Phase Measurements of a 140-GHz Confocal Gyro-Amplifier

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Abstract
The phase stability of a 140-GHz, 1-kW pulsed gyro-amplifier system and the phase dependence on the cathode voltage were experimentally measured. To optimize the measurement precision, the amplifier was operated at 47 kV and 1 A, where the output power was \( \sim 30 \) W. The phase was determined to be stable both pulse-to-pulse and during each pulse, so far as the cathode voltage and electron beam current are constant. The phase variation with voltage was measured and found to be \( 130 \pm 30^\circ/kV \), in excellent agreement with simulations. The electron gun used in this device is non-adiabatic, resulting in a steep slope of the beam pitch factor with respect to cathode voltage. This was discovered to be the dominant factor in the phase dependence on voltage. The use of an adiabatic electron gun is predicted to yield a significantly smaller phase sensitivity to voltage, and thus a more phase-stable performance. To our knowledge, these are the first phase measurements reported for a gyro-amplifier operating at a frequency above W-band.

Keywords Gyro-amplifier · Gyrotron · Phase stability · Vacuum electronics · DNP-NMR

1 Introduction
Phase stability of an amplifier is an important property for many applications. For example, one approach for improving dynamic nuclear polarization (DNP) efficiency of nuclear magnetic resonance (NMR) spectroscopy is the exchange of...
continuous wave microwave irradiation for short, strong pulses as a means of increasing the bandwidth of a DNP experiment without increasing average power [1]. Gyro-amplifiers can produce the high power at high frequencies needed for pulsed DNP-NMR experiments [2, 3]. By sending a tailored train of short pulses into the gyro-amplifier, a high-power train can be generated for use in the spectrometer. Control over the phase of the microwaves could allow even broader bandwidths through manipulation of electron spins [4]. The input source is responsible for generating the pulses and controlling the phase, and it is important to verify that the relative phase between pulses is not altered during amplification. For this approach to be successful, the phase must be stable to within 10°.

Other phase-sensitive applications include coherent radars, communication systems, accelerators, and linear colliders. The phase stability of gyro-amplifiers has been the subject of intensive theoretical and experimental research [5–15], but thus far it has only been measured up to W-band, for any amplifier. Existing techniques are challenging at higher frequencies because of high ohmic loss in fundamental waveguides and limited availability of crucial components, such as a balanced mixer.

A 140-GHz pulsed gyro-traveling-wave-tube (gyro-TWT) amplifier has been developed at MIT for pulsed DNP-NMR spectroscopy [16–18]. The gyro-amplifier uses a confocal geometry to achieve an overmoded interaction circuit with reduced mode competition and is designed to operate without severs. The confocal gyro-amplifier operates in the confocal HE_{06} mode and demonstrated a peak circuit gain of 35 dB, a bandwidth of 1.2 GHz, and a peak output power of 550 W at 140 GHz.

## 2 Methodology

A simplified schematic of the phase measurement diagnostic setup is given in Fig. 1. The 2-μs, 140-GHz radio frequency (RF) pulsed input is generated by an extended interaction oscillator (EIO) from Communications & Power Industries, Inc. (CPI), Canada, and split by a beam splitter prior to entering the amplifier. The diverted branch of the RF is fed into the local oscillator (LO) port of a balanced mixer (SFB-08-E2 from Eravant, formerly SAGE Millimeter, Inc.), via a variable attenuator and a phase shifter (STP-18-08-M2, also from Eravant). The amplifier output is fed into the RF port of the mixer via a variable attenuator. The mixer’s intermediate frequency (IF) output is given by $f_{\text{IF}} = |f_{\text{RF}} - f_{\text{LO}}|$. Since the RF and LO frequencies are split from the same source, they are identical and $f_{\text{IF}} = 0$. Therefore, the IF output is a DC voltage, with its value a function of the phase difference between the RF and the LO.

