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**Abstract** – High resolution frequency measurements during TEXTOR plasma operation have been carried out of the 110 GHz gyrotron as used for fast ion collective Thomson scattering diagnostics. A pickoff sample of the gyrotron beam was frequency downshifted by both homodyne and heterodyne methods and fast Fourier transformed (FFT) by a 300 MHz bandwidth digitizing oscilloscope. The gyrotron frequency was found to be relatively clean and stable from plasma shot to plasma shot except for  $\pm 18$  MHz components at about -40 dB below peak in some of the data. During a single plasma shot a downward frequency drift of 14 MHz was observed over a 936 ms period of about 90, 2 ms gyrotron pulses. An instrumentally limited instantaneous linewidth of <100 kHz at half maximum was also observed. The TEXTOR ICRH system did not fire reliably during these measurements to assess its effect on the gyrotron spectrum.

## Introduction

The application of gyrotron radiation to fast ion collective Thomson scattering (CTS) diagnostics [1] requires precise knowledge and control of the gyrotron frequency and spectrum. The gyrotron frequency must be accurately tuned to the notch filter frequency of the receiver system and the gyrotron linewidth must be less than 100 MHz over a large dynamic range. Also there can be no spurious frequency components for a bandwidth of about  $\pm 5$  GHz around the center frequency to levels many orders of magnitude below the peak center frequency.

Many factors determine the gyrotron frequency and spectrum. The gyrotron frequency is set by the dimensions of the resonator cavity and through the control of the operating parameters including the magnetic field, beam voltage, and current [2]. Suppression of spurious modes is also accomplished through control of the gyrotron operating parameters. Typically, the gyrotron operating parameters for optimum CTS frequency and clean spectrum do not coincide with the operating parameters for maximum gyrotron output power.

In addition to the gyrotron operating parameters, external interference is possible in the environment of a major tokamak experimental facility from other high power electrical systems. Of particular concern is the ICRH system at TEXTOR interfering directly with the gyrotron. This report summarizes high resolution spectrum measurements over a 300 MHz bandwidth of the 110 GHz gyrotron obtained during TEXTOR plasma shots.

Attempts were made to obtain data during ICRH firing, but unfortunately that system was not operating reliably when these measurements were made.

## **Experimental Setup**

Frequency spectrum measurements were accomplished by homodyning or heterodyning the gyrotron frequency down to within the bandwidth of a fast digitizing oscilloscope and performing a fast Fourier transform (FFT). The oscilloscope was a Tektronix Model TDS3032B with a 300 MHz bandwidth. It was primarily used on the 1  $\mu$ s per division scale with a 1 GS/s sampling rate. The total record length was limited to 10 K points by the internal memory so that only a 10  $\mu$ s portion of the gyrotron pulse could be monitored on any one shot. Using a variable trigger delay the gyrotron frequency spectrum could be monitored early or late in the gyrotron pulse on a shot to shot basis.

The gyrotron output beam was sampled by a movable pickoff horn previously installed just after the universal polarizer adjacent to the gyrotron. This pickoff signal was brought out of the enclosed optical beam line by WR-8 waveguide with an attached variable attenuator. Initially a fast Schottky diode detector was connected to the output of the variable attenuator. The position of the pickoff horn and attenuator were adjusted for a signal of about 50 mV ( $\sim$  0.1 mW). This Schottky diode detector signal was also used for the initial homodyne frequency measurements.

For heterodyne frequency measurements the Schottky diode was replaced by a mixer from Farran Technology, Model BMC-10, and a local oscillator (LO) from ZAX Millimeter Wave Corp., Model ZVT 10/10/110/1. The circuit for the heterodyne measurements is shown in Figure 1. The LO was a voltage tuned Gunn oscillator and its frequency tuning curve was checked with a millimeter wave spectrum analyzer the day of the measurements. This frequency tuning curve is not precisely reproducible and is therefore the source of about a  $\pm$  50 MHz uncertainty in the absolute frequency measurements presented here. A photo of the heterodyne components connected to the pickoff waveguide is shown in Figure 2.

## **Measurements**

The gyrotron operation was optimized for fast ion CTS diagnostics, which were being carried out during these frequency measurements. Consequently, the peak gyrotron output power did not exceed about 50 kW and spurious gyrotron modes within the  $\pm$ 5 GHz CTS receiver bandwidth were suppressed. The gyrotron was operated in a burst of about 100, 2 ms pulses distributed over about a 1 s time period during the flat top of the TEXTOR plasma pulse.

