Environmental Space Effects on Electronic Systems

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Introduction

CubeSats are a low-cost platform transforming access to space. Their standardized design allows universities, researchers, and private organizations to rapidly develop and conduct missions, enabling scientific and technological advancements within a compact form factor. In any CubeSat mission, **electronics** are critical for data acquisition, system control, and communication, but are exposed to damaging space environments. In a collaboration between The Electric Propulsion Lab and The Laboratory of Advanced Space Systems at Illinois, this work supports the development of **MonARCH**, a CubeSat designed to test a novel **monopropellant multi-mode propulsion system**. This system uniquely integrates both chemical and electrospray thrusters within a low-volume package to improve **propulsion efficiency** for small satellites. This research focuses on the design and implementation of a reliable, **radiation-tolerant electrical system** for **payload control and instrumentation** using commercial-off-the-shelf (COTS) components not inherently designed or qualified for the space environment. The use of such electrical components is an active area of research because, while they offer significant cost and performance advantages compared to radiation-tolerant alternatives, they risk **insufficient protection** against space environments. This presentation focuses on **custom-designed printed circuit boards (PCBs)** researched, designed, and constructed by researchers in the Electric Propulsion Lab in collaboration with The Laboratory of Advanced Space Systems at Illinois. This analysis highlights the **critical factors** researchers must consider when **integrating electronics** onboard CubeSats, including radiation types, temperature extremes, and vacuum-related effects. Finally, the effects of Total Ionizing Dose (TID), Single Event Latch-Up (SEL), and Single Event Upsets (SEU) on semiconductor devices used in critical PCBs are discussed.

Design Process

Evaluating Payload Needs

- Temperature, pressure, power processing unit current and catalyst level readings.
- UART, I2C, SPI communication protocols for data transmission and control with on-board computer (OBC), breakout boards, power processing unit, and IC's.
- IEP, LFN valve control for catalyst circulation in feed system.
- Heater control for chemical thruster ignition.

Evaluating Space Environment

- The space environment for MonARCH will be in Low Earth Orbit (LEO) with an expected altitude of 400km. However, unknown beta angle and inclination.
- Some shielding from Earth's magnetosphere against GCR and SEP particles.
- "In LEO and in low inclination (<28 degrees) typical dose rates include 100-1000 rad(Si)/year [9]. In higher inclinations there's an increase in number of trapped electrons and typical dose rates include 1000-10,000 rad(Si)/year" [9].

Choosing Components

- According to [9] Bi-Polar technologies with a TTL/STTL package have a total dose hardness of 1e6 Rads(Si). Significantly bigger compared to MOS technologies, for example, NMOS with a TDH of 7e2
- Components from Texas Instruments, Analog Devices, STM were used for reliability, documentation, extreme precision, and accuracy.
- Commercial Components
  - Total Dose: 2 to 10krad
  - SEU Threshold LET: 5MeV/mg/cm^2
  - SEU Error Rate: 10^{-5} errors/bit-day

