Design and development of a broadband real-time 100 – 175 GHz frequency measurement system for gyrotron diagnostics

Abstract— **A broadband real-time frequency measurement system for frequency diagnostics on megawatt gyrotrons has been developed. It is based on a broadband superheterodyne receiver operating between 100 GHz and 175 GHz. The aim is to determine the oscillating cavity mode. The concept is introduced and first measurements are presented.**

Keywords—**Gyrotron, broadband receiver, contiguous filter bank, frequency time analysis, high-power microwaves.**

I. Introduction

The name "Gyrotron" is composed of the Greek words "**Gyro**s" (English: circle) and "Elek**tron**". The operation mechanism is based on the interaction of the gyrating electrons with the magnetic field inside a cavity (Electron Cyclotron Maser, ECM). The advantage of gyrotrons is the feasibility of very high power levels because cavities with a large diameter compared to the wavelength are used. The magnetic field in the cavity determines the output frequency. Therefor large diameters and high order modes can to be used. The selected mode minimizes the wall currents which leads to a minimum of losses. The principle can be used for oscillators and amplifiers. In this paper high power oscillator tubes are discussed. They produce output powers up to megawatts at wavelengths in the range of millimeters [1], [2]. The main application is plasma heating in large fusion devices. Different gyrotrons [3], [4], [5], [6] are currently under development at Forschungszentrum Karlsruhe for specific requirements. A minor field is materials processing [7].

The aim of a gyrotron experiment is to show the conformity of theory and experiment. The output power and frequency are the key parameters to be monitored. The power measurement is done with a calorimeter which is integrated into the liquid cooled load. The frequency measurement shows the output frequency what corresponds to an operating cavity mode and at the same time it can be observed if any other competing modes are resonating. In addition thermal effects can be detected through the frequency shift during longer periods of operation. This is for example the increase of the cavity's diameter during long pulses which results in a frequency decrease. The principle of the frequency measurement is illustrated on the basis of the block diagram and the feasibility is shown through the first measurements.

As the frequency is above 100 GHz a direct, exact frequency measurement is extraordinary challenging. The solution is to convert the gyrotron's output to an intermediate frequency (IF) where a measurement is easier. A wide band of several GHz has to be observed and at the same time an exact measurement with a frequency resolution in the range of kHz has to be performed.

Different frequency measurement systems were investigated whether they can fulfill the needs. As the gyrotrons currently developed are pulse operated a quasi real-time system is needed. A spectrum analyzer [8] is a standard equipment but the disadvantage is that the time required for scanning is too long. Acousto optical spectrometers [9] have an excellent frequency resolution and the measurement time is just dependent on the interpretation of the data; but it can not separate two input signals if they are present simultaneously. An instantaneous frequency measurement (IFM) receiver [10] can monitor a large bandwidth with a good resolution but two or more input signals with similar level can not be separated. The spectrum analysis in the time domain does not provide the required bandwidth because appropriate analog-to-digital converters are not available; another disadvantage would be the time shift between measurement and result — but it could be used for line width measurements [11].

A filterbank spectrometer [12] does real-time processing; the bandwidth can be chosen with the filter bandwidth; but it can be costly. A frequency counter with its gate time is useless for this application, but the advancement to a frequency and time interval analyzer [13] counts the frequency continuously and works in quasi real-time.

The frequency measurement system combines the advantages of a filterbank spectrometer which is used for a broadband measurement with a coarse frequency resolution and a frequency and time interval analyzer which is used for a narrowband measurement with a fine frequency resolution. As both measurement systems are working at lower frequencies the input signal has to be down converted. A superheterodyne receiver architecture is used.

The real-time measurements which are performed at an IF up to 18 GHz pay special attention to three major aspects:

- broadband frequency measurement with a coarse frequency resolution,
- narrowband frequency measurement with a fine frequency resolution, and
- measurement of the pulse length.

II. Principle of the gyrotron

Gyrotrons are vacuum electron tubes [2], [14]. An electron beam emitted by the electron gun is shaped into a cylindrical hollow beam. It provides energy to the electromagnetic (EM) field in the cavity. Figure 1 shows the cross section of a modern gyrotron with radial output.

