Cyclotron Detector Development for $\bar{\mathrm{p}}$ Transport at BASE-STEP

Matthew Everette

Clemson University

August 8, 2024

Baryon Asymmetry

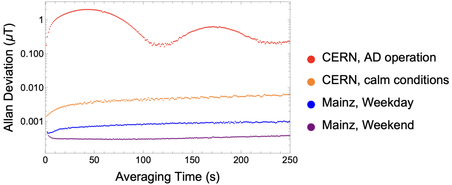
- It is an observational fact that our universe is almost completely made up of matter.
- Both the standard model and our current understanding of cosmology fail to explain the lack of antimatter in the universe – **the baryon asymmetry problem**.
- CPT violating processes, if they exist, could provide a solution to baryon asymmetry.

The BASE Experiment

- The **Baryon-Antibaryon Symmetry Experiment** (BASE) performs high-precision measurements of the charge-to-mass ratio of protons and antiprotons as well as the antiproton g-factor to test CPT invariance.
- Antiprotons produced at CERN's Antimatter Decelerator (AD) are captured and measured in BASE's four Penning trap setup.
- BASE has measured the proton-to-antiproton charge-to-mass ratio with a precision of 16-parts-per-trillion.

BASE-STEP

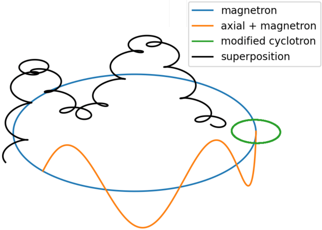
- Currently, the high level of magnetic noise in the AD hall is the bottleneck for increasing measurement precision.



- **BASE-STEP** (Symmetry Tests in Experiments with Portable antiprotons) is developing a portable antiproton trap to solve the problem.
- Antiprotons will be loaded into the trap in the AD hall and driven to an off-site laboratory with less magnetic noise.

Penning Traps

- A quadrupole electric field and an axial magnetic field confine particles.
  - In the trap, particles exhibit three modes of oscillation: magnetron motion, axial motion, and modified cyclotron motion.



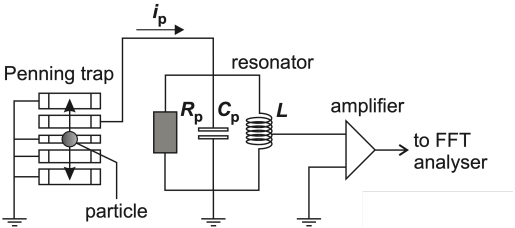
- The **invariance theorem** relates the oscillatory frequencies of these modes to a particle's free cyclotron frequency, ν_c:

$$\nu_c^2 = \nu_-^2 + \nu_z^2 + \nu_+^2$$

- Precise measurements of ν_c are necessary for both charge-to-mass ratio and g-factor measurements.

Non-Destructive Particle Detection

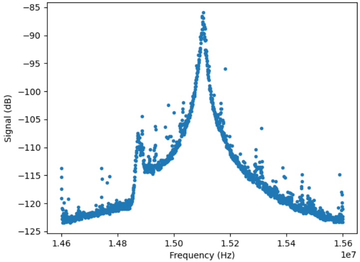
- A particle oscillating in the trap produces an image-current in the traps electrodes.
- This image-current is fed through the detector, which consists of an RLC **resonator** followed by an **amplifier** circuit.
- There are both axial detectors and cyclotron detectors.
    - Magnetron motion is typically measured with the axial detector through sideband coupling.
- While the cyclotron detector can be used for particle detection, it is mainly used to cool the particle's cyclotron motion.



My Project

- This summer, I have been working to develop a new cyclotron detector for BASE-STEP.

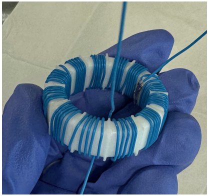
- The experiment's two cyclotron detectors are highly coupled, distorting their frequency responses.
    - This results in both a larger cooling time constant τ and a lower signal to noise ratio (SNR).