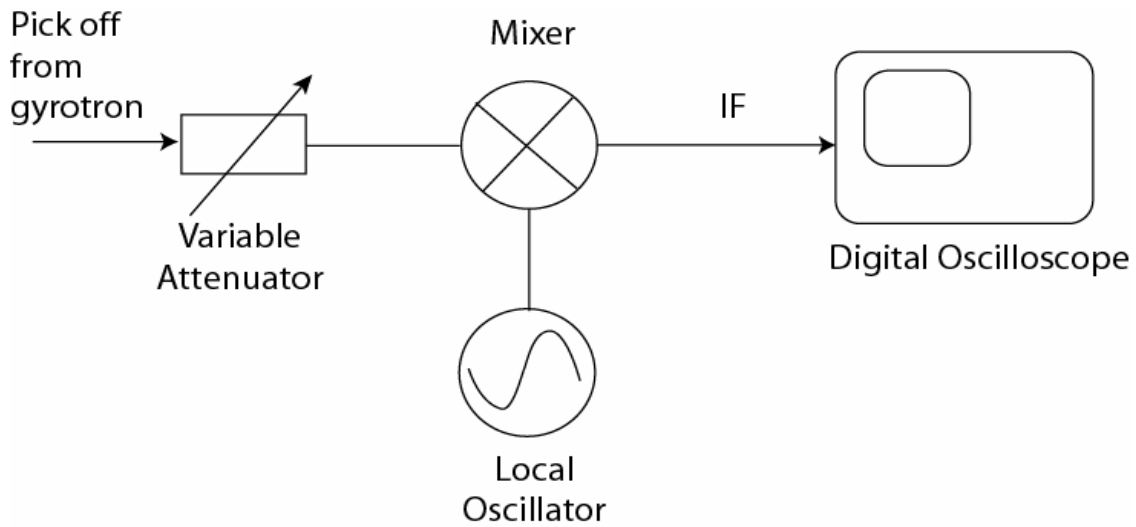


Figure 1. Heterodyne detection circuit.

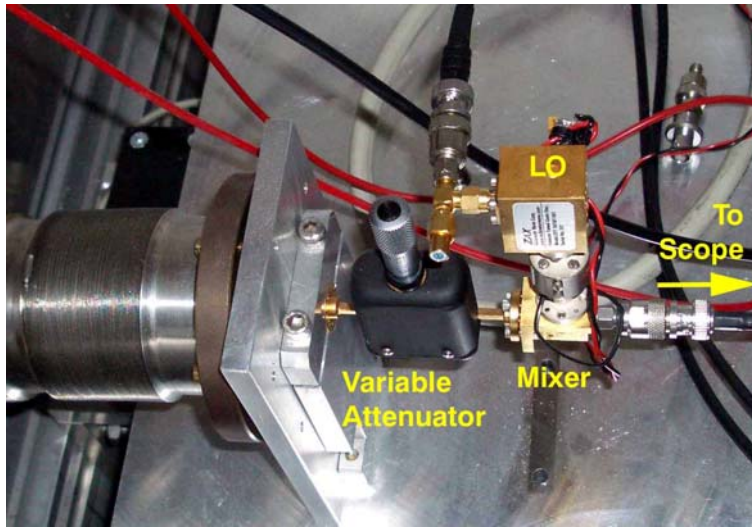


Figure 2. Photo of heterodyne pickoff circuit beside the gyrotron beam line.

### Homodyne

Data was recorded on a total of 16 plasma shots summarized in Table I. The first column gives the TEXTOR shot number during which the data was taken. Data for the first three shots listed were obtained in homodyne mode, directly digitizing the Schottky diode signal. The trigger delay of 5.24 seconds after the initial trigger to the gyrotron put the measurement in the middle of the second 2 ms pulse of the gyrotron multiple 2 ms pulsing during each plasma shot. The resulting homodyne spectra are shown in Figure 3 normalized to the level at 0 MHz (DC). The noise spectra are at the dynamic range limit of the oscilloscope, which has only a 9-bit vertical resolution. There are weak ( $< -45$  dB)

frequency components at 2.0, 9.4, 11.0, and 17.7 MHz. Also there are weak peaks at 166.7, 191.9, and 227.3 MHz. These weak peaks are present in most of data presented here with or without the gyrotron on. Consequently, the gyrotron spectrum in homodyne detection mode is very clean.

**Table I. TEXTOR Gyrotron Frequency Measurements Recorded June 1, 2005**

Plasma Shot #	Digitizing Rate (GS/s)	Trigger Delay (ms)	Detection Mode	Intermediate Freq. (MHz)	Gyrotron Freq. (GHz)*
97976	0.001	none	homodyne	0	-
97978	1	5.24	homodyne	0	-
97979	1	5.24	homodyne	0	-
97981	1	5.24	heterodyne	101.2	110.10
97982	1	5.24	heterodyne	36.2	110.11
97983	1	5.24	heterodyne	36.7	110.11
97984	1	5.24	heterodyne	37.7	110.11
97985	1	5.24	heterodyne	39.3	110.11
97987	1	5.24	heterodyne	144.6	110.06
97989	1	941.24	heterodyne	130.5	110.05
97990	1	941.24	heterodyne	130.9	110.05
97992	1	941.24	heterodyne	132.3	110.05
97993	1	943.40	heterodyne	gyrotron off	-
97994	1	941.24	heterodyne	gyrotron off	-
97995	1	941.24	heterodyne	gyrotron off	-
97996	1	941.24	heterodyne	132.3	110.05

\* Obtained by adding the IF frequency to the LO frequency as previously determined for the LO tuning voltage. The apparent change in gyrotron frequency from 110.11 to 110.06 GHz when the LO was tuned is probably due to an inaccuracy in the LO tuning curve.