The computer-aided design (CAD) drawing in Fig. 2 illustrates further details of the system. The output of the EIO passes through an isolator and an attenuator and is monitored by a diode, to control the power level and ensure consistency across all measurements. Then, the fundamental TE_{10} mode of the rectangular waveguide is converted to an HE_{11} circular mode and tapered into an over-sized (12.7-mm diameter) corrugated waveguide. This waveguide is used to transmit the microwaves over several meters with minimal loss and is matched to the input of the gyro-amplifier. The beam splitter was designed for the HE_{11} mode in the corrugated waveguide, and is made of a 1.046-mm-thick quartz plate positioned at 45° to the wave [19]. Both the

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LO and the RF signals are converted back to a TE$_{10}$ mode in a rectangular waveguide before entering the attenuators.

The purpose of the LO and RF attenuators is to ensure that the signals reaching the mixer are equal and within its operating parameters. To drive the mixer, the LO signal must be stronger than 1 mW, but the total power into both ports must be lower than 20 mW to avoid damage. We have chosen a nominal power level of 2.5 mW in each port. At the beginning of every set of measurements (consisting of hundreds of shots), the mixer was taken out of the circuit and a calibrated diode was used to tune both arms to the desired setting, with the phase shifter set to 0°. Then, a monitor diode was used to keep track of the amplifier output power. When a change in the power level was observed, either due to the system’s fluctuations or when the voltage was changed, the RF attenuator was used to adjust it back to the nominal level. In
addition, the phase shifter was carefully calibrated in situ with a Virginia Diodes, Inc. PM5 power meter. Since the phase shifter introduces loss (Fig. 3), for every change in the phase shifter, the LO attenuator was adjusted to compensate for the added loss. It should be noted that the attenuators also introduce a phase shift. However, we have examined our attenuators using a vector network analyzer (VNA) and found that the phase varied by only 1° over an LO attenuation range from 0 to 25 dB. The effect becomes more pronounced with higher attenuation values: 5° of total phase was added at 40 dB attenuation, and 15° at 50 dB. The RF attenuator introduced a slightly higher phase shift: ∼ 2.5° from 0 to 25 dB. Since the attenuators were never varied by more than 4 dB during measurements, and were never set beyond 30 dB, this effect was neglected in the analysis.

The VNA measurements also revealed that slight bending of the waveguides attached to the phase shifter can introduce a significant phase shift (∼ 10°) when the setting is close to 360°. For this reason, calibration with the diode was only done immediately before a set of measurements. In addition, to ensure system stability while acquiring data over the entire range of voltages, no changes were made to the setup and no components were power cycled. The only adjustments made were to the operating voltage and current, and to the attenuators in the LO and RF arms, strictly when needed.

Table 1 lists the experimental parameters used in this research. While the gyro-amplifier previously demonstrated a peak gain of 35 dB with a current of 3 A, in this study, the current was held at 1 A to provide strong reproducibility over hours of running and throughout the entire range of voltages, 46 to 48 kV. This range of voltages was instrumental for measuring $d\phi/dV_k$. Attempts to operate the gyrotron over a sufficient range of voltages closer to the peak gain failed to produce the consistency required for reliable measurements. While the 35-dB, 3-A operation point is stable,
Table 1  Experiment parameters used in this research

| Parameter                  | Symbol | Value     |
|----------------------------|--------|-----------|
| Frequency                  | $f$    | 140 GHz   |
| Magnetic field             | $B$    | 5.08 T    |
| Cathode voltage            | $V_k$  | 46–48 kV  |
| Modulating (mod) anode ratio$^a$ | $V_{MA}/V_k$ | 0.76     |
| Beam current               | $I$    | 1 A       |
| Gun coil current           | $I_{GC}$ | 60 A     |
| Beam radius$^b$            | $r_{beam}$ | 2.1 mm   |
| Perpendicular velocity spread$^c$ | $\Delta v_{\perp}/v_{\perp}$ | 6%        |
| Input power                | $P_{in}$ | 2 W      |
| Pulse duration             | –      | 2 $\mu$s  |

$^a$ Set as a fraction of the cathode voltage
$^b$ Calculated by MICHELLE, see below
$^c$ Based on previous studies [18, 20, 21]

small variations in the operational parameters resulted in strong oscillations. The lower current used in this study resulted in lower gain, which was determined by measuring the output of the amplifier with a calibrated diode at several voltage settings and dividing by the input power, taking into account the calibrated losses introduced by all passive elements. For 1 A of current, the gain increased with voltage, from 6.3 dB at 46.5 kV to 11.5 dB at 47.6 kV.