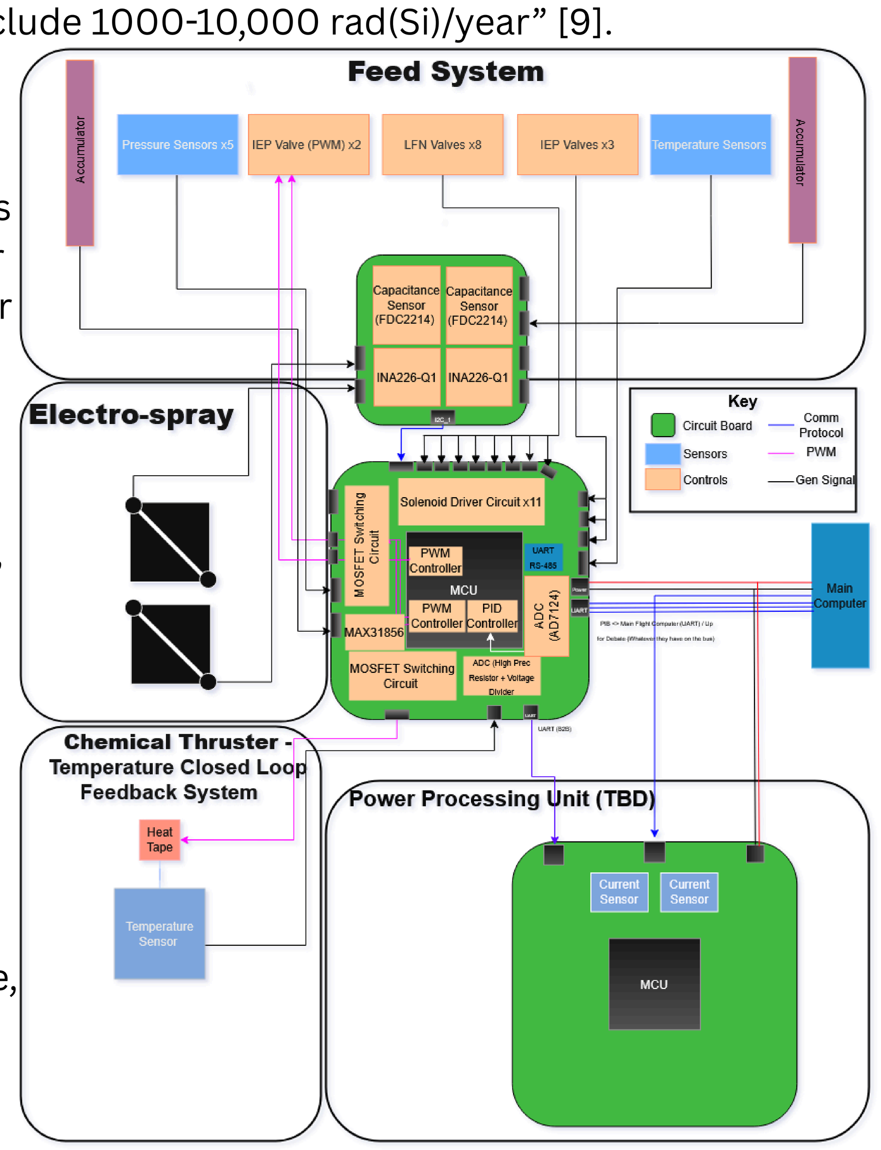


Figure 1: Initial Diagram of the Payload Electrical System

→ ***Micro-controller Unit***

- Ultra-low-power, high-performance, 32-bit Cortex-M4 micro controller
- Built on a larger geometry process
- Two PWM Pins, Error code correction (ECC)
- Four I2Cs, three SPIs, three USARTs, two UARTs and one Low-Power UART, two SAIs, one SDMMC, two CANs, one USB OTG full-speed, one SWPMI (single wire protocol master interface), a camera interface and a DMA2D controller.

The Grainger College of Engineering

Radiation

Particle Interactions

- Coulombic Interactions
  - Delta rays are secondary electrons from ionization
- Nuclear Interactions and material defects
- Photon-Matter Interactions (Photoelectric effect)
- Ion Trace → Ion Drift → Ion Diffusion
- Galactic cosmic rays (GCE) 100's MeV to GeV
- Solar particle events (SPE) 10's MeV to 100's MeV
- Earth radiation belts 10's keV to 100's MeV

