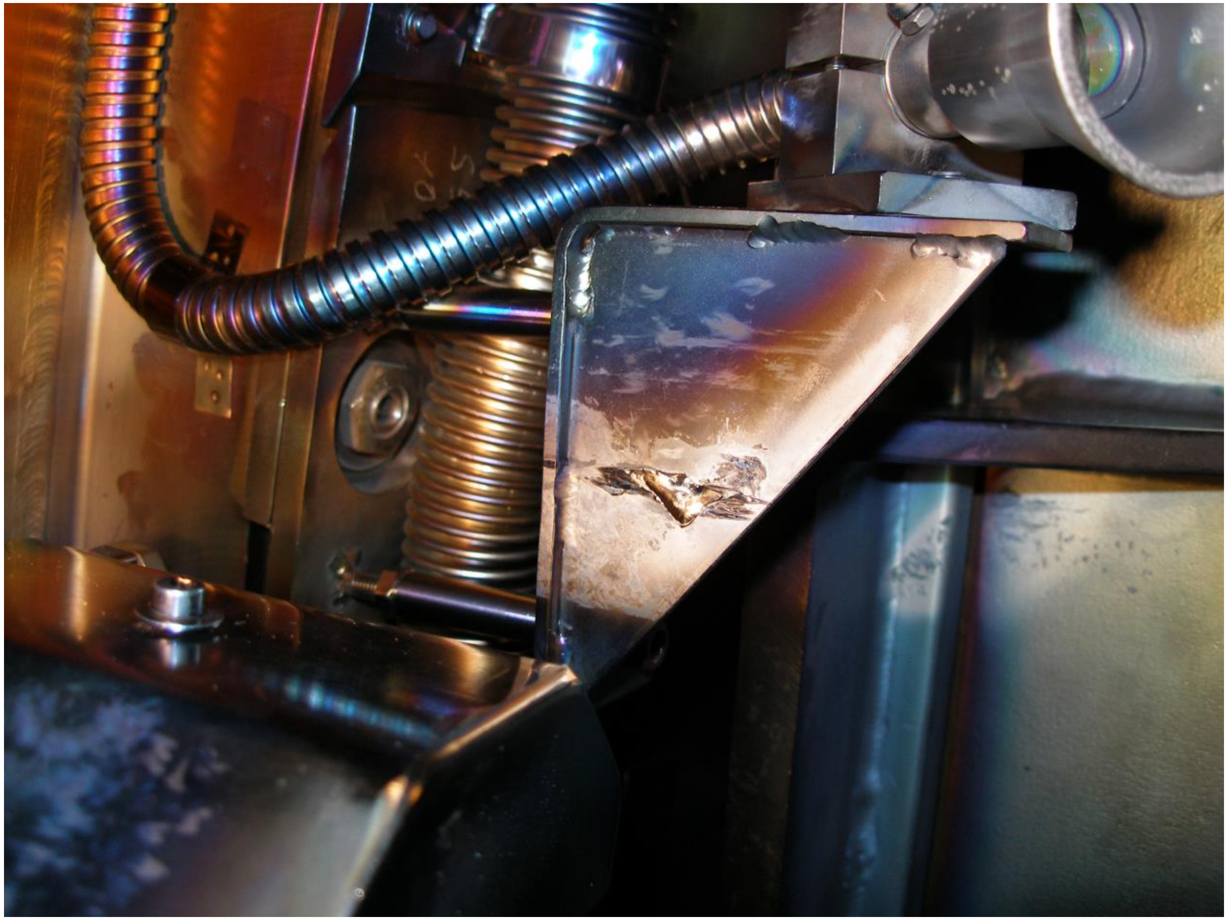
EXAMPLES FOR LOW ECRH ABSORPTION (5)



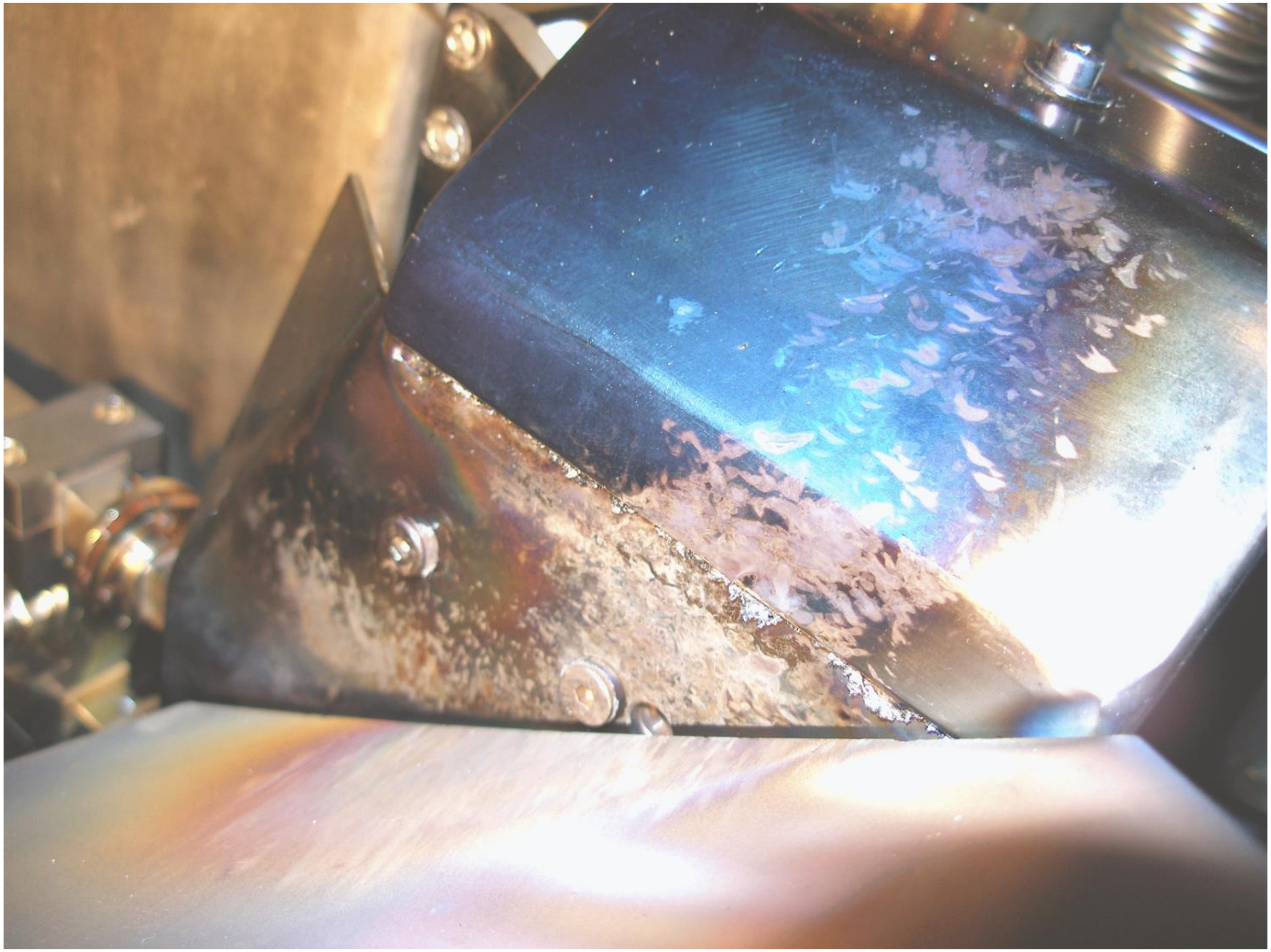
EXAMPLES FOR LOW ECRH ABSORPTION (6)



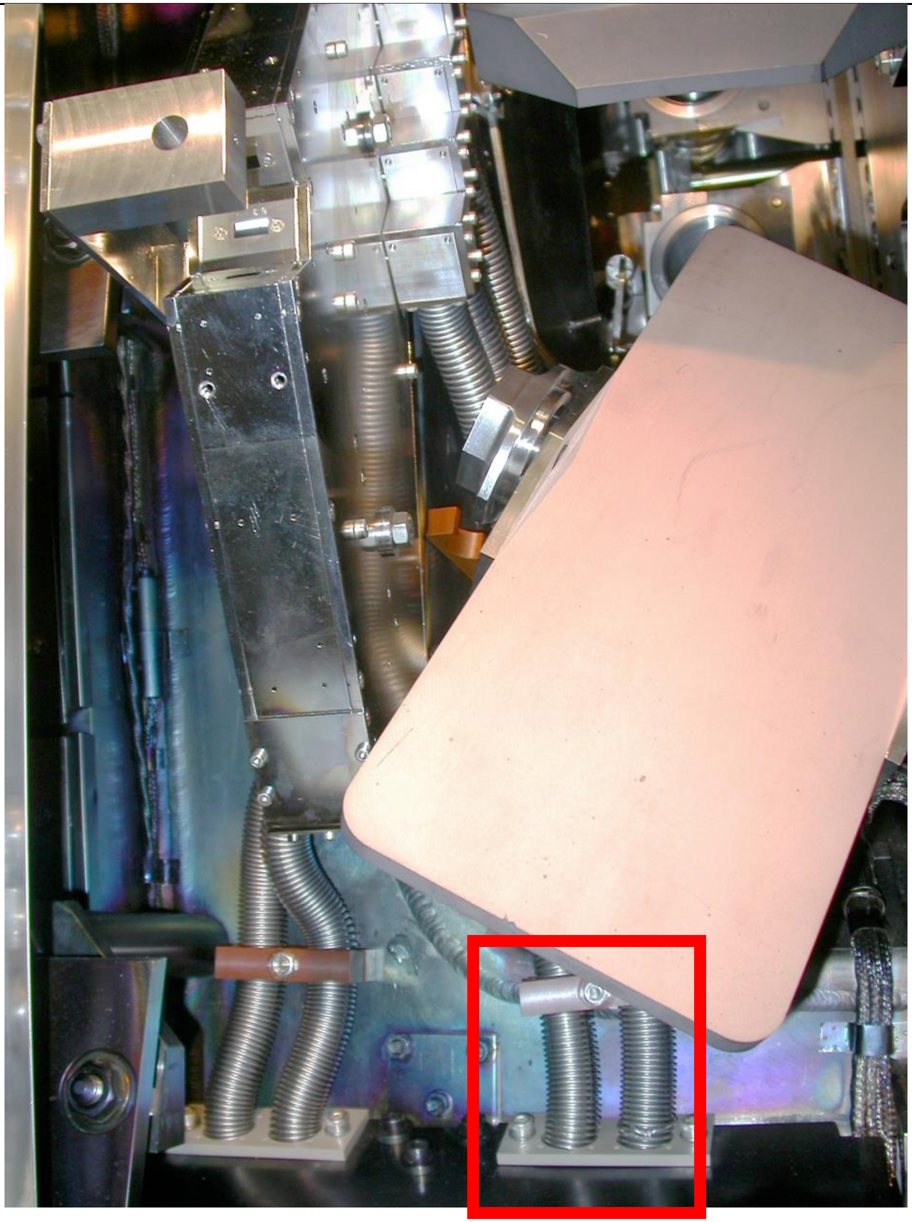
EXAMPLES FOR LOW ECRH ABSORPTION (7)



EXAMPLES FOR LOW ECRH ABSORPTION (8)

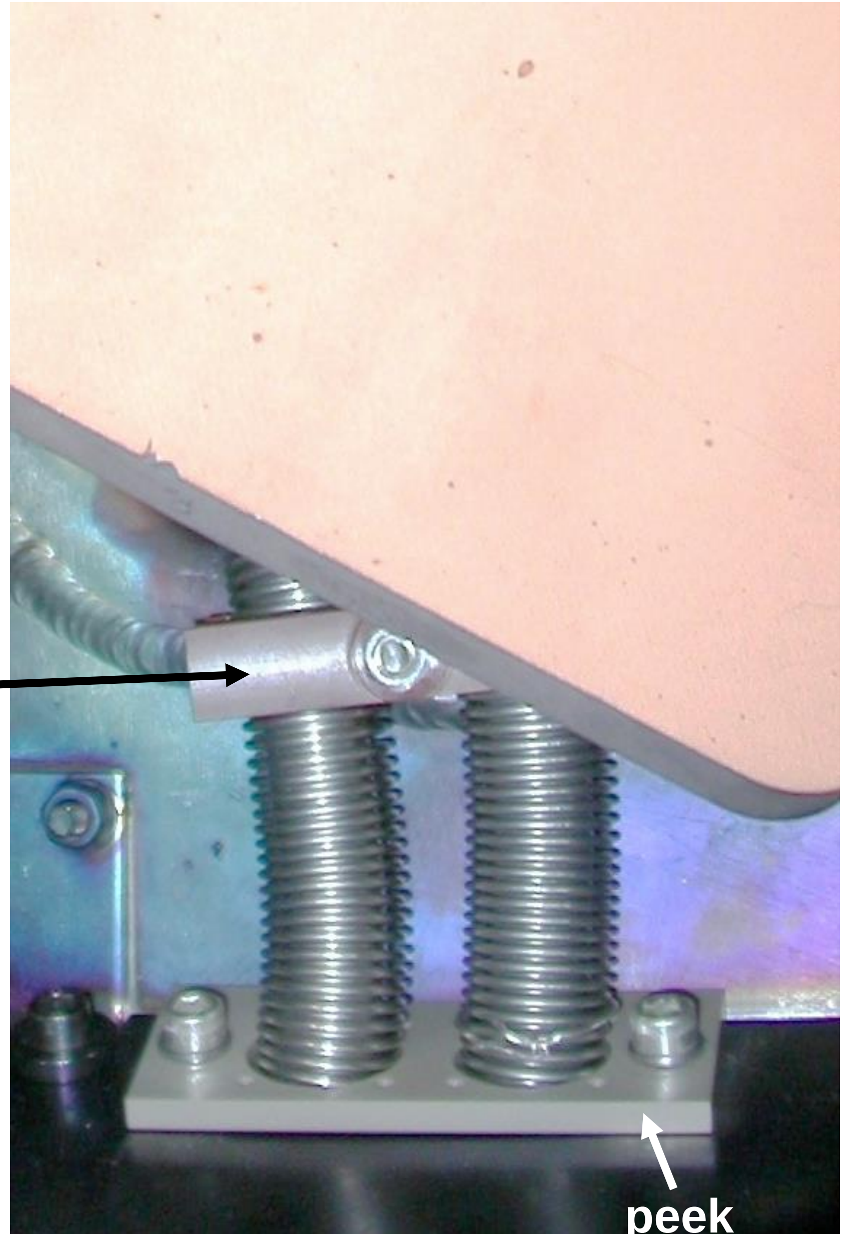


EXAMPLES FOR LOW ECRH ABSORPTION (9)