#### Heterodyne Shots 97981-97985

The Schottky diode was replaced with the heterodyne mixer and LO for TEXTOR shots after shot 97979. Initially it was assumed that the gyrotron frequency was 109.9 GHz and the LO was set to about 109.7 GHz to produce an IF beat at about 200 MHz for shot 97980. No beat was observed on the oscilloscope.

For shot 97981 the LO frequency was increased to about 110.0 GHz and a beat was observed at an IF frequency of 101.2 MHz. For the next shot (97982) the LO frequency was further increased to 110.07 GHz and the IF frequency beat decreased to 36.9 GHz. This confirmed that the gyrotron frequency was above the LO and at about 110.1 GHz. This also explained why a beat was not observed for shot 97979, because the beat would have been at about 400 MHz, outside the bandwidth of the oscilloscope.

For the next three plasma shots 97983 through 97985 the LO and trigger delay were not changed. At this trigger delay of 5.24 ms the gyrotron spectrum was sampled after TEXTOR reached current flattop, but before neutral beams or ICRH were turned on. The

resulting spectra are shown in Figure 4. The gyrotron spectrum is generally clean to about  $-40$  dB except for 2.0 and 17.7 MHz components in shot 97984, which are also weakly present in shot 97983. The spurious peaks above 100 MHz appear to be mostly noise. The shot to shot stability of the gyrotron and LO appears to be very good.

#### Change of LO and Trigger Delay

At shot 97987 the LO frequency was decreased to change the IF beat frequency to 144.6 MHz as shown in the upper plot of Figure 5. Using the previously measured LO voltage tuning curve, this resulted in a determination of the gyrotron frequency to be 50 MHz lower than the previous shot. It is unlikely that this is a real shift in the gyrotron frequency because otherwise it was very stable from shot to shot before and after the LO frequency change. The apparent shift in frequency is most likely due to a thermal drift of the LO voltage tuning curve.

After plasma shot 97987 the trigger delay was increased by 936 ms to 941.24 to sample the gyrotron frequency near the end of its burst of 2 ms pulses during the scheduled timing of the ICRH pulse. At shot 97988 the gyrotron failed to fire, but a spectrum was recorded for the following shot 97989 as shown in the lower part of Figure 5. The beat frequency decreased to 130.5 MHz and a spurious harmonic of this beat appears, as indicated, due to clipping of the recorded waveform on a too sensitive of a vertical scale setting of the oscilloscope. The 14 MHz decrease in the beat frequency with the increase in delay sampling of the gyrotron frequency is likely due to the thermal expansion of the gyrotron cavity.

Otherwise the gyrotron spectra appear relatively clean except for a pair of satellite peaks around the gyrotron main peak at about  $-40$  dB at  $\pm 17.7$  MHz in shot 97987 and at  $\pm 18.0$  MHz in shot 97989. The ICRH did not fire on shot 97989.

#### Measurements During ICRH Attempts

Attempts to obtain a gyrotron spectrum during ICRH were made at shots 97990, 97992, and 97996 as shown in Figure 6. Unfortunately, the ICRH system did not fire at shot 97990 and misfired at shots 97992 and 97996. During the misfired shots the ICRH system was energized on the floor below the gyrotron but no RF was launched into the tokamak. Therefore these measurements are not definitive as to the possible direct effects of the ICRH on the gyrotron.

All the spectra in Figure 6 are similar, each showing a clean gyrotron peak with weak  $\pm 18$  GHz satellite peaks below  $-40$  dB. The other spectrum features include a weak harmonic of the gyrotron peak and other frequency structure that is present when the gyrotron is off.

#### Gyrotron off Spectra

The trigger delay time was advanced 2 ms on shot 97993 to a total delay of 943.4 ms, a time when the gyrotron was cycled off between 2 ms pulses, to obtain a background spectrum with all conditions being the same except for the gyrotron millimeter wave beam being off. The top spectrum in Figure 7 shows this data. The relative power axis

was arbitrarily referenced to the DC value and of this particular data set and cannot be related to the other spectra shown in this or other Figures. The spectral features at 9.4, 17.7, 166.7, 191.9, and 227.3 MHz are all present without the gyrotron.

Two more similar background spectra were obtained for shots 97994 and 97995 when the trigger delay was returned to 941.24 ms, but the gyrotron pulse timing was also change to move the gyrotron pulse outside the sampling time of the oscilloscope. These two spectra shown in the middle and lower part of Figure 7 are similar to the previous shot.

### Gyrotron Linewidth

The total length of 10  $\mu$ s for the digital data sets recorded corresponds to a Fourier transform limit of about 100 kHz for the frequency resolution of the FFT spectra. It is therefore of interest to expand the frequency resolution of the spectra to this limit to observe the linewidth of the gyrotron. Expanded homodyne and the heterodyne spectra are shown in Figure 8. Each of these spectra shows the gyrotron linewidth to be at or near the instrumental limit. In the heterodyne case the linewidth is actually the convolution of the Gunn oscillator with the gyrotron and would not necessarily be a true indication of the gyrotron linewidth if it were narrower than the Gunn oscillator. These results show that the instantaneous linewidth of the 110 GHz TEXTOR gyrotron when operated for CTS is very narrow. In the homodyne measurement it is <100 kHz at half maximum and <200 kHz at -40 dB maximum. Longer record lengths will be needed to determine the true linewidth.

