International Journal of Infrared and Millimeter Waves, Vol. 18, No. 8, 1997

D-BAND FREQUENCY STEP-TUNING OF A 1 MW GYROTRON USING A BREWSTER OUTPUT WINDOW

O. Braz,[1,2] G. Dammertz,[1] M. Kuntze,[1] and M. Thumm[1,2]

[1]*Forschungszentrum Karlsruhe (FZK), ITP*
Association EURATOM-FZK
Postfach 3640, D-76021 Karlsruhe, Germany
[2]*and Universität Karlsruhe*
Institut für Höchstfrequenztechnik und Elektronik
Kaiserstr. 12, D-76128 Karlsruhe, Germany

Received June 12, 1997

Abstract-- **In order to demonstrate the usability of gyrotron oscillators as frequency step tunable high power millimeter-wave sources, experiments on a 1 MW, 140 GHz $TE_{22,6}$ gyrotron with a built-in quasi-optical (q. o.) mode converter have been performed. By varying the operating parameters of the tube, a series of oscillations in the frequency range from 114 GHz to 166 GHz were excited. To avoid reflections, caused by the required vacuum barrier window, the gyrotron was equipped with a Brewster window. The achieved output power levels between 0.85 and 1.05 MW are compared to measurements carried out with the same tube using a conventional single-disk window. These experiments showed that even by using a q. o. mode converter, the influence of window reflections on the gyrotron oscillatory behavior cannot be removed completely.**

Keywords: **Gyrotron, Brewster window, single disk window, frequency step-tuning**

INTRODUCTION:

Electron Cyclotron Resonance Heating (ECRH) is one of the most important candidates for plasma heating, non-inductive current drive, profile control and start-up of the plasma current in the next generation of fusion plasma machines such as the ITER tokamak. To meet these requirements with a maximum of efficiency it will be necessary to heat the fusion plasma at different positions. This can be achieved either by radiating fixed frequency millimeter (mm)-wave power via a movable antenna (mirror) into the plasma, or by applying mm-wave power at different frequencies. Since the magnetic field of the tokamak decreases from the inner to the outer torus wall, so too does the electron cyclotron resonance frequency. In addition, this second concept avoids the need for mechanical movable components in the nuclear environment inside the torus.
In order to reduce the ECRH system costs, it is desirable to provide these frequencies by using only one type of mm-wave source, such as a stepwise frequency-tunable gyrotron oscillator. As an example, Table I shows a proposal made by the European Home Team for the ITER heating, current drive and

0195-9271/97/0800-1465$12.50/0

startup system. It is intended to use 3-frequency gyrotrons in both ECRH systems. The exact frequencies are given by the gyrotron cavity modes which can be excited at these frequencies. The thickness of the proposed single-disk water edge-cooled diamond window has been chosen in order to remove the window reflections at the main frequencies of 170 GHz and 114 GHz and to have low reflections at the two others.

ITER Heating and Current Drive

Frequency	131.4 GHz	150.7 GHz	170 GHz
Mode	$TE_{25,6}$	$TE_{28,7}$	$TE_{31,8}$
Diamond Window Thickness: 3.34 mm	7 $\lambda/2$	8 $\lambda/2$	9 $\lambda/2$

ITER Start-Up

Frequency	95.9 GHz	114.0 GHz	132.0 GHz
Mode	$TE_{19,5}$	$TE_{22,6}$	$TE_{25,7}$
Diamond Window Thickness: 3.31 mm	5 $\lambda/2$	6 $\lambda/2$	7 $\lambda/2$

Table I: Window designs for the ITER heating, current drive and startup.

The present article reports about model experiments on such step-frequency tunable 1 MW gyrotrons at a center frequency of 140 GHz.

THE $TE_{22,6}$ GYROTRON

Figure 1 shows a schematic outline of the gyrotron installed in its magnet. The gyrotron consists of a diode-type magnetron injection gun with a LaB_6-emitter. The velocity ratio α (transverse velocity component divided by the axial one) can be modified in the range from 1.1 to 1.7 by the change of the magnetic field gradient in the gun region. The beam tunnel is equipped with alternating staggered copper and highly RF-absorbing ceramic rings (aluminum nitride and 40% silicon carbide) in order to suppress parasitic oscillations in this region.

