MINIATURIZATION FOR SPACE EXPLORATION

APPLIED NANOTECHNOLOGY AND MICROSYSTEMS

HARISH MANOHARA

PRINCIPAL MEMBER OF THE TECHNICAL STAFF
GROUP SUPERVISOR
NANO AND MICROSYSTEMS GROUP

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

ACKNOWLEDGMENTS

The research presented here were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

I thank the sponsoring agencies that supported projects reported in this presentation:

NASA (JPL R&TD), DARPA, and the SKULL BASE INSTITUTE

National
Aeronautics and
Space
Administration

TEAM MEMERS/COLLABORATORS

Team Members

Risaku Toda

Sam Y. Bae

Michael Shearn

Lee Hall

R. Korniski

K. Yee

Robert H. Lin

Collaborators

M. Mojarradi

A. Yen

Industrial Partners

NGC – Rolling Meadows

Photon Systems

Past Contributors

M. Bronikowski

E. Wong

E. Urgiles

R. Kowalczyk

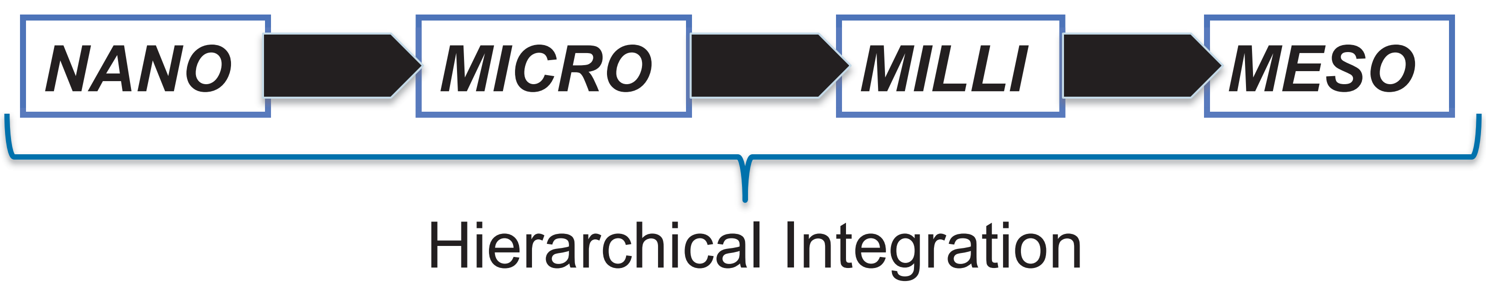
A. Liao

L. Del Castillo

INTRODUCTION

- Nano and Micro Systems group charter
  - To develop application-driven micro and nano devices/ techniques for *in situ* as well as remote planetary exploration

- Application examples
  - Planetary mineralogy, Spacecraft G&N/precision pointing of instruments, Extreme environment sensors and electronics, Microimaging, Heterodyne Spectroscopy
  - Ideally related to NASA science missions (earth, planetary, astro/physics)
  - Many developments are multi-use (Space, Defense, Commercial)

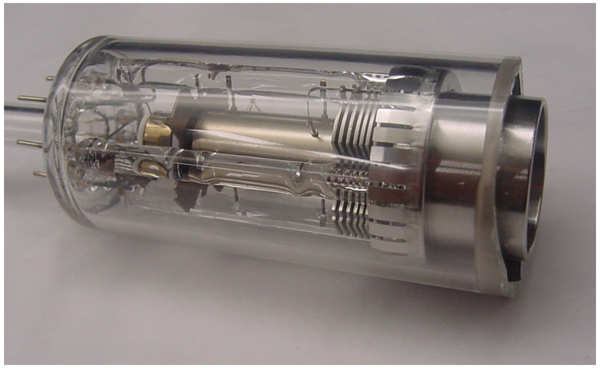


OUTLINE

- Vacuum Microelectronics/Instruments Using CNTs
  - Field emission of electrons
  - High current density CNT bundle arrays
  - Applications
    - X-rays for Mineralogy
    - 700°C Logic Gates
- Distributed Capacitor (DisC) Sensor for Sample Verification
  - Need and rationale
  - Design and Test Results

FIELD EMISSION OF ELECTRONS

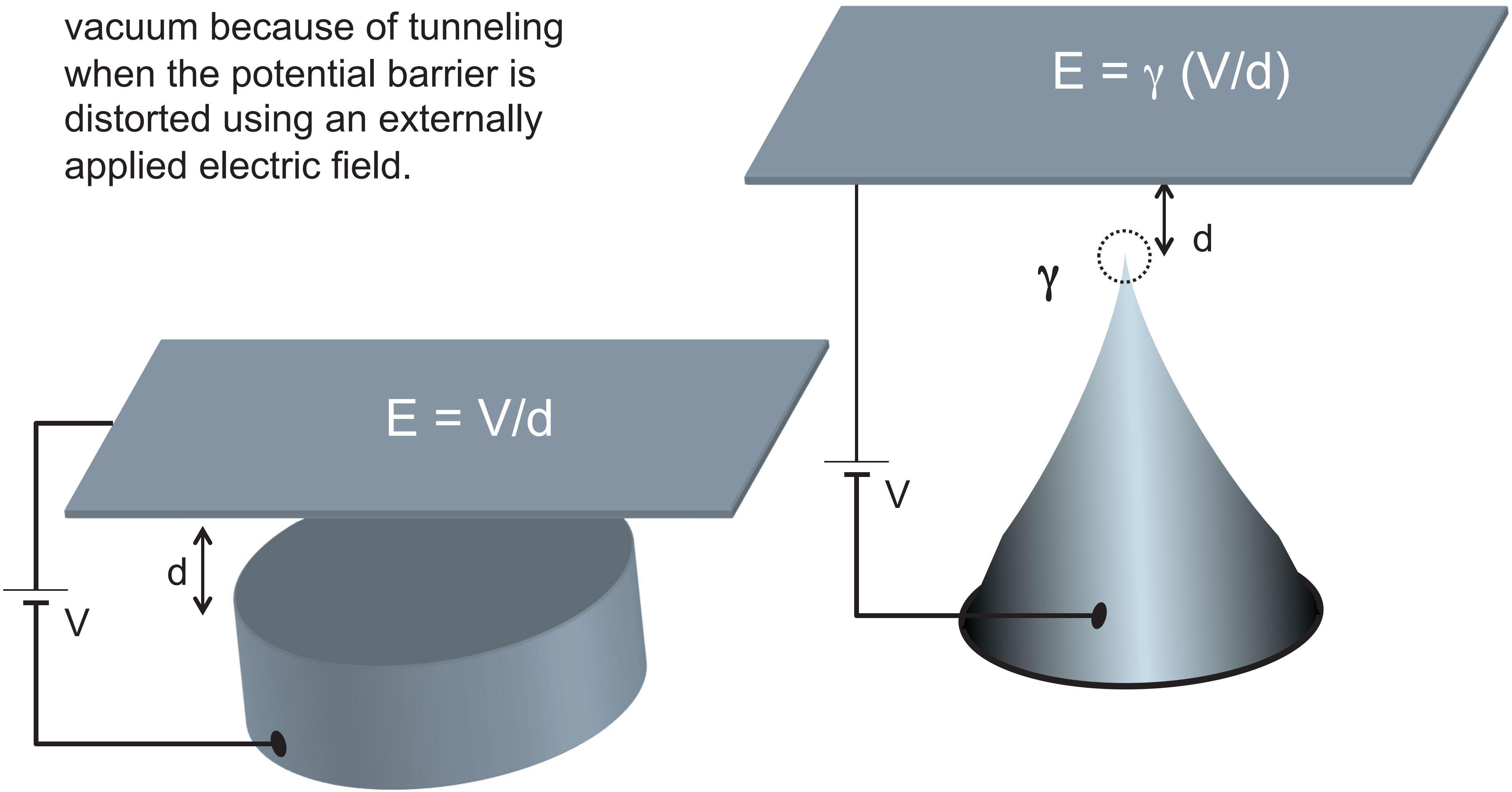
- Electron sources are fundamental components of many analytical instruments and certainly of vacuum electronic devices.
- Miniaturization of analytical instruments, for example, enables larger science payload.
- Vacuum electronics in combination with Silicon Micromachining enables miniature extreme environment components.
- Traditionally popular thermionic electron sources (boil off electrons at >1200°C) are power hungry, bulky, need thermal management, and are not conducive for miniaturization.
- **Cold cathodes is the answer…but which one?**



FIELD EMISSION OF ELECTRONS

Principle

Emission of electrons into vacuum because of tunneling when the potential barrier is distorted using an externally applied electric field.