### **Discussion**

The heterodyne frequency measurement setup went together rather easily in less than one day due to the availability of the millimeter-wave components and fast oscilloscope brought to the site by Risø National Laboratory and the previously installed WR-8 waveguide pickoff on the gyrotron beam line. It proved to be effect for observing the fine details of gyrotron spectrum during TEXTOR plasma shots. The main uncertainty was with the exact frequency setting of the voltage tuned Gunn oscillator for determining the absolute gyrotron frequency. However, the frequency structure of weak spurious components relative to the main gyrotron peak, its linewidth over a large dynamic range, and frequency drift for a fixed LO voltage setting were resolved within the 300 MHz bandwidth limit of the oscilloscope.

The results in general show a relatively clean gyrotron linewidth during TEXTOR plasma shots when the gyrotron is adjusted for CTS operation. Various small (< -40 dB) spurious frequency components are generally present whether the gyrotron is on or off. The one possible exception is a pair of satellite peaks about  $\pm 18$  GHz relative to the main frequency that appears in many of the spectra. Since there is also a noise component present at about 18 MHz (17.7 MHz) without the gyrotron, it is possible that the source of this noise may be interfering with the gyrotron at a very small level.

As to the question of interference from the ICRH system, it has not been definitively answered because measurements were not obtained coincident with a successful firing of

ICRH. The nearest measurements to this condition are shots 97992 and 97996 in Figure 6 when the ICRH system was energized but misfired. The spectra for those shots are not much different from other spectra without attempted ICRH firing. More measurements will be needed in the future to resolve the question of ICRH interference with the gyrotron.

## References

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2. K. E. Kreischer, B. G. Danly, P. Woskoboinikow, W. J. Mulligan, and R. J. Temkin, "Frequency Pulling and Bandwidth Measurements of a 140 GHz Pulsed Gyrotron," *Int. J. Electronics*, vol. 57, 851-862, 1984.