The operating mode has been chosen to be the $TE_{22,6}$ mode [1, 2] with a designed output power of 1 MW at a beam current of 40 A and a beam voltage of 80 kV (see Table II). The peak value of the Ohmic loss-density was calculated to be 3.5 kW/cm^2 for an output power of 1 MW and a surface temperature of 300°C. A factor of 1.3 is included to account for surfaces roughness, and RF losses of 15% between cavity power and output power were assumed in these calculations. The collector employs an insulation gap allowing a retarding voltage. This allows the study of efficiency enhancement by beam energy recovery in a single-stage depressed collector [3].

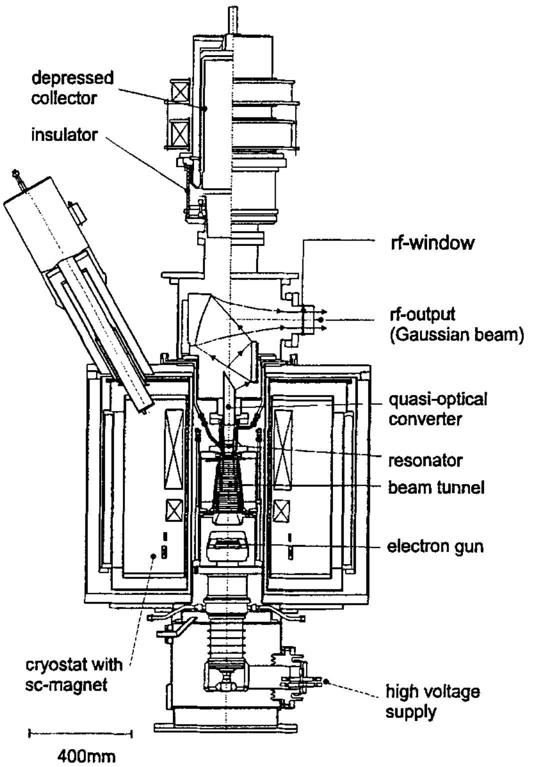

Fig.1: Schematical layout drawing of the $TE_{22,6}$-gyrotron

gun		cavity	
cathode voltage	80 kV	output power	1 MW
beam current	40 A	efficiency η	30%
emitter current density	3.6 A/cm^2	magnetic field (140 GHz)	5.5 T
emitter radius	45.2 mm	Ohmic loss density	3.5 kW/cm^2
cathode angle	21.48°	velocity ratio α	1.4
magnetic field	0.187 T	beam radius	7.93 mm
		beam thickness	0.53 mm
		compression ratio	36
		cavity radius	15.57 mm
		cavity length	15 mm
		input taper angle	3°
		output taper angle	2.5°
		diffraction Q-value	1000

Table II: Design values of the $TE_{22,6}$-gyrotron

In a gyrotron the frequency can be step-wise varied by changing the operating TE-cavity mode via variation of the cavity magnetic field. The different working modes should have approximately the same caustic radius $R = m/\chi'_{mp}\ R_{cav}$, where R_{cav} is the cavity radius, m the azimuthal mode index and χ'_{mp} the p-th root of the derivative of the Bessel function J_m, so that the coupling of the electron beam to the mm-wave electric field is comparably good.
The operating parameters of the gyrotron required for excitation of different cavity modes, and the measured frequencies, are summarized in Table III.

