

# Microwave Injection System Upgrades for Antihydrogen Gravity Experiments in ALPHA-g

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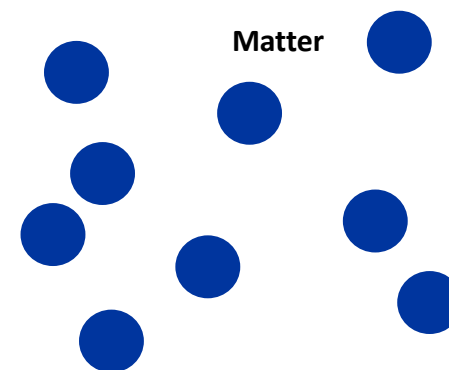
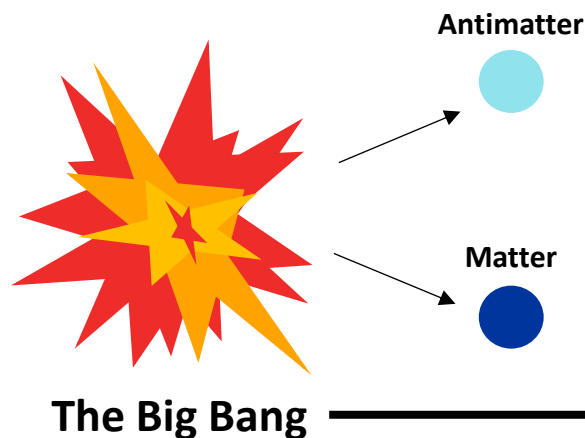
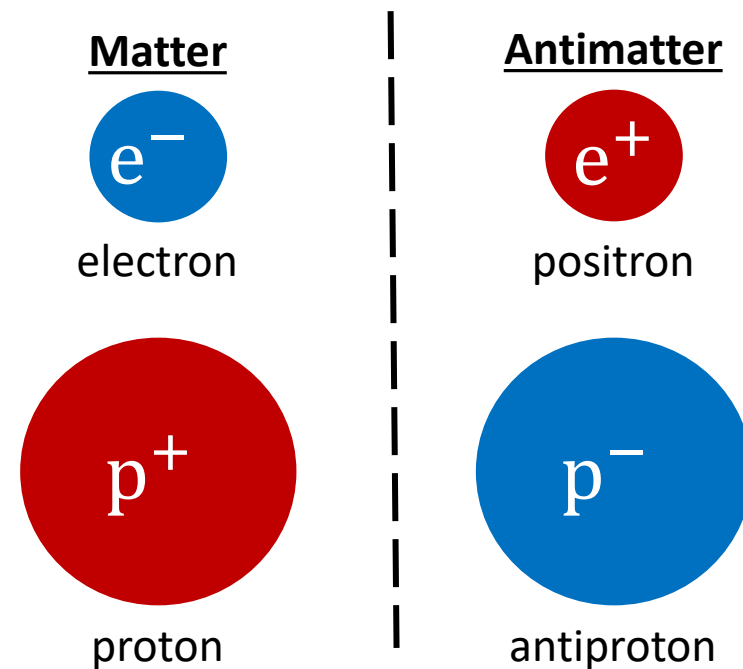
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August 12, 2026



# Matter and Antimatter

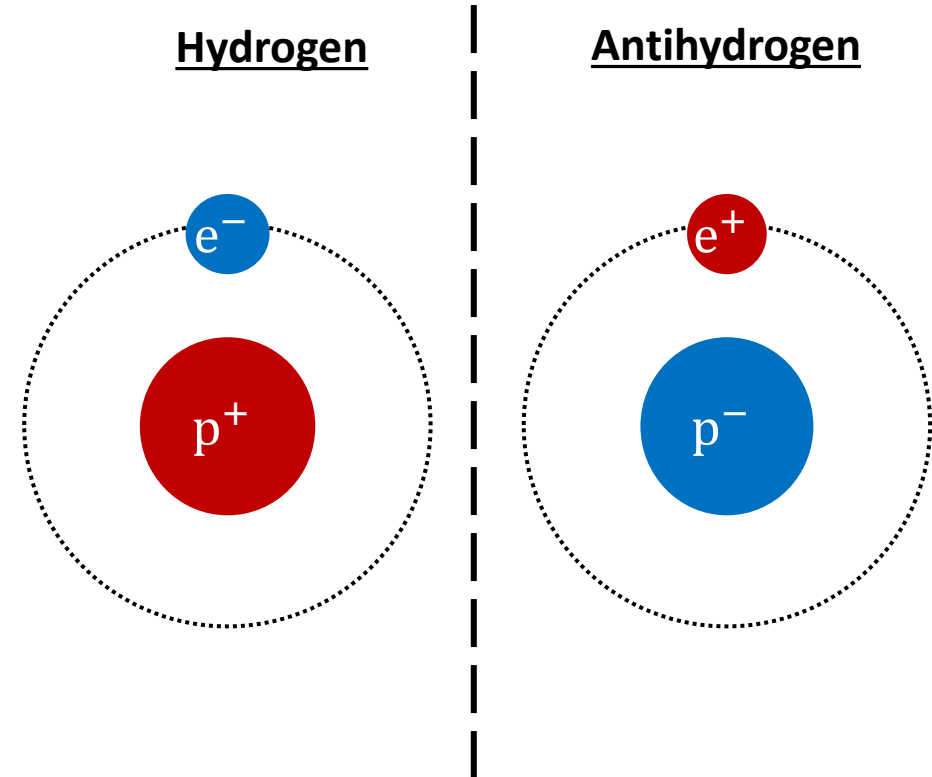
- Every particle has an antiparticle equivalent with the same mass but opposite charge
- Matter and antimatter are produced in pairs
- When an antiparticle meets its matter equivalent, they annihilate