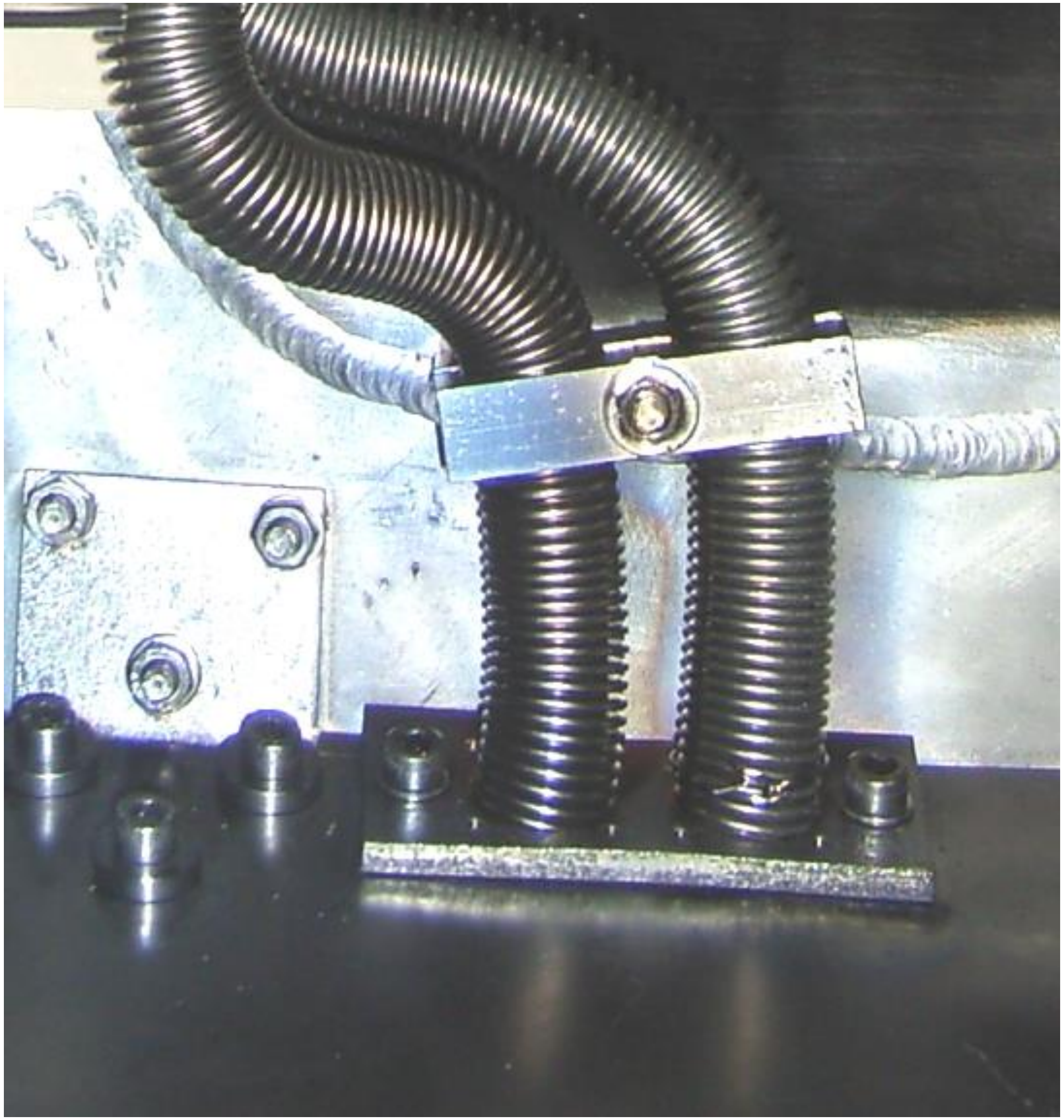


EXAMPLES FOR LOW ECRH ABSORPTION (10)

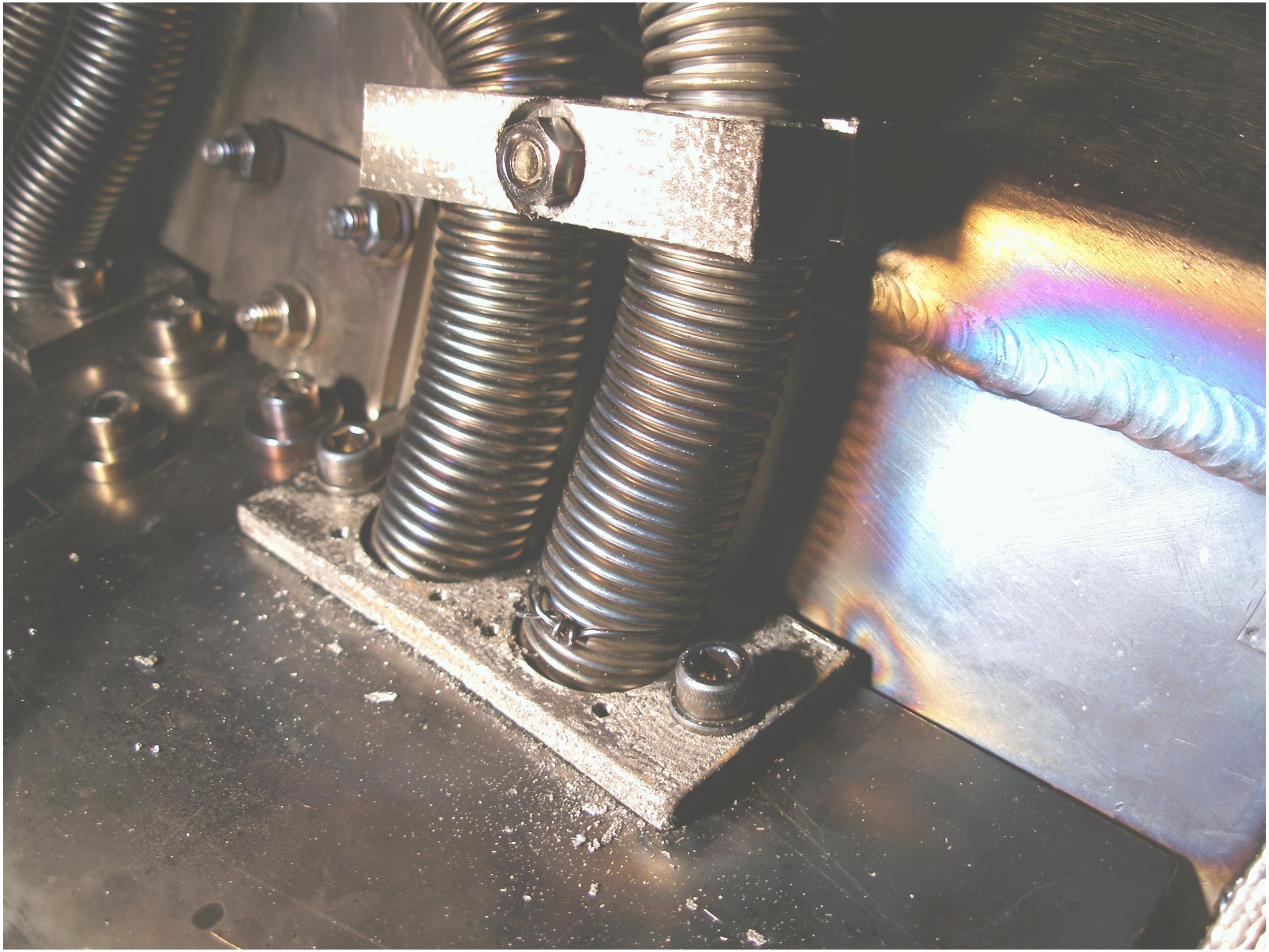
vespel



EXAMPLES FOR LOW ECRH ABSORPTION (11)



EXAMPLES FOR LOW ECRH ABSORPTION (12)



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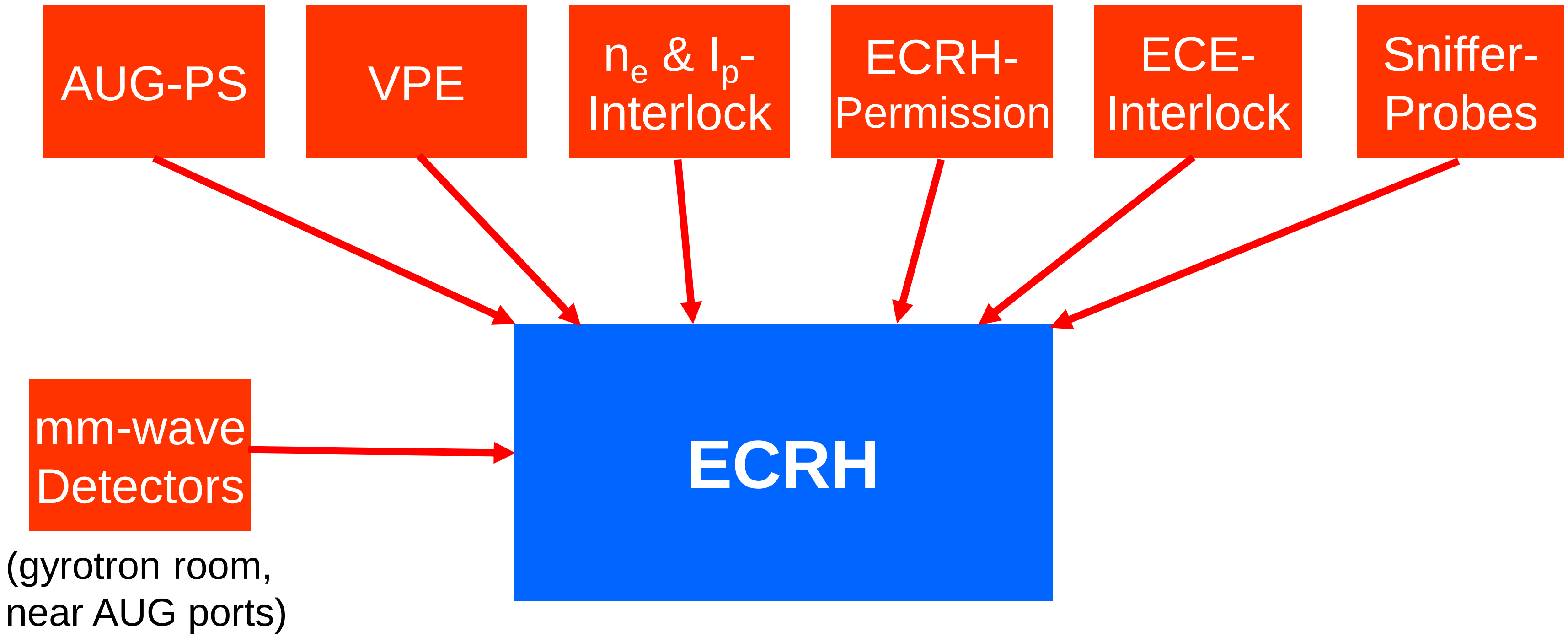
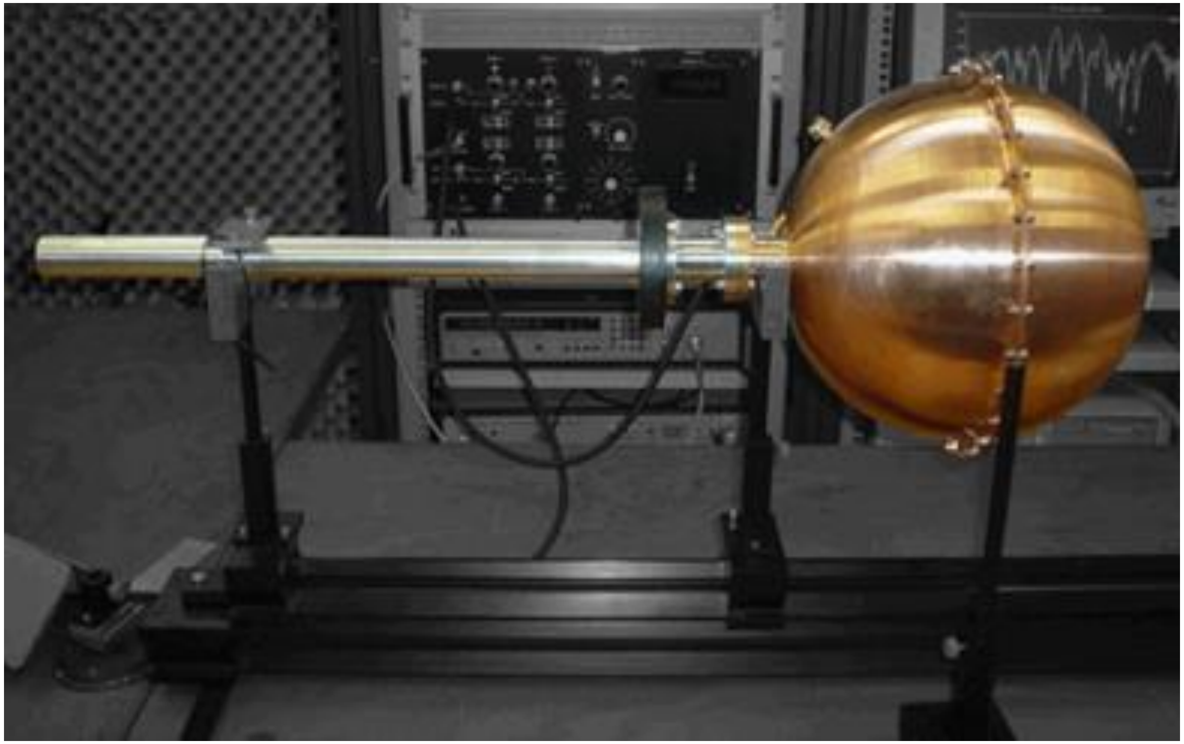
ECRH SAFETY