3 Results

Figure 4 demonstrates all channels recorded for each shot, with the mixer channel given for three shots with three different phase shifter settings (solid green). The cathode voltage (dashed blue) has a 47.6-kV flat top, the current (dash-dotted red) a 1-A flat top, and the monitor signal (dotted cyan) represents the $\sim$ 2.5 mW delivered to the mixer RF port. The sensitivity of the mixer IF output to the phase can be seen by observing the three mixer signals presented for phase shifter settings of 90°, 120°, and 150°.

Figure 5 displays a set of twelve consecutive measurements taken with fixed experimental parameters. The variation seen between shots corresponds to a spread of $\sim$ 7°. Examination of the cathode voltage and beam current traces of these shots reveals jitter in their flat-top values. Indeed, a small jitter of $\pm$ 0.1% observed in the cathode voltage ($\pm$ 47 V) alone can cause phase variations of up to $\pm$ 6°. We therefore conclude that the gyro-amplifier is extremely stable shot-to-shot, to the extent that its operating parameters are stable. Using the device with a voltage modulator that generates a voltage trace with less jitter would provide an amplifier with remarkable phase stability.

After conducting cold tests of the mixer on the VNA, further calibration of the mixer output with respect to phase change was achieved by recording many measurements with identical experimental parameters at a fixed cathode voltage, and varying only the phase shifter (see Fig. 6). Since the dependence of the mixer IF DC output on the phase difference is sinusoidal [22], a sine wave was then fitted to the measured
results, providing the mixer’s phase response. By repeating this sequence of measurements and fitting sine waves at different cathode voltages, as seen in Fig. 6, the phase shift as a function of voltage, \( d\phi/dV_k \), was determined. Throughout this study, all experimental parameters except the voltage were fixed to the values given in Table 1. As seen in Fig. 5, several (∼ 10) measurements were made at each voltage and phase
Fig. 6  Mixer DC output as a function of phase shifter setting measured at three cathode voltages. The solid curves show sine waves fitted to the data, with the uncertainties in the fit represented by the shades areas.

shifter setting to provide both the phase stability of the gyro-amplifier and the error bars of the data. The SFB-08-E2 mixer is in fact a biased-balanced mixer. The ability to bias the mixer output with a DC voltage increases the measurement sensitivity in various applications. In this study, however, no benefit was gained by biasing the mixer, so to avoid additional experimental parameters and equipment this option was not used. This resulted in the sine waves having a non-zero average value, as seen in Fig. 6, but did not affect the accuracy or interpretation of the results.

The error bars in Fig. 6 represent the standard deviation of the set of measured mixer outputs at each given setting and are mainly the result of small fluctuations in the cathode voltage and beam current. The shaded areas show the uncertainties of the sine wave fits and were calculated to include all the measured data points. The phase variation with voltage, $d\phi/dV_k$, was calculated from the shift of these sine curves with respect to cathode voltage, and from sine fits to additional measurement sessions, and found to be $130 \pm 30^\circ$/kV.