# Antihydrogen atoms

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- Antihydrogen is a strong choice to study matter-antimatter asymmetry
  - The simplest antiatom
  - Hydrogen, its matter counterpart, has been thoroughly studied



# The ALPHA Experiment



- Antihydrogen Laser **PH**ysics **A**pparatus



# ALPHA-3 and ALPHA-g

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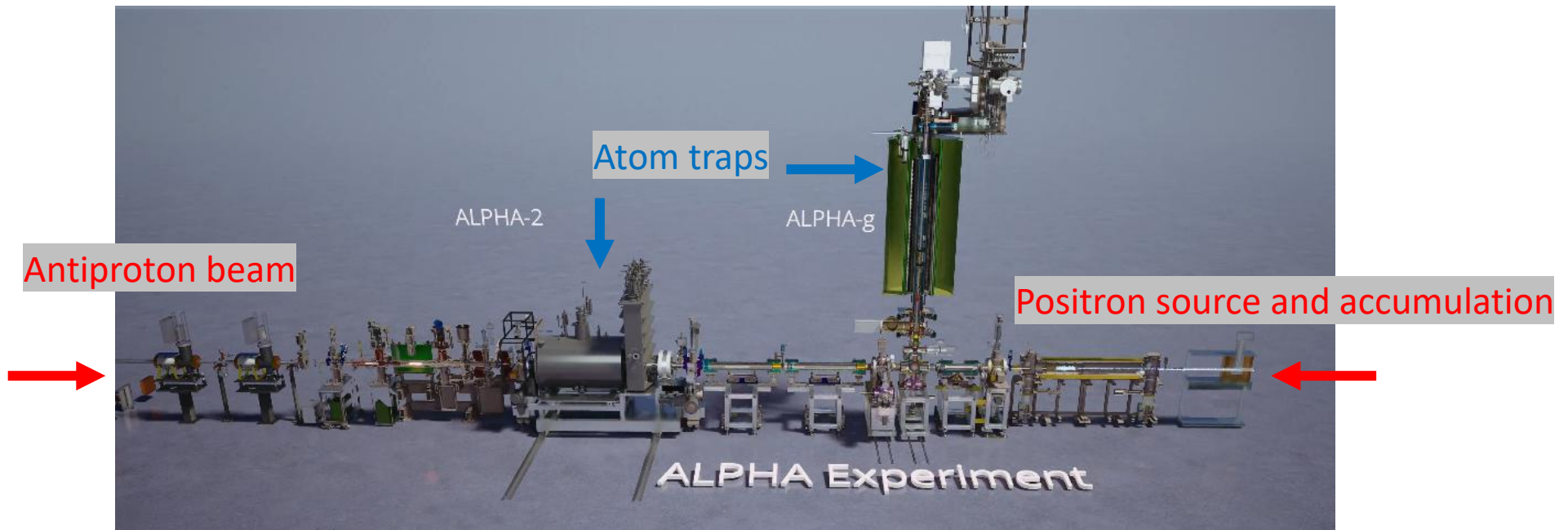


Image credit to CERN, <https://videos.cern.ch/record/2298631>

# ALPHA-g

- Charged particles are confined using Penning-Malmberg Traps
  - Axial confinement by an electrostatic potential well
  - Radial confinement by a 1 T axial magnetic field

