

High-power tests of a remote steering Launcher mock-up at 140 GHz

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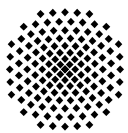
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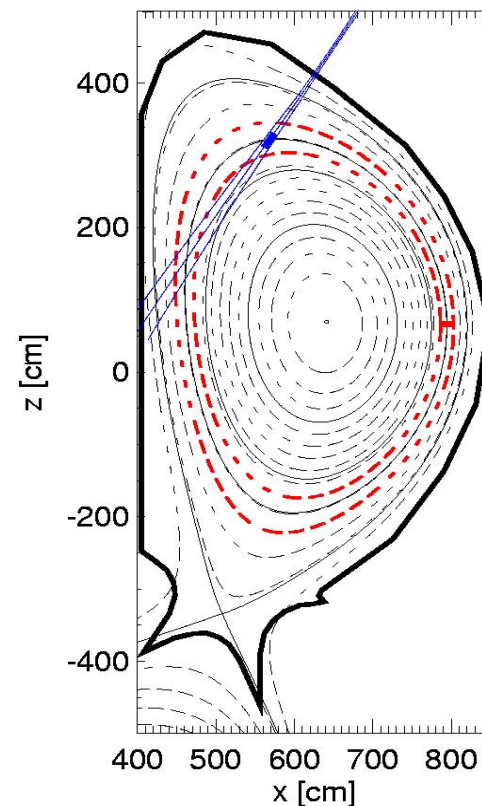
Outline

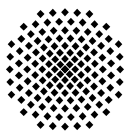
- Introduction
- Theoretical Results
- Experimental set-up
- Diagnostics
- Temperature measurements
- Summary



Upper launcher for ECRH/ECCD at ITER:

- NTM stabilisation (3/2), (2/1)
- Current drive at the respective surface
- Poloidal steering of the RF beam
- Possible solution: Rectangular square waveguide (avoidance of movable components close to the plasma)
- Low power tests around 140 GHz have been performed and are reported in: Kasperek et.al., NF **43** (2003) 1505-1512
- High power tests with the existing waveguide at IPP, Greifswald, Germany (140 GHz)





Propagation constant for TE_{m,n} - modes:
$$k_{m,n} = k_0 \cdot \sqrt{1 - \left(\frac{m\lambda}{2a}\right)^2 - \left(\frac{n\lambda}{2a}\right)^2}$$

For low-order modes,

i.e. for $m\lambda/2a \ll 1$ and $n\lambda/2a \ll 1$:

$$k_{m,n} \approx k_0 \cdot \left(1 - \frac{(m^2 + n^2) \cdot \lambda^2}{8a^2}\right)$$

These approximations are also valid for **balanced HE_{m,n}** modes propagating in square corrugated waveguides

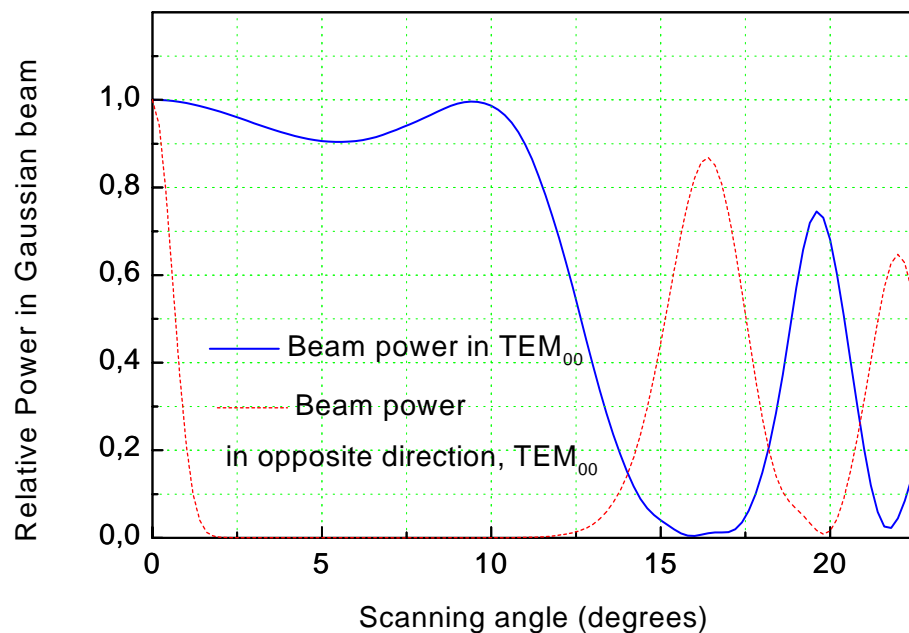
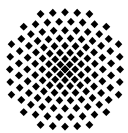
Propagation constants of the modes differ by a multiple of: $\Delta k = \pi\lambda/(4a^2)$

Phase difference of adjacent modes n,n+1 after a waveguide length of $L = 4a^2 / \lambda$:

$$\delta \approx (2n+1) \cdot \pi$$

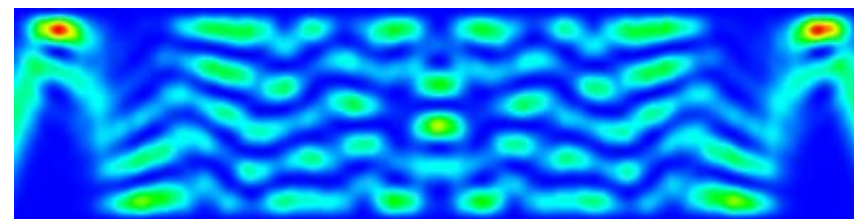
==> Antisymmetric image of the input field, scanning mechanism outside vacuum vessel

==> Limit: phase slippage of the waveguide modes $\Delta\delta \approx k \cdot a \cdot \varphi^3 \cdot (n_1 - n_2)$

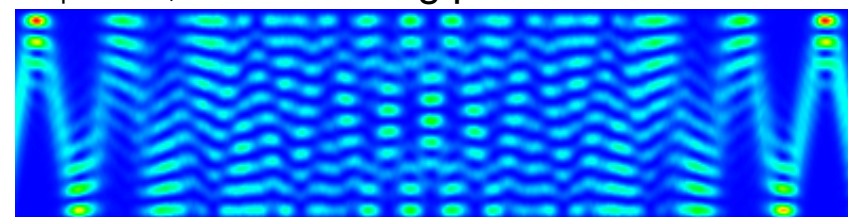


- Coupling integral of a gaussian beam radiated at the nominal angle from the centre of the waveguide output aperture and the beam obtained from numerical calculations.