Cavity Mode	Main magnetic field [T]	Acceleration voltage [kV]	Frequency [GHz]	Relative Caustic Radius R / R_{cav}
$TE_{18,5}$	4.43	75.0	(114.20)	0.484
$TE_{19,5}$	4.59	80.6	117.80	0.495
$TE_{20,5}$	4.78	83.4	121.60	0.505
$TE_{21,5}$	4.91	83.4	125.30	0.515
$TE_{19,6}$	5.07	82.6	128.94	0.453
$TE_{20,6}$	5.25	84.0	132.62	0.463
$TE_{21,6}$	5.37	81.2	136.34	0.473
$TE_{22,6}$	5.49	81.2	140.10	0.482
$TE_{23,6}$	5.67	84.0	143.83	0.491
$TE_{24,6}$	5.83	84.8	147.50	0.499
$TE_{22,7}$	6.09	84.0	151.12	0.447
$TE_{25,6}$	5.97	83.4	151.23	0.508
$TE_{23,7}$	6.14	89.0	154.73	0.456
$TE_{26,6}$	6.15	85.4	154.94	0.456
$TE_{24,7}$	6.25	84.8	158.54	0.456
$TE_{25,7}$	6.37	80.6	162.30	0.473
$TE_{26,7}$	6.48	78.0	166.03	0.481

Table III: $TE_{22,6}$ gyrotron operating parameters required for frequency-step tuning at a beam current of approximately 47 A.

Due to the helical cut-antenna of the internal q. o. mode converter [4, 5], the different modes, which have to be launched into a linear polarized "Gaussian" beam profile, must have the same rotation. The q. o. launcher fixes its applicability to either right-hand (co-rotating with the electrons "-") or left-hand rotation (counter-rotating "+"). Because of the field distribution of the existing super-conducting magnet at FZK it was not possible to use a fully optimized rippled-wall q. o. launcher (Denisov-type). In order to couple out as much as possible of the excited mm-power, a shortened type, without the intention to achieve a pure Gaussian beam profile, was used. However, a Gaussian distribution can be obtained by applying a phase-correcting mirror outside the tube. Figure 2 shows the measured power distribution for the design frequency of 140 GHz at a distance of d = 300 mm from the window flange outside the gyrotron.

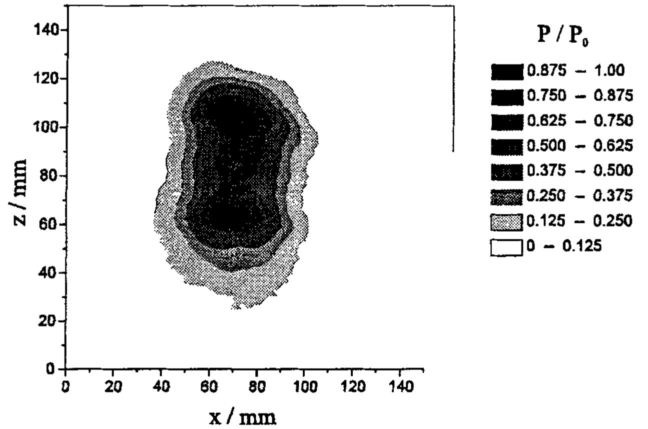

Fig. 2: Field pattern measured at 300 mm from gyrotron window flange.

Since the reflections at the Brewster window plate only can vanish if the oblique incident beam is linearly polarized, it is important to notice that the excited TE-modes as well as it's launched beam pattern don't show any mentionable part of an longitudinal electric field (cross polarization). This can be proven easily by placing a polarization grid in the gyrotron output beam.

WINDOW DESIGN AND HIGH POWER MEASUREMENTS

Due to the available power supply at FZK, the possible pulse length for the high power experiments are currently limited to several milliseconds. Depending on the required beam current of approximately 47 A, and an accelerating voltage of 80 kV for a RF power of 1 MW, a maximum pulse length of 10 ms can be reached. Due to the low dielectric losses of the common window materials, this results in negligible thermal restrictions. Therefore no special attention had to be paid to the cooling system of the window and the thermal conductivity of the window material itself. For this reason Infrasil 301 from Heraeus, a fused silica quartz glass with guaranteed isotropic material properties, was used. Quartz glass is attractive due to its low permittivity, low loss tangent and low cost.

The relevant material properties are listed in Table IV. Sapphire, silicon-nitride and diamond are included to show some alternative materials suitable for CW demands.