Gyrotron switch-off within t < 10 μs



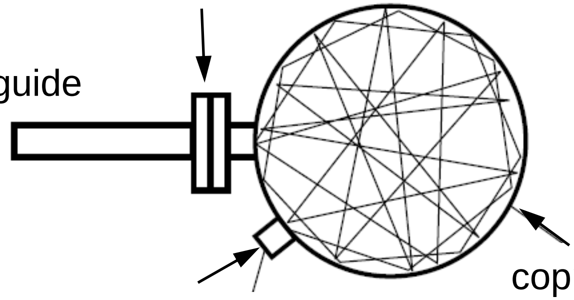
MEASURING ECRH STRAY RADIATION (1)

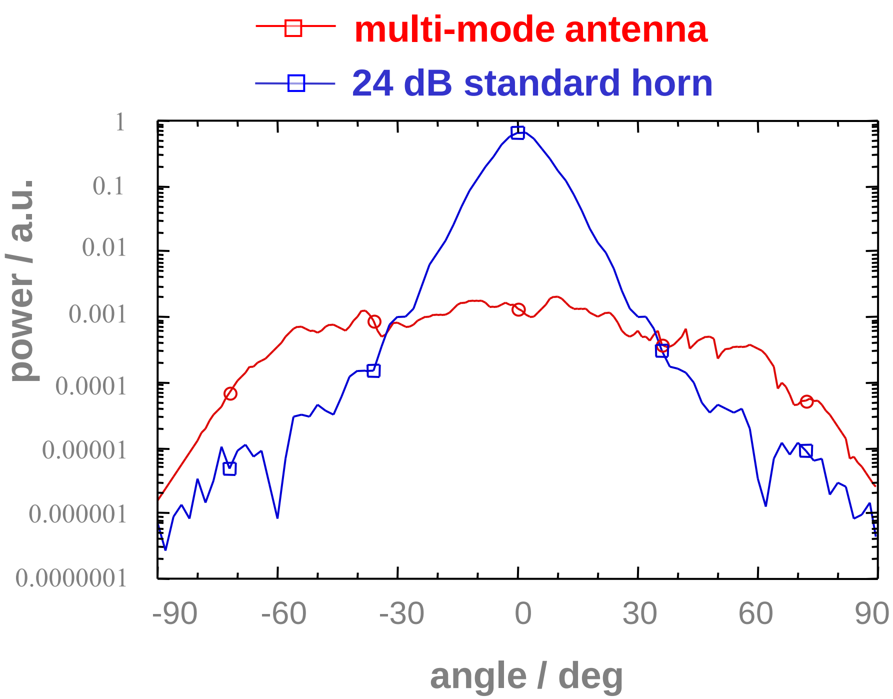
sniffer : a low-gain multimode large-aperture antenna

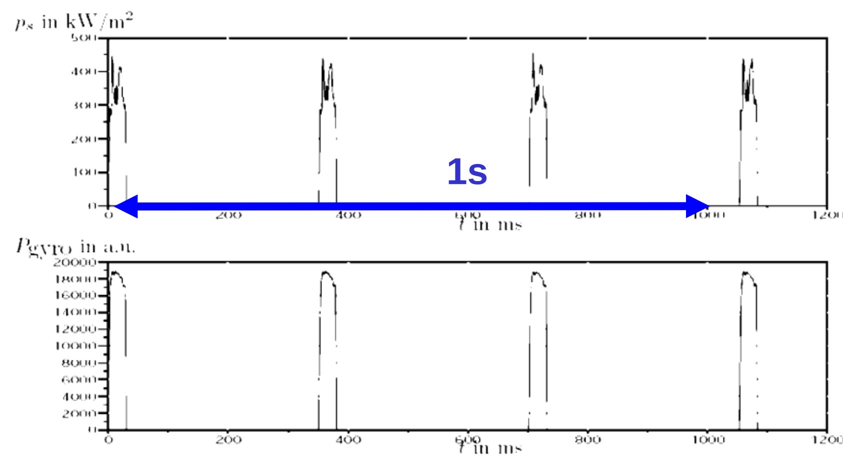


R&D by F. Gandini, S. Cirant,
Milano, Frascati

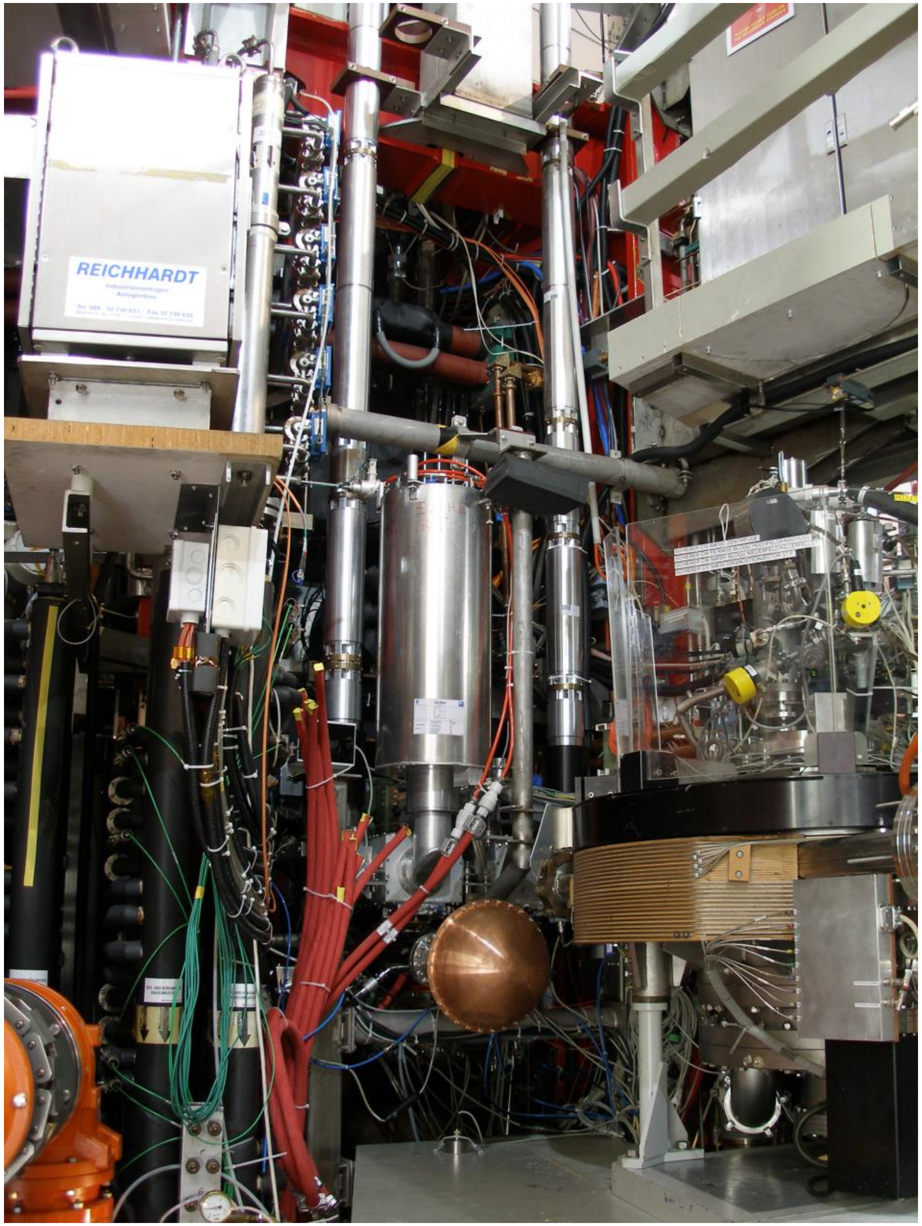
MEASURING ECRH STRAY RADIATION (2)