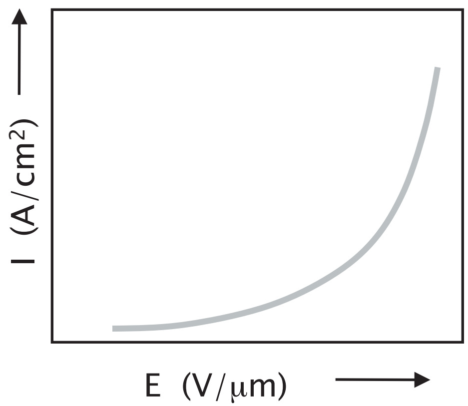


National Aeronautics and Space Administration

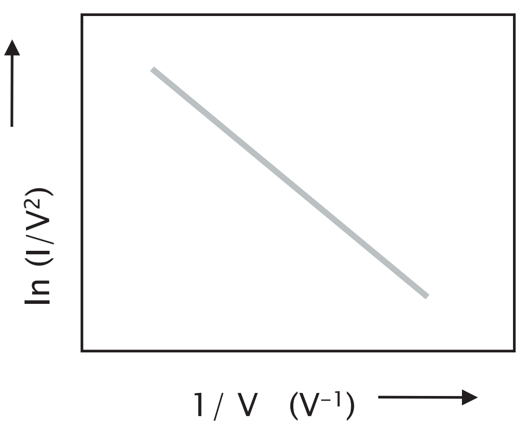
FIELD EMISSION OF ELECTRONS

Fowler-Nordheim Equation

I-V Curve



Fowler-Nordheim Curve



$$I = 1.54\times10^{-6}\,\frac{\gamma^2 A_{(e)}}{\phi}\cdot\left(\frac{V}{d}\right)^2\cdot e^{\left[-6.8\times10^{7}\cdot\frac{\phi^{3/2}\cdot d}{\gamma V}\right]}$$

$$ln\left(\frac{I}{V^2}\right) = ln\left(a\right) - \frac{b}{V}$$

$I \ \alpha \ \gamma^2$

"γ" is the key!

I : Emission current (A)

V: Biasing voltage (V) ; d : gap

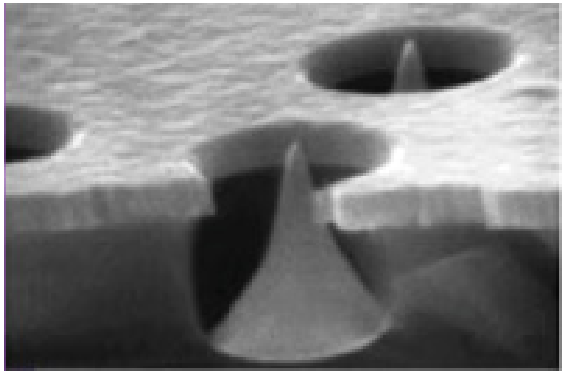
a, b: constants

ϕ: Work function

γ: Field enhancement factor

$A_{(e)}$: Emission area

FIELD EMISSION OF ELECTRONS



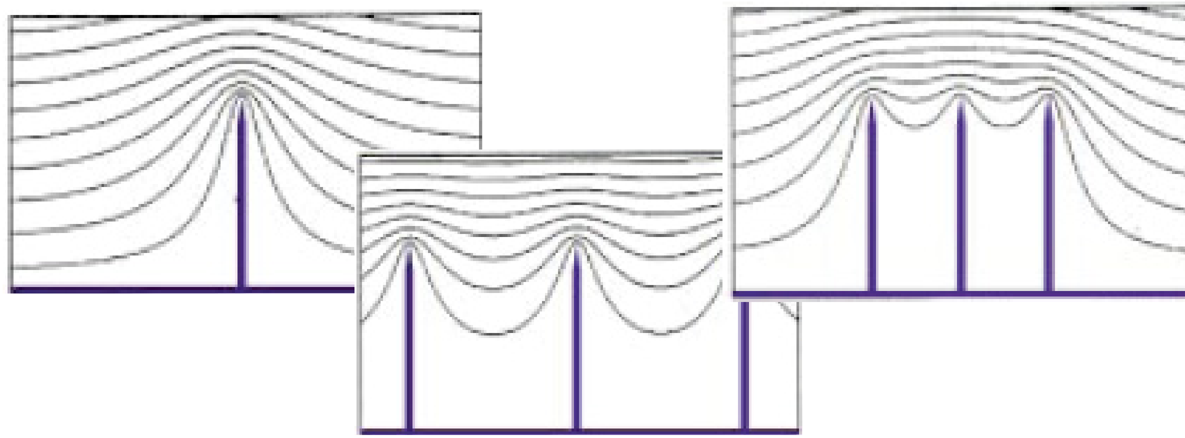
- Sharp metallic tips or metal-coated Silicon tips are commonly used cold cathodes.
- They are sensitive to poor vacuums- very short lifetimes, and tips sputter easily.
- Most miniaturization applications using cold cathodes need vacuum packaging of microcavities.

  - Typical vacuums achieved is 10^{-6} to 10^{-5} Torr.

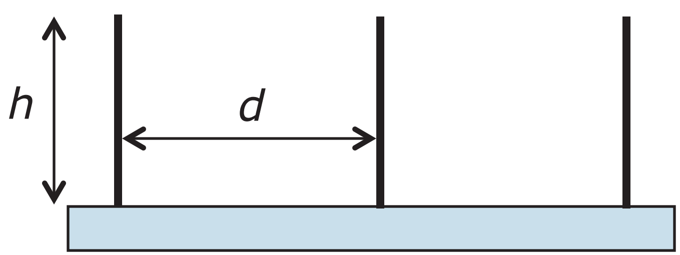
- **Carbon nanotubes seem robust to such poor vacuums- redundancy, conducive emission mechanism, ease of synthesis, low emission threshold, and higher current density per tip compared to other types of cold cathodes.**

FIELD EMISSION OF ELECTRONS

Simulation of field penetration
by L. Nilsson *et al*
APL 76(15) 2071-2073 (2000)



$I \propto \gamma^2 \Rightarrow$
- $\gamma \propto$ Aspect Ratio (reciprocal of the tip radius)
- $\gamma_s \propto$ Reciprocal of CNT number density → For the sample



d = 2 h (simulation)

L. Nilsson *et al*, APL 76 (15), 2071-2073 (2000)

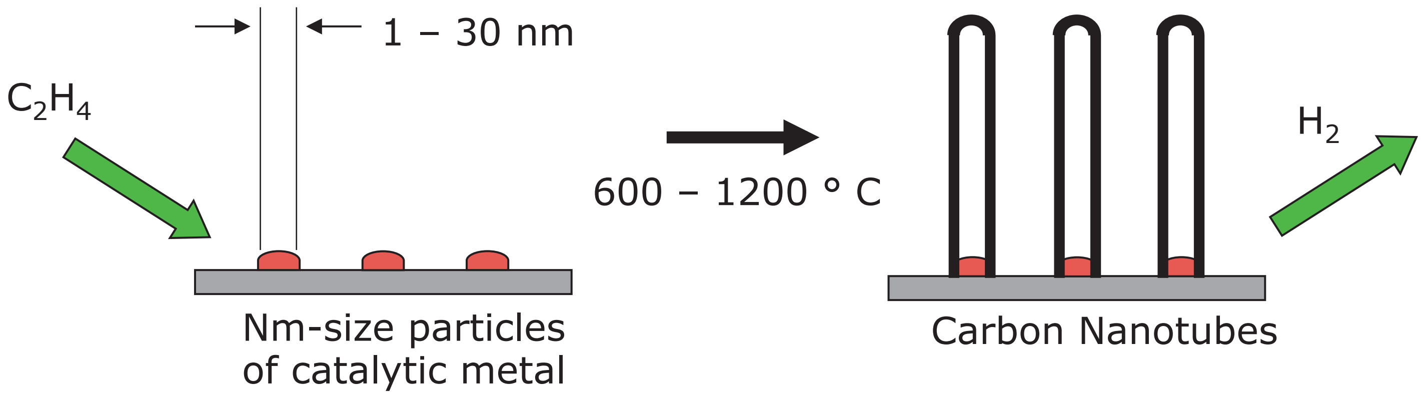
d = h (experiment)

J.S. Suh *et al, APL,* 80, 2392-2394 (2002)

Achieving high-current density is really an OPTIMIZATION problem.