Material	fused silica SiO_2	Si_3N_4 composite (SN-B).	sapphire (Al_2O_3) s.c.	Diamond (PACVD) p.c.
Thermal Conductivity k [W/mK]	1.4	59	40	1900
Ultimate Bending Strength σ_B[MPa]	67	800	410	600
Poissons Number ν	0.17	0.28	0.22	0.1
Density ρ [g/cm³]	2.2	3.4	4.0	3.5
Specific Heat Capacity c_p [J/g K]	0.75	0.6	0.8	0.5
Young's Modulus E [GPa]	73	320	385	1050
Therm. Expans. Coeff. α [10^{-6}/K]	0.5	2.4	5.5	0.08
Permittivity (145 GHz) ε_r'	3.81	7.9	9.7	5.66
Loss Tangent (145 GHz) $\tan\delta$ [10^{-5}]	20-50	24	20	2

Table IV: Thermophysical, mechanical and dielectric parameters of window materials.

- conventional single disk window:

In order to decrease the window reflections at least for a few frequencies, a conventional single disk window, manufactured by UKAEA, was mounted perpendicular to the RF beam as an output window. Due to the circular shape and the moderate diameter of 104 mm, the edge of the disk could be metallized and brazed to a water-cooled housing (see Fig. 3).

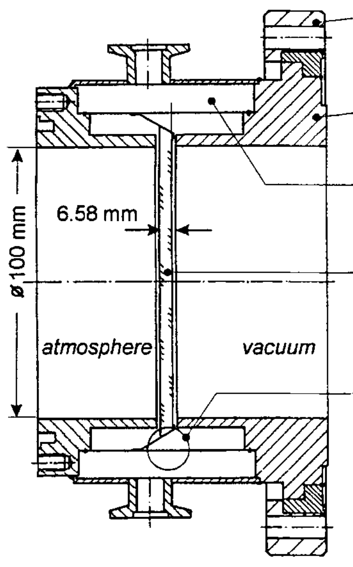

Fig. 3: Technical drawing of the conventional edge-cooled single-disk quartz glass window.

By choosing a window thickness of $d = 6 \cdot \lambda_n = 6.58$ mm at the gyrotron design frequency of 140 GHz, the transmission characteristics for 117 GHz, 128 GHz, 140 GHz, 152 GHz and 163 GHz are optimized. Figure 6 shows the calculated dependency for the window reflection and the measured gyrotron output power versus the frequency and the applied cavity magnetic fields respectively. One has to keep in mind that only oscillations at discrete frequencies can be excited in a gyrotron cavity. However, it is obvious that only modes located at frequencies with low window reflections are coupled out with power levels up to 1 MW. For the comparison with measurements performed employing the Brewster window, it is important to notice that all other modes are significantly below this power level.

• Brewster window

In a second step the gyrotron was equipped with a Brewster window. The, with respect to the mechanical stress, unnecessarily big thickness of 7 mm of the quartz glass window plate simply was taken from the standard thickness available from Heraeus. Figure 4 shows a schematic drawing of the complete window assembly.

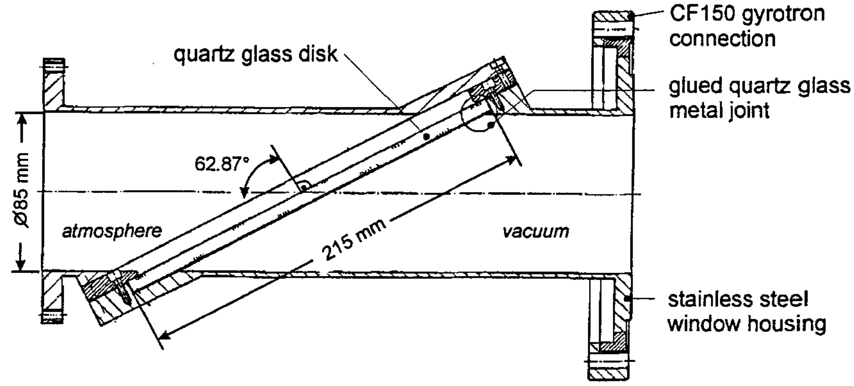

Fig. 4: Technical drawing of Brewster quartz glass window.