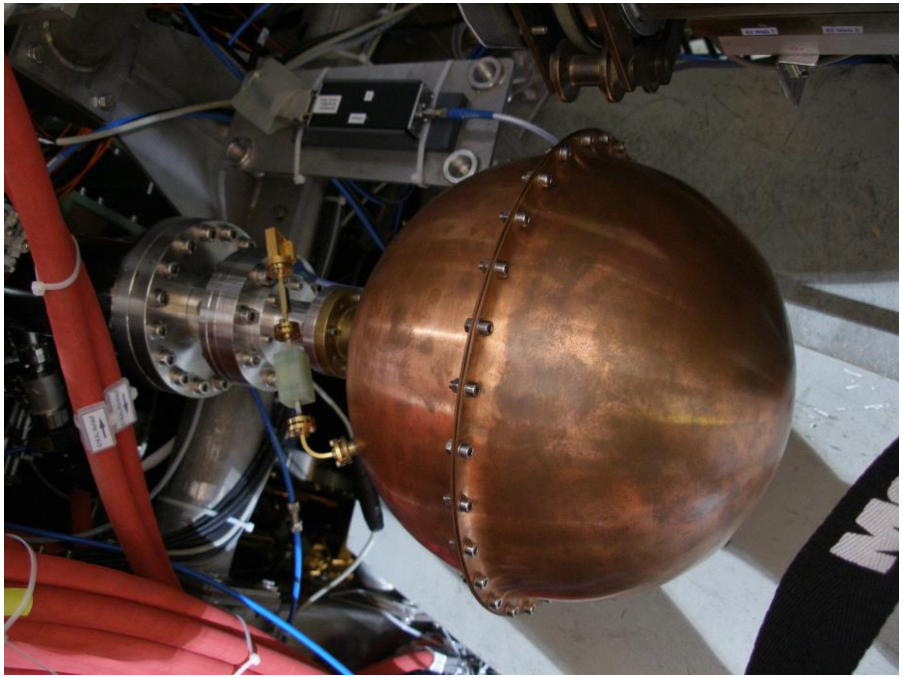




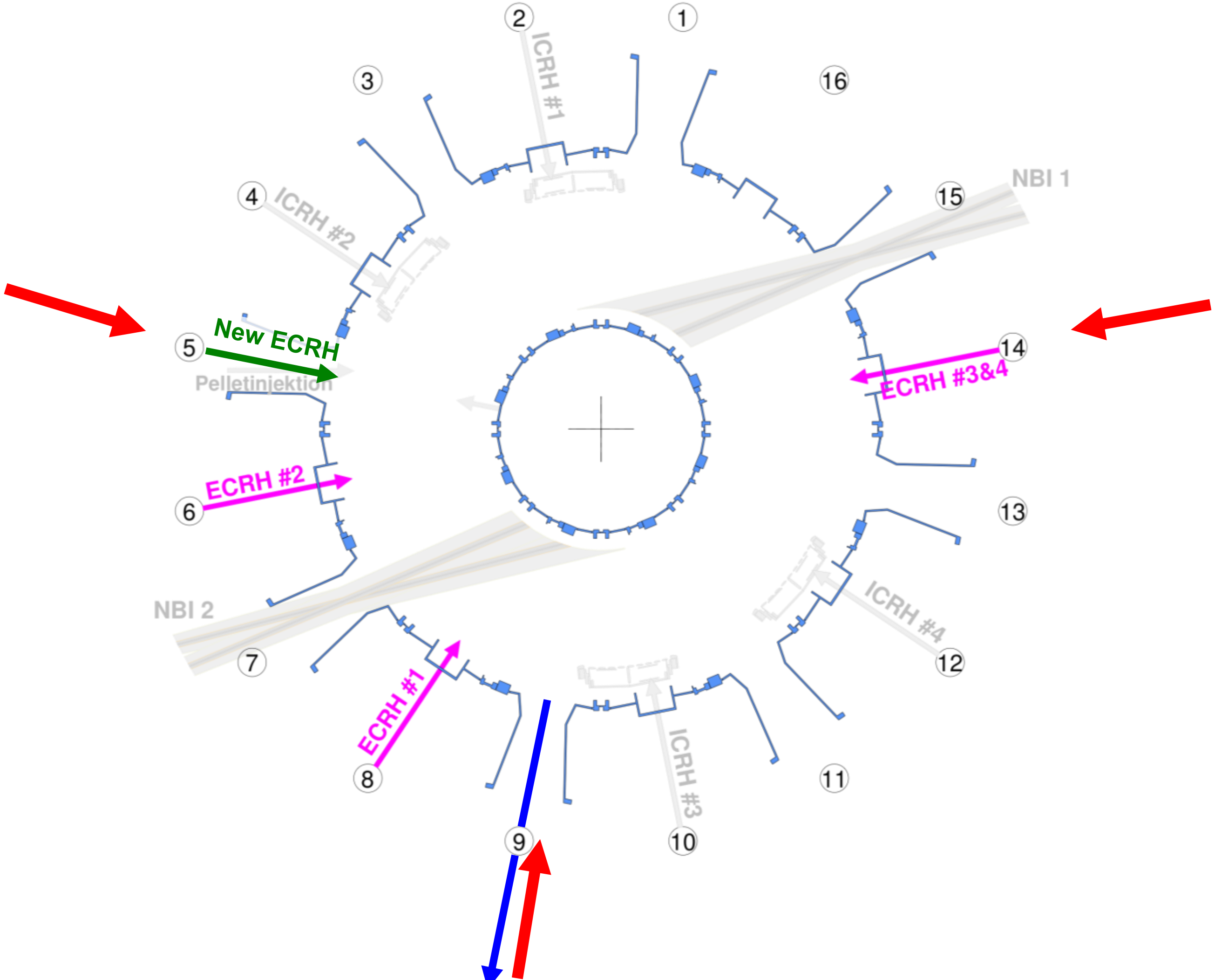


W7-X SNIFFER PROBE CONNECTED TO PORT 5





POSITIONING OF SNIFFER PROBES IN AUG



ECE diagnostic + diode

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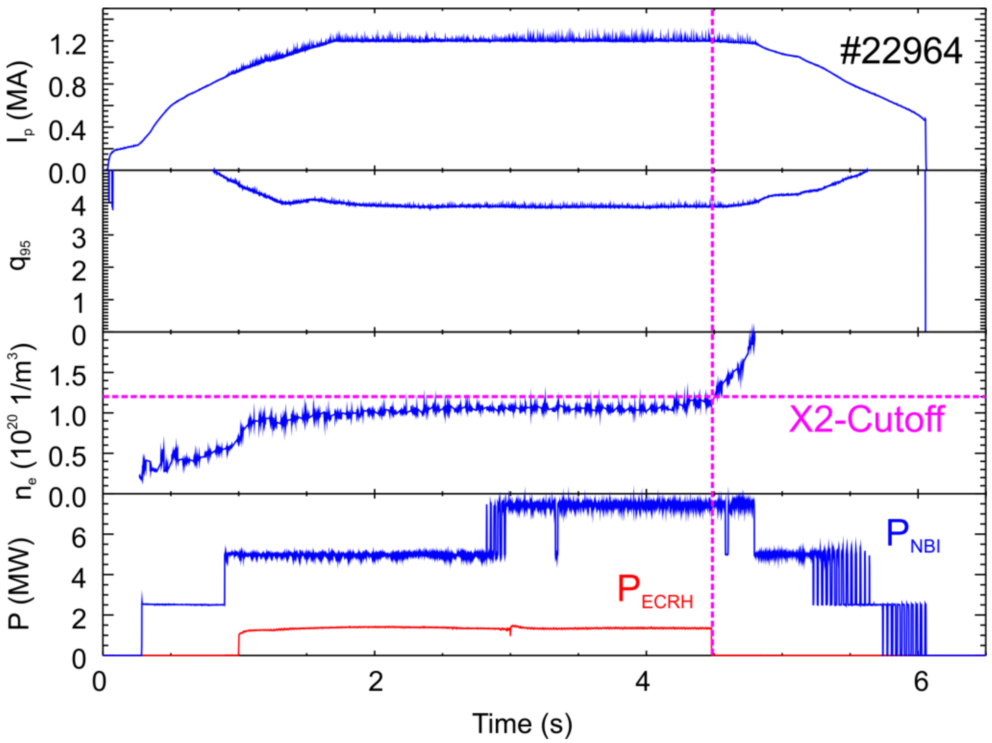
O2, X3 HEATING OF HIGH-DENSITY PLASMAS

Central ECRH (f=140 GHz) in ITER-relevant plasma discharges at ASDEX Upgrade

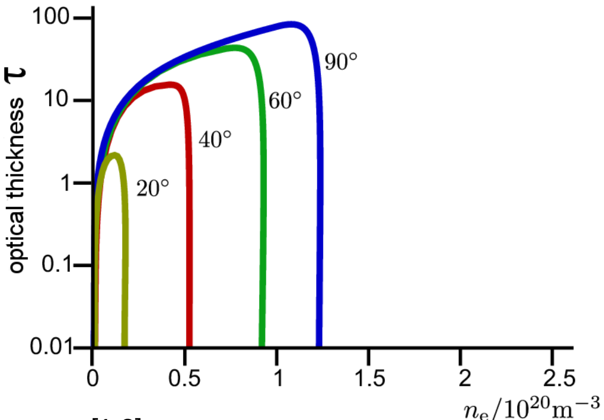
- ITER-relevant plasmas:
  improved H-Mode, $q_{95} \approx 3$
- ECRH must be switched off, if the X2-cutoff ($n_{cut}^{X2} = 1{,}22 \cdot 10^{20} 1/m^3$) is achieved.
- It is possible to heat the plasma with the O2-mode (O2-cutoff: $n_{cut}^{O2} = 2{,}43 \cdot 10^{20} 1/m^3$)
- For a lower magnetic field it is also possible to heat with the X3-mode (X3-cutoff: $n_{cut}^{X3} = 1{,}62 \cdot 10^{20} 1/m^3$)



ECRH AT HIGHER HARMONICS

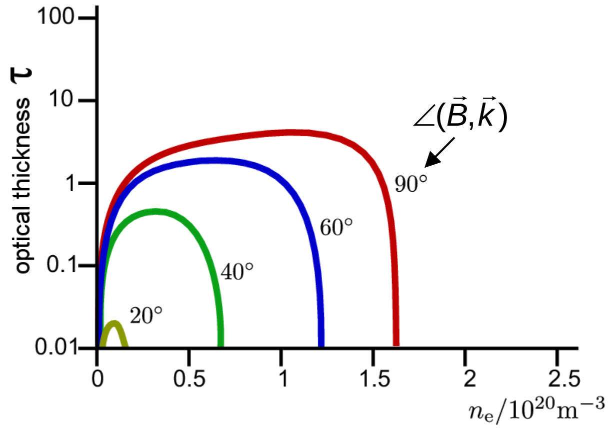
$$P_{abs} = P_{in}(1 - e^{-\tau})$$

X2

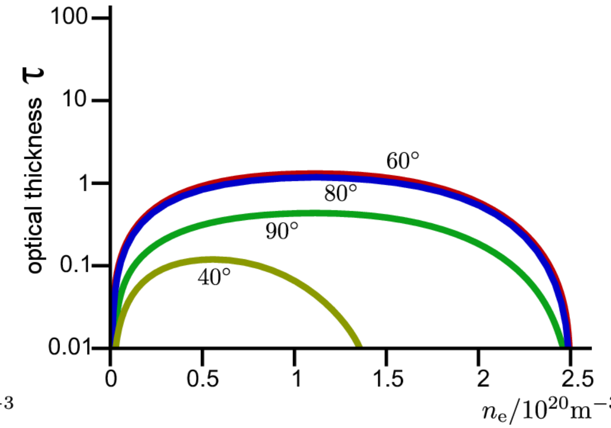


[1,2]

X3



O2



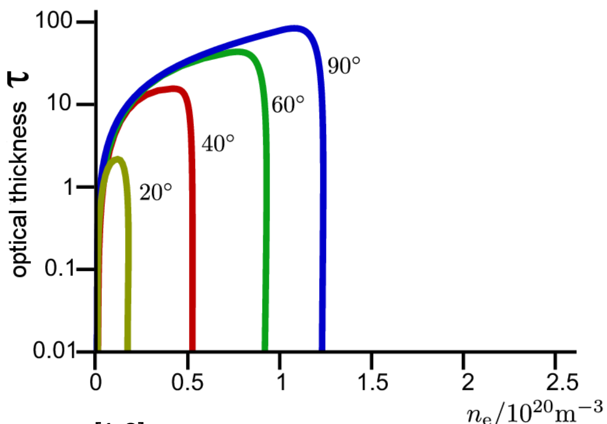
	X2	X3	O2
B_0	2,50 T	1,67 T	2,50 T
f	140 GHz	140 GHz	140 GHz
n_{cut}	$1{,}22 \cdot 10^{20}\, 1/m^3$	$1{,}62 \cdot 10^{20}\, 1/m^3$	$2{,}43 \cdot 10^{20}\, 1/m^3$
T_e	2 keV	4 keV	4 keV
$\tau \propto$	T_e	$T_e^{\,2}$	$T_e^{\,2}; T_e$
P_{abs}	100 %	98 %	85 %

[1] V. Erckmann, U Gasparino; Plasma Phys. Control. Fusion 36 (1994) 1869-1962
[2] O. Mangold, W. Kasparek; Proceedings of 14th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating - EC-14 (2006)

ECRH AT HIGHER HARMONICS

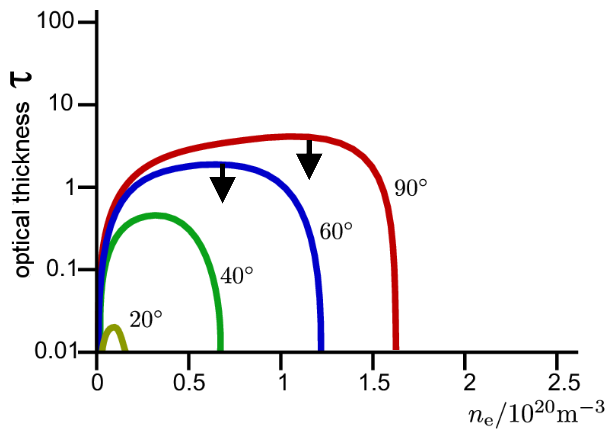
$$P_{abs} = P_{in}(1 - e^{-\tau})$$

X2

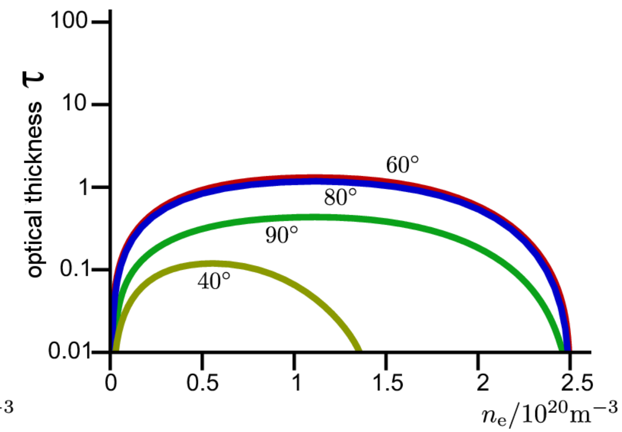


[1,2]

X3



O2

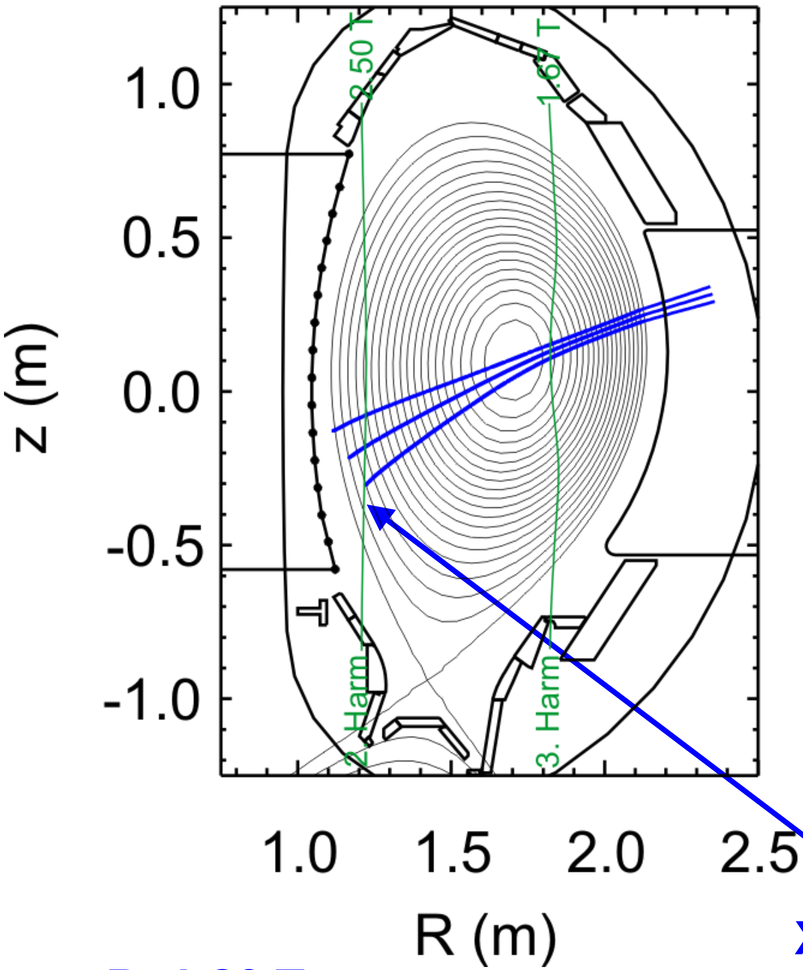


	X2	X3	O2
B_0	2,50 T	1,67 T	2,50 T
f	140 GHz	140 GHz	140 GHz
n_{cut}	$1{,}22 \cdot 10^{20}\, 1/m^3$	$1{,}62 \cdot 10^{20}\, 1/m^3$	$2{,}43 \cdot 10^{20}\, 1/m^3$
T_e	2 keV	2 keV	4 keV
$\tau \propto$	T_e	$T_e^{\;2}$	$T_e^{\;2}; T_e$
P_{abs}	100 %	< 70 %	85 %

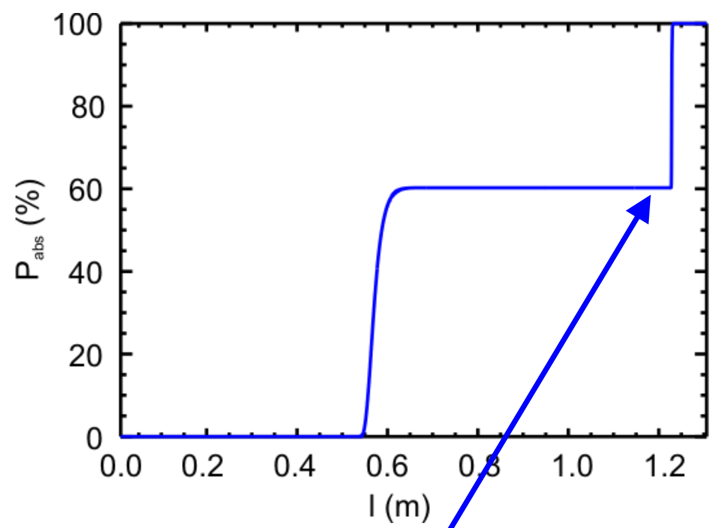
[1] V. Erckmann, U Gasparino; Plasma Phys. Control. Fusion 36 (1994) 1869-1962
[2] O. Mangold, W. Kasparek; Proceedings of 14th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating - EC-14 (2006)