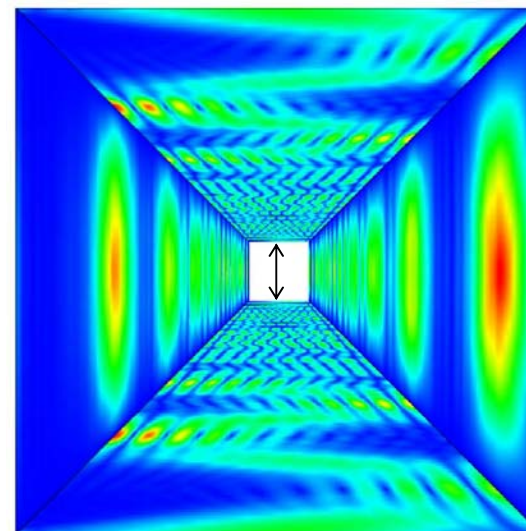
⇒ Losses in case of small angular or spatial deviations of the radiated beam from the nominal (e.g. $\varphi = 5^\circ$)



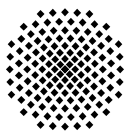
$\varphi = 5^\circ, \vec{E} \perp \text{scanning plane}$



$\varphi = 10^\circ, \vec{E} \perp \text{scanning plane}$



Longitudinal magnetic field for $\varphi = 10^\circ$



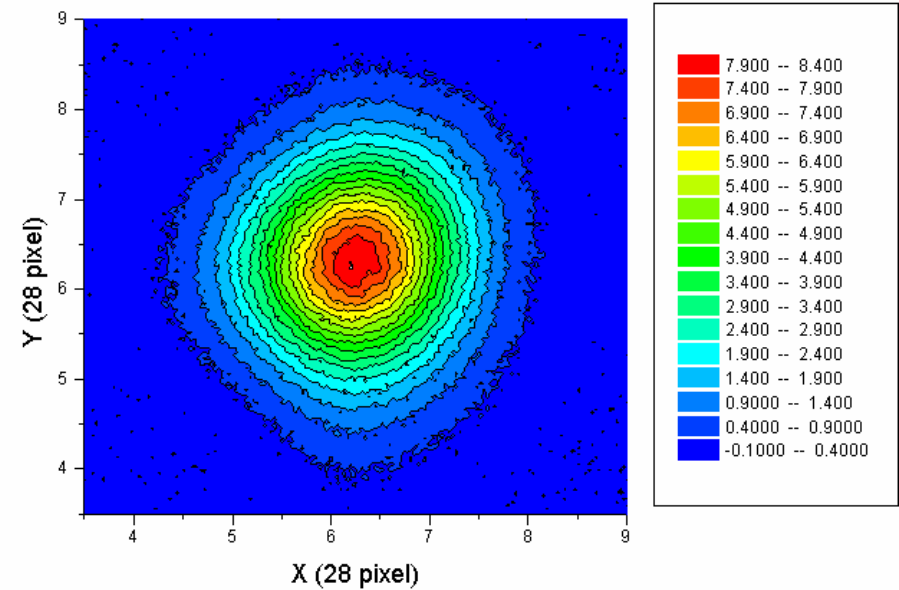
Experimental set up

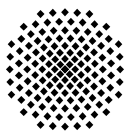
IPF



THALES Maquette
operates since Nov.2003

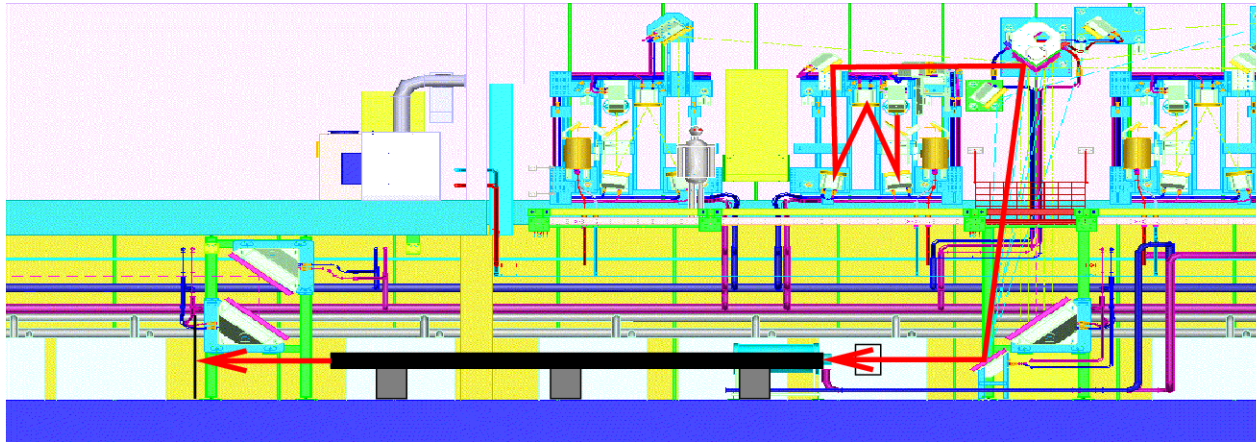
Gyrotron: 140 GHz,
1.05 MW/5 s,
470 kW/180 s





Experimental set up

IPF

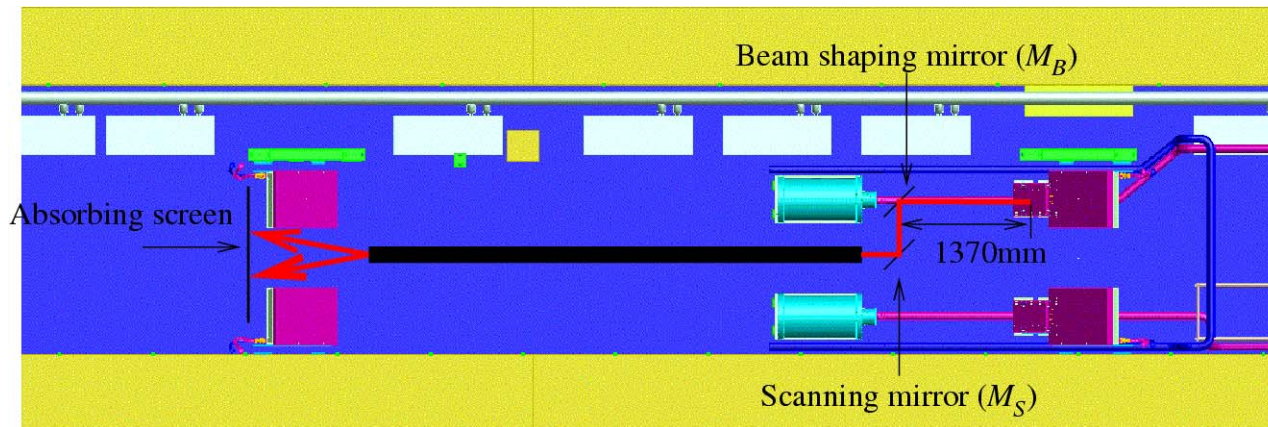


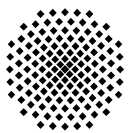
Operation under air
W7-X components:
cooled for cw operation