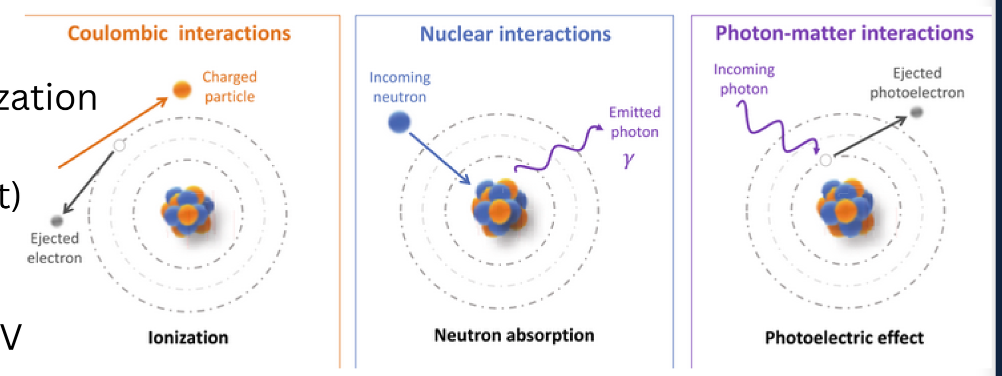


Figure 4: Coulombic, Nuclear, and Photon Matter Interactions [1]

Galactic Cosmic Rays (GCR)

- "High energy particles/waves believed to be produced by accelerated magnetic fields of supernova remnant events such as supernovae explosions." [1], [12]
- 85% Protons, 14% Alpha Particles, 1% Heavy Ions [12]

Solar Energetic Particles (SEP)

- Solar flares, coronal mass ejections, solar winds (continuous stream of charged particles (plasma))
- "Sun continuously emits a low-energy stream of particles primarily consisting of protons and electrons" [1]

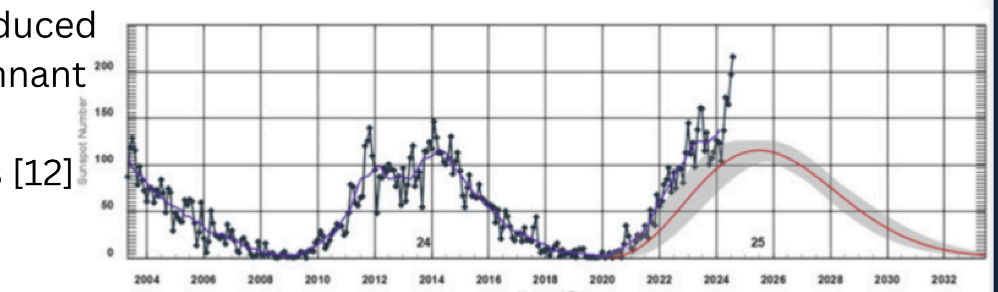
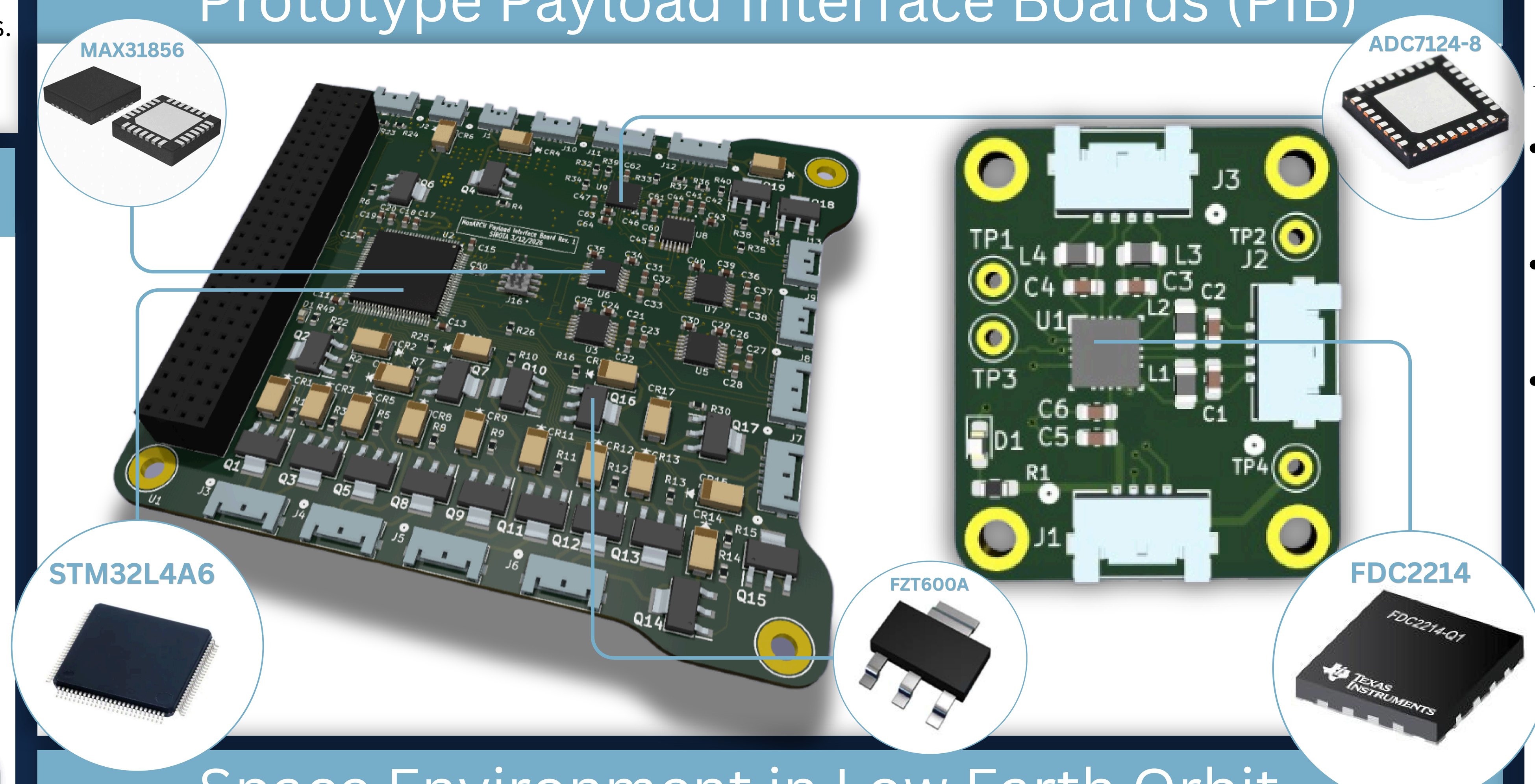