The electron gun at the bottom of figure 1 emits an annular electron beam with the optimized beam radius r_B. The axial magnetic field (left side figure 1) which has its maximum in the cavity, forces the electrons onto helical trajectories. It is essential for the interaction inside the cavity that the helical radius r_L, also called Larmor radius, is of a smaller magnitude than the beam radius r_B. The Larmor radius r_L can be calculated by the mass of an electron m_e, the charge of an electron e, the axial magnetic field B, and the velocity $v_\perp$ of the electrons orthogonal to the magnetic field:

$$r_L = \frac{m_e v_\perp}{eB} \tag{1}$$

The electrons pass through the compression zone before they enter the cavity. Because the time invariant magnetic field in the compression zone rises, the transversal velocity of the electrons is increased and at the same time the beam radius decreases. So the rotation of the electrons, called gyration here, is accelerated. The frequency of gyration is called electron-cyclotron-resonance-frequency Ω_c:

$$\Omega_c = 2\pi f_c = \frac{eB}{m_e \gamma} \tag{2}$$

As the electrons are already in the order of the speed of light, the mass of the electron is relativistic. This fact is taken into consideration by the relativistic factor γ:

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} \tag{3}$$

Energy conservation forces a decrease in the velocity of the electrons in longitudinal direction, while the transversal velocity increases.

The cavity shown in figure 1 is a cylindrical waveguide which is located in the bore hole of the superconducting magnet. The cavity is open at the bottom and the top so that the electrons can pass through. At the bottom, which points toward the electron gun, the diameter narrows. The EM wave is reflected back into the cavity because this mode can not propagate (cut-off). The upper side of the cavity is up tapered, so a part of the EM wave is reflected back into the cavity. The other part is coupled into the waveguide antenna.

Inside the cavity there is an interaction between the electron beam and the EM field. Energy is passed from the transversal velocity of the electrons to the transversal electric mode. There are two fields that coexist in the cavity: the static magnetic field and the EM field, which is synchronous to the rotation of the electrons. Depending on the phase shift of the electrons in relation to the dynamically changing EM field, the electrons are either accelerated and take over energy from the EM field, or they are decelerated and pass their rotation energy to the EM field. When the relative phase shift is statistically distributed there is no overall energy exchange. During the process of energy exchange the electron-cyclotron-resonance-frequency changes because the relativistic factor γ changes. If the frequency in the EM field is just a little higher than the electron-cyclotron-resonance-frequency the statistically distributed

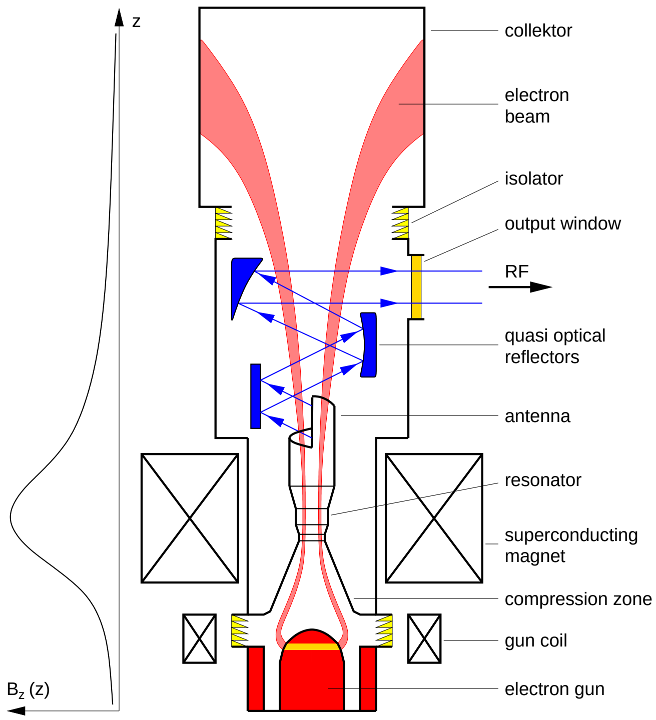

Fig. 1. Cross section of a gyrotron with radial output.

phase shifts of the electrons are focused such that energy from the electron beam is passed to the EM field. The phase shift of the electrons decreases. This is called electron phase bunching.