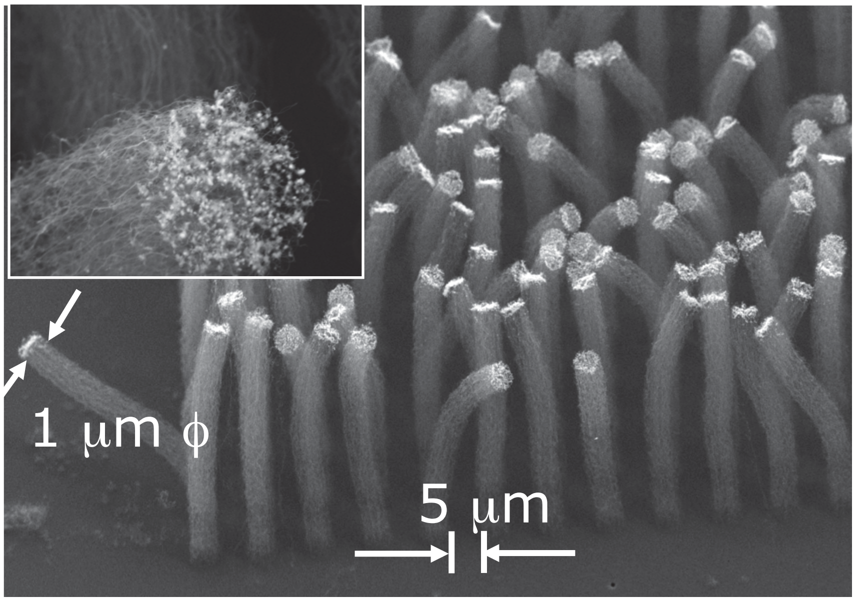
FIELD EMISSION OF ELECTRONS

- High electron emission from a single CNT (30 to 100 nA) does not scale up with increased number of CNTs on a sample.
- Electrostatic screening and number density limit emission levels.
- But, CNTs are great for application in miniature systems that have poor vacuums (10^{-4} to 10^{-5} Torr)
- **Optimum arrangement needed.**

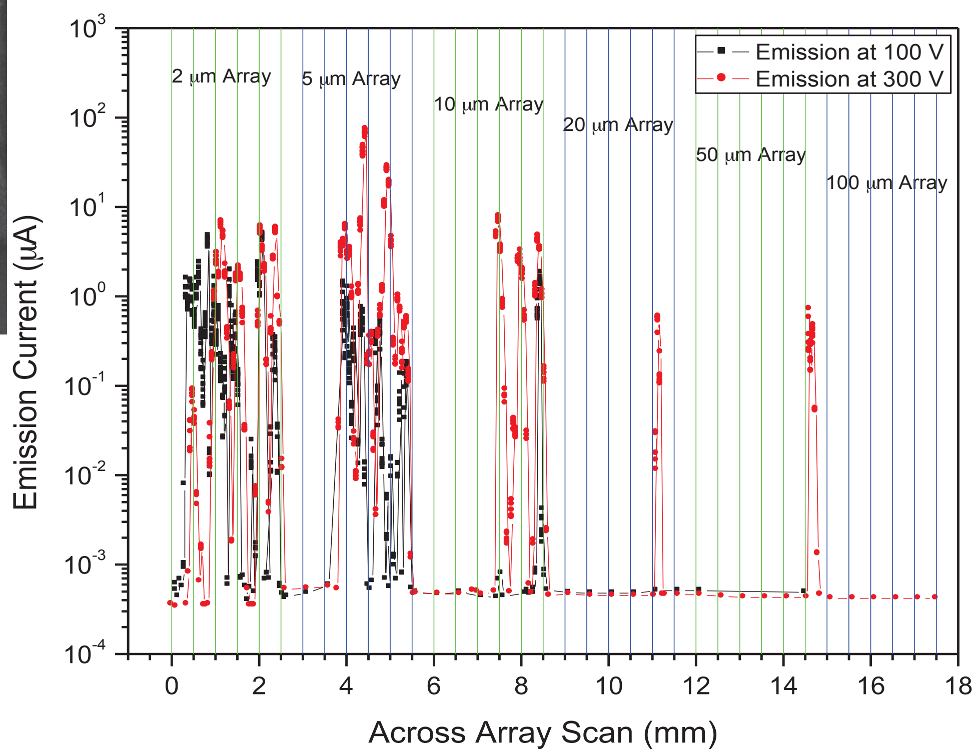


National
Aeronautics and
Space
Administration

HIGH-CURRENT DENSITY CNT BUNDLE ARRAYS



CNT bundles of 1-2 µm diameter spaced 5 µm edge-to-edge produced the highest field emission current.

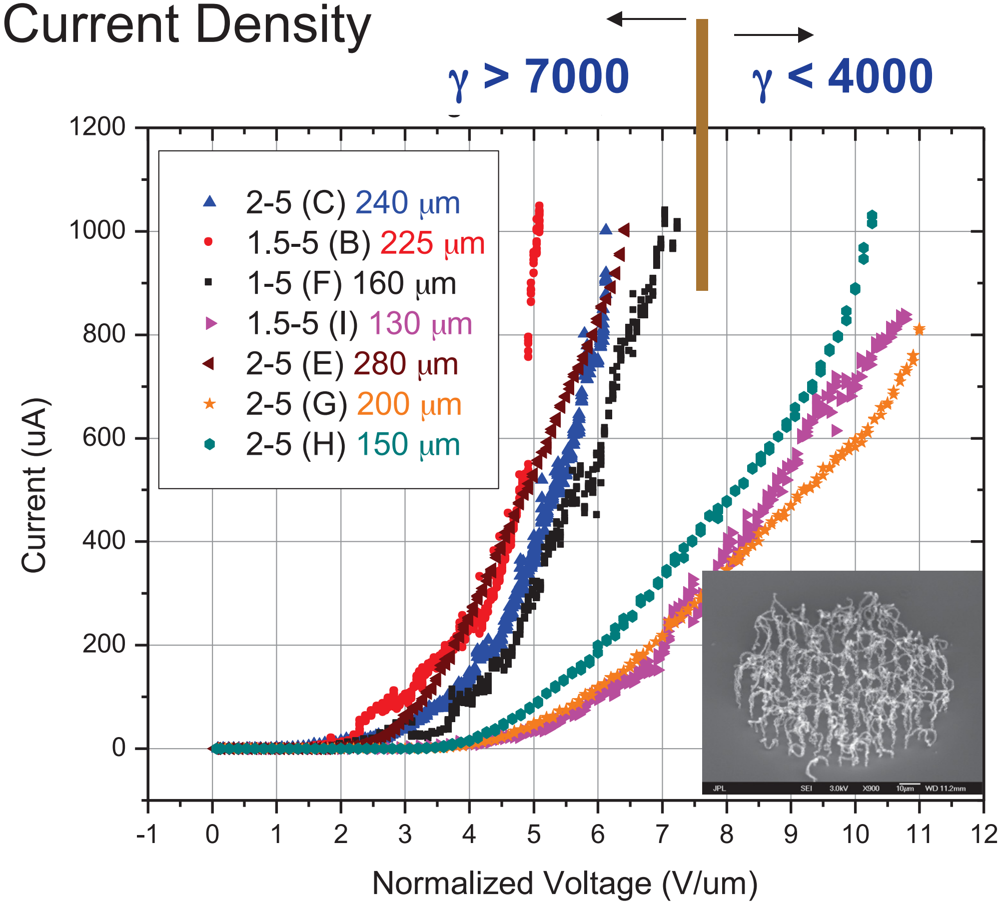


This arrangement is being used in multiple applications routinely producing 2 to 10 A/cm^2 current density at low fields of 4 to 8 V/µm