Optical transmission
system with focussing
mirrors and polarisers

Beam waist at the input of
the waveguide 17 mm

Waveguide: corrugated
square waveguide,
 $L = 6.62$ m, inner
width = 60.08 mm,
grooves: $w = 0.4$ mm,
 $p = 0.7$ mm, $d = 0.45$ mm

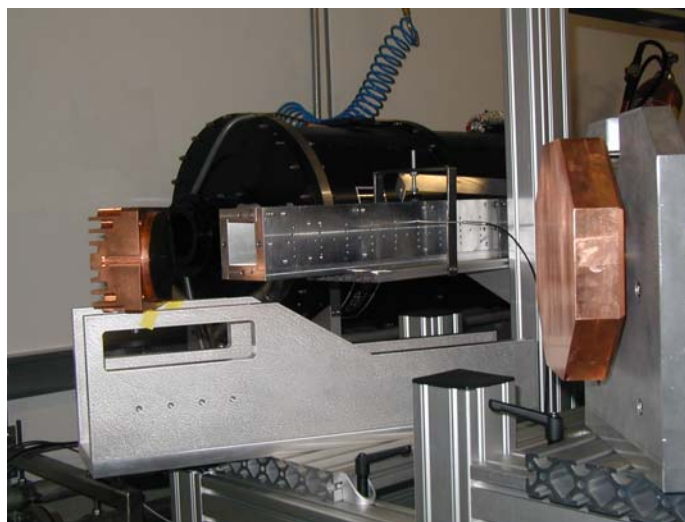
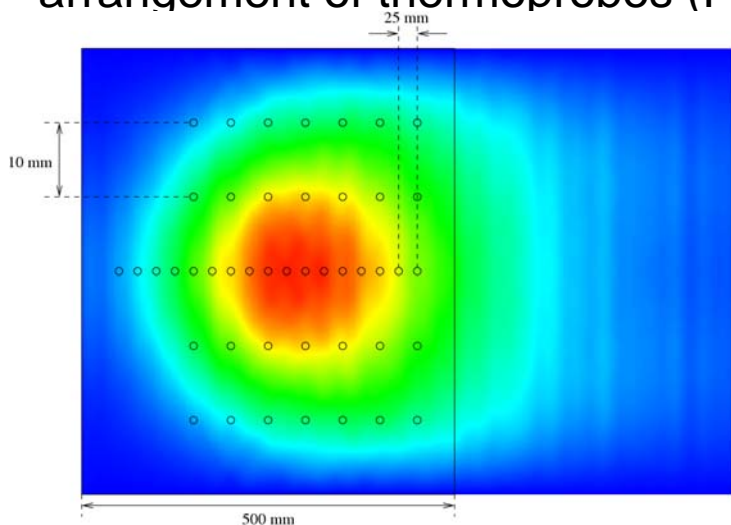
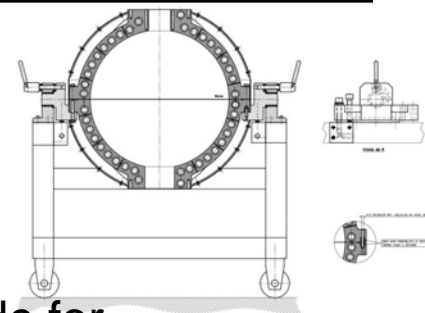


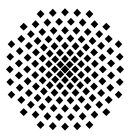


Diagnostics

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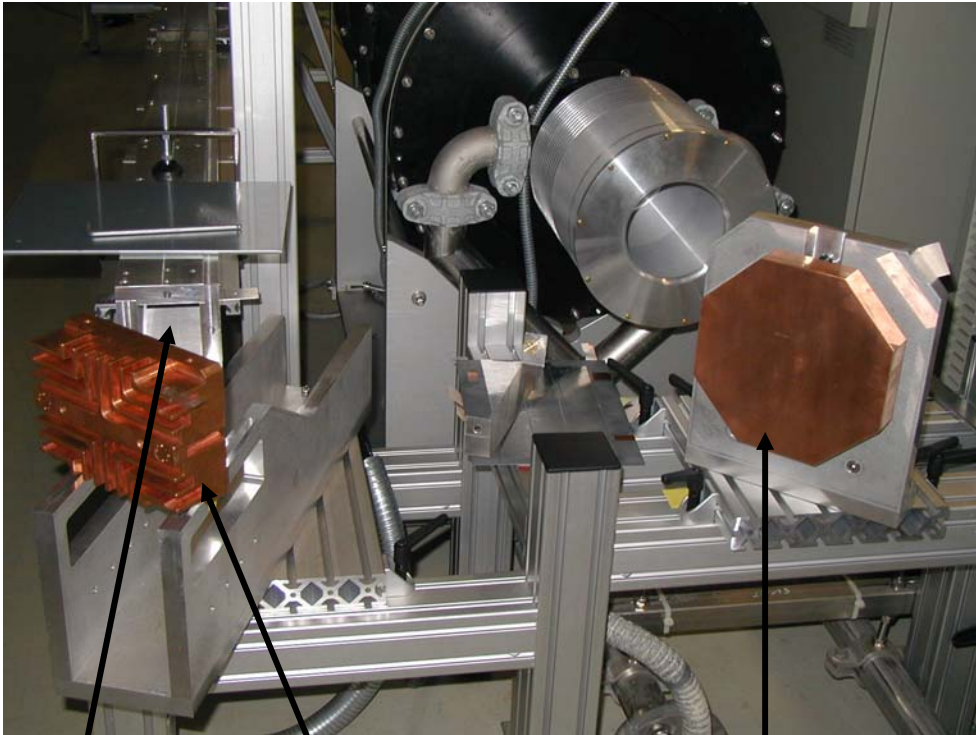
- Measurement of the beam pattern by thermographic recording of absorbing screen
- Arc detectors at the input and output of the waveguide
- Calorimetric measurements of the power at the end of the waveguide for different angles
- Waveguide coupler on scanning (input) mirror (75 x 125 mm)
- Temperature measurement near the inner surface of the waveguide: arrangement of thermoprobes (PT 100) in the area of highest heat load