The coupling to the antenna is done through a taper from the cavity diameter to the waveguide antenna. This antenna, also called launcher, transforms the guided mode into a high frequency beam [1], [2]. The antenna also separates the electron beam from the EM wave which is focused on the first of three quasi optical reflectors. They transform the EM wave into a Gaussian free-space-mode which leaves the gyrotron through the output window. The window separates the vacuum inside the tube whereas the EM beam passes with a minimum of losses and reflections.

The electrons passing through the resonator are guided by the magnetic field. Thus, the target area on the collector can be controlled through the profile of the magnetic field. To enhance the efficiency of gyrotrons, beam energy is recovered by a depressed collector. The principle is that the full accelerating voltage is between the cathode and the cavity section and not the collector. The collector is on a lower potential which is sufficient to attract the electrons.

The static magnetic field is provided by a superconducting solenoid magnet which is situated around the cavity. The amplitude of the axial magnetic field, as shown at the left side of figure 1, rises from the gun region to the maximum in the cavity and decreases towards the collector. Additional coils are placed around the gun to focus the annual electron beam.

The coils in figure 1 which are situated outside the vacuum provide a static magnetic field. The gun coil which is situated around the electron gun focuses the electron beam. The superconducting solenoid magnet is situated around the cavity. Its static magnetic field along the axis of the gyrotron is small at the electron gun, increases to a maximum in the cavity, and decreases towards the collector as shown in figure 1 on the left side.

III. Concept of the frequency measurement system

As discussed above two different systems carry out the measurement to fulfill the needs: filterbank spectrometer and frequency time analysis. First the input signal has to be downconverted. Figure 2 shows the block diagram.

A. Superheterodyne Receiver

A very small amount of the gyrotron's output power is coupled into a waveguide and propagates to the frequency measurement system as shown on the left side of figure 2. To extend the dynamic range of the frequency measurement system a variable waveguide attenuator is located in front of the isolator. As stray radiation is mostly used for the frequency measurement the power level may differ. The attenuator is set to protect the downconverter. The next stage, an isolator, provides a better match and suppresses reflected waves. As shown in figure 2 the isolator is followed by the downconverter. It converts the input frequency range of 100 GHz to 175 GHz down to the IF band. As the IF bandwidth is limited to 18 GHz the downconverter converts an input band of 36 GHz (upper and lower sideband of 18 GHz each) dependent of the local oscillator (LO) frequency to the IF band of 100 MHz to 18 GHz. To achieve such a broadband system the LO signal has to be variable in a wide range. In order to use a source with a rather low frequency the mixer itself works on the third harmonic and at the LO port a frequency tripler is flange mounted. All together the LO-signal is multiplied by nine and a Ku-band source generated by a commercial available synthesizer is used. As the maximum level of the generator is not sufficient to drive the passive tripler an amplifier is inserted between synthesizer and LO-port. The concept of the harmonic mixer with the tripler at the LO port makes it possible to build up such a broadband receiver. From the downconverter's output the signal with a frequency range of 100 MHz to 18 GHz as labeled in figure 2 propagates into a coaxial attenuator to optimize the match between the mixer's output and the following amplifier. This amplifier divides the signal into two paths: one for the filterbank spectrometer and one for the frequency time analysis. The combination of amplifier and splitter has the advantage that the feedback of the two paths to each other is minimized to 30 dB or more.

B. Filterbank Spectrometer

Figure 2 depicts the second driver amplifier in front of the filterbank. The filterbank consists of three multiplexers which split the IF into eight bands of 2 GHz bandwidth and one of 1.9 GHz bandwidth. The output of each filter is connected to a broadband detector diode which detects if there is a signal available in that band. The detector's output voltage is amplified and shown on a storage oscilloscope. In that way it is possible to perform a real-time measurement in a 36 GHz band with a resolution bandwidth of 2 GHz.

C. Frequency Time Analysis

The path of frequency time analysis is shown on the right side of figure 2. Here the IF amplifier is followed by a second mixer. The mixer converts a segment out of the IF range to the band between 1 MHz to 2.5GHz. The LO signal is provided by a second synthesizer. At the mixer's output port there is a 2.5 GHz lowpass filter to suppress higher frequencies which may cause problems at the analyzer's input. With the frequency and time interval analyzer, a frequency measurement with a resolution better than 100 Hz is possible.