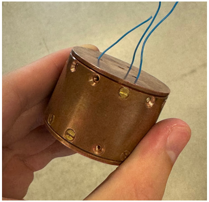


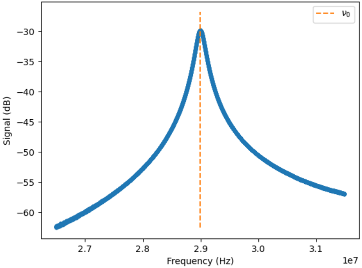
- The goal of my new detector implementation is to reduce τ and increase the SNR by optimizing the resonator design, as well as improving the detector's tuning range by designing a more robust varactor setup.

The Resonator

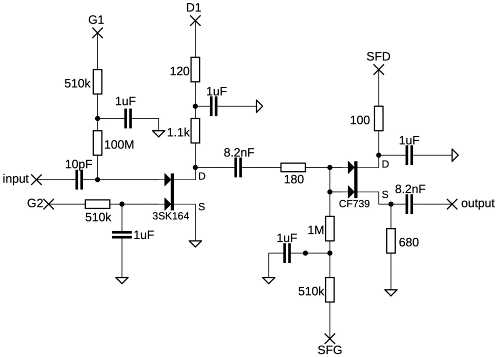
- The resonator is an inductor consisting of Cu wire wound around a toroidal PTFE core, all of which is placed inside of a Cu housing.
- Measurements of the resonator's resonance frequency ν_0 allow for its inductance L and capacitance C to be determined.

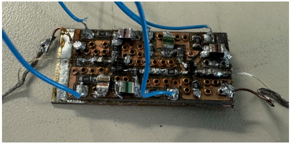






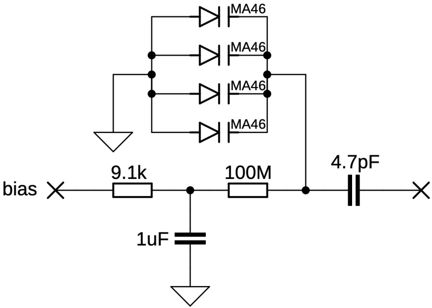
The Amplifier

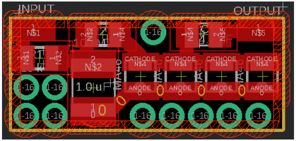




- The amplifier circuit consists of two field effect transistors (FETs).
    - The first acts as a common-source amplifier and the second acts as a source follower.
- Measurements were done to determine the amplifier's gain G, the amplifier's equivalent input noise e_n, and optimal gate voltages G_1 and G_2 for operation.

The Varactor Board





- The varactor board allows the detector's resonance frequency to be tuned.
    - Varactors are a type of reverse-biased diode that have a voltage tunable capacitance.
- The varactor circuit was placed in parallel with the resonator to maximize the detector's tuning range.

Results

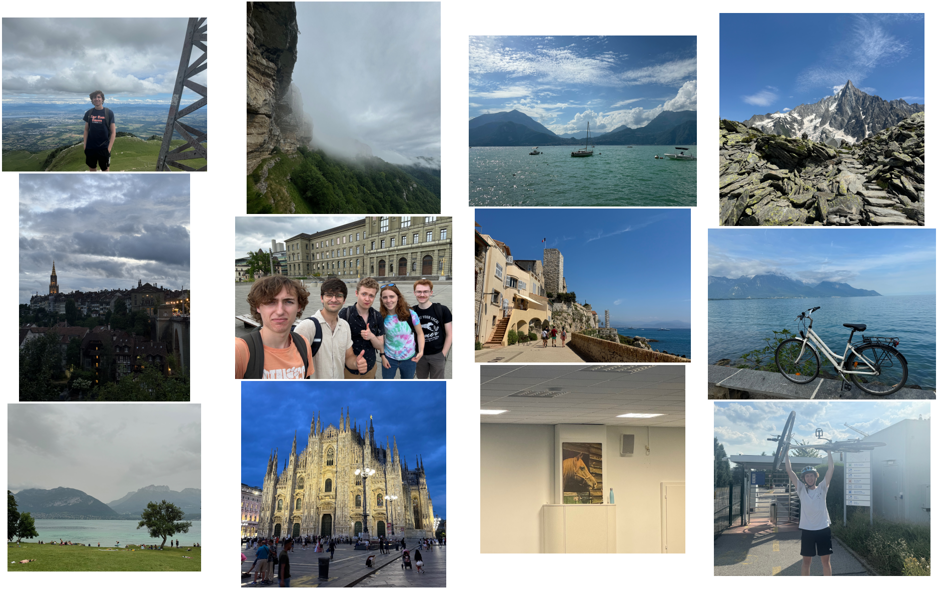
- Values of $L = 3.7\mu\text{H}$ and $C = 8.2\text{pF}$ were measured from the resonator.
- The detector was characterized at both room temperature (RT) and at 11K.
- The following table summarizes the measurement results:

	RT	11K
$G_1,\ G_2$	-1.55V, 0.93V	-1.03V, -0.45V
ν_0	~17.8MHz	~16.8MHz
Amplitude	14.0dB	19.4dB
Q	105.998	609.834
e_n	~4nV/$\sqrt{\text{Hz}}$	~2nV/$\sqrt{\text{Hz}}$
Tuning range	~565kHz	~540kHz

Conclusion

- The measured values of L, Q, and e_n correspond to a **25% lower cooling time constant** τ and an approximate **SNR of ~16dB** at low operating temperatures.
- The tuning range of ~540kHz is a substantial improvement over the two current detectors' tuning ranges of ~150kHz and ~80kHz.
- Moreover, all this improvement was done with only a ~10% decrease in the detector's Q factor.
- **Next step: installing the detector!**

Travel Pics



Supplementary Slides

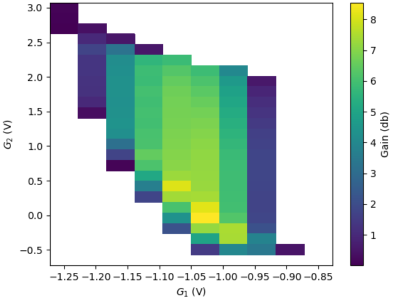
Important Equations

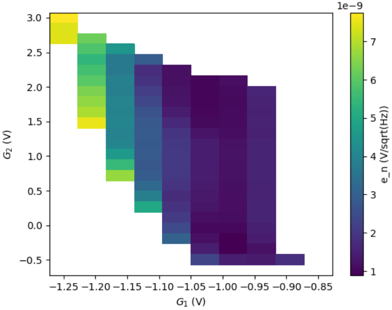
$$Q = \frac{R_{eff}}{2\pi\nu_0 L}$$

$$\tau = \frac{m}{R_{eff}}\frac{D^2}{q^2}$$

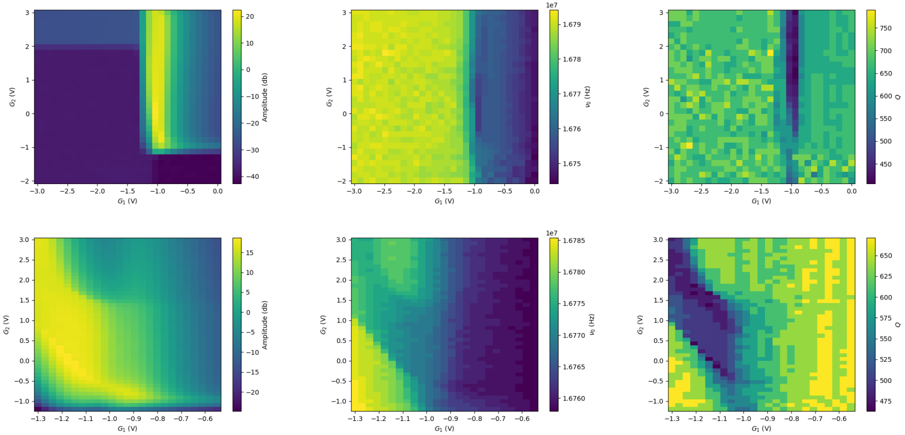
$$\mathrm{SNR} \approx \frac{\sqrt{4k_B T R_{eff}}}{e_n}$$

(Low Temp) Amplifier Measurements 1





(Low Temp) Amplifier Measurements 2



Note: It appears that the amplifier's working point shifted between the coarse and fine scan, likely because the amplifier was not yet fully thermalized.

(Low Temp) Varactor Measurements