X3-HEATING (1 MA, 1.8 T)

- **Reduction of q95 at constant Ip**



TORBEAM-Simulationen
$T_{e,max}$ = 2 keV;
$n_{e,max}$ = $1.2 \cdot 10^{20}$ $1/m^3$



B=1.80 T
140GHz

X2-Resonance serves as „beam-dump“

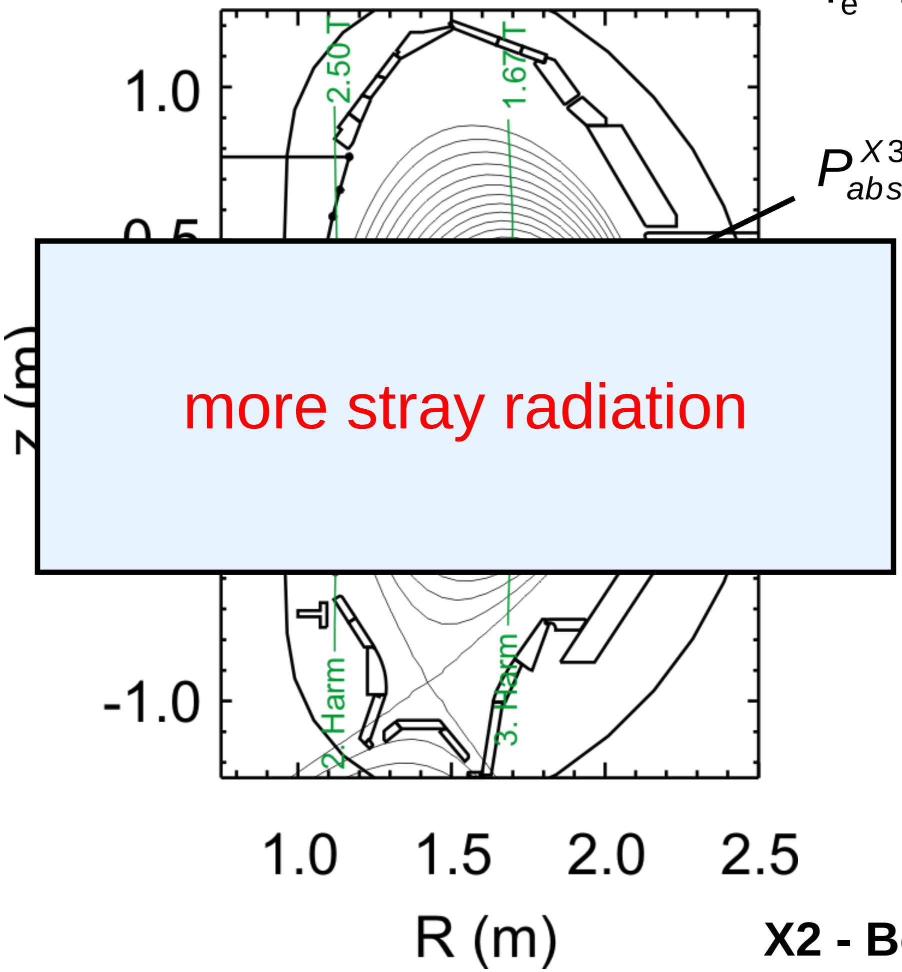
X3 HEATING SCENARIO – TORBEAM SIMULATION

$n_e = 1.2 \cdot 10^{20}\ m^{-3}$

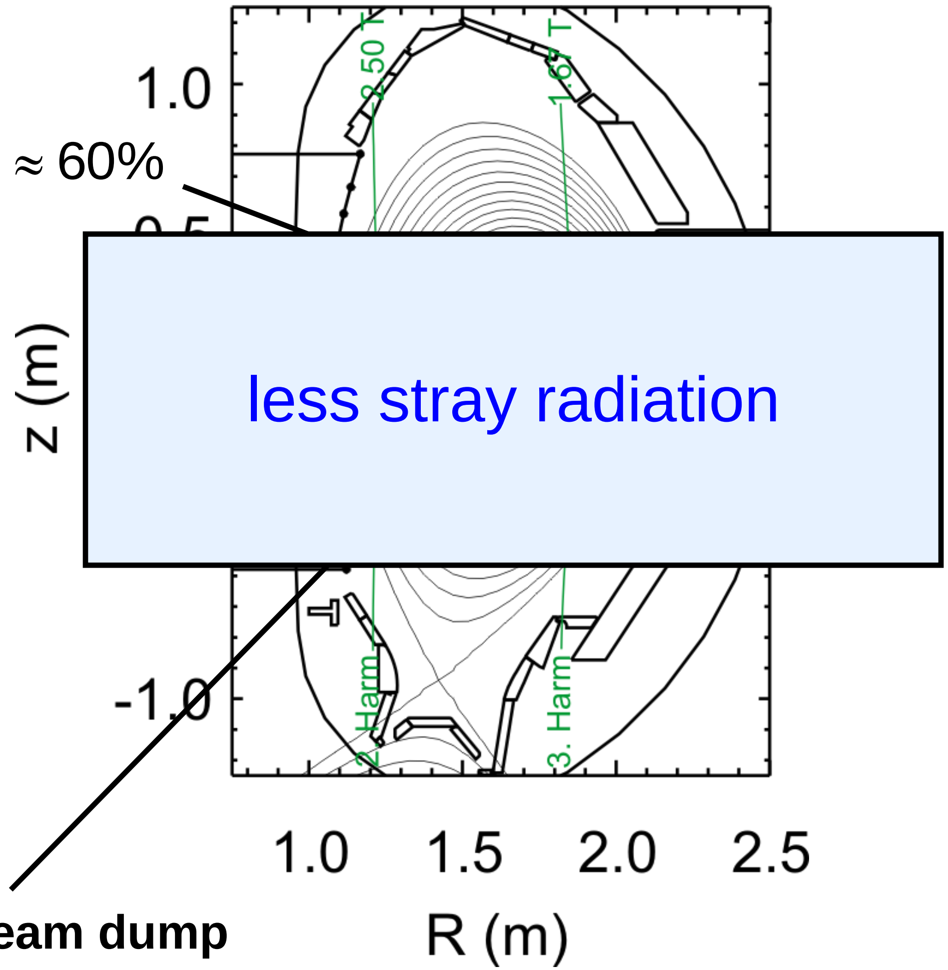
$T_e = 2$ keV

$P_{abs}^{X3} \approx 60\%$

B=1.67 T

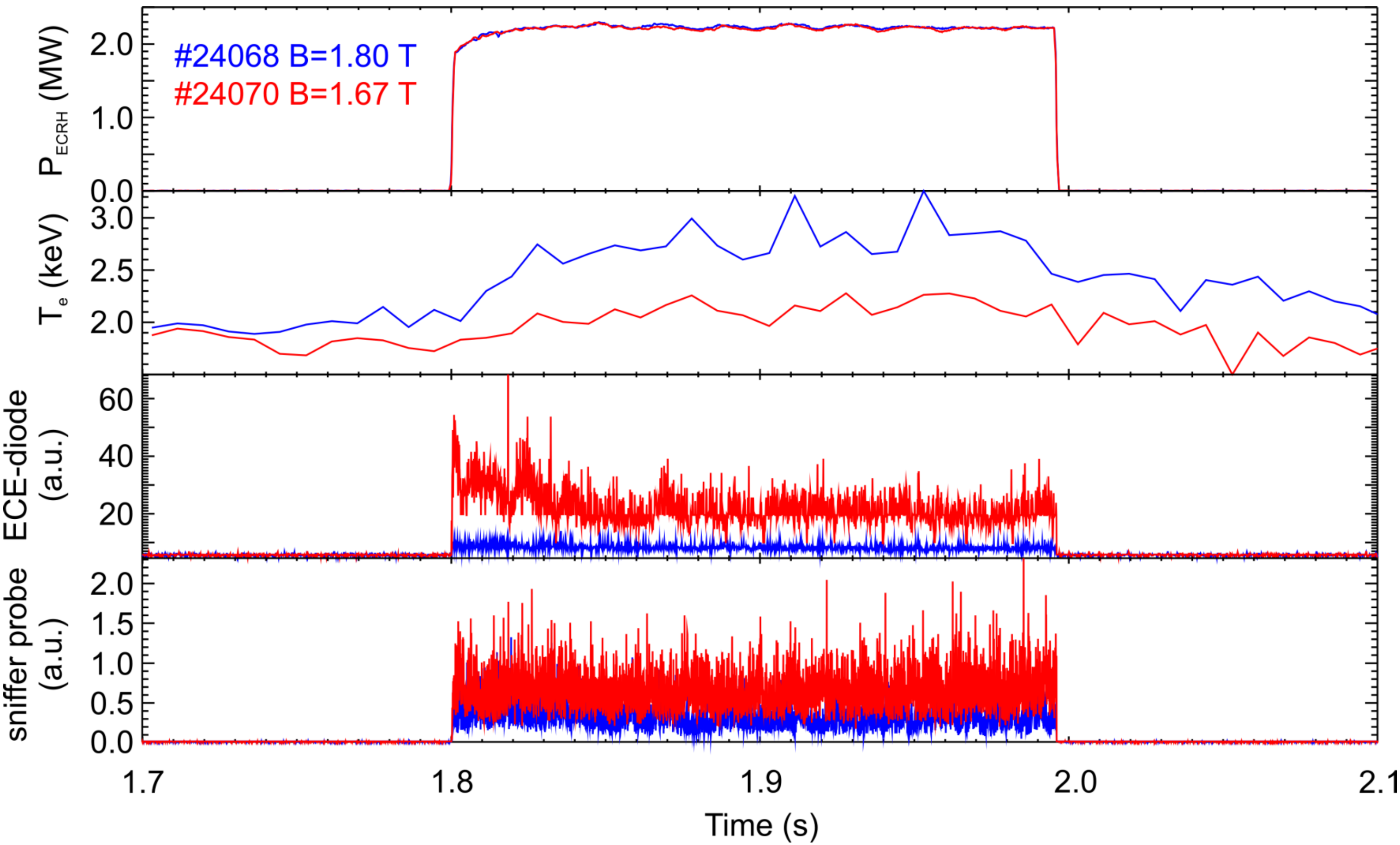


B=1.80 T



X2 - Beam dump

X3 HEATING SCENARIO – FIRST SHOTS

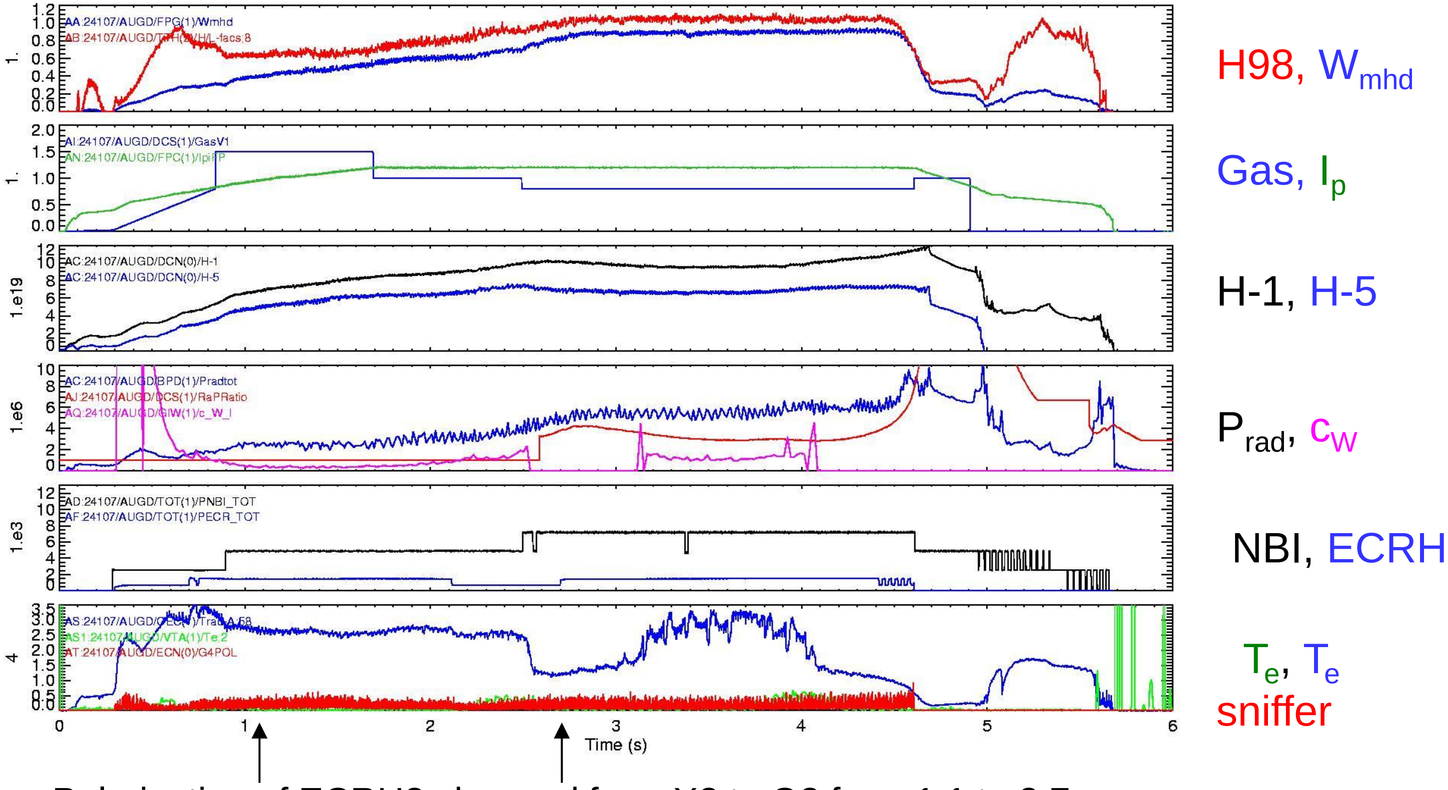


O2-HEATING OF HIGH-DENSITY PLASMAS (1)