National Aeronautics and Space Administration

HIGH-CURRENT DENSITY CNT BUNDLE ARRAYS

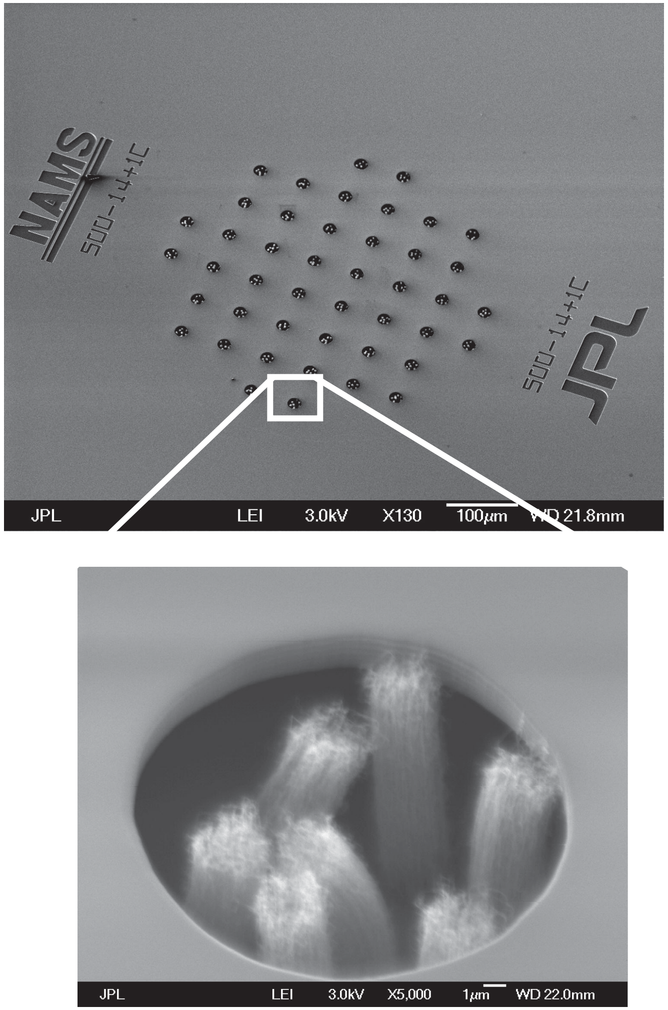
Repeatable High Current Density



Range of current density = **10 to 15 A/cm^2**

2x10^{-5} Torr; 1 mA = 12.7 A/cm^2; 785 μA = 10 A/cm^2

Monolithic Gate Integration

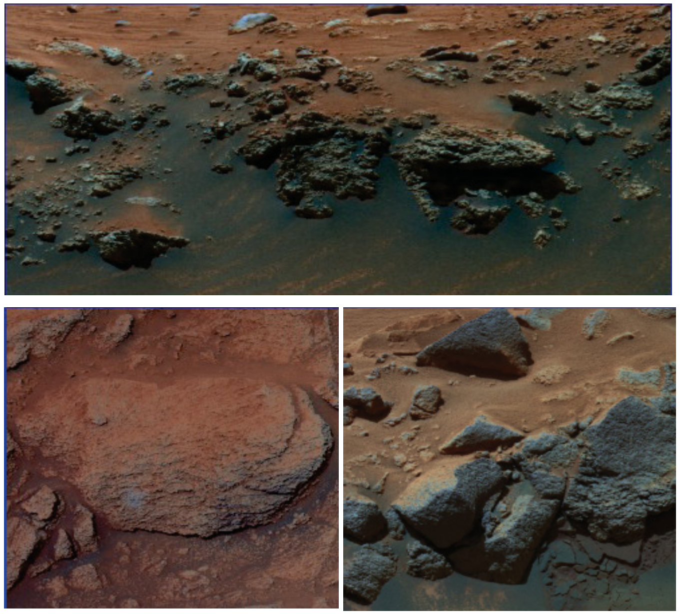


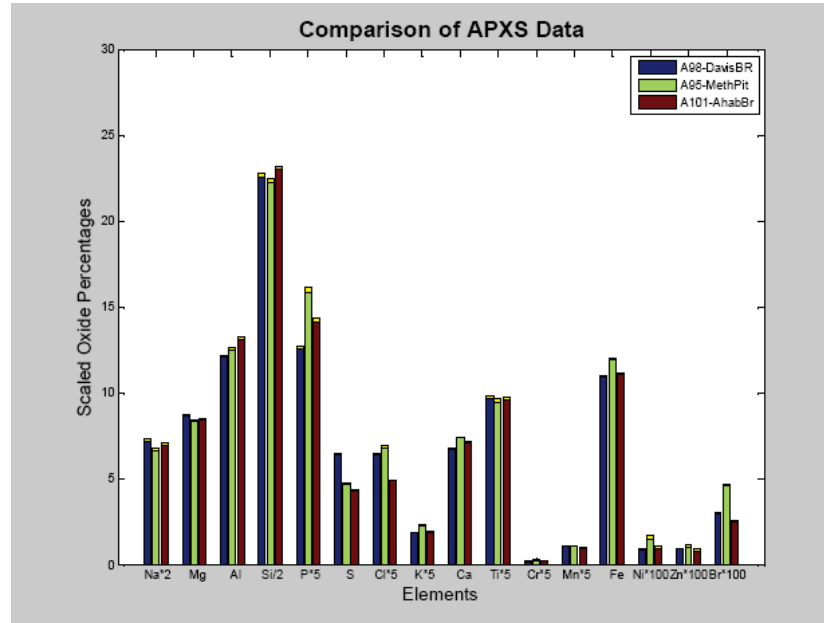
APPLICATIONS

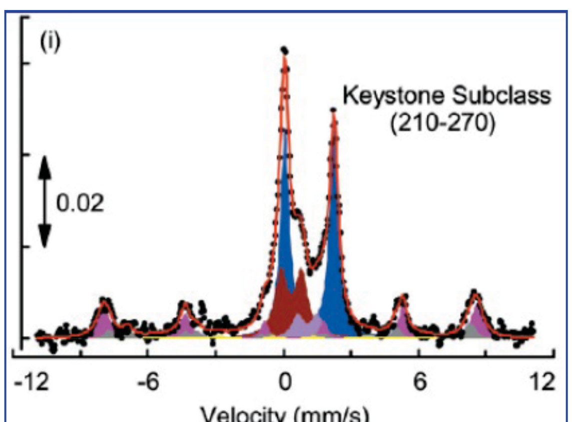
National
Aeronautics and
Space
Administration