Some pictures of the set-up

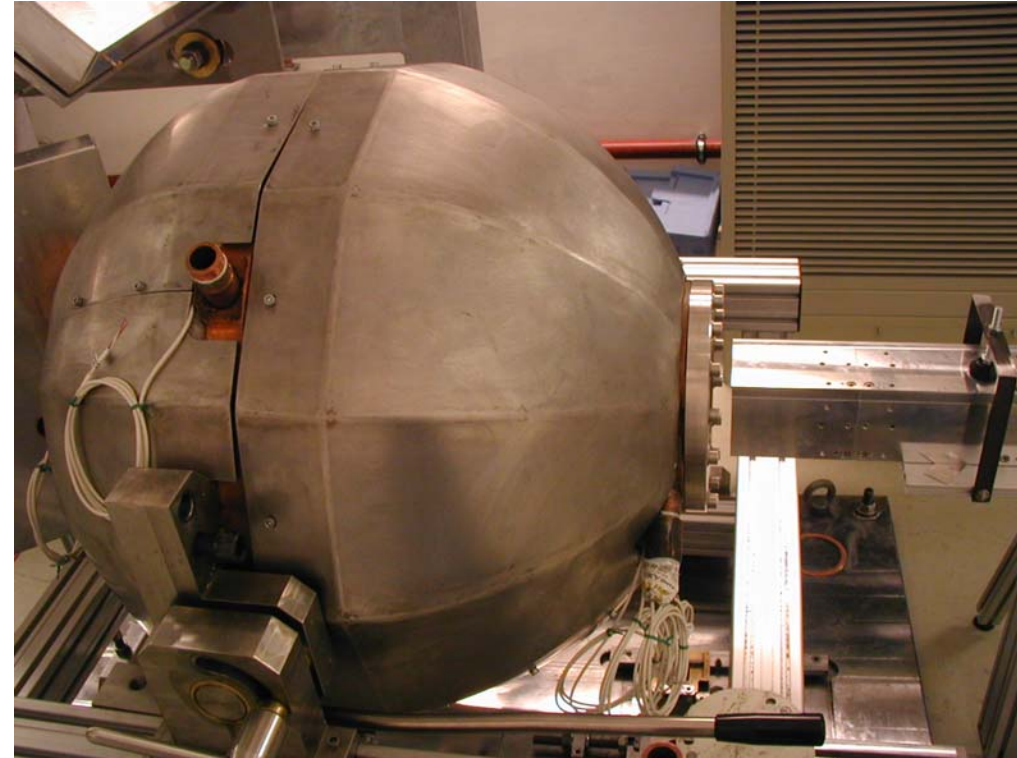
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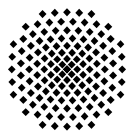
Waveguide entrance

Scanning mirror (M_s)

Beam Shaping mirror (M_B)



Load for calorimetric measurements



Temperature increase of waveguide wall *IPF*

Pulse length: 8 s, ~500 kW,
 $\varphi = 11.6^\circ$

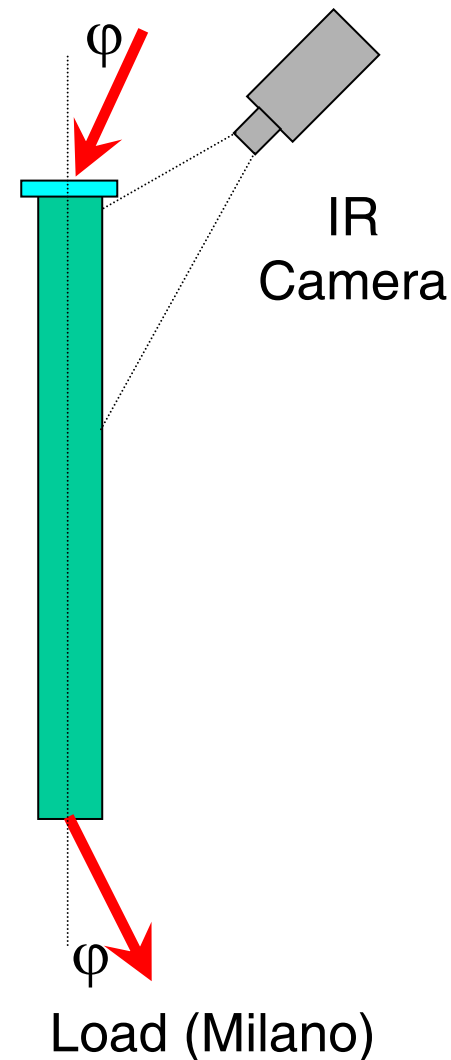
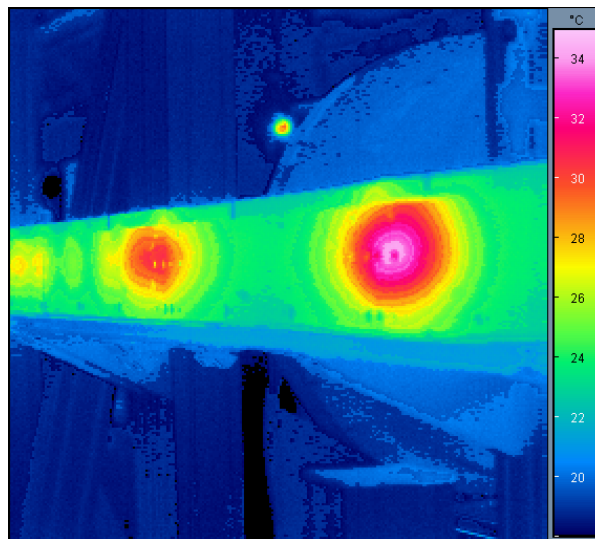
parallel Polarisation (E-field in scanning plane)

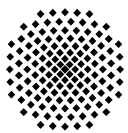
Monitoring of the temperature of the outer surface of the waveguide wall