O2-heating: Increase of I_p Reduction of q95 at constant Bt

Increase of plasma current → Increase of density →X-mode cut-off → O-Mode

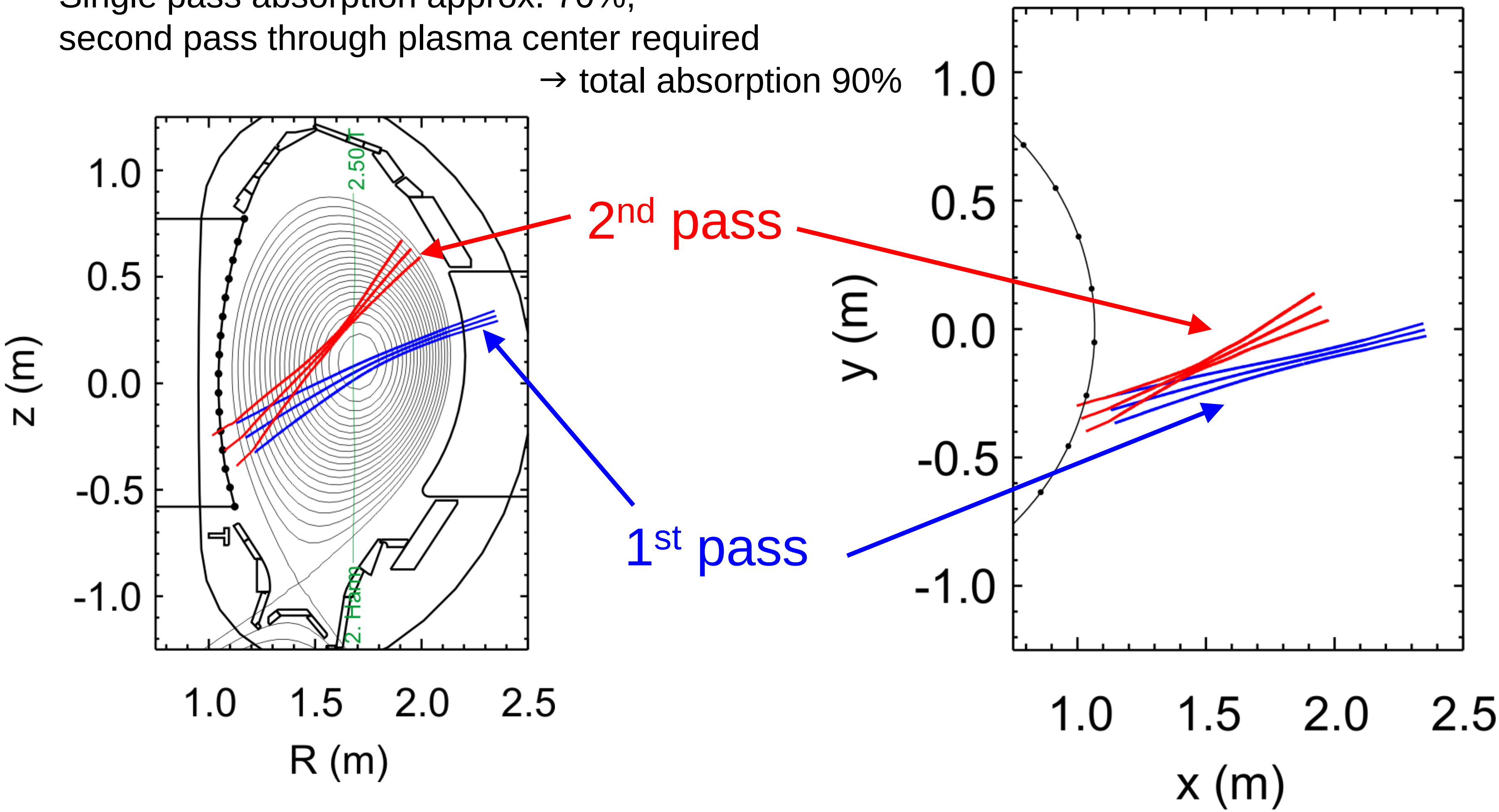
O2 : Proof of principle



Polarisation of ECRH2 changed from X2 to O2 from 1.1 to 2.7 sec

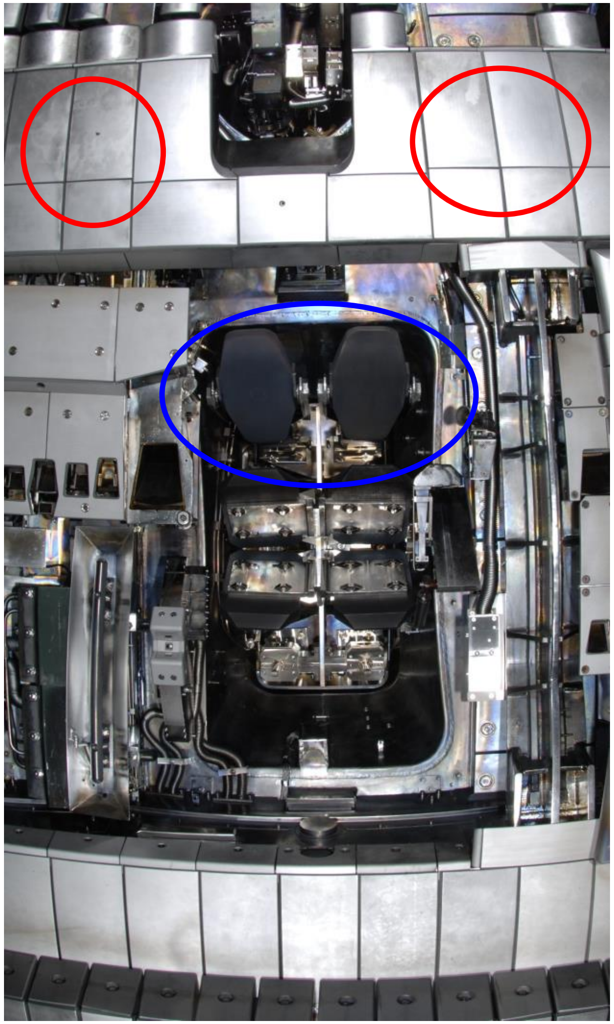
O2-HEATING OF HIGH-DENSITY PLASMAS (2)

Single pass absorption approx. 70%,
second pass through plasma center required
→ total absorption 90%

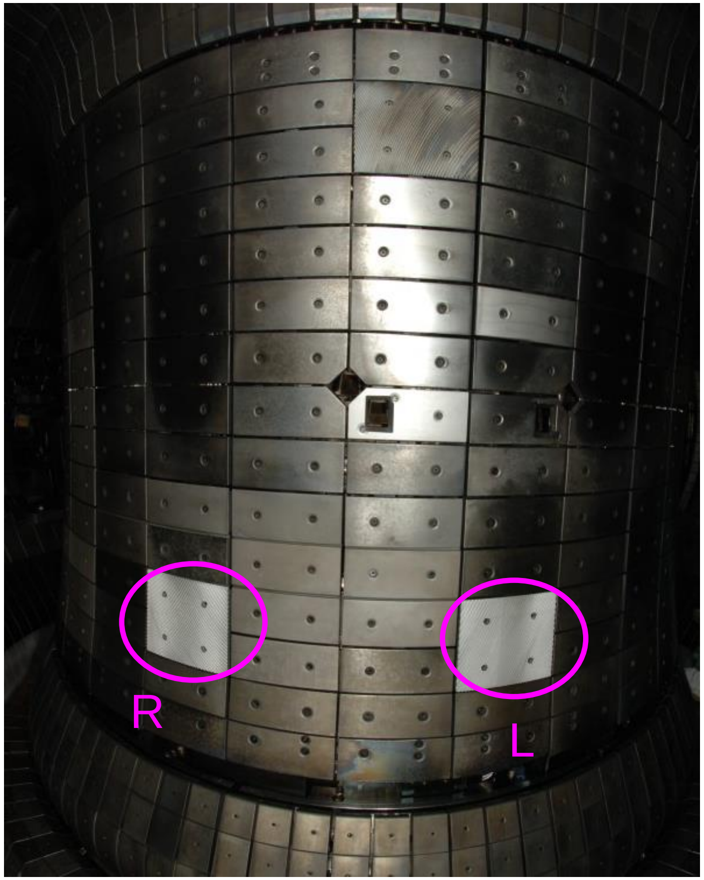


Special reflection grating required, which also keeps polarisation
Design and manufacturing: IPF, Uni Stuttgart *(H. Höhnle, W. Kasparek)*

O2-HEATING OF HIGH-DENSITY PLASMAS (3)



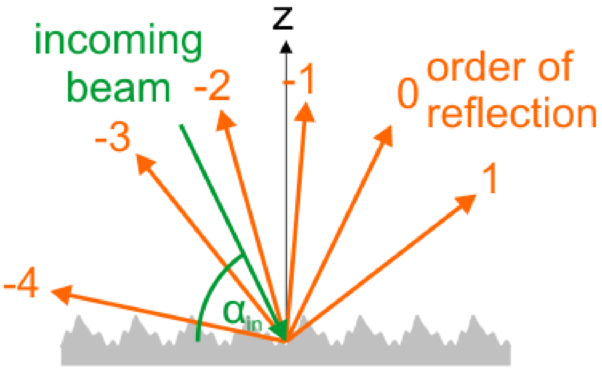
- second beam-pass through the plasma after reflection@ inner wall



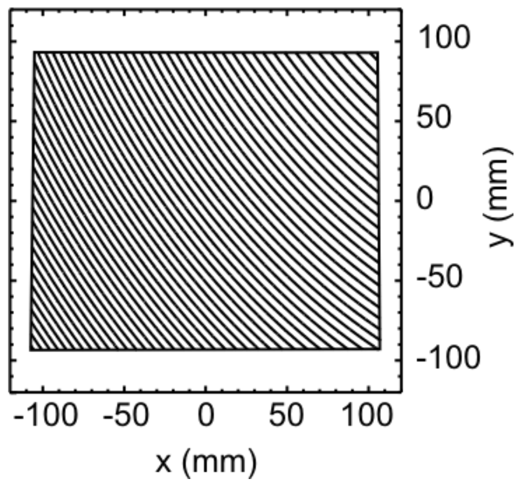
- holographic reflector for polarisation independent and directed reflection of the beam

HOLOGRAPHIC GRATING (1)

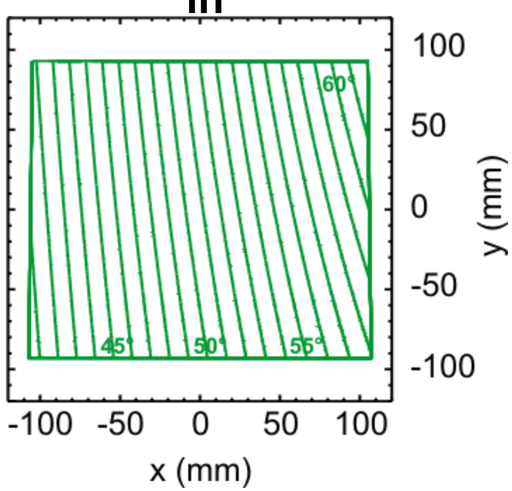
Phases and angles of the incoming and outgoing beams on neighbouring tiles calculated using beam tracing code TORBEAM.