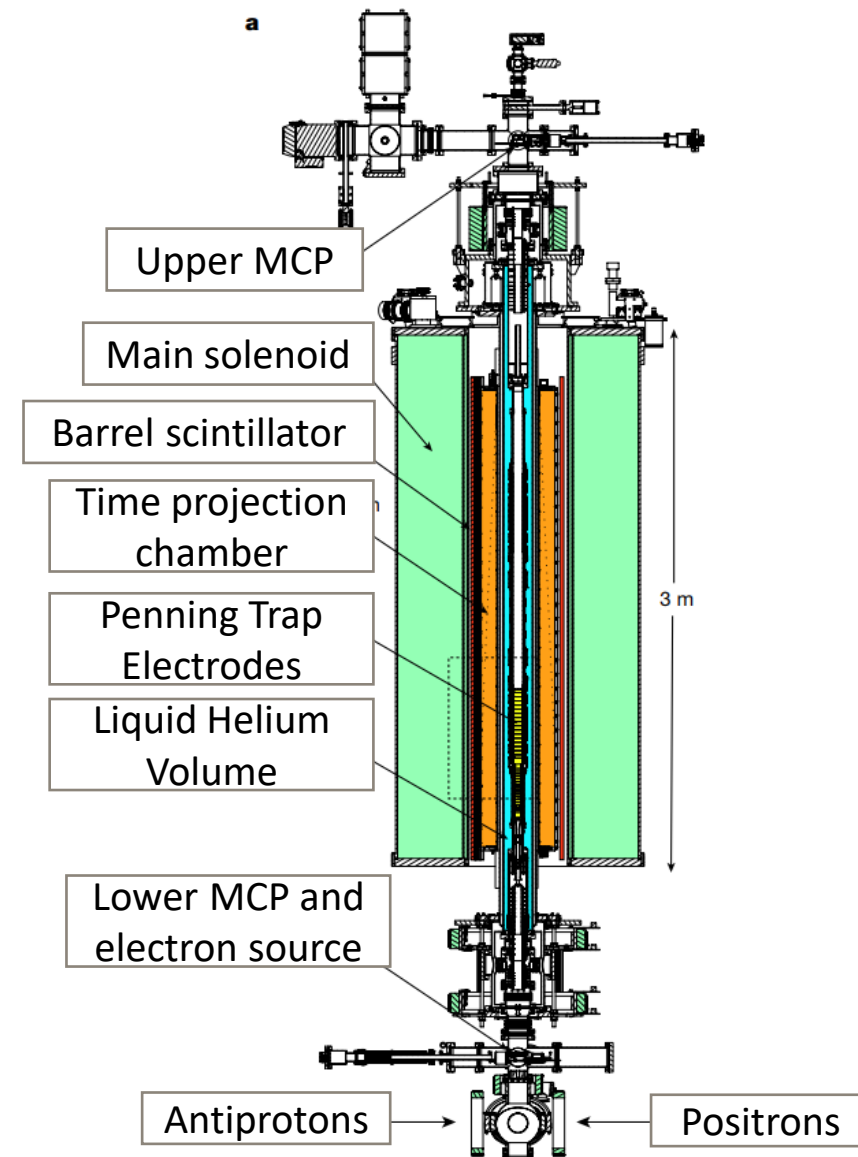


Image from Anderson, E.K., Baker, C.J., Bertsche, W. *et al.* Observation of the effect of gravity on the motion of antimatter. *Nature* **621**, 716–722 (2023).

# ALPHA-g

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- Antihydrogen is formed and trapped using a magnetic minimum trap
- To be trapped, the antihydrogen needs to be
  - Low energy,  $\sim 500$  mK
  - In a trappable spin configuration
- Antihydrogen is released so the fall can be observed

Simplified 1D On-Axis Model

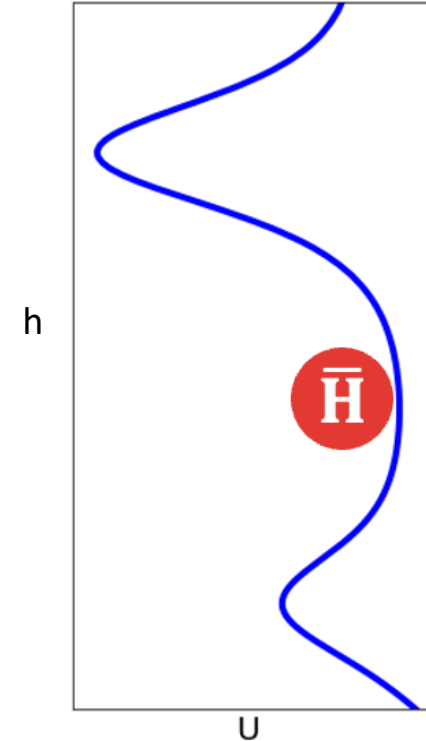


Image credits to Abbygale Swadling

# The ALPHA-g Microwave System

- States  $1S_d$  and  $1S_c$  are low field seekers and are initially trapped
- Microwaves can induce positron spin flips from
  - $1S_d \rightarrow 1S_a$ ,  $1S_c \rightarrow 1S_b$
- The driving transition frequency is a function of magnetic field