Second and fourth (sixth) reflexion visible

Rectified image of the outer surface of the waveguide

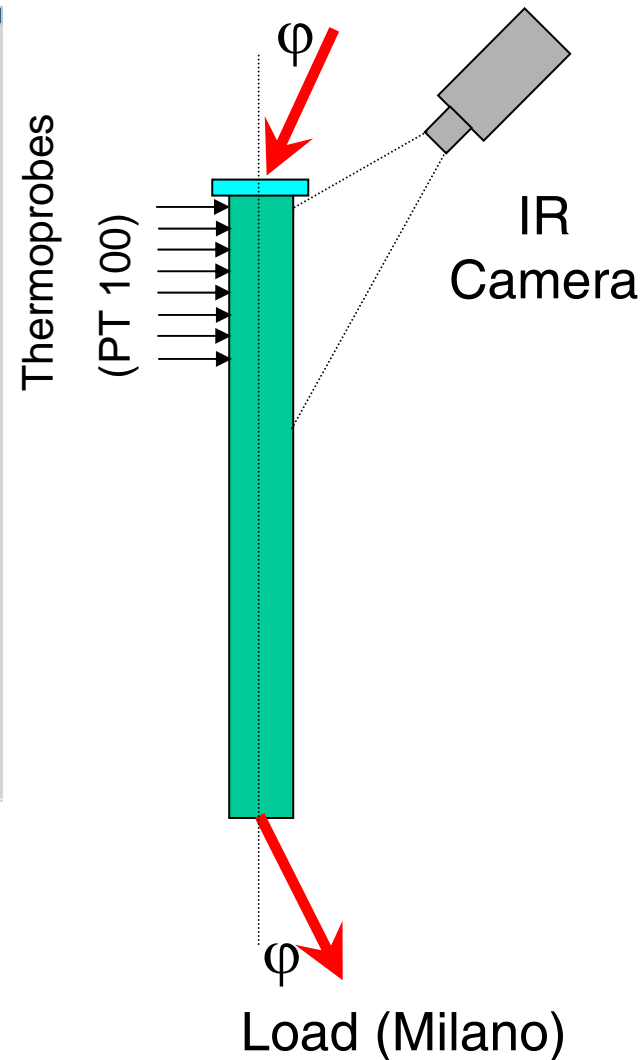
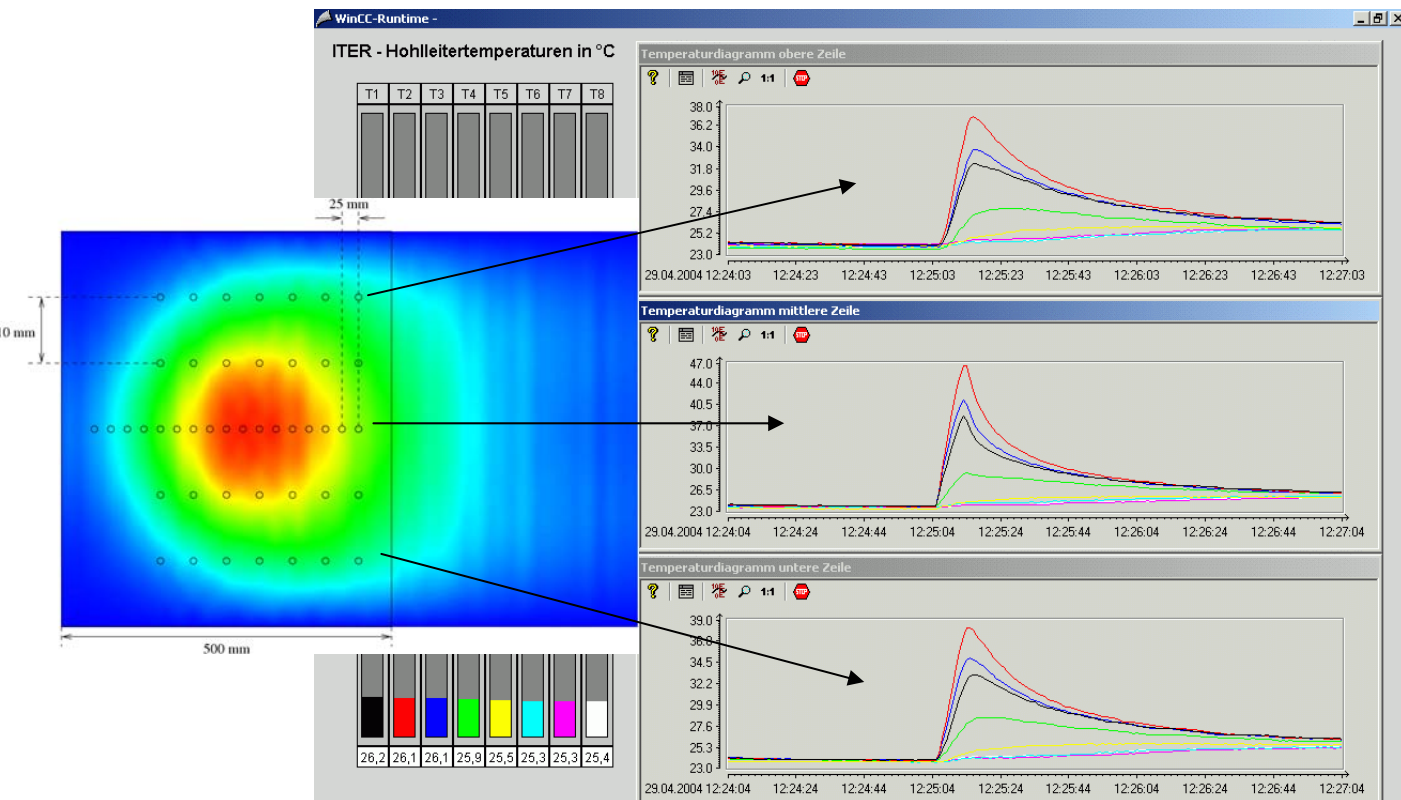
Calculated power density at the inner waveguide wall



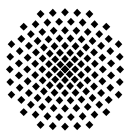


Temperature increase of inner wall

IPF

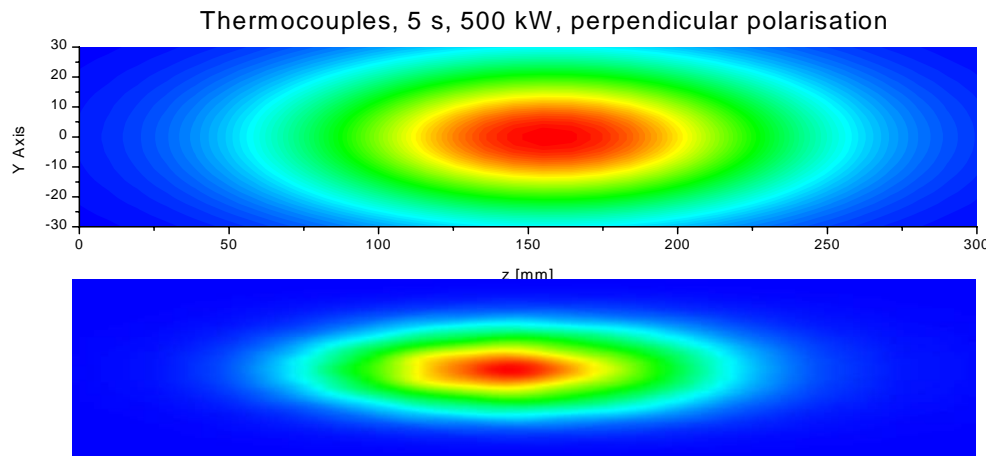
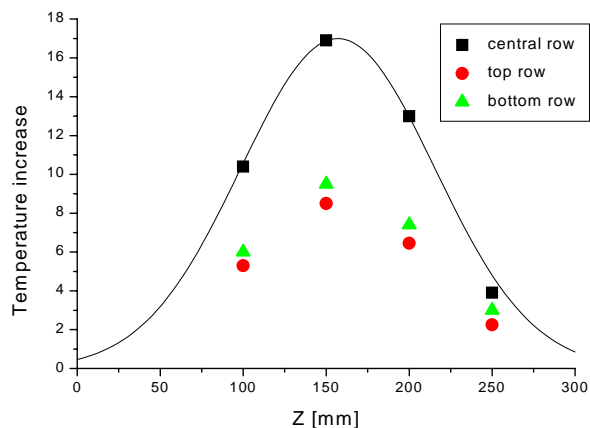