Figure 5: Solar Activity Measurements and Predictions [1]

Prototype Payload Interface Boards (PIB)



Space Environment in Low Earth Orbit

Vaccum

"Out gassing causes a cloud of contaminants around the spacecraft" [6]

- Tin Whiskers → Using lead based solder
- "Using ceramic rather than plastic components eliminates this problem in electronics" [5]

Plasma

- Coating spacecraft with a conducting material
- Charge build up on spacecraft and possible bolts of discharge (I_IN = I_OUT)

Atomic Oxygen

"The atmosphere in LEO is comprised of about 96% atomic oxygen" [5]

- "Material degradation - AO oxidizes many metals, especially silver, copper, and osmium."[6]
- MonARCH is not sealed and thus can degrade PCB

Thermal

- Required automotive rated components and temperature rated components around -55C-125C
- Thermal Fluctuations

Radiation ***"Radiation is simply the transmission of energy from a source via waves or particles." [7]***

- "In the last 25 years the National Geophysical Data Center recorded over 4500 spacecraft anomalies or malfunctions that have been traced to the effects of the space radiation environment." [8]
- The radiation environment close to Earth is divided into two categories: particles trapped in the Van Allen belts (P+,E-, and Heavy Ions) and transient radiation.
- Most of the radiation dose to the ISS occurs when flying through the South Atlantic Anomaly [6]