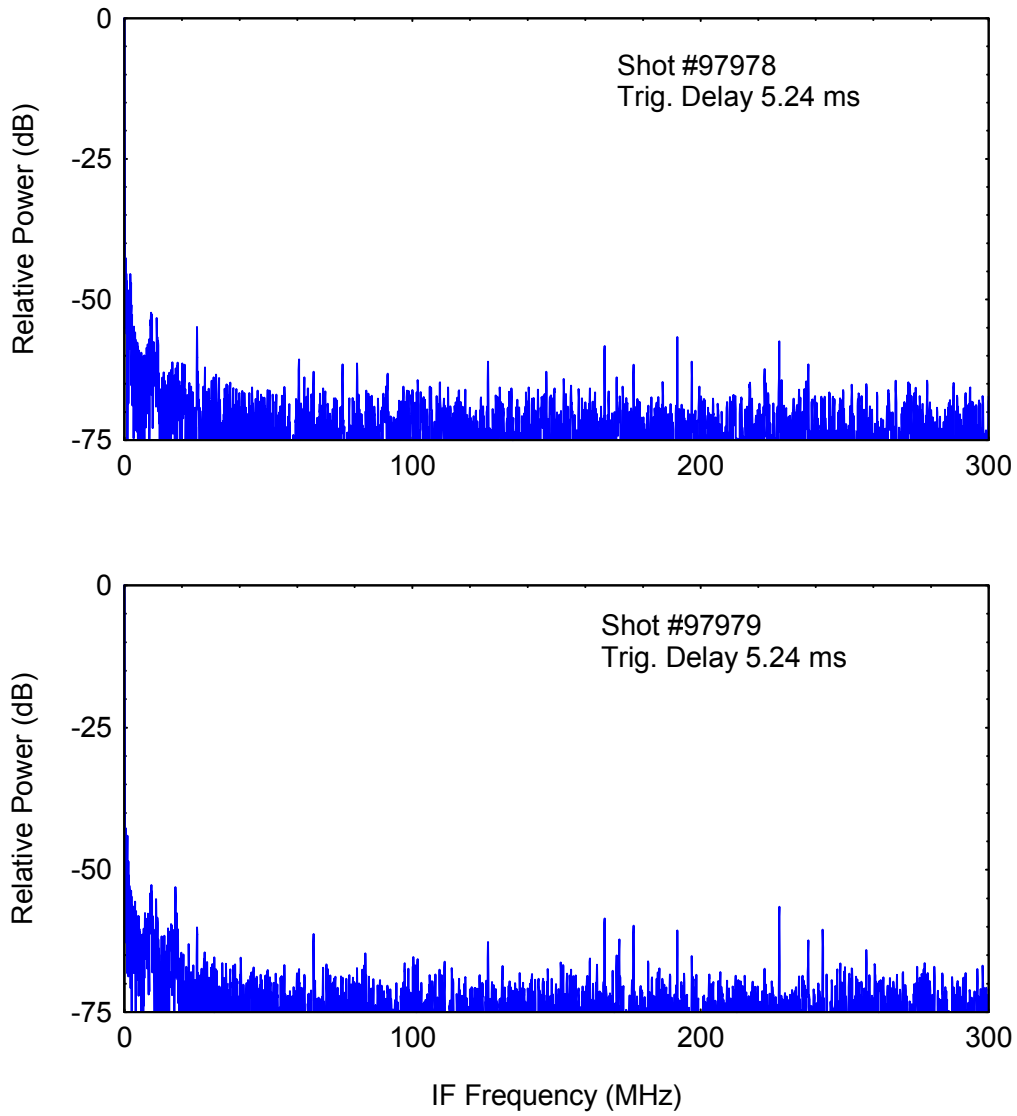


Figure 3. Homodyne spectra of the TEXTOR 110 GHz gyrotron during plasma shots 97978 and 97979.

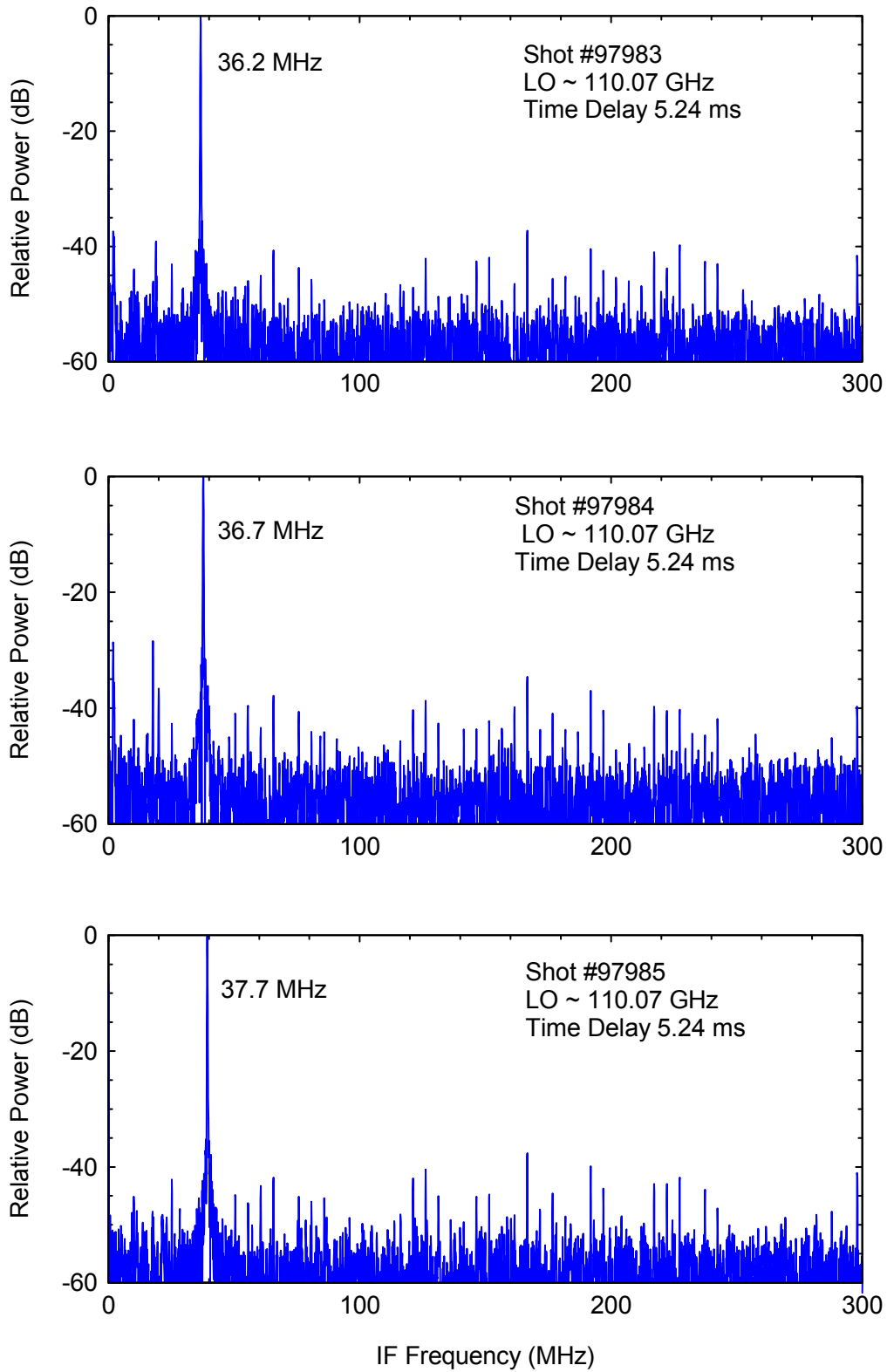


Figure 4. Heterodyne spectra of the TEXTOR 110 GHz Gyrotron with the LO at 110.07 GHz.