In order to achieve a simple window design, and due to the negligible thermal demands, the quartz plate was glued to the metal housing without any additional cooling system. The angle between the incident beam and the normal to the window plate was chosen according to Snell's law of refraction for vanishing reflections in case of parallel polarization:

$$\Theta_{Brew} = \arctan\left(\sqrt{\varepsilon_2 / \varepsilon_1}\right) = 62.87°$$

where $\varepsilon_2 = 3.81$ is the permittivity of quartz glass and $\varepsilon_1 = 1$ is that of air or vacuum. The dependency of the reflection coefficient versus frequency and the angle of incidence are shown in Figure 5. It is interesting to notice that the reflections in a band from 55° to 70° are below 5 % independent from frequency. Figure 5 b shows the excellent agreement between the calculated and measured reflection curve for a frequency of 140 GHz. Since all rays are reflected at the same angle as they fall onto the plate surface, it is extremely unlikely that any significant part is scattered back into the gyrotron.

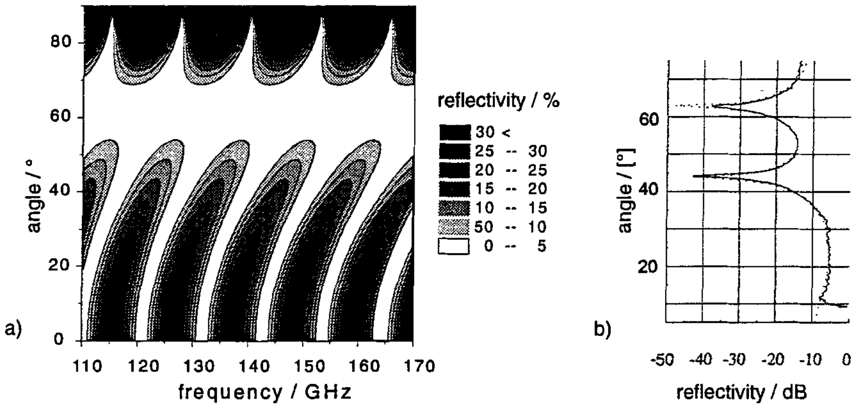

Fig. 5: a) Reflectivity of a 7 mm thick fused quartz plate versus frequency and angle of incidence.
b) Measured reflectivity at a frequency of 140 GHz

The significant influence on the mode spectrum of the measured output power can be seen in Figure 6. Practically all modes are coupled out with the same intensity. Only at frequencies where the radial mode indices change (see Figure 7), the power levels are slightly reduced.

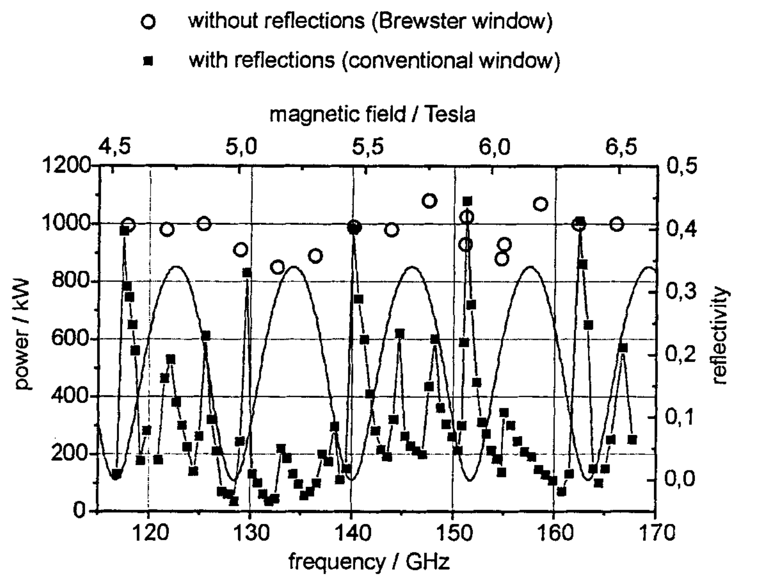

Fig. 6: Reflectivity of the conventional single disk window versus frequency and calorimetrically measured output power versus magnetic field.