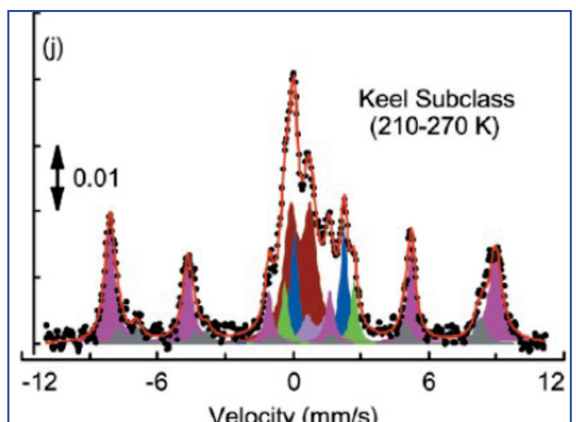
APPLICATIONS: X-rays for Mineralogy

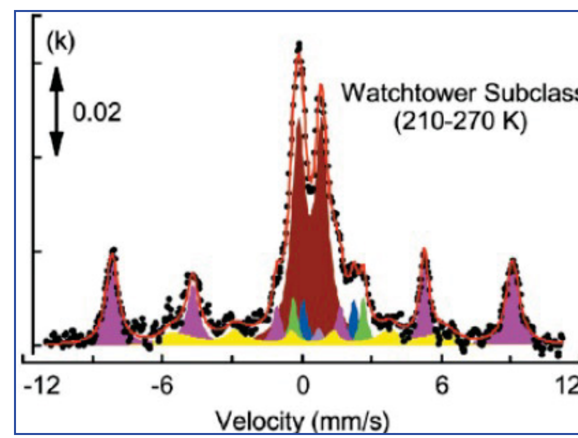
The Importance









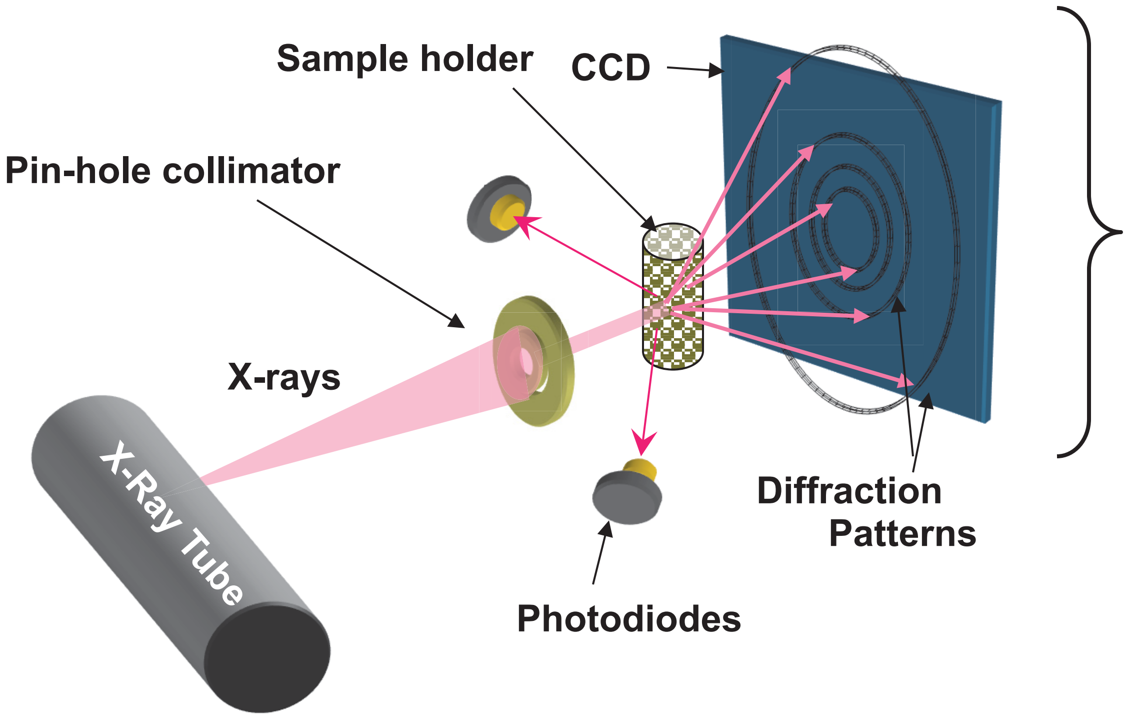


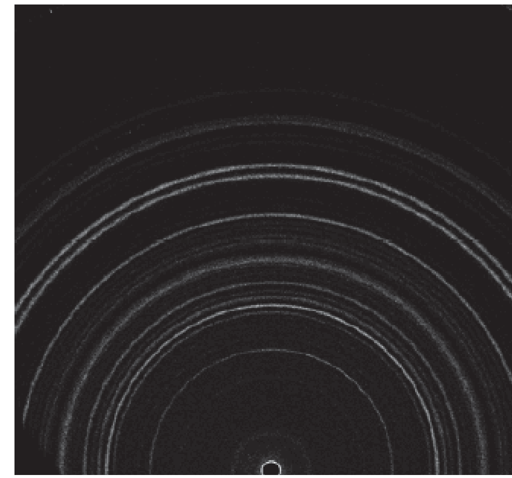
Courtesy: A. Yen (JPL)

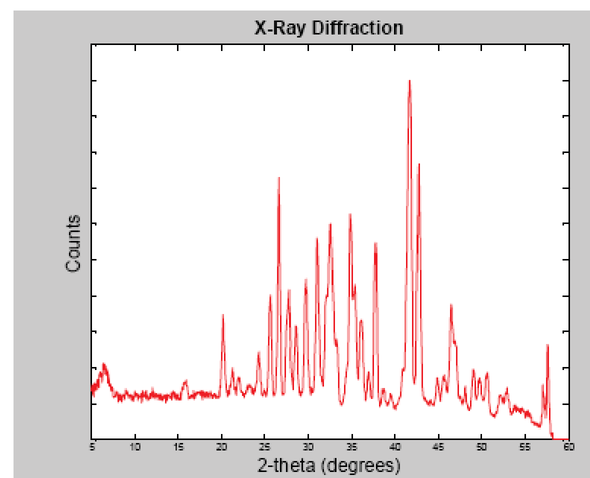
National
Aeronautics and
Space
Administration

APPLICATIONS: X-rays for Mineralogy

Planetary Instrument







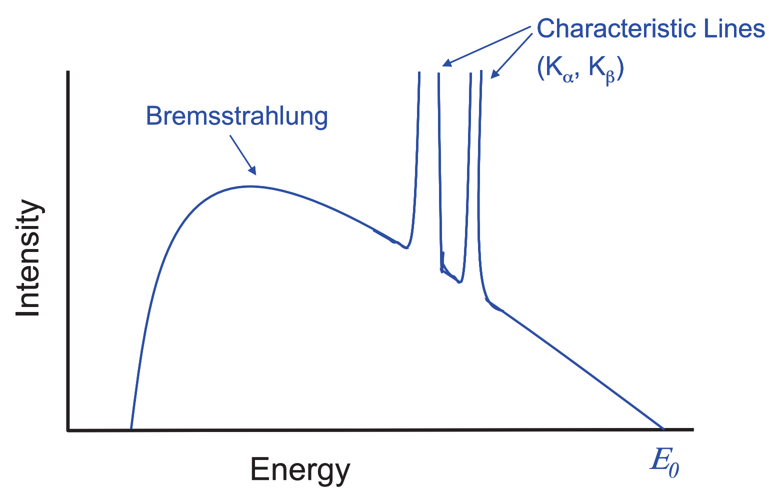
Design conceived/developed by ***Dr. D. Blake et al*** of NASA-Ames

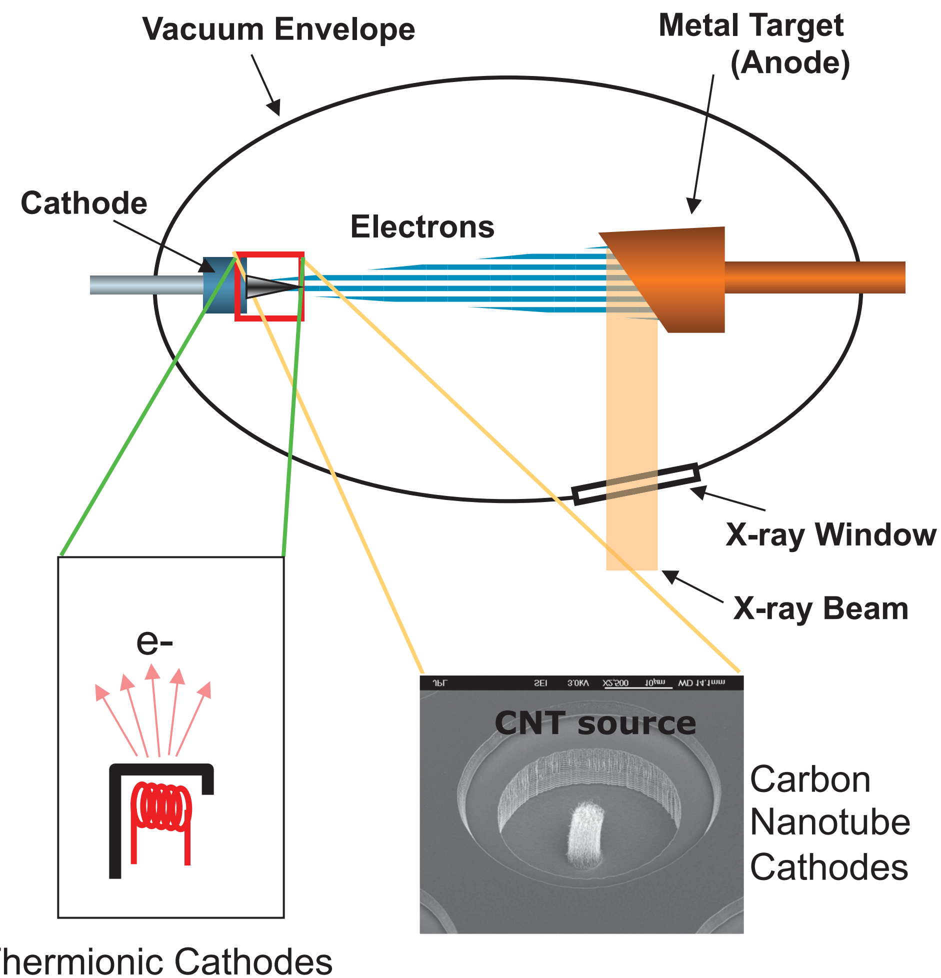
Schematic is somewhat similar to the CheMin instrument on Mars Science Laboratory.

APPLICATIONS: X-rays for Mineralogy

X-Ray Based Techniques

- Accelerated electrons bombard with a metal target to produce a continuous X-ray spectrum (Bremsstrahlung) as well as characteristic X-ray lines.
- The upper limit of the Bremsstrahlung radiation energy is limited by the acceleration voltage (Duane-Hunt Law).