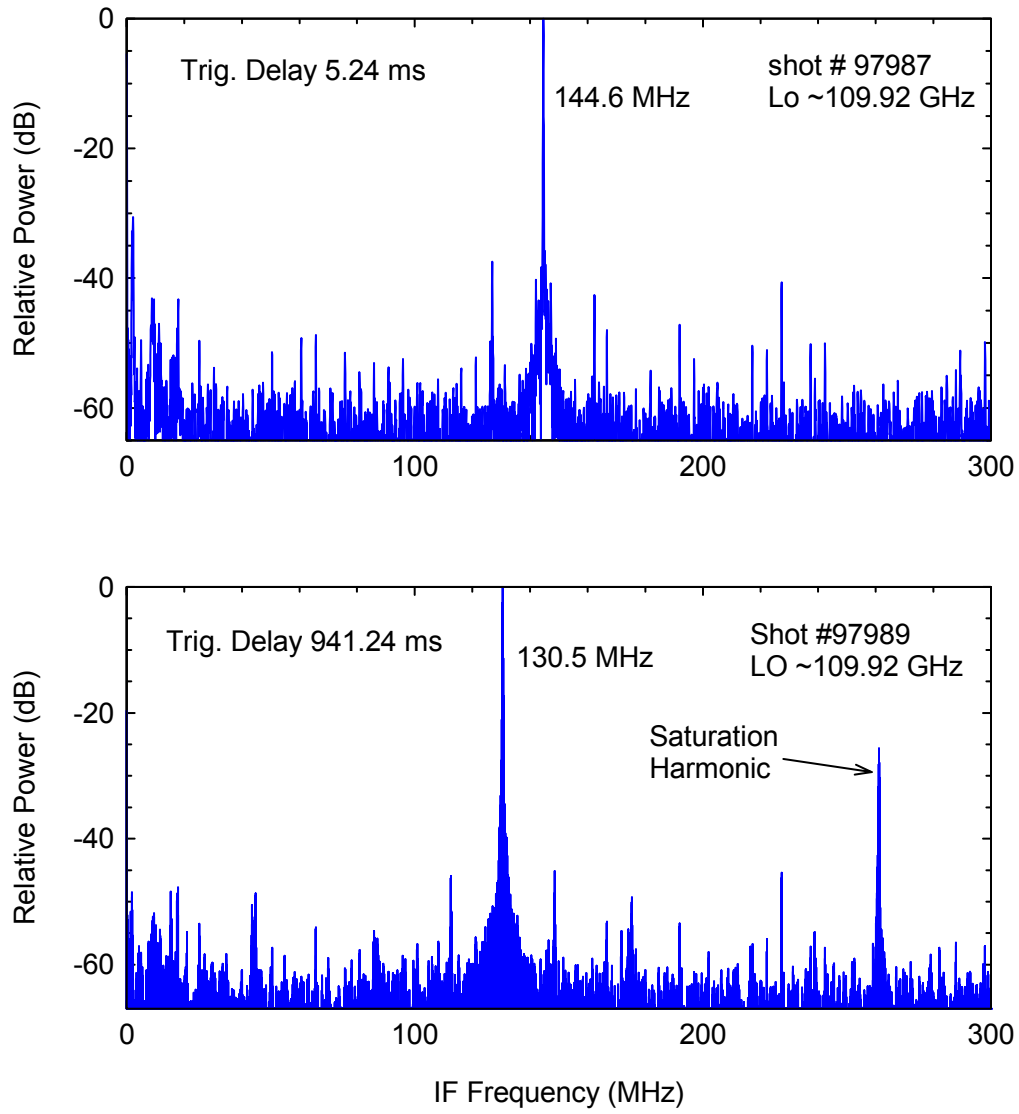


Figure 5. A 936 ms change in the trigger delay for sampling the gyrotron shows a 14 MHz frequency down chirp due to the thermal expansion of the resonance cavity.