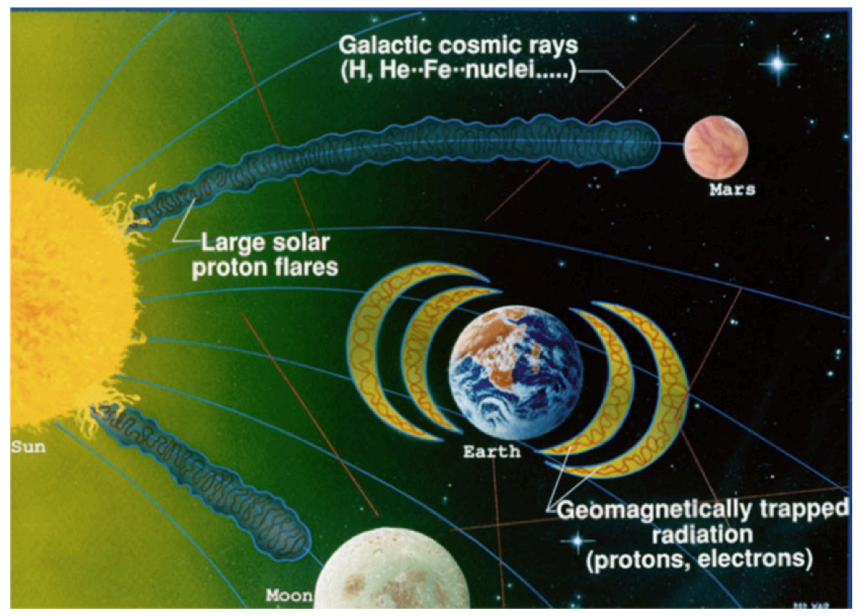


Figure 2: Sources of Radiation in Space [1]

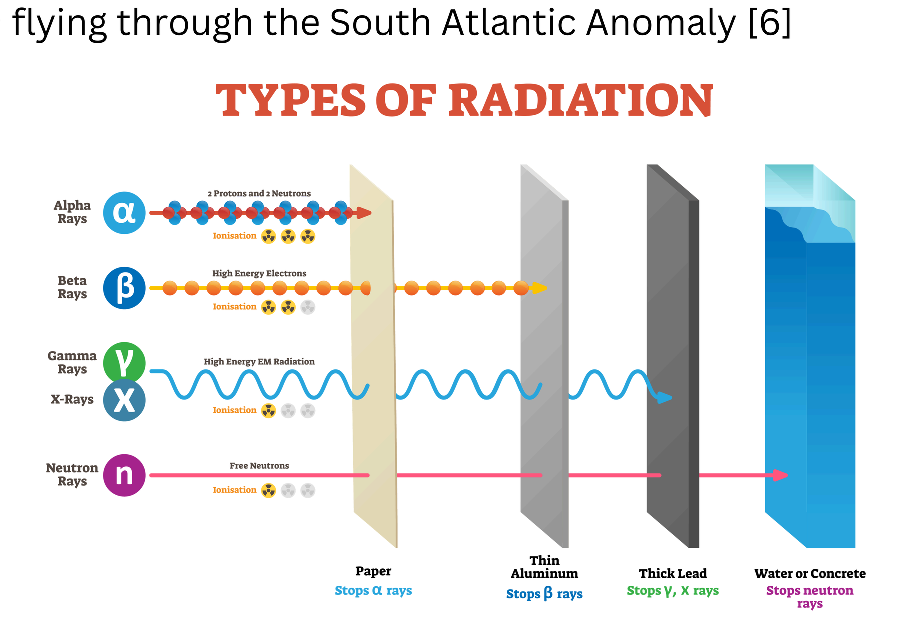


Figure 3: Types of Radiation and Penetrations [7]

Electronic Single Event Effects (SEE)

Single Event Upset (SEU)

- Bit flips, changes in the state of SRAM (memory cells) and registers.

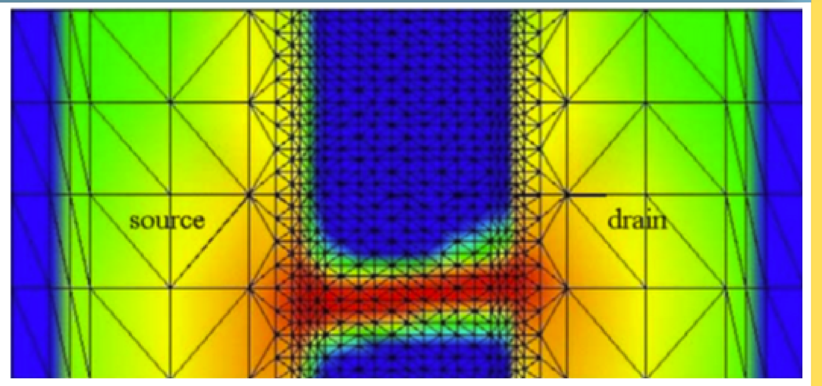


Figure 6: Leakage Current in SRAM Cell [2]