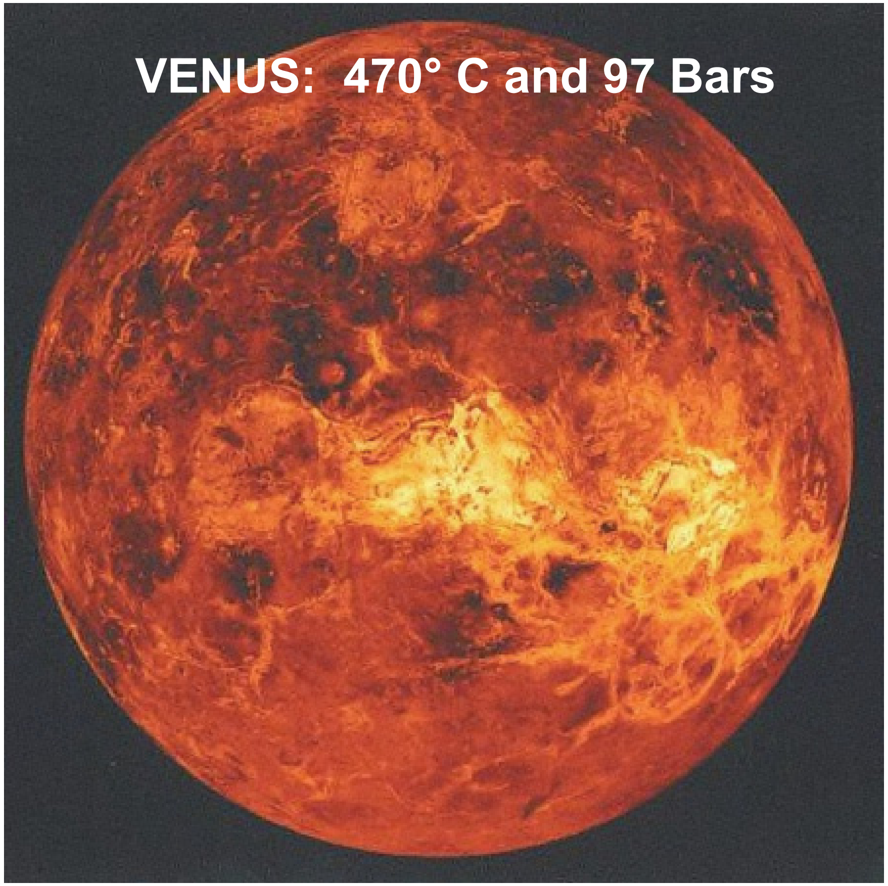




APPLICATIONS: X-rays for Mineralogy

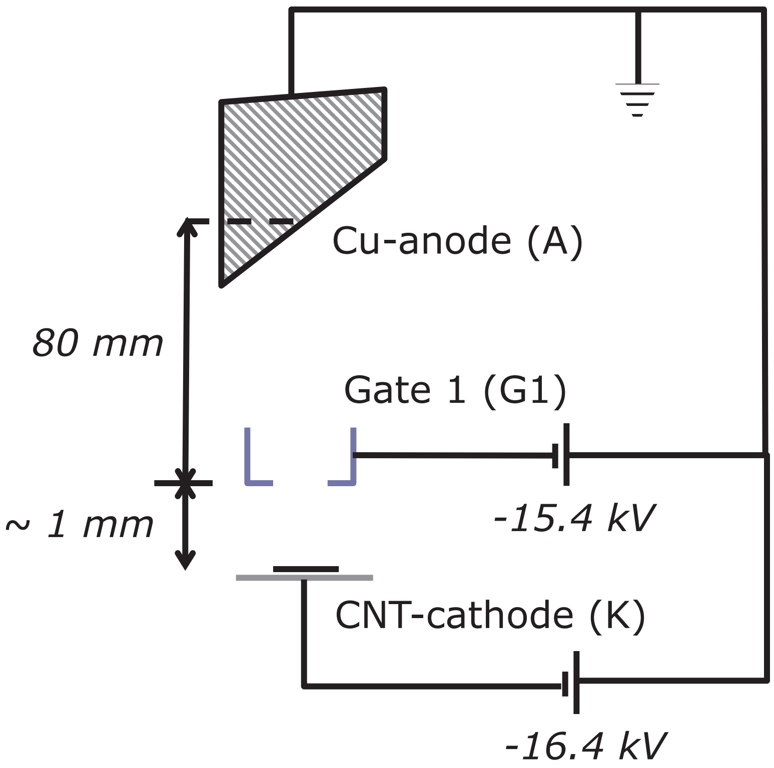
Why CNTs?

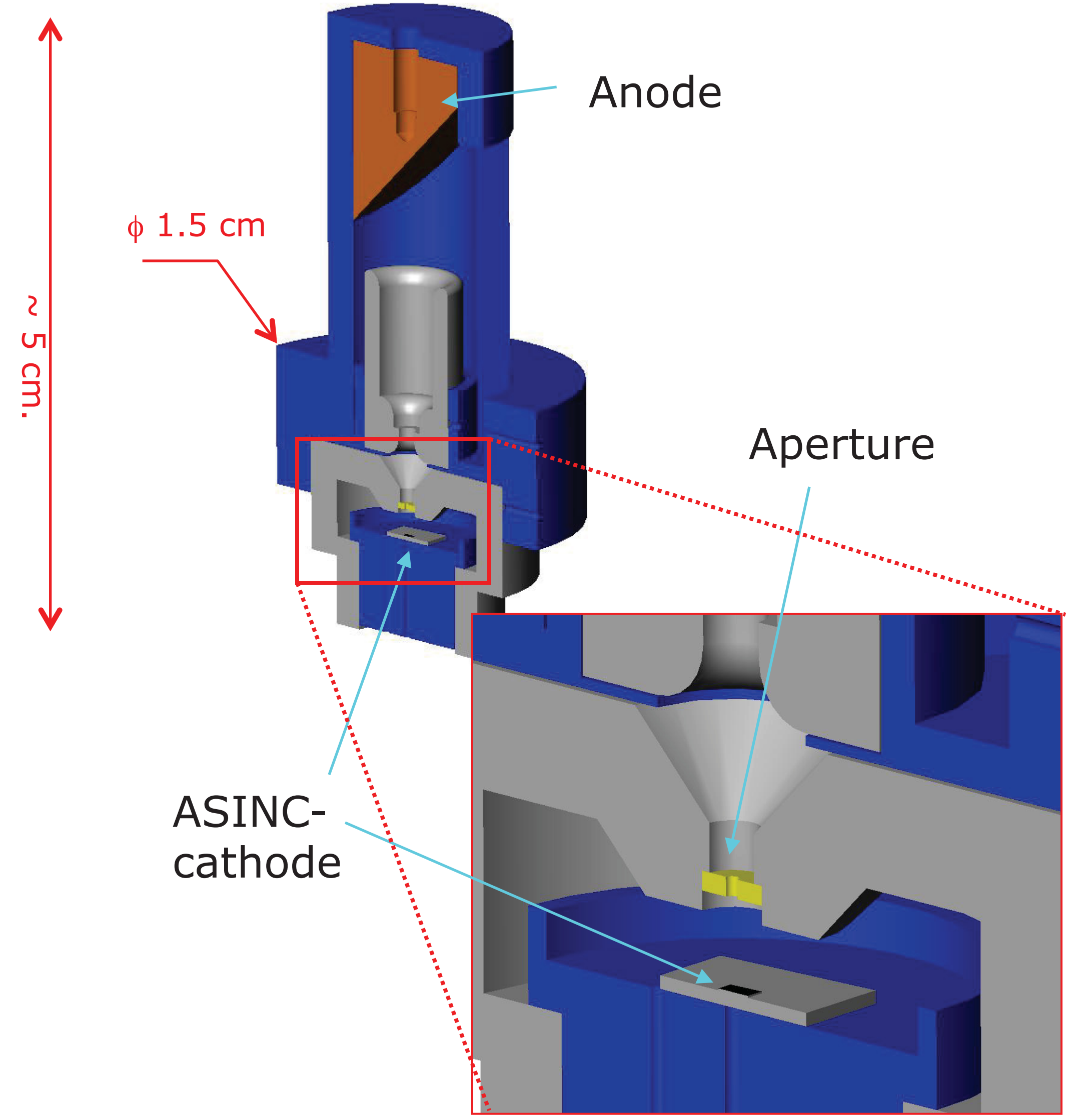
- No heater: Save on power, mass, volume
- Small source: Easier focusing >> Smaller spot size >> Sharper diffraction patterns
- Lower Voltage of Operation: 15 kV in stead of 30 to 50 kV! *{lower arcing probability}*
- Higher current density helps >> Faster data collection (only detector speed limited)
- Especially important on Venus where shorter integration times would be required (mission life would be in hours).