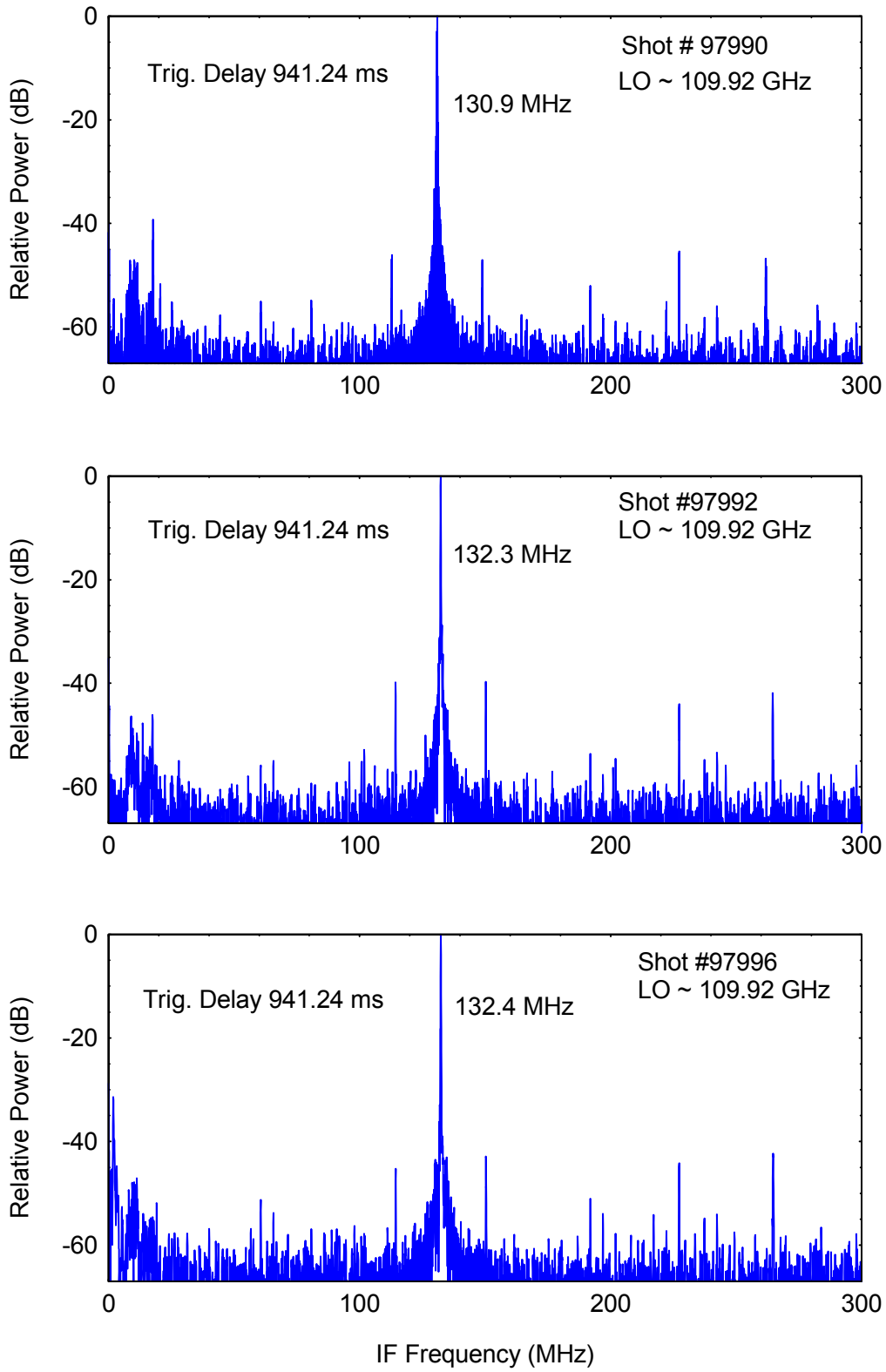


Figure 6. Spectrum measurements during attempts to fire ICRH.