Pulse length: 8 s, ~ 500 kW, $\phi = 11.6^\circ$
parallel polarisation



Estimation of Ohmic losses

IPF

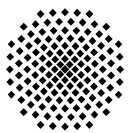


Straight forward integration of temperature distribution (Gaussian fit of thermocouple values) of the first reflection (neglecting heat exchange due to different temperature gradients within the wall and assuming a constant temperature profile across the wall)

gives: $P_{\text{Loss, ||}} = 0.9 \text{ kW}$ (parallel polarisation)

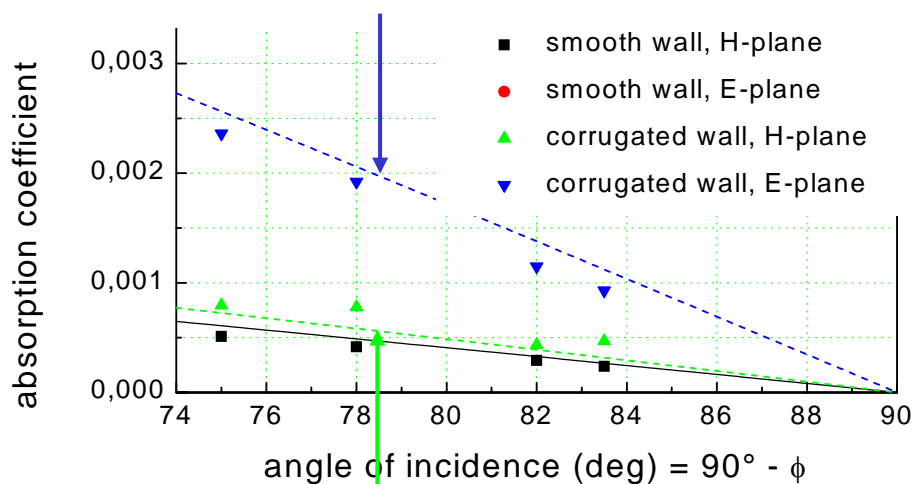
$P_{\text{Loss, } \perp} = 0.3 \text{ kW}$ (perpendicular polarisation)

at $P_{\text{RF, total}} \approx 500 \text{ kW}$, one reflection



Total transmission efficiency for **perpendicular** and **parallel** polarisation
⇒ difficult to measure in high power tests: Stability of gyrotron output power, reproducibility of shots, precision of calorimetric measurement

Low power measurement of absorption coefficient with precise 3-mirror resonator set-up:



Low power results for absorption coefficient:

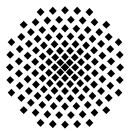
$$P_{\text{Loss, II}} / P_{\text{Loss, \perp}} = 3.5$$

High power tests:

$$P_{\text{Loss, II}} / P_{\text{Loss, \perp}} \approx 3.0$$

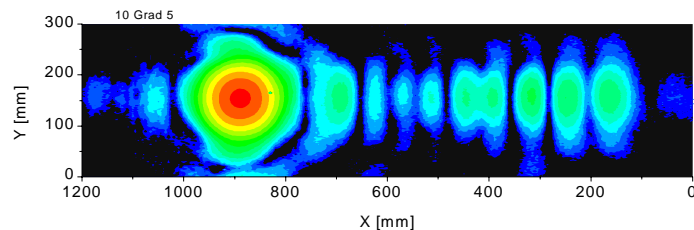
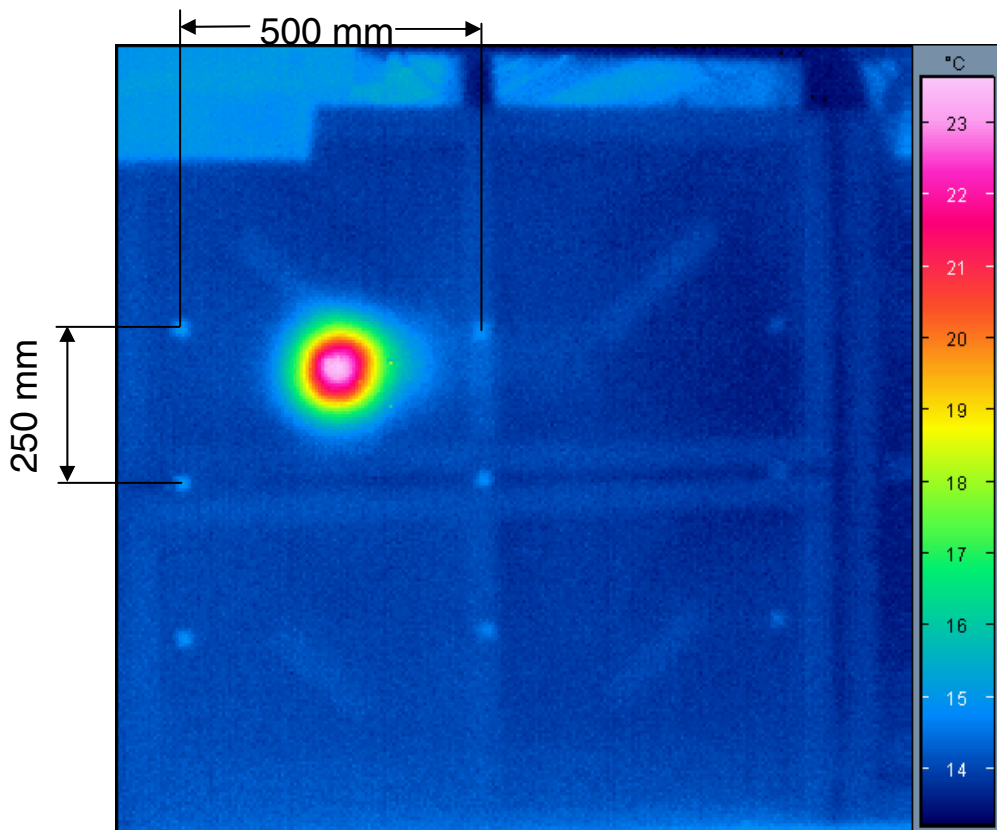
and

$$\Delta T_{\text{max, II}} / \Delta T_{\text{max, \perp}} \approx 3.1$$



Far-field pattern

IPF

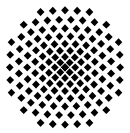


79.00	--	82.00
76.00	--	79.00
73.00	--	76.00
70.00	--	73.00
67.00	--	70.00
64.00	--	67.00
61.00	--	64.00
58.00	--	61.00
55.00	--	58.00
52.00	--	55.00
49.00	--	52.00
46.00	--	49.00
43.00	--	46.00
40.00	--	43.00