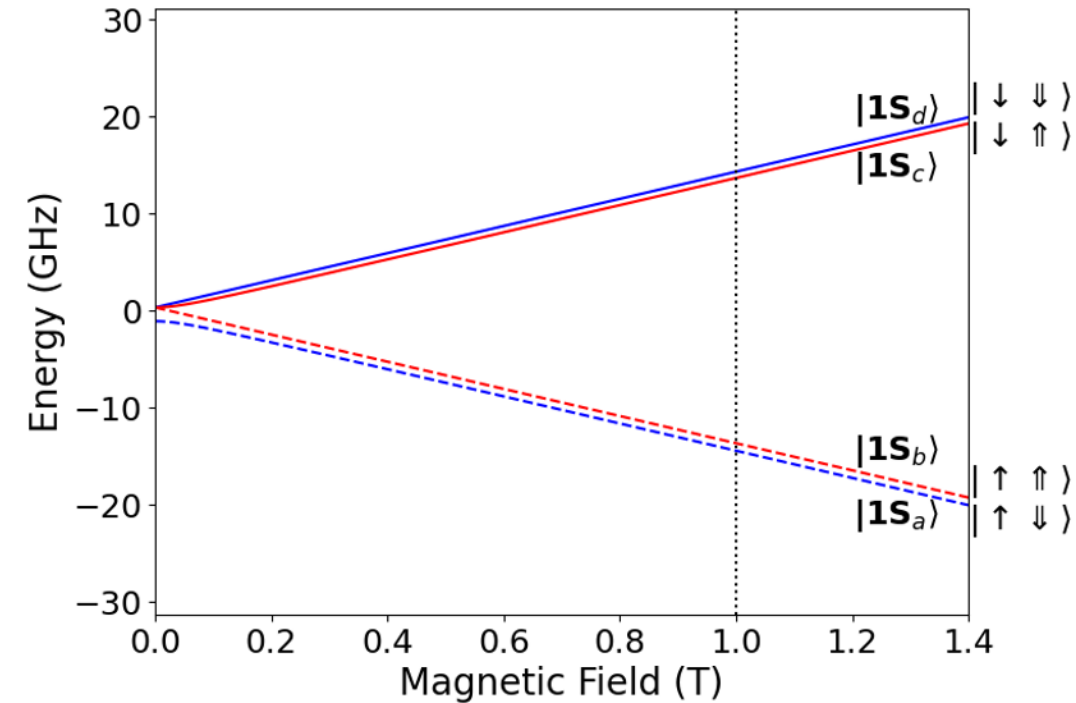


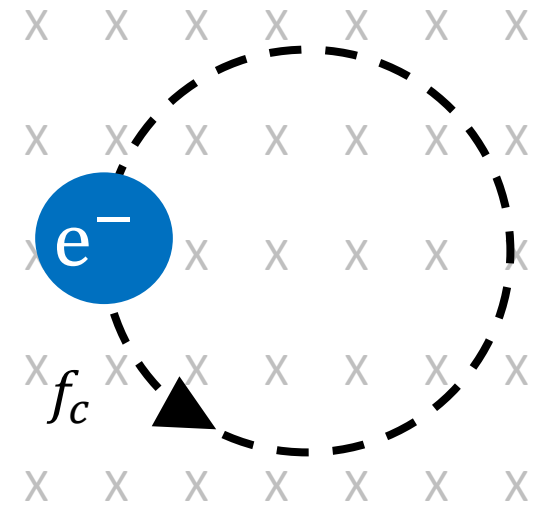
Image credits to Abbygale Swadling

# The ALPHA-g Microwave System

- Trap magnetic field is measured by **Electron Cyclotron Resonance (ECR)**

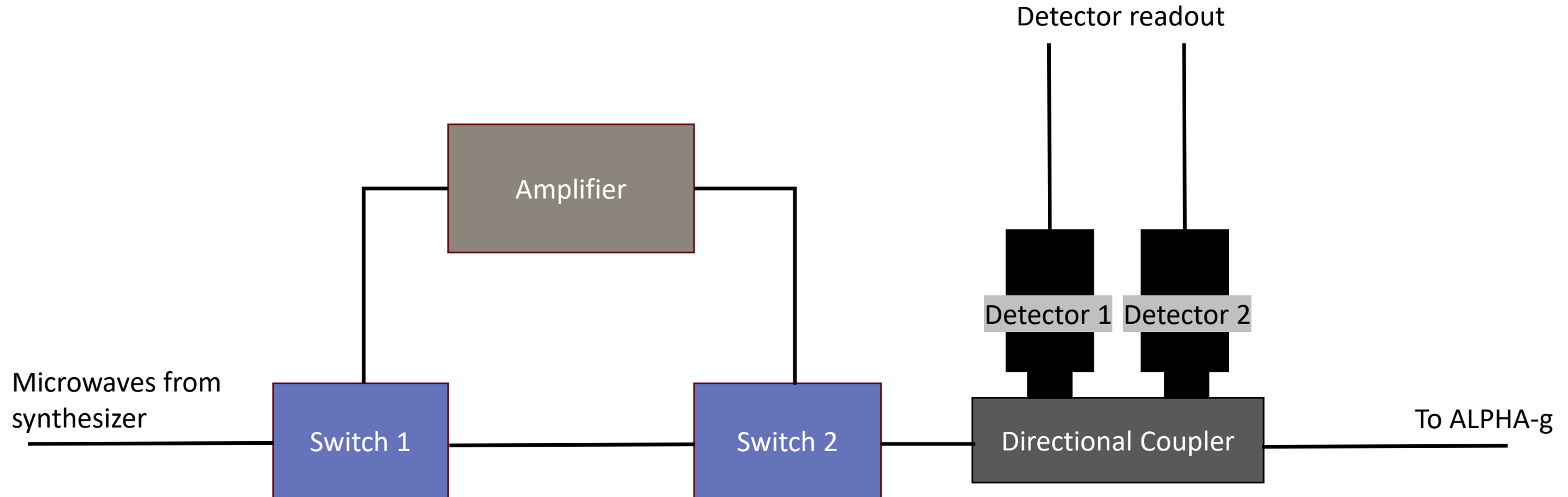
$$B = \frac{2\pi m_e f_c}{|q|}$$

- A cloud of electron rotates in the trap, and microwaves of different frequencies are injected one by one
- Microwaves that are resonant with  $f_c$  will cause heating