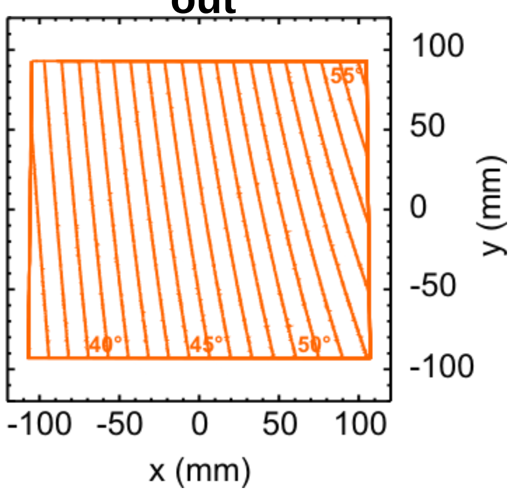
phase



α_{in}



α_{out}

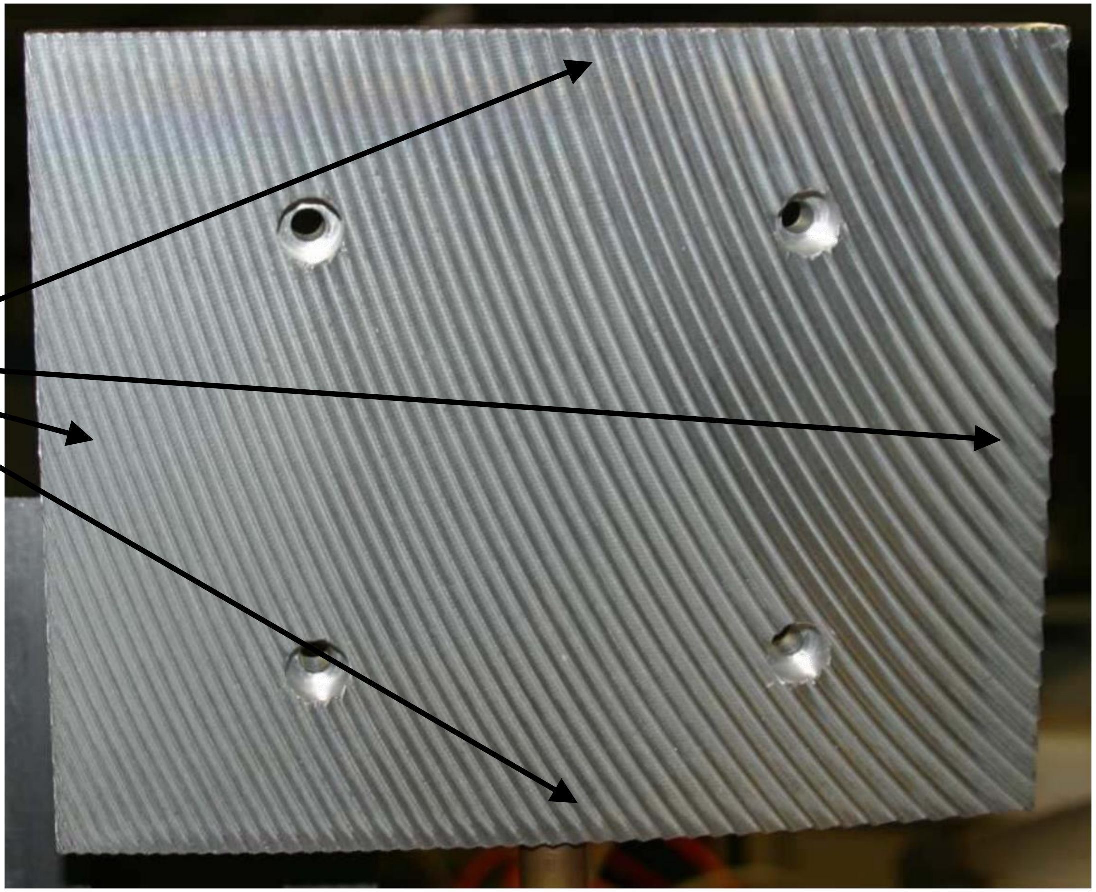


Optimization of the holographic grating for good efficiency in TE- and TM-polarization using Boundary Element Code.

Trade-off between efficiency and smooth profiles (possible plasma erosion of small structures

HOLOGRAPHIC GRATING (2)

Thermocouples for feedback signal for the fast steerable ECRH-launcher or emergency stop of ECRH Unit



O2 reflector:
Beam must stay in center of reflector, even when density changes.

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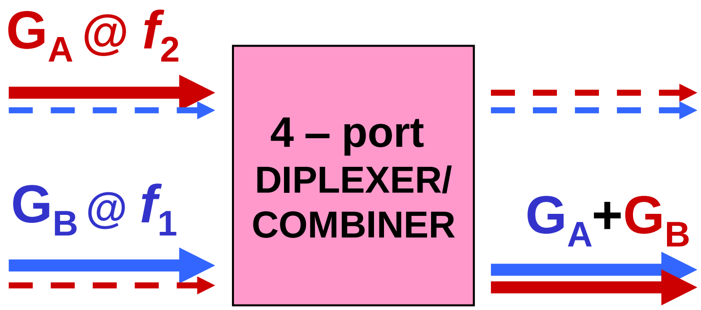
FADIS TEST AT ASDEX UPGRADE (1)

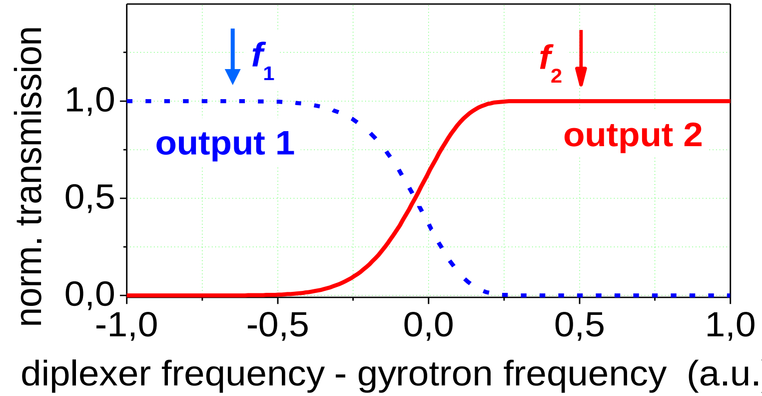
FADIS: COMPACT DIPLEXERS FOR POWER COMBINATION AND FAST SWITCHING IN ECRH SYSTEMS

*The Virtual Institute **„Advanced ECRH for ITER“,*** *supported by the Helmholtz-Gemeinschaft:*

IPF Stuttgart, Germany
IAP Nizhny Novgorod, Russia
IPP Garching and Greifswald, Germany
IFP Milano, Italy
FZK Karlsruhe, Germany

FADIS TEST AT ASDEX UPGRADE (2)



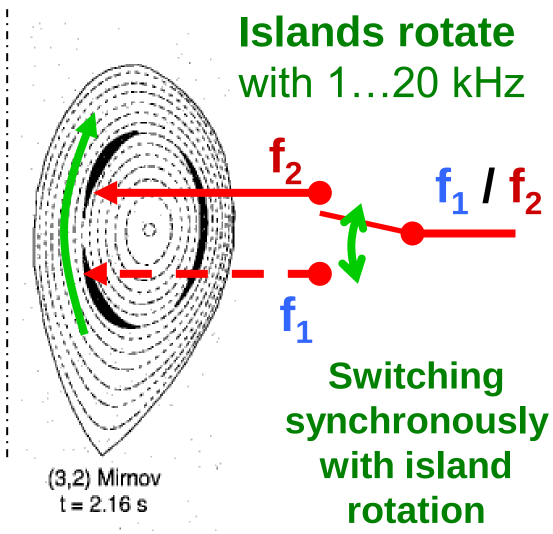


Motivation for ECRH application:

- **switching** by frequency-shift keying:
  $\Delta f / f \approx 10^{-4}$, with ΔU_{GA} or ΔU_{GB} $\approx$ kV
  ➔ power toggles between outputs
  ➔ switch has no undefined state, cw operation

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

- **power divider** for ECRH and low-power diagnostics

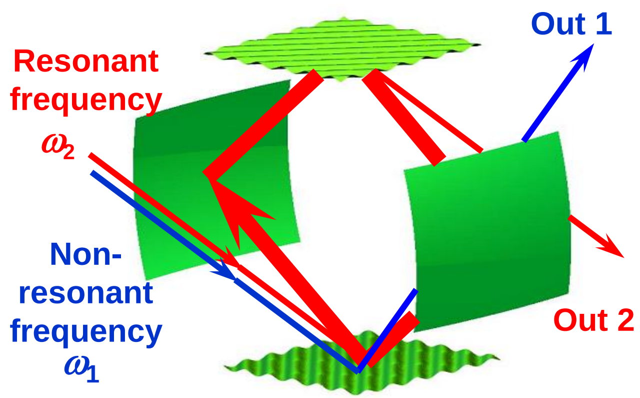


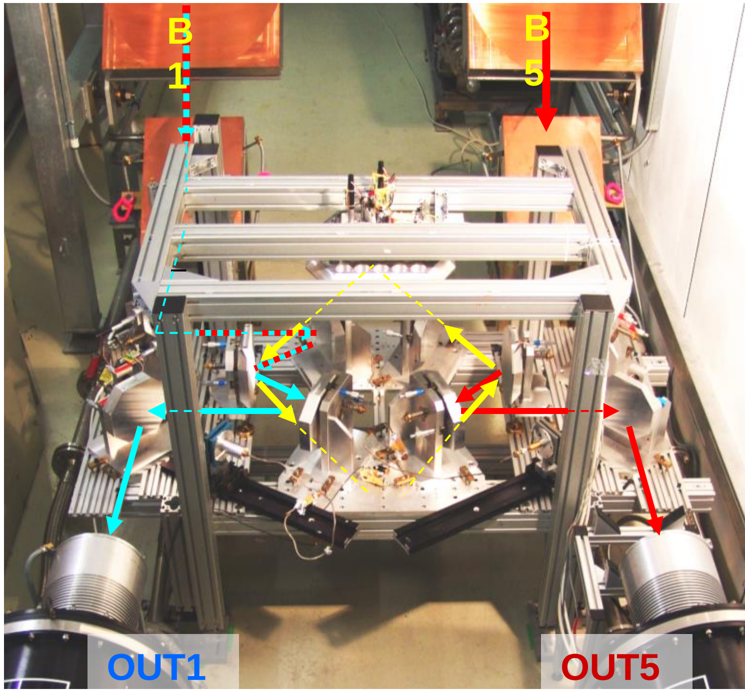
FADIS TEST AT ASDEX UPGRADE (3)

Principle:

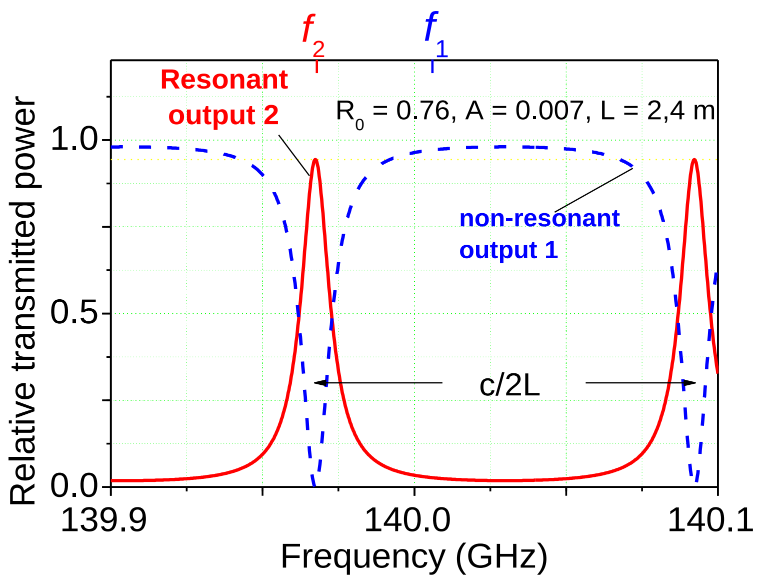
ring resonator
with
coupling gratings

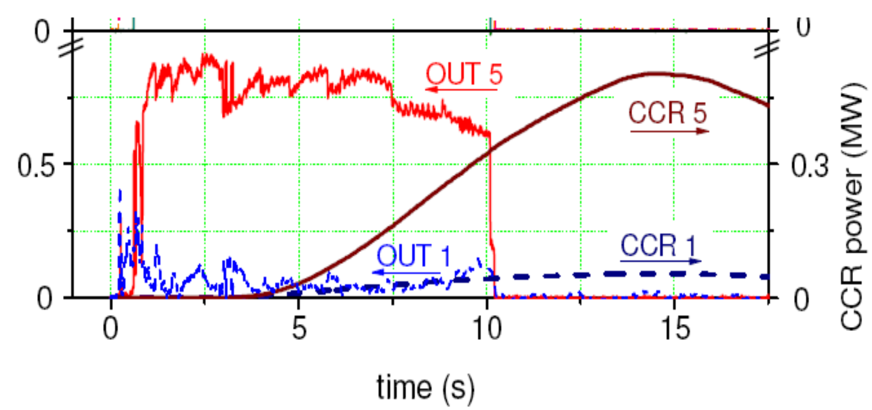
(≈ Fabry-Perot)





Transmission function:

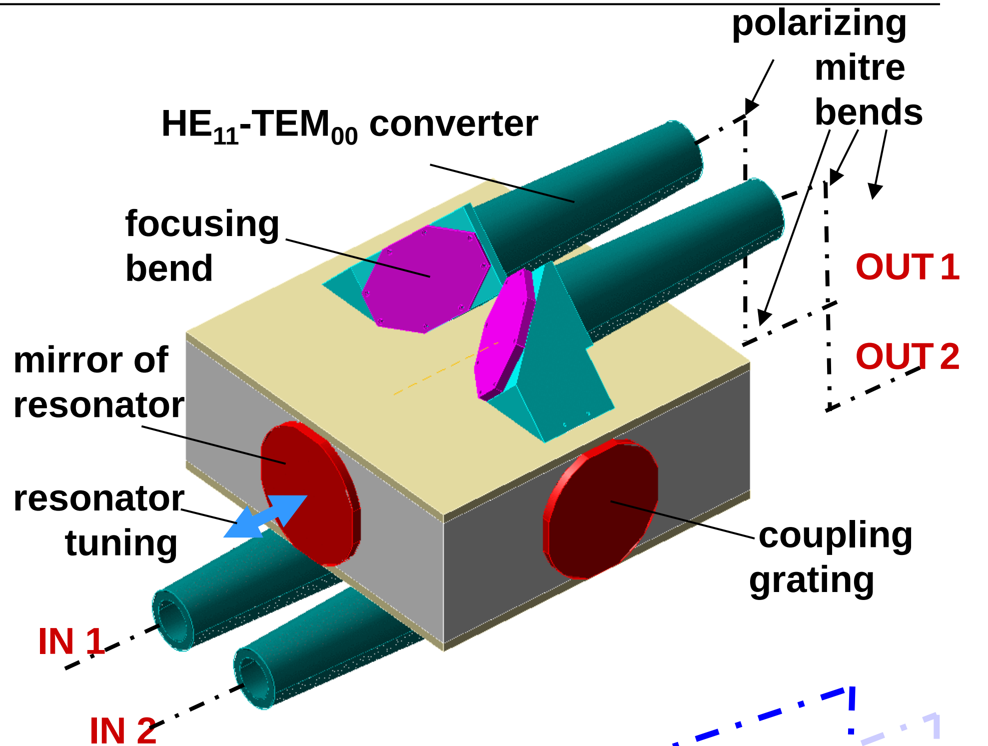


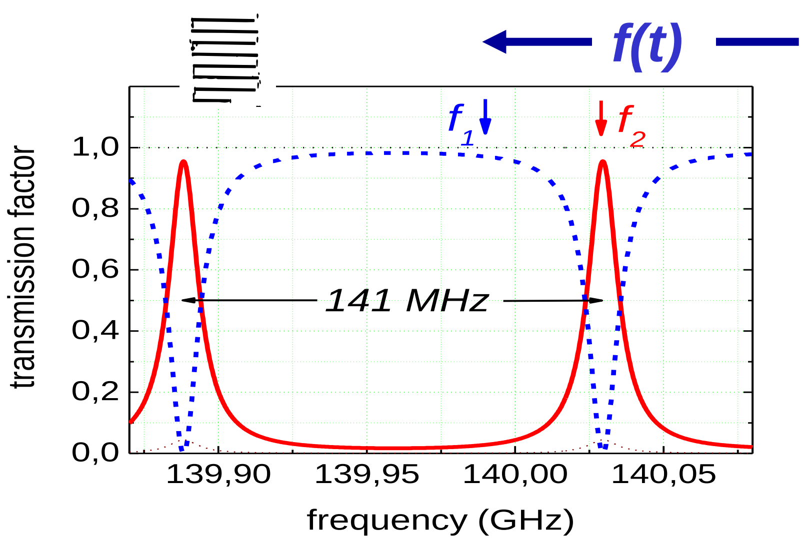


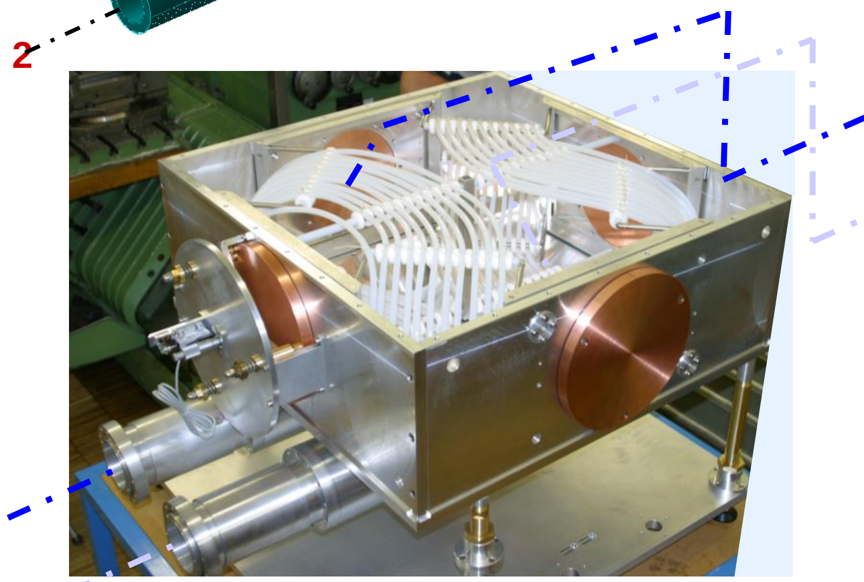
FADIS TEST AT ASDEX UPGRADE (4)

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)

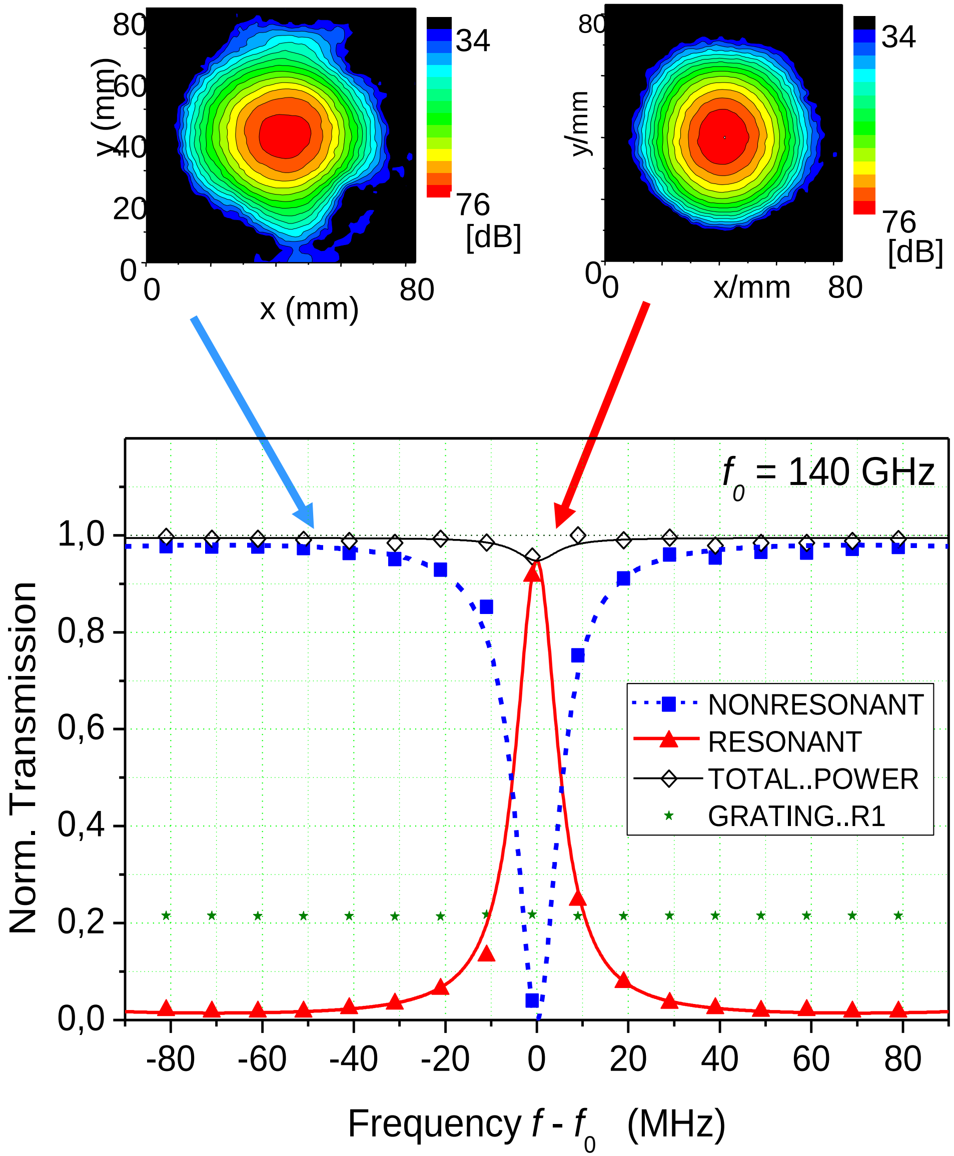




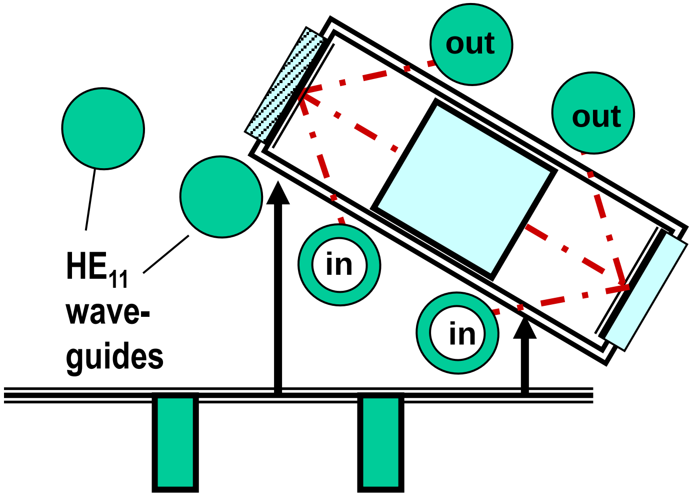


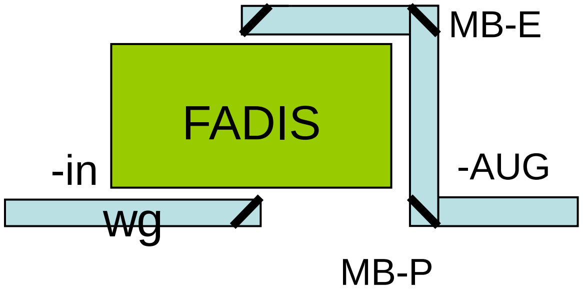
FADIS TEST AT ASDEX UPGRADE (5)

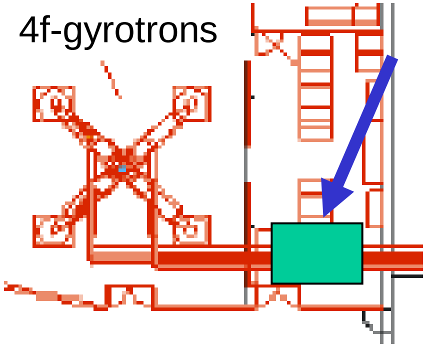
- Transmission functions for **non-resonant output** and **resonant output** in good agreement with calculation
- **Insertion loss, non-resonant ch.:**
  absorption (mainly coupling): 0.8 %
  cross-talk (about theory): typ. 2.2 %
  Total insertion loss 3.0 %
- **Insertion loss, resonant channel:**
  absorption (resonator, coupl): 4.4 %
  cross-talk (wrong modes!): 3.9 %
  Total insertion loss 8.3 %
- The q.o. diplexer is an efficient mode filter (especially in the resonant channel).
  Expected average insertion loss for pure HE_{11} input is 4 %.

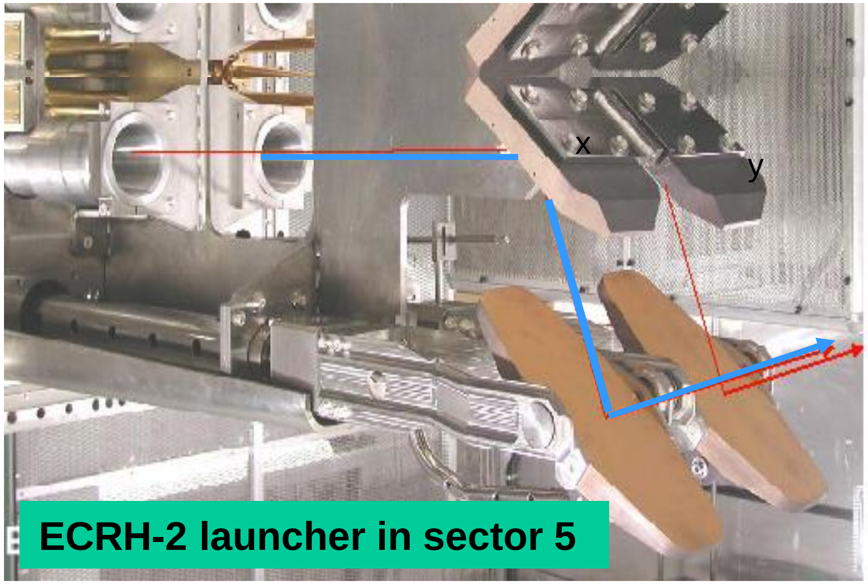


FADIS TEST AT ASDEX UPGRADE (6)



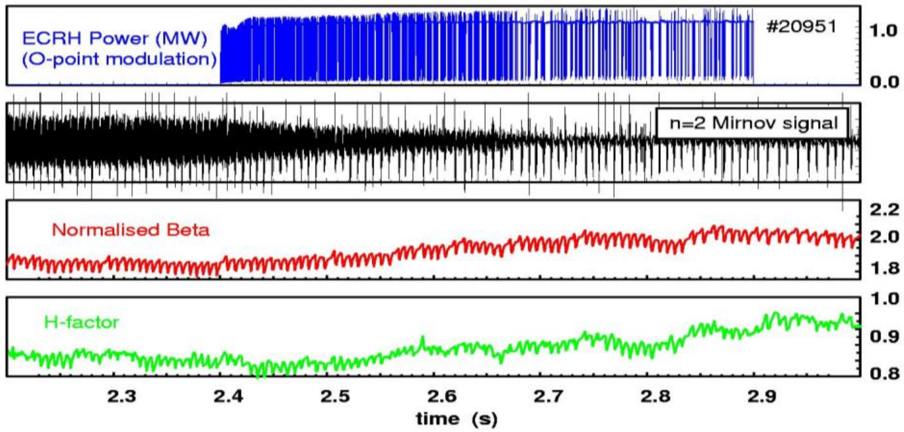


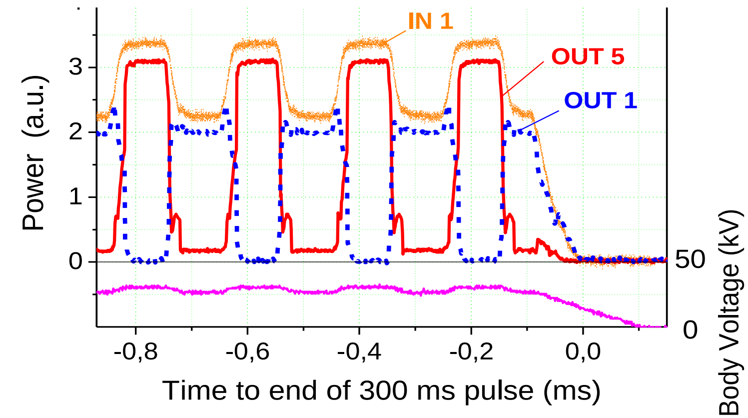




- connection to any adjacent waveguides
- insertion length in waveguide is 1494 mm
- start: integration into lines 3 and 4
- operation with gyr. Elissey-2 (2010)
- connected to lower launchers sector 5

POSSIBLE EXPERIMENTS AT ASDEX UPGRADE





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

- **independent experiments (ITER!)**
  - 1 beam for NTM stabilization
  - 1 beam for other purpose

- **applications for plasma diagnostics**
  - in-line ECE (IPP - FOM)