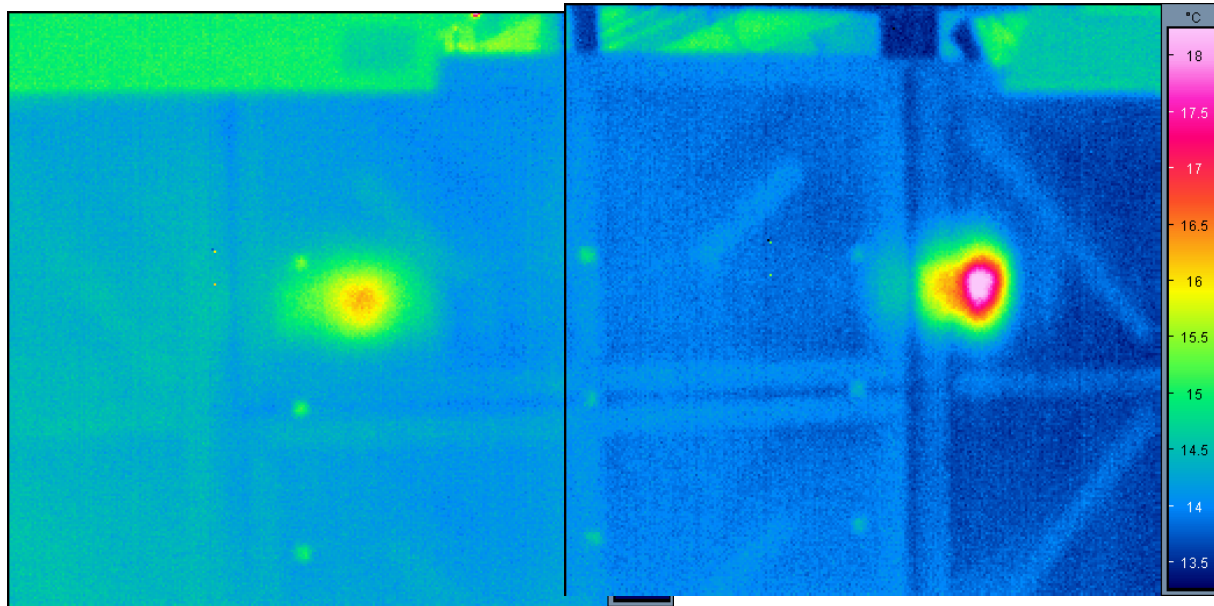
$\varphi = 10^\circ$, parallel polarisation,
distance to waveguide: 2175 mm

Low power measurement,
distance: 1700 mm

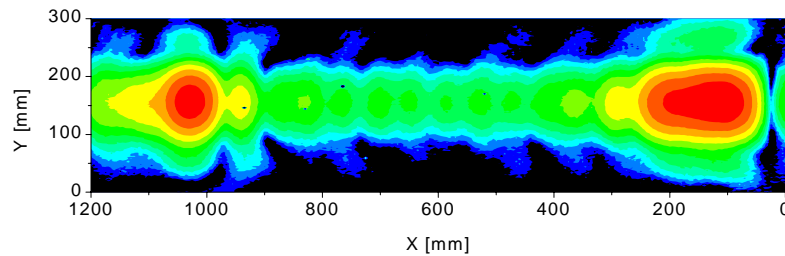


Far-field pattern

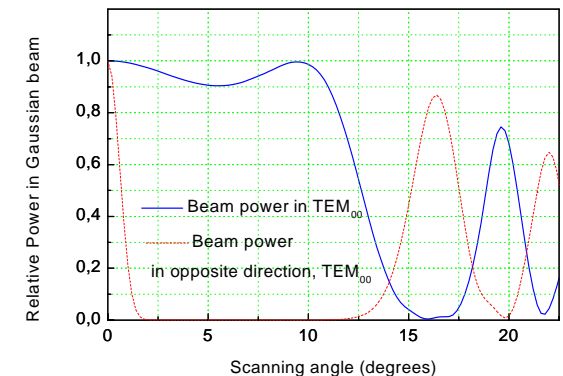
IPF

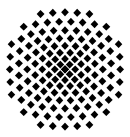


$\varphi = 15^\circ$, parallel polarisation, distance to waveguide: 2175 mm



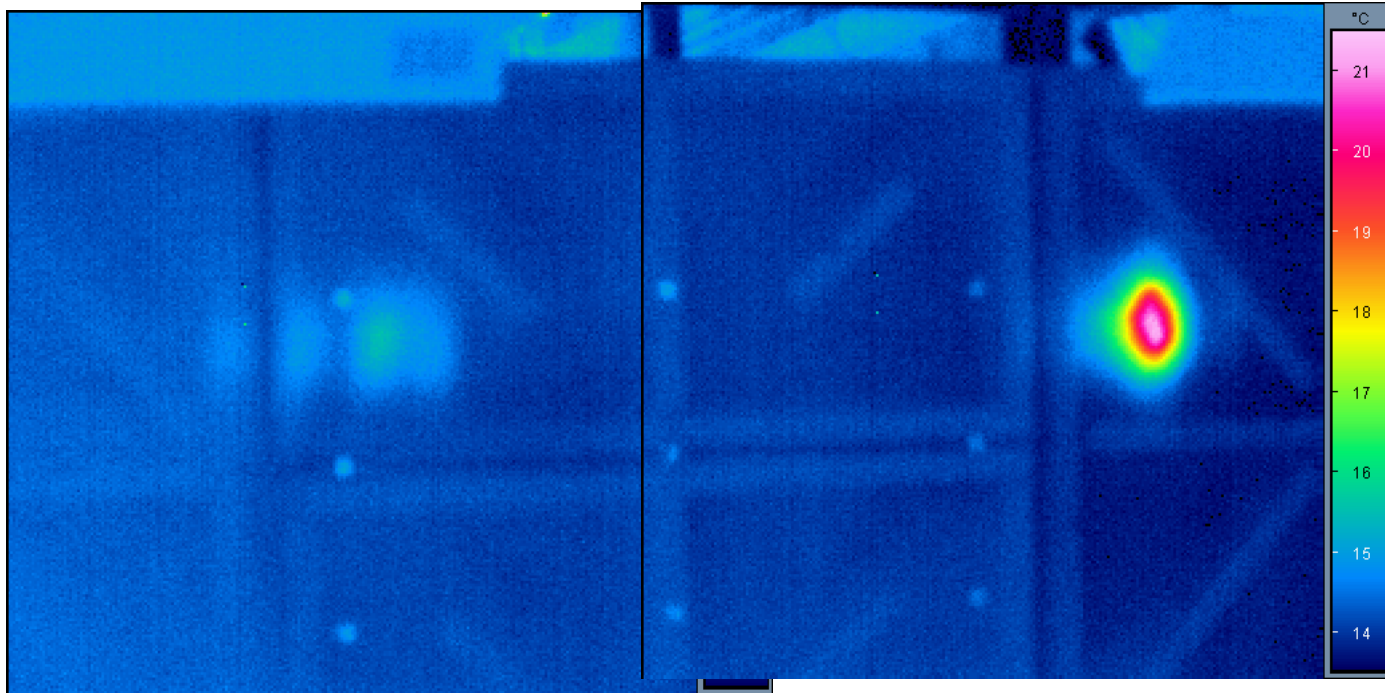
Low power measurement, distance: 1700 mm