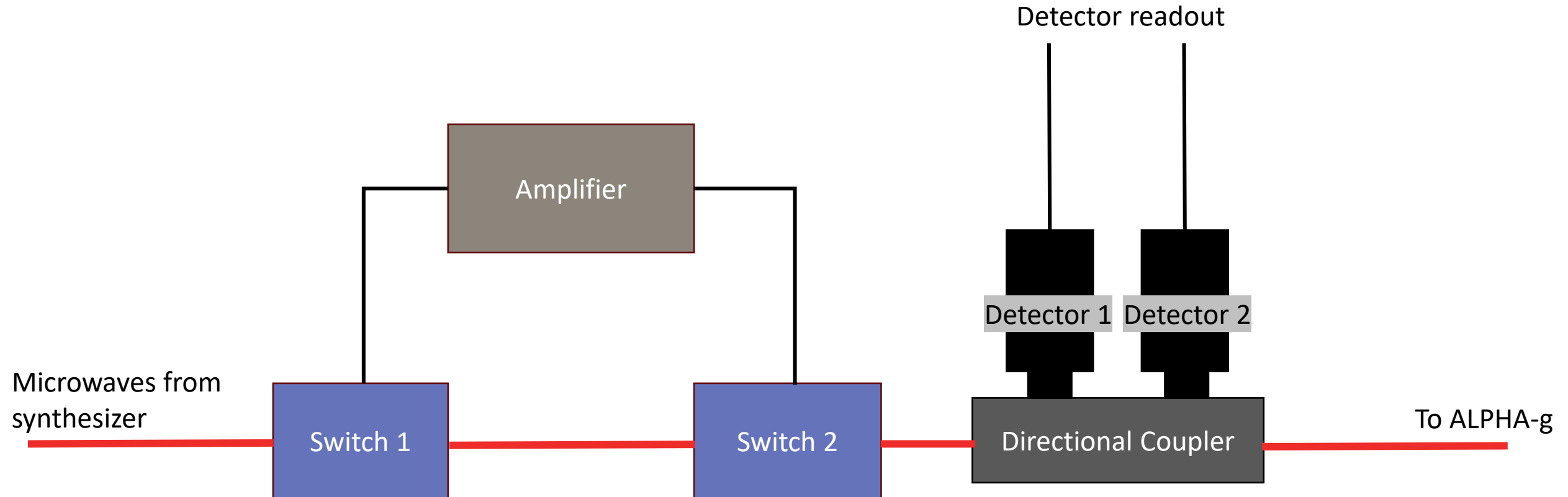


\*this is an oversimplified diagram of this motion

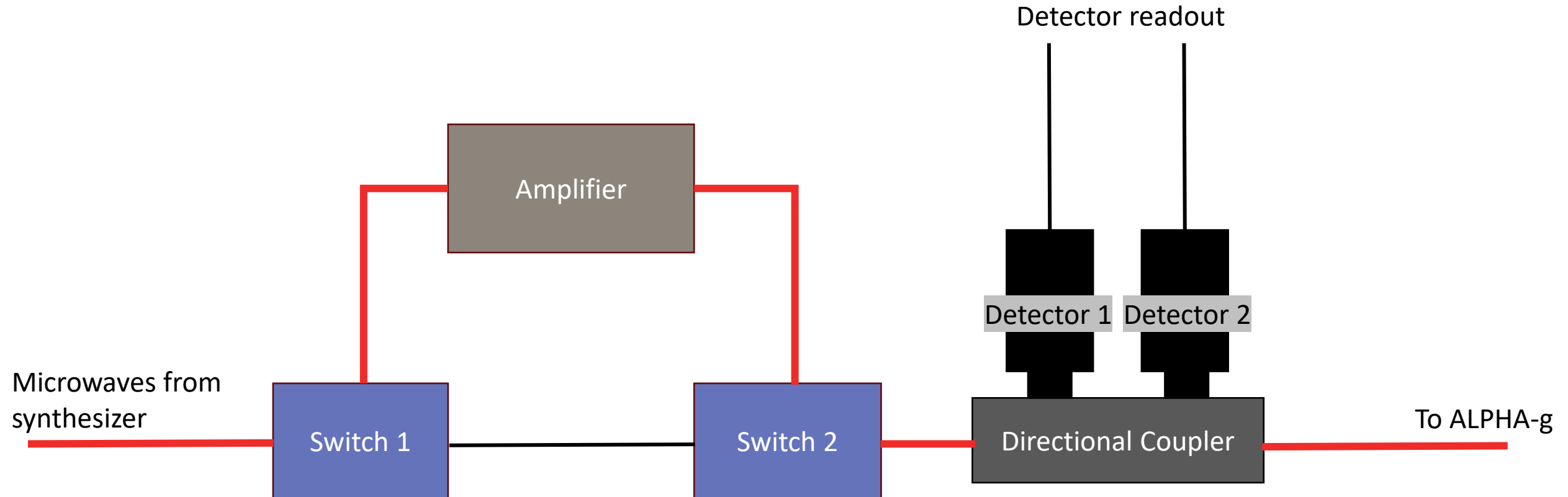
# The ALPHA-g Microwave System



# The ALPHA-g Microwave System



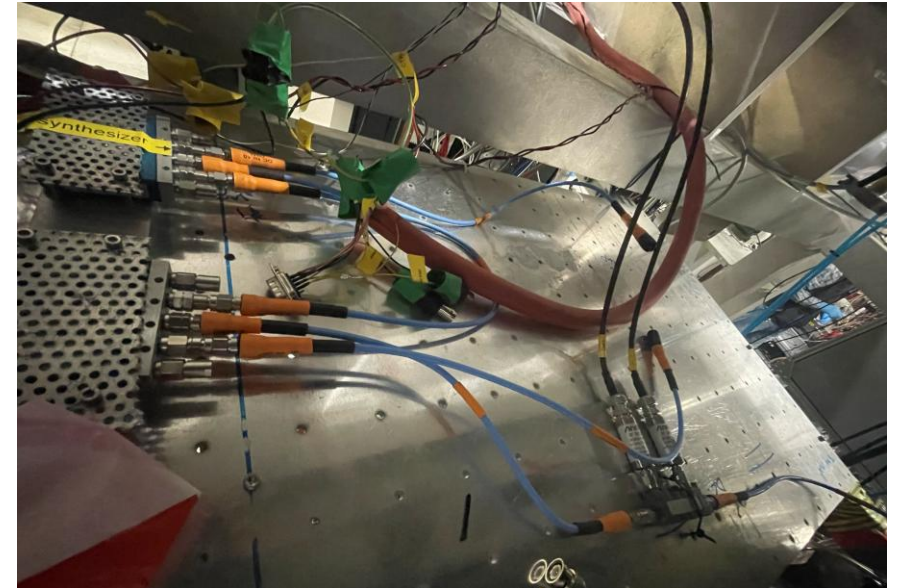
# The ALPHA-g Microwave System



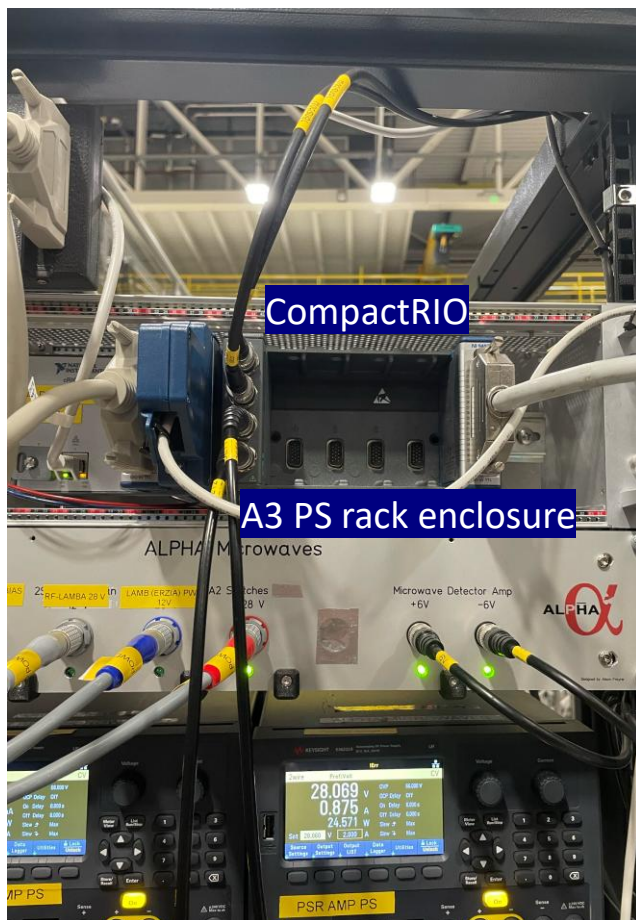