Single Event Transient (SET)

- "A SET is a transient voltage pulse generated by a charge injected into the device from a high energy particle." [5]
- Sequential vs combinational logic circuits

Single Event Latchup (SEL)

- "A SEL is where the formation of parasitic bipolar action (Parasitic Thyristors) in CMOS wells induces a low impedance path between power and ground, producing a high current condition." [5]

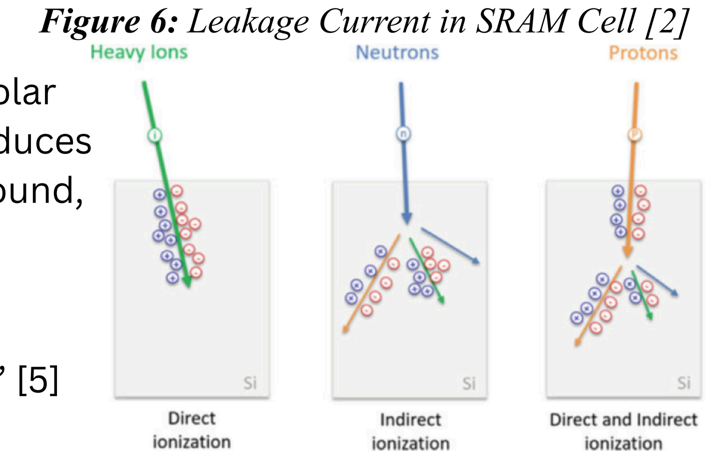


Figure 7: Direct Ionization and Indirect Ionization [1]

Total Ionizing Dose (TID)

- "TID is a long-term failure mechanism vs. SEE, which is an instantaneous failure mechanism." [5]
- "Collector current is affected as a result of radiation exposure" [9]
- Each C has a critical charge and if exceeded SEE occurs, voltage glitches, and transient current spikes, PN junction leakage currents

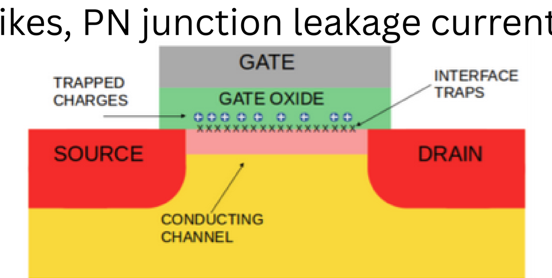


Figure 8: Trapping of Positive Charges in Gate Oxide [3]

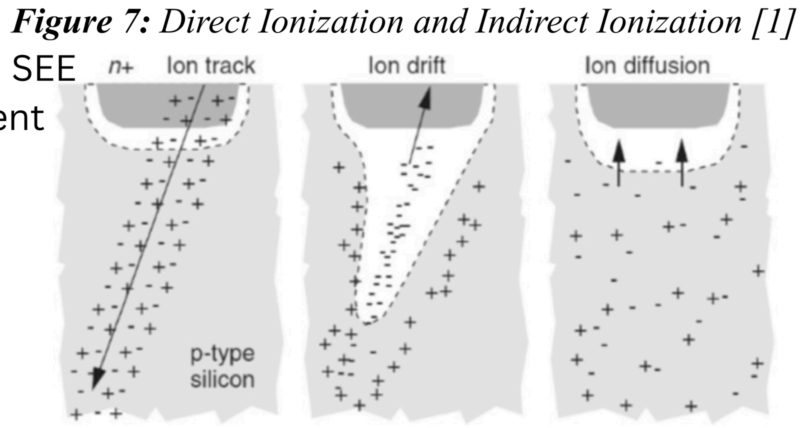


Figure 9: Charge Collection [1]