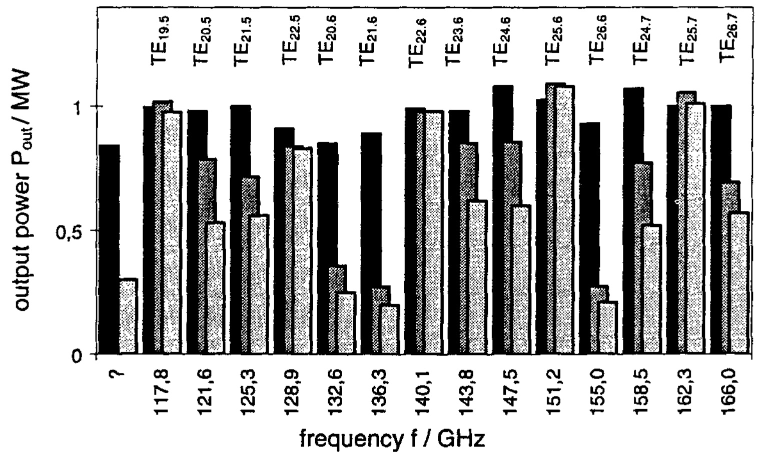

Fig. 7: Output power at different frequencies for
a) Brewster window (dark bars)
b) conventional window (light bars) and values corrected for reflections (gray bars).

COMPARISON BETWEEN THE TWO WINDOW DESIGNS

To be able to compare the gyrotron cavity internal field levels for corresponding modes in the two different designs, the values measured with the single disk window are corrected for the window reflection. ($P_{cor} = P_{out} / (1 - r^2)$). The results are summarized in Figure 7.

Only for vanishing window reflections the same results were achieved. Whereas modes located at high reflections are coupled out even less than that expected by the correction. These results indicate that even by using a q. o. mode converter, window reflection cannot be neglected.

Another advantage of the Brewster window assembly can be seen in Figure 8. For minimal reflections in the conventional design the window plate has a resonant thickness with respect to the wavelength inside the material. This, of course, results in a local maximum of absorption given by the following formula:

$$A \approx \frac{\pi \cdot f \cdot d \cdot \tan(\delta) \cdot \left(1 + \varepsilon_r^{'}\right)}{c_0}$$

where f is the resonance frequency, d is the plate thickness and c_0 is the velocity of light in vacuum. For a plate mounted at the Brewster angle each ray passes the window material only once, which results in the following equation:

$$A \approx \frac{2 \cdot \pi \cdot f \cdot \sqrt{\varepsilon_r} \cdot \tan(\delta)}{c_0} \cdot \frac{d}{\sin\left(\Theta_{Brewster}\right)}$$

From these equations it is obvious that the amount of power absorbed in the conventional window, compared to that in a Brewster window of similar thickness, increases at a stronger rate with permittivity. Figure 9 shows the ratio of the two absorptivities as a function of the disk permittivity. It can be seen especially for a sapphire disk, that the Brewster window could reduce the absorption by a factor of 1.6. In addition the RF spot size on the window is increased due to the oblique incidence. This results in a lower peak temperature and less critical thermal stress conditions.