# Upgrades to the current system

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1. Improving safety
  - For long-term use
2. Legibility
  - Clear labelling to improve user accessibility
3. Organization
  - A centralized space to hold power supplies for increased organization



# System Upgrades: Objectives

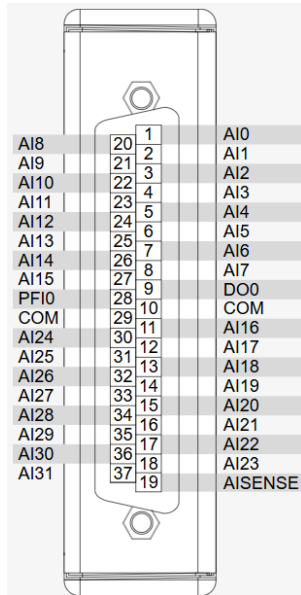


1. Power supplies centralized in a rack enclosure
2. The addition of a breakout panel for the ALPHA-g microwave system
3. Implementation of National Instruments CompactRIO

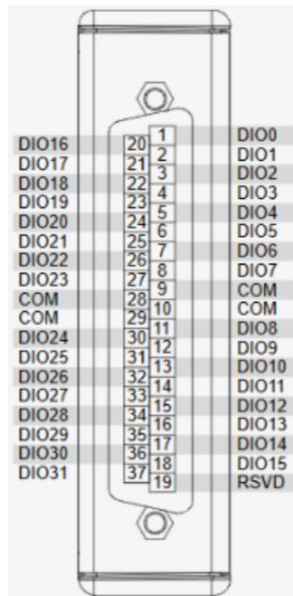
A3 Microwave Rack set up that this system is based on

# National Instruments CompactRIO and PCB

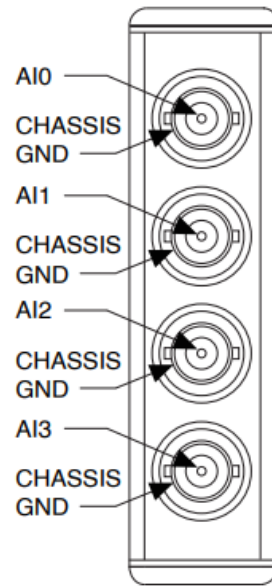
- Used for switch control (digital) and RF amp signal readout (digital + analog)



