Performance of an indigenously developed tuned-couple amplifier for the operation of Penning Trap at 300 K

N. Chaddha[1,2,*], A. K. Sikdar[1,2], J. Nandi[1,2,], P. Das[1,2], A. Ray[1]

[1]Variable Energy Cyclotron Centre, 1/AF Bidhannagar, Kolkata-700064, INDIA.
[2]Homi Bhabha National Institute, 2nd floor, BARC Training School Complex, Anushaktinagar, Mumbai,
Maharashtra 400094, INDIA.
** email: nchaddha@vecc.gov.in*

Introduction

A Penning trap confines charged particles using a combination of a strong homogeneous magnetic field and a weak quadrupole electric field. The complex motion of trapped particles exhibits three characteristic frequencies: the modified cyclotron frequency, the magnetron frequency, and the axial frequency [1]. Precise measurement of the frequencies allow highly accurate determination of the masses of the trapped charged particles. The axial motion is typically detected using resonant detection methods, where a helical resonator is employed and it is coupled with either a low-noise amplifier (LNA) [2] or a tuned coupled amplifier [3]. For optimal performance, the amplifier should have high input impedance for maximum power transfer and low output impedance to match the 50-ohm transmission line.

In earlier experiments, we used a broadband amplifier with a bandwidth of approximately 50 MHz [2]. However, it was found that a tuned coupled amplifier offers several advantages over a broadband amplifier, including higher gain, improved frequency selectivity, and reduced susceptibility to noise within its resonance band, enabling reliable operation down to liquid helium temperatures [3]. Considering these benefits, a tuned couple amplifier was designed [3] and developed using a GaAs based High Electron Mobility Transistor (HEMT), SKY65050. This amplifier is coupled with a helical resonator and the Penning trap. It is observed that the overall Q-factor of the detection electronics is improved significantly by coupling this tuned coupled amplifier. It has been tested for detecting trap signals using both resonance absorption [5] and noise dip detection techniques [2].

Design Framework

The axial oscillation frequency of the trapped particle in an ideal Penning trap can be written as [1]

$$2\pi f_z = \sqrt{\frac{qU}{md^2}} \qquad (1)$$

where U represents the depth of the trapping potential, d denotes the characteristic dimension of the trap, and the remaining symbols have their usual meanings. For the VECC Penning Trap, the axial frequency is approximately 40 MHz for electrons. However, by varying the load capacitance and the trapping potential depth, this frequency can be adjusted within a specified range.

The trapped electrons create an image current in order of femto-ampere. Detection of such feeble current essentially requires a very high input impedance to minimize the loading effect of the connecting cable. Accordingly, a tuned coupled amplifier is designed to have two stages where the first stage provides a high input impedance and the output impedance is 50 ohm. The second stage of the amplifier provides 50 ohm as both, input and output impedance. The first stage functions primarily as a buffer with a broader bandwidth whereas the second stage provides gain as high as 25 dB at tuned frequency at room temperature, depending on the biasing conditions. The value of the resonance frequency largely depends on the RC time constant of the input side of the second stage.

The amplifier is designed to perform efficiently, even at very low quiescent power. The estimate of maximum power dissipation was kept around 1 mW. Hence, the amplifier can be used in liquid helium environment without much heat load on the bath. As the targeted zone of operation was beyond the datasheet descriptions, a detailed DC and AC testing was performed. The DC characterization includes correlation between gate voltage (V_g), drain voltage (V_d) and drain current (I_d), giving calculated values of drain resistance (R_d) and trans-conductance (g_m) at different biasing conditions. The gate was biased from -0.8 V to -0.7 V and drain voltage was varied from 0.05 V to 1.0 volts while keeping the drain current limited to 2mA for all tests. A pair of Keithley source meter (Model no. 2450) was utilized to set the gate and drain voltages while acquiring and logging all the data through computer based Graphical User Interface (GUI). Similarly, the AC characterization provided the variation of quality factor (Q) and gain with the change in bias.

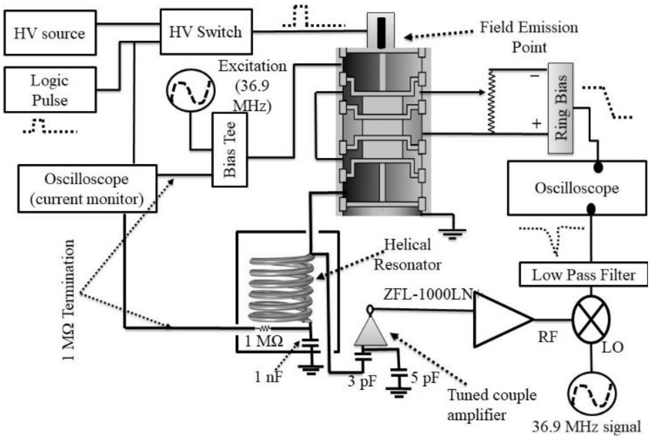

Figure 1: Schematic circuitry for the detection of trap signal using tuned couple amplifier.

Testing with Penning Trap

The developed amplifier was coupled to the lower endcap electrode of the Penning trap, as shown in Fig. 1. The resonance frequency of the detection circuit results from the combined effects of the trap capacitance, helical resonator, connecting cables, and the input capacitance of the first-stage amplifier. To minimize the capacitance loading from the connecting wires, the amplifier was positioned very close to the resonator tank. A vacuum of approximately 2.8 x 10^{-7} mbar was maintained in the chamber using a turbo-molecular pump.