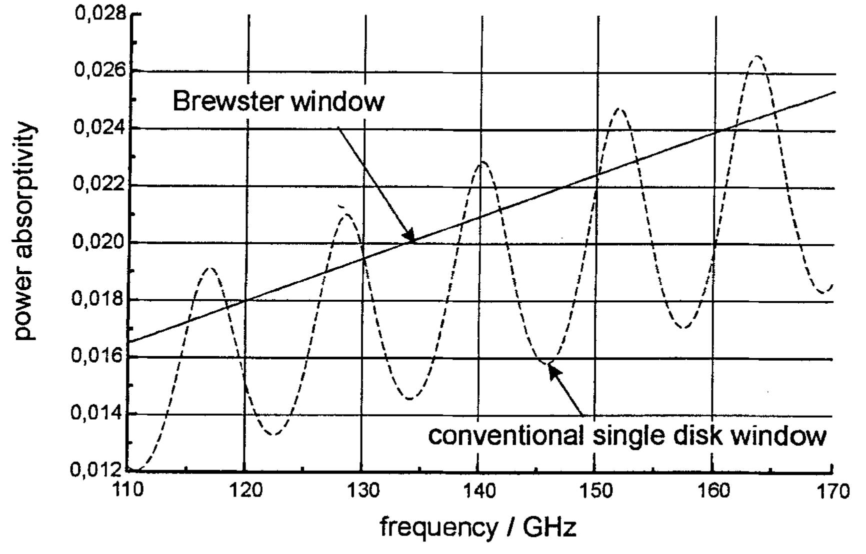

Fig. 8: Dependence of absorbed power in fused silica quartz glass windows (d = 6.58 mm) on frequency.

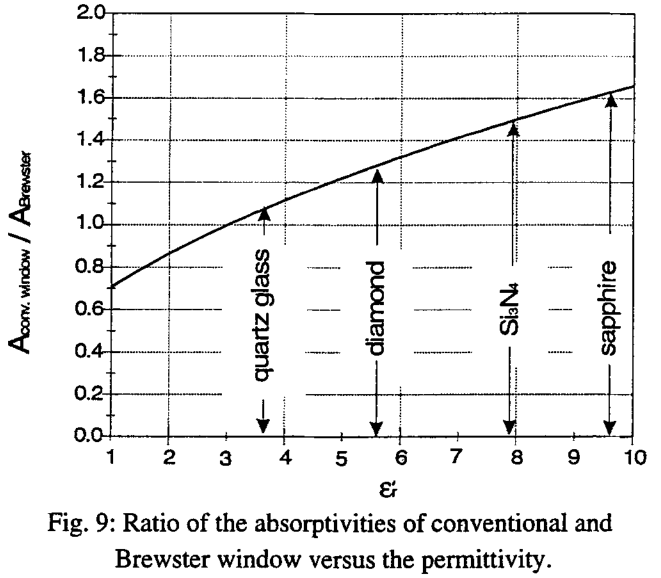

Fig. 9: Ratio of the absorptivities of conventional and Brewster window versus the permittivity.

CONCLUSIONS

To check the influence of window reflections on the oscillatory behavior of a step-wise frequency tuned high power gyrotron (design values $TE_{22,6}$ - 140 GHz, 1 MW) with a built-in q. o. mode converter the tube was fitted with two types of output windows. By choosing the appropriate operating parameters a series of cavity modes oscillating at frequencies in the range from 114 GHz to 166 GHz were excited.

For reference measurements a conventional single disk window, with optimal transmission characteristics for only a small number of frequencies, was mounted. To estimate the generated power levels in the gyrotron the measured output power was corrected for the window reflections.

By exchanging this window with a Brewster window the output spectrum was improved significantly. Oscillations located at frequencies where the conventional design shows high reflections are coupled out with higher power levels than what could have been expected by taking the window reflections into account. These results indicate that even by using a q. o. mode converter the influence of window reflections on the gyrotron oscillation behavior cannot be removed completely.

In addition to the excellent mm-wave transmission characteristics the Brewster window offers the opportunity of a low absorption coefficient. Together with the enlarged mm-wave beam spot size on the window (due to the oblique incidence) this results in much lower thermal stress conditions (especially for window materials with a high permittivity).

REFERENCE

[1] Gantenbein, G., et al., Int. J. Electronics, **78**, (1995), 771-787.

[2] Thumm, M., et al., Proc. 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), USA, (1995), 281-282.

[3] Piosczyk. B., et al., IEEE Trans. on Plasma Science, PS-24, (1996), 579-585.

[4] Möbius, A., Thumm, A., Gyrotron output launchers and output tapers in Gyrotron Oscillators, C. Edgecombe, ed., Taylor & Francis, London 1993, Chapter 7, 179-222.

[5] Thumm, M., et al., Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, Germany, (1996), AT6.