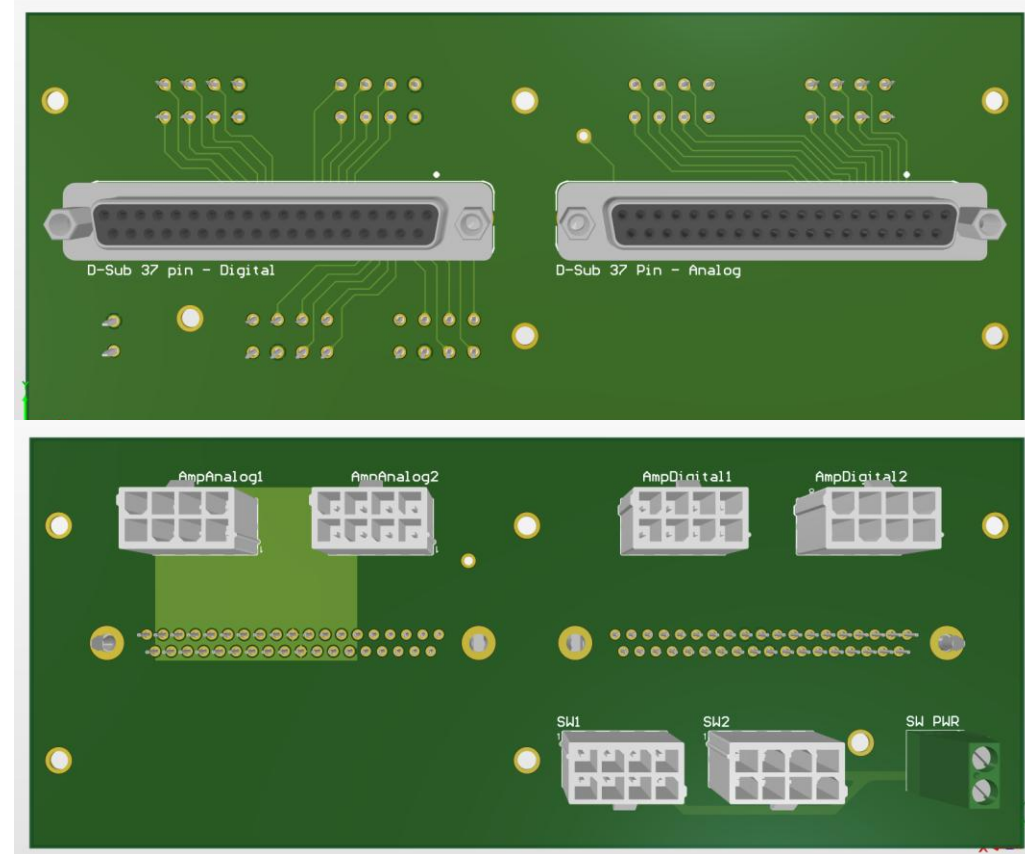
Analog Pinout



Digital Pinout



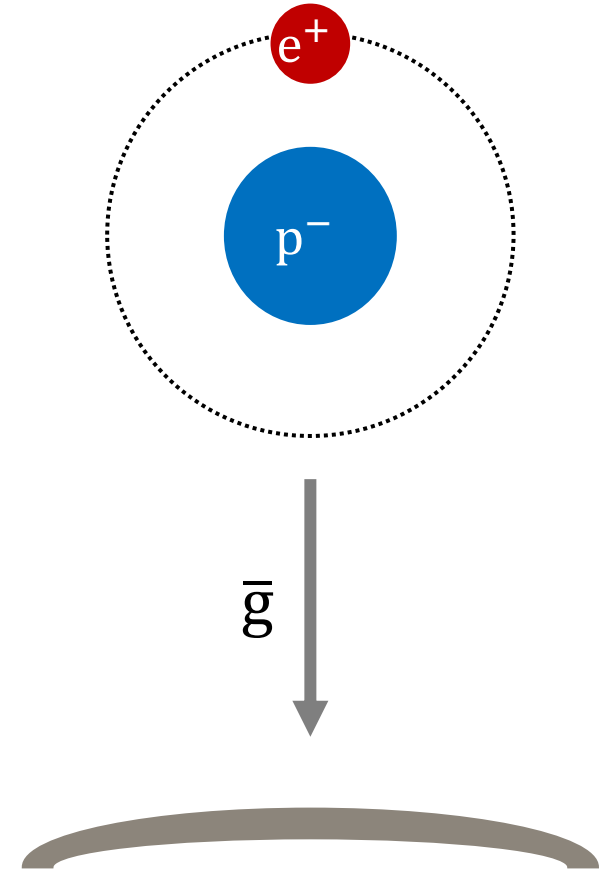
Analog BNC Pinout



# The next steps for ALPHA-g

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- In 2023, ALPHA-g was the first to determine that antimatter falls down<sup>1</sup>
- The future goal: measure  $g$  for antimatter within 1% precision
- Compare  $g$  for matter and antimatter



<sup>1</sup> Anderson, E.K., Baker, C.J., Bertsche, W. *et al.* Observation of the effect of gravity on the motion of antimatter. *Nature* **621**, 716–722 (2023).

# Thank you

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**Thank you to Dr. Tim Friesen, Abbygale Swadling, and the ALPHA experiment**

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