STM32 Series Research

- "[STM] is also capable of withstanding significant TID without failure. Through analysis, a 10 year 800km sun synchronous orbit would equate to approximately 10 kRads of radiation dose. Under the destruction test, the chip only began to fail at 47 kRads." [11]
- "At the 47 kRad point, where the CRC failures begin to occur, the current consumption begins to increase exponentially. By the time the test was stopped at 96 kRads, the current had increased to 46.6 mA." [11]
- "Since launch, the project has received more than 5000 telemetry frames from SONATE. At the moment the satellite is being commanded regularly in order to test the satellite's components." [10]

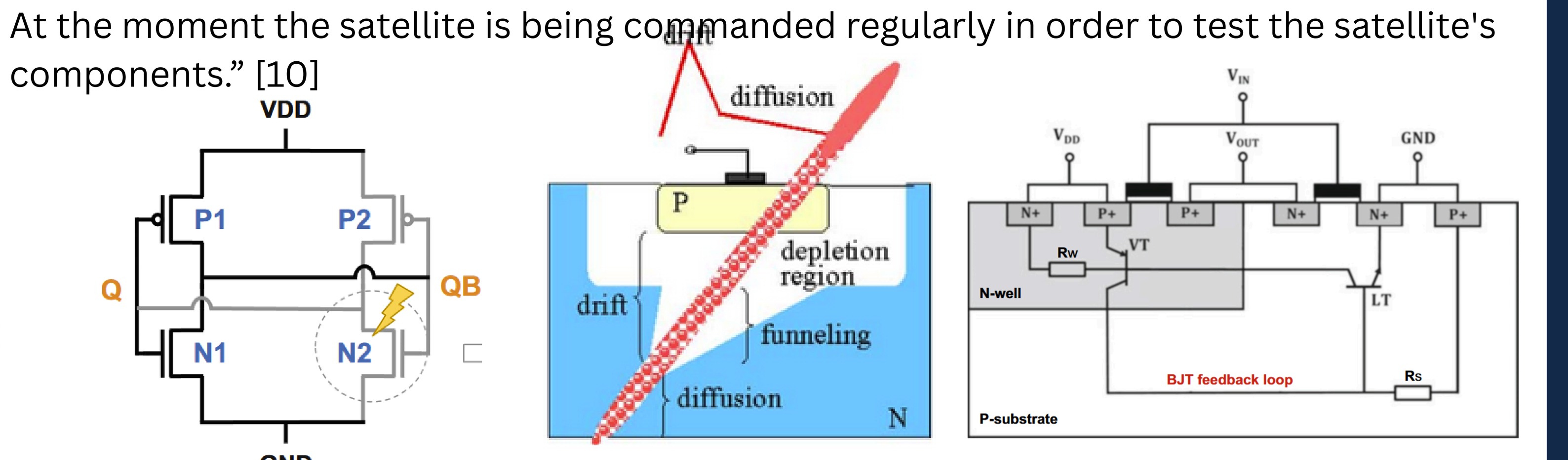


Figure 10: Cross Coupled Inverter Pair [1] **Figure 11:** Charge Deposition Model [2] **Figure 12:** CMOS-based inverter design [1]

Conclusion & Future Plans

The PIB prototype is currently in the testing phase and during the summer of 2026, testing the PIB for functionality is the main objective. This includes interfacing with K-type thermocouples and pressure transducers, measuring catalyst levels, and testing controls such as feed system sequencing events through UART commands from the OBC. Additionally, we will continue improving the payload electrical system and will be implementing techniques to protect the system and its data from the harsh space environment. Furthermore, testing will be done to evaluate the space effects on electronic systems discussed. This includes testing performance under harsh temperature conditions, re-designing prototype boards to reduce possible measurement drift due to EMI and parasitic capacitance replacing components for environmental stresses and out gassing potential. Our goal is to develop a robust and reliable instrumentation and control system capable of supporting accurate payload operation aboard MonARCH.

Sources

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