The output of the amplifier was connected to an oscilloscope to determine the Q factor. At biasing potentials $V_g = -0.76V$ & $V_d = 0.2V$ the Q factor was found to be 405 at the central resonance frequency of 36.9 MHz. At a different biasing condition with $V_g = -0.78V$ & $V_d = 0.8V$, the quality factor was improved to 595. The drain current in both the settings was around 1.3 mA. In earlier experiment with broadband amplifier, we achieved a maximum Q factor of 400 at room temperature [2,4]. So, with tuned couple amplifier, we achieved Q factor much better than broadband amplifier.

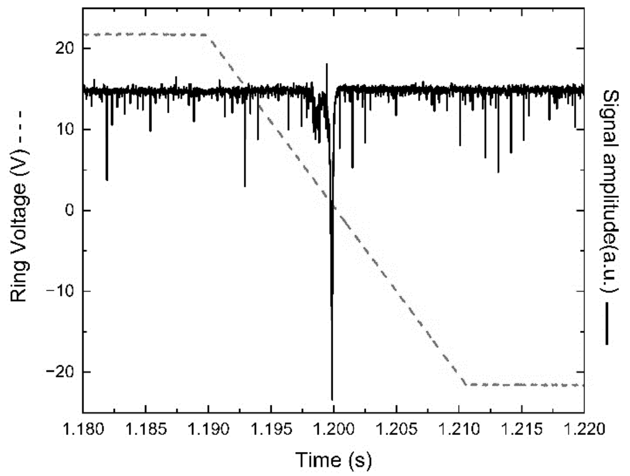

Figure 2: Signal of electron cloud in resonance detection technique

As shown in Fig. 1, a Field Emission Point (FEP) based on carbon nanotubes was used to generate the primary electron beam. The FEP was operated at 850 V, with a current of approximately 100 nA recorded at the upper endcap, and around 50 nA passing through the trap, recorded at the lower endcap. The developed amplifier was tested using the resonance absorption technique. A ramp signal ranging from +22 V to -22 V was applied to the ring and a fraction (0.8 times) to the compensation electrodes. The upper and lower endcap electrodes were kept at ground potential via 1 Mega ohm termination of oscilloscope. This configuration felicitate to measure the current falling on both electrodes. An RF signal with a frequency of 36.9 MHz was applied to the upper endcap electrode to excite the electrons at resonance.

The axial oscillation of the electrons was observed as a dip in the beat spectrum, as shown in Fig. 2, when the axial frequency of the electrons matched the natural frequency of the LCR circuit, creating a resonance condition for a specific value of ring voltage. To generate the beat signal, the output from the amplifier was further amplified by a Mini-Circuits amplifier (model ZFL1000LN+), then passed through a mixer where it was combined with the same resonance frequency. The signal was then passed through a low-pass filter, producing a beat signal that showed changes in absorbed power as the axial frequency of the trapped electrons resonated with the tank circuit's frequency. The details of the experimental setup are provided in Ref. [5].

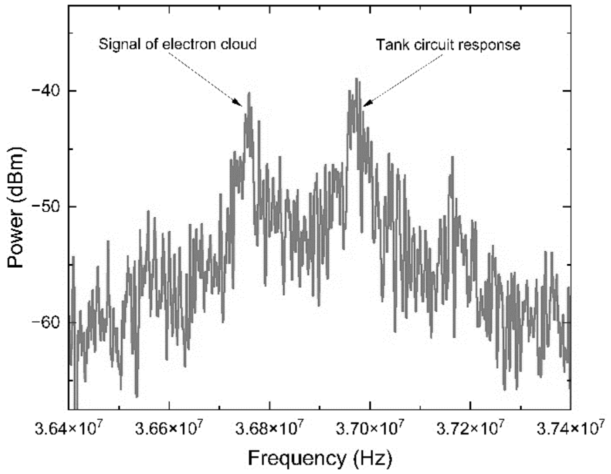

Figure 3: Frequency spectrum of tank circuit in the presence of cloud of 10^5 electrons.

The amplifier was also used for signal detection in the noise dip detection technique, where the ring voltage was held constant at +2 V instead of giving ramp voltages. Both endcap electrodes were grounded as earlier. The signal was observed in the frequency domain, where the output of ZFL 1000 LN+ connected directly to the spectrum analyzer. As shown in Fig. 3, the signal from the trapped electrons, along with the noise response of the tank circuit, was clearly visible. During both tests, the amplifier was operated at $V_g = -0.78$ V and $V_d = 0.8$ V. Since this is a narrow-band amplifier with a bandwidth of approximately 1.5 MHz, signals in the frequency domain were observed only when the axial frequency of the trapped electrons fell within the amplifier's bandwidth.

In conclusion, a tuned-coupled amplifier was developed specifically for detecting signals from trapped electrons at temperatures down to 4K. The amplifier has been tested and has functioned satisfactorily in both time-domain and frequency-domain detection techniques.

ACKNOWLEDMENTS

Amlan Ray (A. Ray) acknowledges financial assistance from the Science and Engineering Research Board (Government of India) grant number: CRG/2020/003237.

Reference

1. K. Blaum, Physics Reports, **425** (2006) 1.
2. J. Nandi, *et.al.*, Rev. Sci. Inst. **95** (2024) 043202.
3. Brian Richard D’Urso, Ph.D. thesis, Harvard, 2003.
4. J. Nandi, *et. al.*,, Nucl. Inst. Meth. A **980** (2020) 164465.
5. A. K. Sikdar *et al.*, Proc. DAE Symp. **61** (2016) 954.