D. Downconverter

The downconverter [15] is the core of the real-time frequency measurement system. The most important fact of this specific development is its outstanding broadbandness with low conversion losses. It converts the whole input frequency range from 100 GHz to 175 GHz in sections to an IF from 100 MHz to 18 GHz. This is only possible through a wide tunable LO signal in the Ku-band. The block diagram of the downconverter in figure 3 shows the principle.

The LO signal, which is in the Ku-band, is multiplied by nine and mixed with the input signal. As the mixer itself works on the third harmonic, the LO signal has to be multiplied by three to be in the right frequency range. This is done by a frequency tripler which is the very right block of figure 3. As a tripler has a nonlinear characteristic, not only the third harmonic of the input signal is generated but also the second, fourth and so on. To suppress the unwanted higher harmonics a lowpass filter follows the tripler. This results in a problem with a very broadband system because adjacent harmonics only have a small frequency separation. The input frequency into the tripler of 13.1 GHz results in an output of 39.3 GHz. At the same time the fourth harmonic is generated, which is at 52.4 GHz. The highest input frequency into the tripler is 17.3 GHz. This frequency multiplied by three results in 52.4 GHz. So the forth harmonic of 13.1 GHz and the third harmonic of 17.3 GHz add up to the same frequency. The lowpass filter can not suppress the unwanted fourth harmonic of the lowest input signal. The consequence at low LO frequencies is that there might be spurious responses at the mixer's IF output. Another fact is the steepness of the lowpass filter which can not be arbitrary. A solution is an optimization of the tripler for the third harmonic. Offsets in the level of 20 dB are reachable. So the undesired mixing products at the mixer's output can be attenuated in the same magnitude.

The next block after the lowpass filter is an isolator used to suppress reflections inside the waveguide and enhance the match of the mixer's LO port. Without this isolator there could be multiple reflections between the mixer's LO input and the lowpass filter. This would result in a degradation frequency response of the whole system.