APPLICATIONS: X-rays for Mineralogy

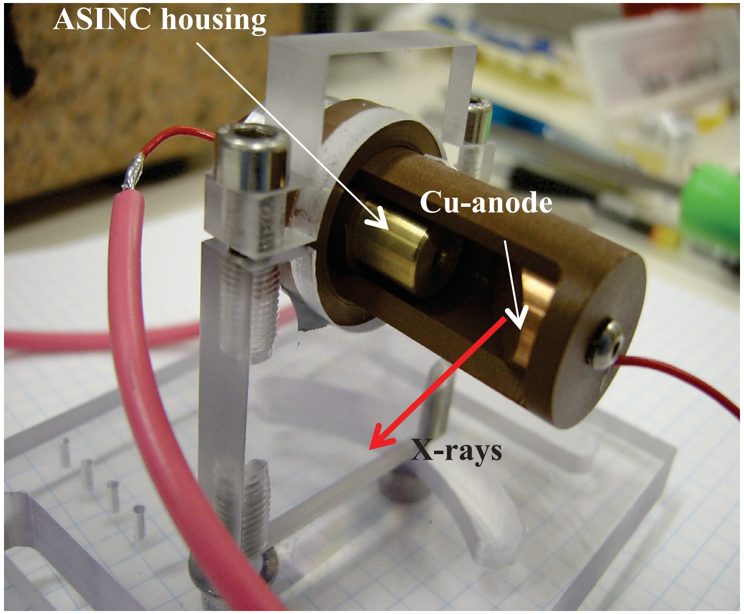
CNT X-ray Tube





APPLICATIONS: X-rays for Mineralogy

CNT X-ray Tube



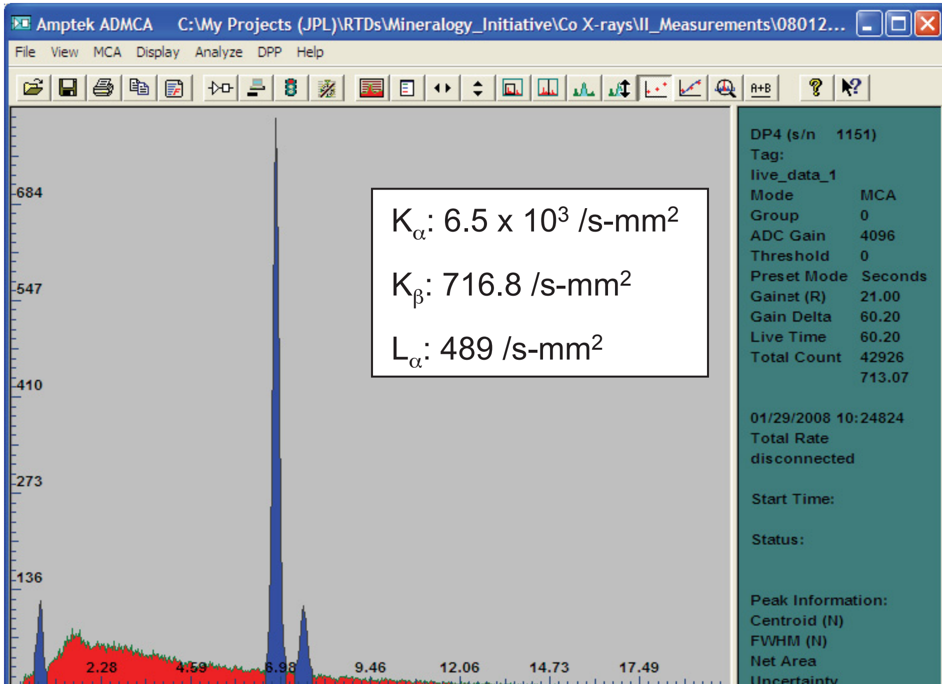
- Uses shaped Cobalt or Copper anode
- CNT bundle arrays are mounted on a screw-on platform
- Electron optics not optimized
- Operates between 15 kV to 20 kV acceleration voltage
- Emitted current at the cathode is in the range of 15 μA to 50 μA
- Max. photon flux produced so far **~ 8.8 x 10^4 /s** (1-mm ϕ aperture)

Emission Efficiency

$$\eta = I_A / I_K$$

APPLICATIONS: X-rays for Mineralogy

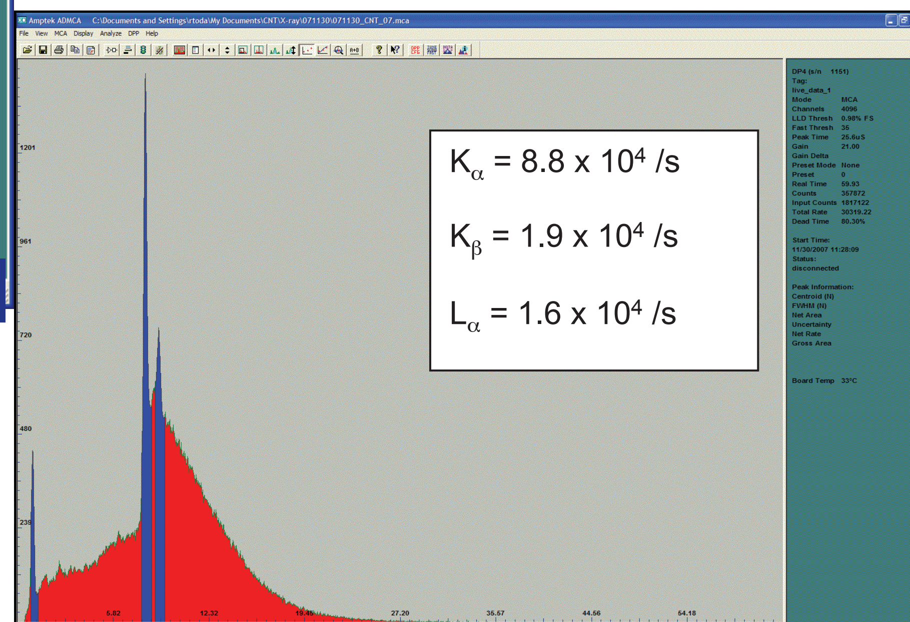
CNT X-ray Tube



Co K_α (6.92 keV) and K_β (7.69 keV)

I_A ~ 3 µA (η~20%); V_A ~ 20.0 kV; V_G = 2 kV; Measured photon fluxes through a 200-µm ϕ collimator are shown in the inset.

I_A ~ 15 µA (η~30%); V_A ~ 16.4 kV; Measured photon fluxes through a 1-mm ϕ collimator are shown in the inset.



Cu K_α (8.04 keV) and K_β (8.91 keV

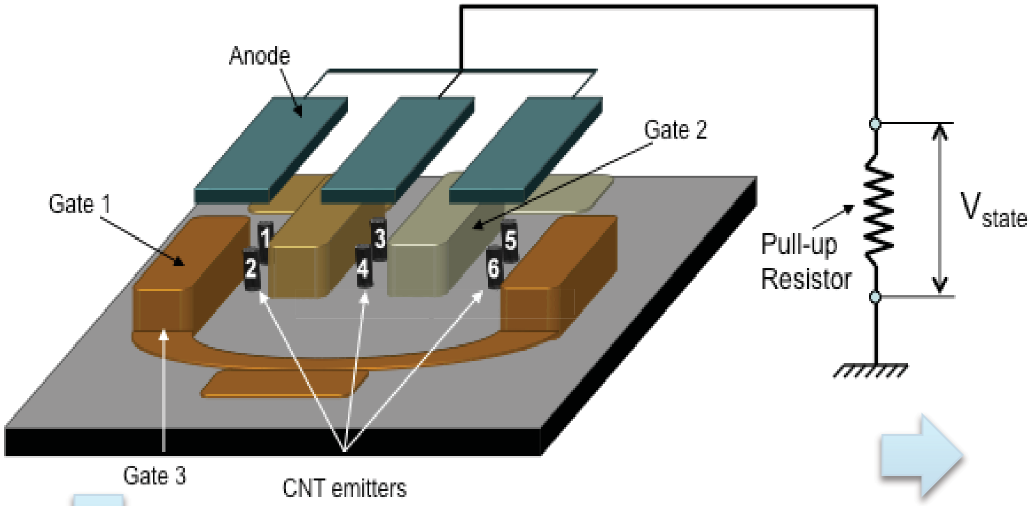
APPLICATIONS: 700° C Logic Gates

- To fulfill the need for extreme environment electronics (700° C and radiation insensitive or hard)
- State-of-the-art: Solid-State devices; demonstrated up to 500° C and tens of Mega Rads (limited component demonstrations).
- NEMS computational components demonstrated up to 600° C (Case Western).
- JPL technology: "Digital" Vacuum Microelectronics – *programmable logic gate demonstrated at 700° C (DC switching)*
  - Turning the "clock" back a "bit" to the tube days; merging micromachining, nanotube field emission and vacuum packaging techniques.
- ***FIRST OF ITS KIND*** device demonstrated under a DARPA Seedling.