The experimental results of $d\phi/dV_k$ and the measured gain were compared with simulated predictions given by Maryland Gyrotron (MAGY) code simulations [10]. Since MAGY can only simulate azimuthally symmetric geometry, it cannot simulate the confocal HE$_{06}$ mode. Therefore, the azimuthally symmetric TE$_{03}$ mode was used instead, which provides an excellent approximation to the HE$_{06}$ mode [23]. These simulations require knowledge of the gyrotron parameters including the waveguide loss, the input power, the magnetic field strength, and the beam properties: voltage, current, radius, perpendicular velocity spread ($\Delta v_\perp/v_\perp$), and pitch factor $\alpha = v_\perp/v_z$ (where $v_z$ is the axial velocity).
The gyro-amplifier uses a CPI VUW-8140 triode configuration magnetron injection gun (MIG), detailed as design #1 in Ref. [24]. The beam perpendicular velocity spread was estimated to be $\sim 6\%$, based on previous studies [18, 20, 21]. Using the electron gun geometry and the magnetic field profile, the beam properties were calculated by the MICHELLE code from Leidos [25]. As given in Table 1, these simulations provided a beam radius $r_{\text{beam}} \simeq 2.1$ mm over the entire range of voltages used in this study. The beam $\alpha$ was calculated for a range of voltages as shown in Fig. 7. The figure also shows this voltage dependence, $\alpha (V_k)$, as calculated using adiabatic equations [5]. Clearly, the adiabatic equations fail to calculate the true pitch factor slope, $d\alpha/dV_k$, for this gun. Indeed, Ref. [24] demonstrates that this is a non-adiabatic gun.

**Fig. 7** Pitch factor, $\alpha$, as a function of voltage, as calculated by MICHELLE (solid blue) and adiabatic theory (dotted red)

**Fig. 8** Phase results from MAGY simulations run with beam parameters calculated by MICHELLE for $V_{MA}/V_k = 0.76$. The absolute value of the phase is arbitrary and has been set to zero at 46 kV. The measured values were obtained from the analysis of the data in Fig. 6
An extensive study of MAGY simulations showed that \( \frac{d\phi}{dV_k} \) depends mainly on \( \frac{d\alpha}{dV_k} \), with only small contributions from other beam parameters. Furthermore, numerous MICHELLE simulations were run while varying experimental parameters. It was found that \( \alpha (V_k) \) is resilient to experimental uncertainties in most parameters but is extremely sensitive to the mod-anode to cathode voltage ratio, \( V_{MA}/V_k \), which is set by resistive voltage dividers. Figure 8 illustrates \( \phi (V_k) \) calculated by MAGY for \( V_{MA}/V_k = 0.76 \), compared with experimental values obtained from the data of Fig. 6. The MAGY calculated curve has a tangent of \( \frac{d\phi}{dV_k} = 118^\circ/kV \) for \( V = 47 \) kV. Considering the accuracy of \( V_{MA}/V_k \) and additional experimental parameters, we set the error bar for the MAGY simulations as \( \pm 10^\circ/kV \), yielding the MAGY prediction of \( \frac{d\phi}{dV_k} = 120 \pm 10^\circ/kV \). As explained in conjunction with Fig. 6, the experimental value of \( \frac{d\phi}{dV_k} \) is estimated to be \( 130 \pm 30^\circ/kV \).

### 4 Conclusions

We have measured the phase difference between the 140-GHz, 2-\( \mu \)s input pulse, generated by an EIO and the output of the gyro-amplifier, a first-of-its-kind measurement at such a high frequency. This phase difference was found to be extremely stable as long as the operating conditions, notably the cathode voltage and electron beam current, are maintained. Using the existing high-voltage modulator, the shot-to-shot phase variation is much less than \( 10^\circ \), meeting the required phase stability for DNP-NMR experiments using pulse trains. The variation of the phase with cathode voltage was found to be \( 130 \pm 30^\circ/kV \), in excellent agreement with the MICHELLE and MAGY simulated value of \( 120 \pm 10^\circ/kV \). Numerous simulations determined that the phase variation with voltage depends mainly on the dependence of \( \alpha \) on voltage.

For a non-adiabatic electron gun, this dependence is rather strong, resulting in the large values measured and simulated for the phase variation. If an adiabatic gun had been used, the phase variation with voltage would have been \( \sim 85^\circ/kV \), which is 1.5 times smaller than for the non-adiabatic gun. The use of adiabatic electron guns is therefore recommended in amplifiers intended for phase-sensitive applications, as they are predicted to be more resilient to voltage fluctuations.

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**Data Availability** The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Compliance with Ethical Standards**

**Conflict of Interest** The authors declare that they have no conflict of interest.
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