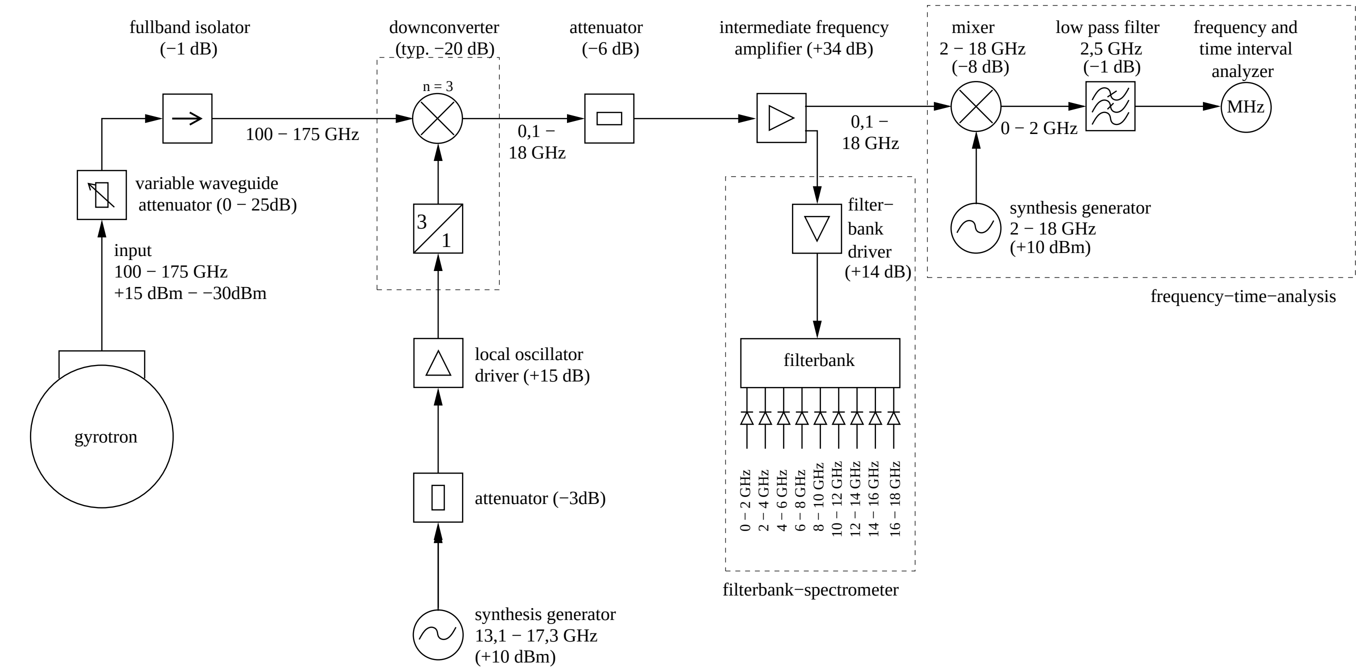

Fig. 2. Block diagram of the frequency measurement system with filterbank spectrometer and frequency time analysis.

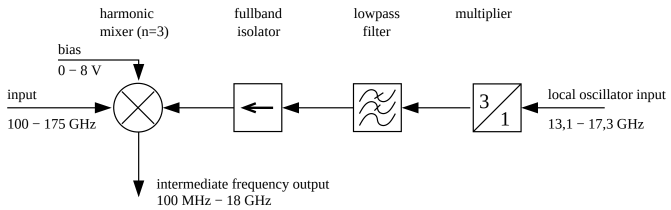

Fig. 3. Block diagram of the downconverter.

The harmonic mixer represented by the very left block in figure 3 is optimized to the third harmonic. This is done through internal arrangements as filters for higher harmonics and external biasing. The conversion loss of the downconverter is typically 20 dB and increases a little at the band edges. It is dependent on the input frequency, the LO frequency, and the bias voltage. A minimum of conversion loss leads to the maximum of sensitivity. Thus, a PC based software knowing the mixer's parameters controls the LO frequency to adjust for minimum conversion loss.

IV. Measurements

The first frequency measurements with the new system at the gyrotron experiment were done at 140 GHz. A small part of the output power was coupled into a waveguide which feeds the real-time frequency measurement system. At the input a 300 µs pulse can be visualized on the filterbank spectrometer with a storage oscilloscope and also on the frequency and time interval analyzer, as shown in figures 4 and 5. The frequency and time interval analyzer shows a frequency of 1060 MHz with a pulse length of 300 µs. Figure 4 shows the output of the filterbank spectrometer as a pulse with nearly no noise. For this measurement the LO frequency for the first mixer was 14.55 GHz with low side injection and the local oscillator frequency of the second LO was 10 GHz with high side injection. Consequently the measured frequency was 139.940 GHz.

A. *Sensitivity*

A fundamental goal beside the broadbandness and the real-time ability is a high sensitivity of the system. As it is difficult to change the coupling at the gyrotron it is important to have a certain dynamic range. To extend it to higher levels the variable attenuator as shown in figure 2 is inserted. As there is theoretically enough power available from the gyrotron a broadband amplifier in the input frequency range of 100 GHz and 175 GHz can be avoided. It is sufficient to minimize the losses to the first amplifier. The major contribution of losses is added by the harmonic mixer's conversion loss. As this parameter is dependent on the input frequency, the local oscillator frequency, and the bias voltage a measurement campaign was carried out to characterize the conversion losses. With this knowledge the parameters for the expected input frequency are adjusted through software for lowest conversion loss which results in the best possible sensitivity for a certain input frequency. This leads to the sensitivities of the subsystems which are shown in figure 6. It depicts the minimum input power for an accurate measurement of filterbank spectrometer and frequency time analysis. It is derived from the measurement of the downconverter's conversion losses and the sensitivity of filterbank spectrometer and frequency time analysis on the IF level.

Comparing the sensitivities of the filterbank spectrometer and the frequency time analysis, figure 6 documents a higher sensitivity of the filterbank spectrometer with about 5 dB over the largest part of the input frequency range. In the range from 110 GHz to 160 GHz the sensitivity of the filterbank spectrometer is better than −30 dBm and the sensitivity of the frequency time analysis is better than −25 dBm. For a system with a bandwidth of 75 GHz this is an excellent result.