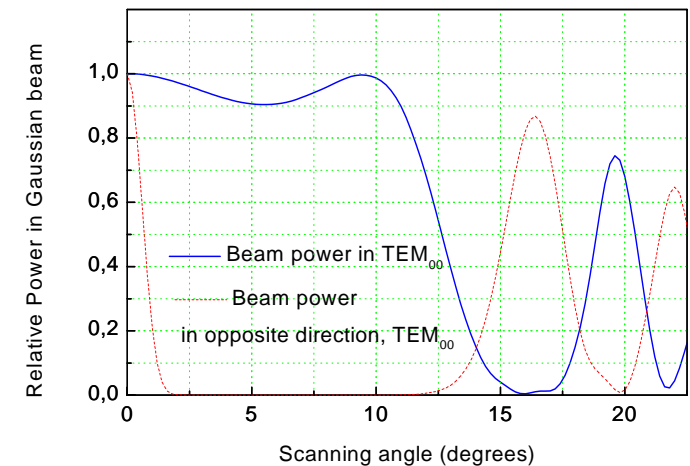
Far-field pattern

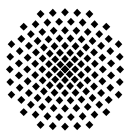
IPF



$\varphi = 17^\circ$, perpendicular polarisation

Main power in opposite direction





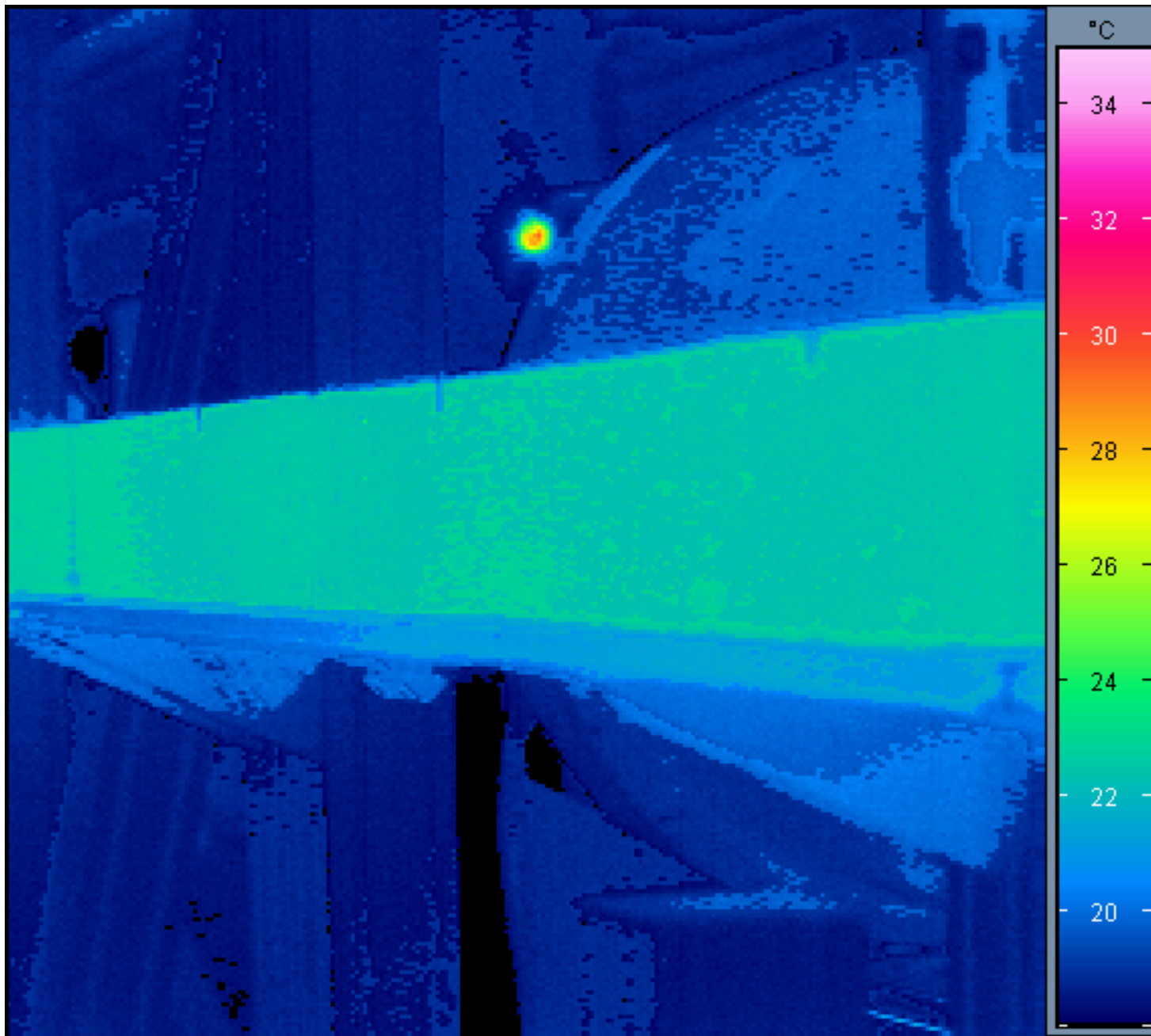
First high power tests have been performed successfully:

Pulse length up to 10 s with ≈ 500 kW (1 s, 700 kW), no limit due to arcing in the waveguide or the load (up to now)

Scanning angles: $0^\circ \dots 20^\circ$

Reasonable agreement of Ohmic losses with low power results

Analysis of data is not completed: more realistic model of temperature distribution in the waveguide wall, quantitative analysis of IR camera, far-field pattern



The 13th Joint workshop on ECE and ECRH, Nizhny Novgorod, May 17-20, 2004