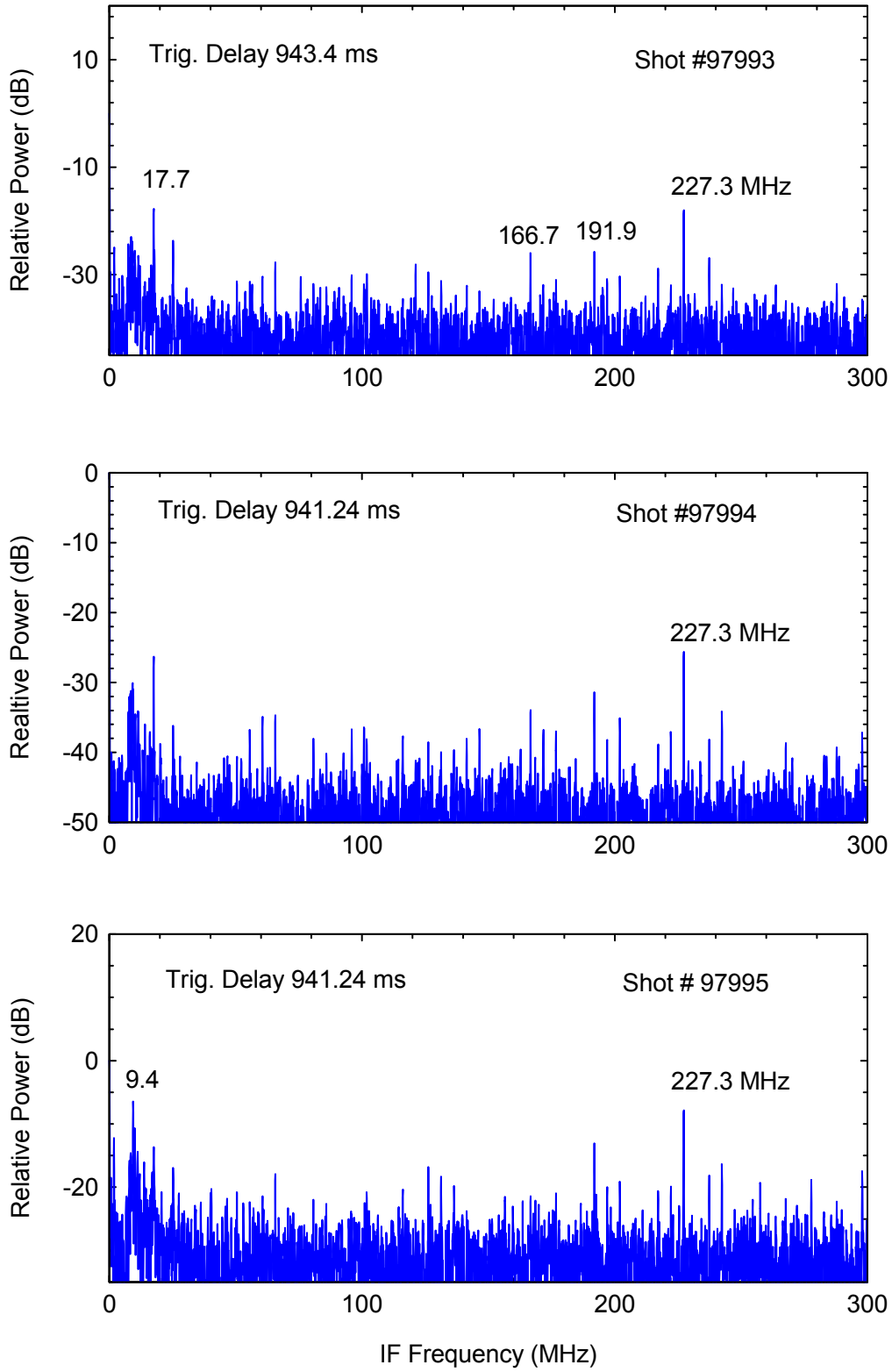


Figure 7. Spectra without gyrotron emission between gyrotron pulses.

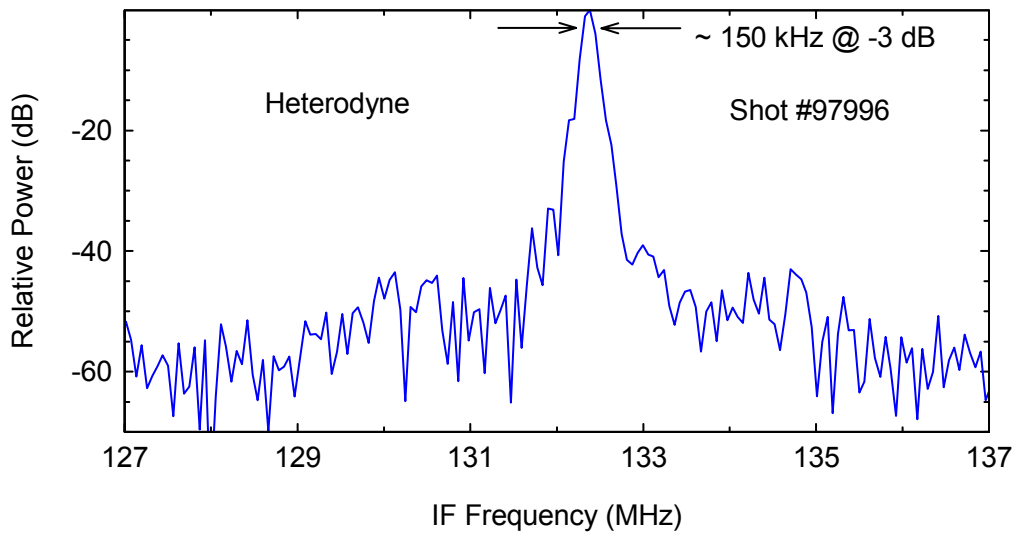
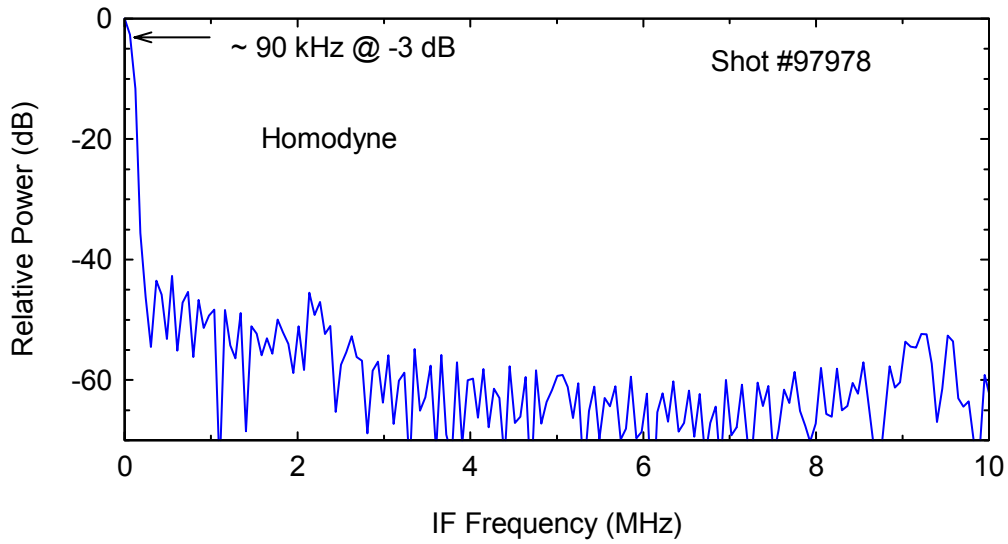


Figure 8. Expanded frequency scale showing the homodyne and heterodyne gyrotron linewidth to be at approximately the instrumental measurement limit.