V. Conclusion

A very cost efficient frequency measurement system for frequency diagnostics of high power gyrotrons in the frequency range of 100 GHz to 175 GHz has been developed. The advantages of this system are the wide bandwidth of 75 GHz, and the typical sensitivity of −30 dBm.

This new frequency measurement system can measure the frequency with an accuracy of better than 10 kHz in real-time. It is easy to observe frequency drifts and oscillating modes of gyrotrons. With the PC based control of the system the operation is very easy. The compact system replaces the previous system as discribed in [12] and will be used for future diagnostics on gyrotrons.

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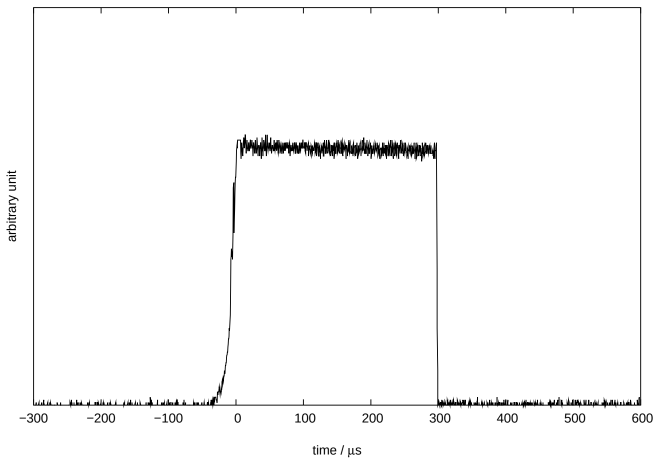

Fig. 4. Output of the filterbank spectrometer; IF: 8 GHz – 10 GHz, RF: 138.95 GHz – 140.95 GHz.

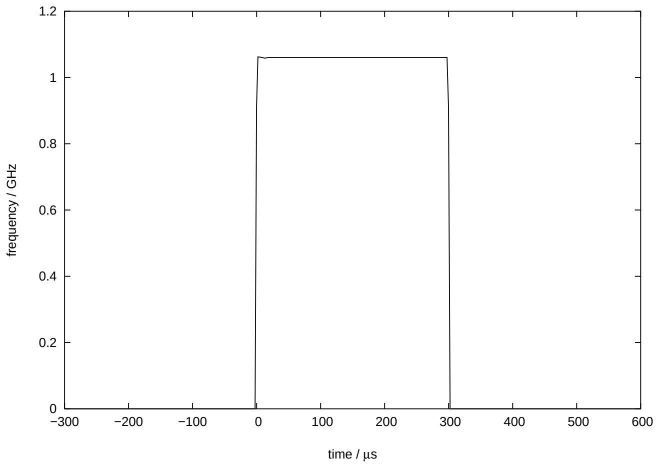

Fig. 5. Gyrotron frequency measured on the IF by the frequency and time interval analyzer.

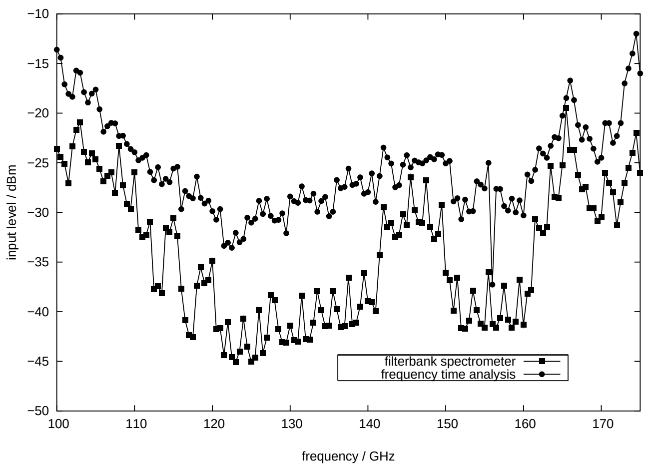

Fig. 6. Sensitivity of the filterbank spectrometer and the frequency time analysis.