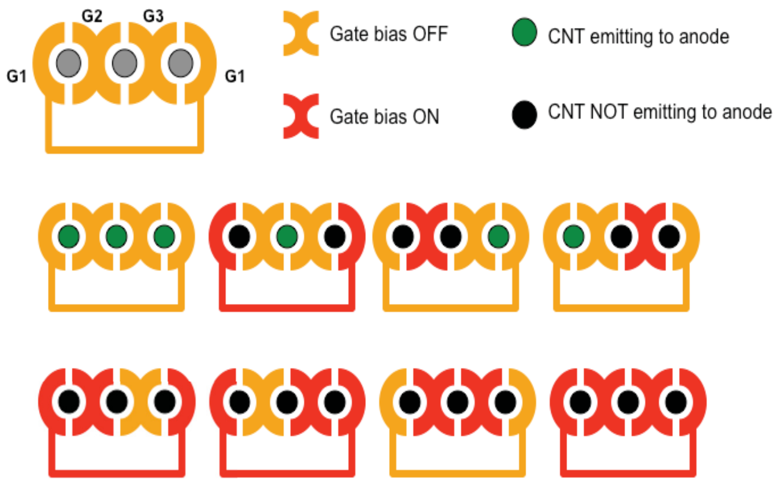
National
Aeronautics and
Space
Administration

APPLICATIONS: 700° C Logic Gates

Inverse Majority Gate Device Schematic



Operational Schematic

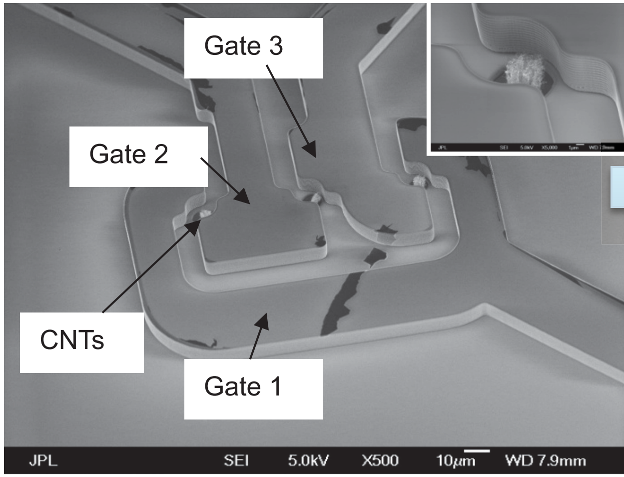


Truth Table

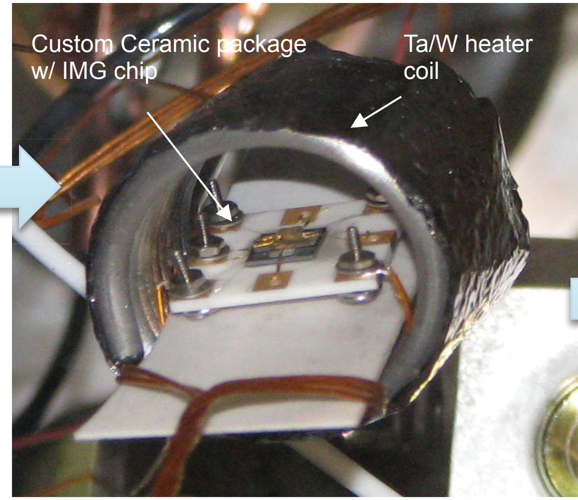
Number of Logic States	Gate 1	Gate 2	Gate 3	Output
1	0	0	0	1
2	0	0	1	1
3	0	1	0	1
4	0	1	1	0
5	1	0	0	1
6	1	0	1	0
7	1	1	0	0
8	1	1	1	0

Combination of NAND and NOR gates

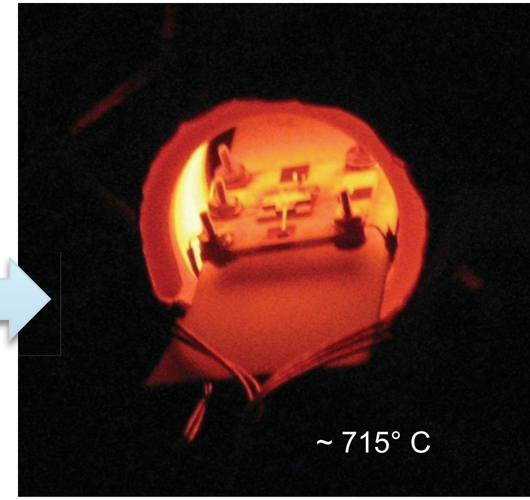
APPLICATIONS: 700° C Logic Gates



IMG Device-SEM micrograph



IMG inside a Ta/W Coil



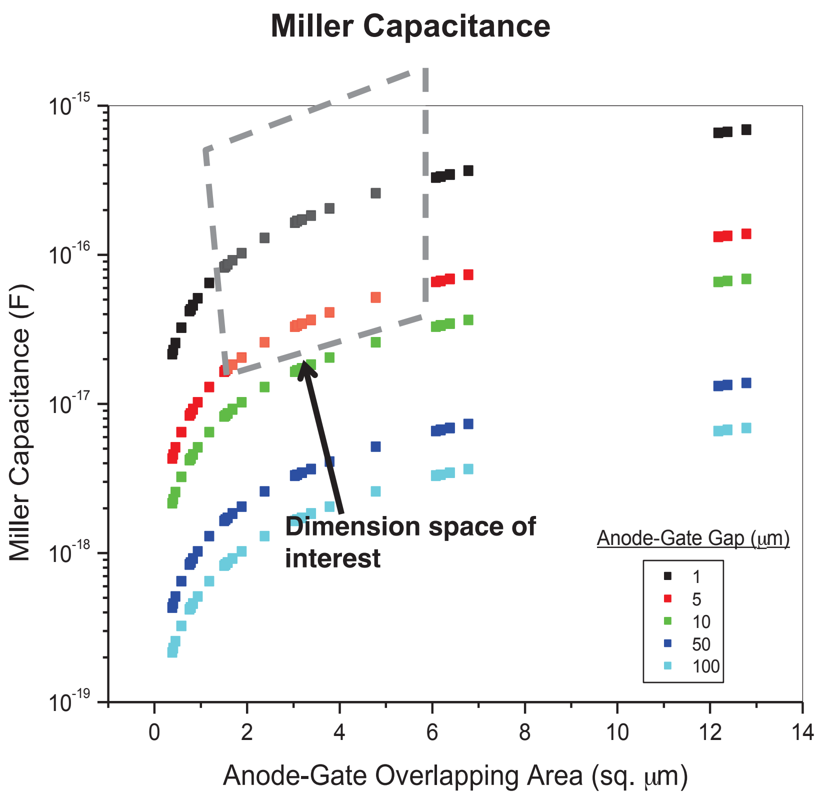
Device Under Test

Three-Gate Operation

Va (V)	Vg1 (V)	Vg2 (V)	Vg3 (V)	Ia (nA)	O/P State
50	0	0	0	3.2	1
50	10	0	0	2.8	1
50	10	10	0	0.7	0
50	10	10	10	0	0
50	0	10	0	3.6	1
50	0	10	10	0.27	0
50	0	0	10	2.5	1
50	10	0	10	0.35	0

APPLICATIONS: 700° C Logic Gates

For a Full Adder	Solid State (0.18 μm process)	Solid State (0.09 μm process)	IMG-based (0.5 μm process)
Footprint (μm)	13.86 x 5.4	8.12 x 2.52	18 x 4



- Traditional vacuum tubes operate at 1300° to 1500° C, so are natural choices for high-temperature electronics.
- Device can be designed for smaller footprint
- Switching frequency- 10-100 GHz possible; *limited only by the K-A electron transit time*
- Low level current (tens of nA) operation ensures long operational lifetime (10,000 hours tested for CNT flat panel displays).
- CNT emission more stable at 700° C (<1% variation tested).

SUMMARY

- Carbon nanotube bundle arrays have been made to realize field emission sources for high current density applications.
- These sources act as the fundamental components of miniature analytical devices and vacuum microelectronics.
- Some applications such as a miniature X-ray tube, and “digital” vacuum electronics for high temperature applications have been developed.

DISTRIBUTED CAPACITOR (DISC) SENSOR FOR SAMPLE VERIFICATION

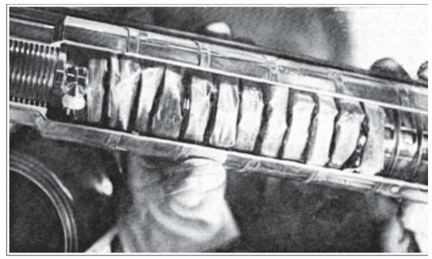
Sample verification sensors would be needed to ensure success of robotic sample return missions.

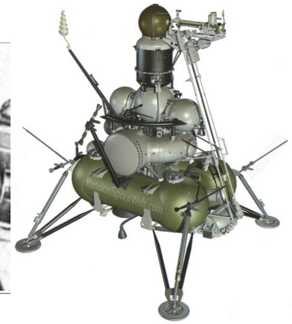
NEED: Past Sample Return Missions

Human Missions:
<u>*Sample collected and verified by astronauts*</u>

Apollo mission sample collection case (1969-1972)

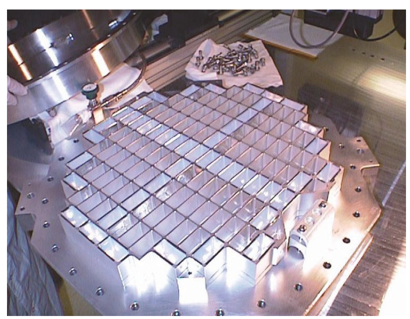
Unmanned Robotic Missions:
<u>*Sample quantity verified only after return to Earth*</u>





Russian *Luna-24* sample collector (Launched 1976)

JAXA's *Hayabusa* re-entry vehicle (Launched 2003)



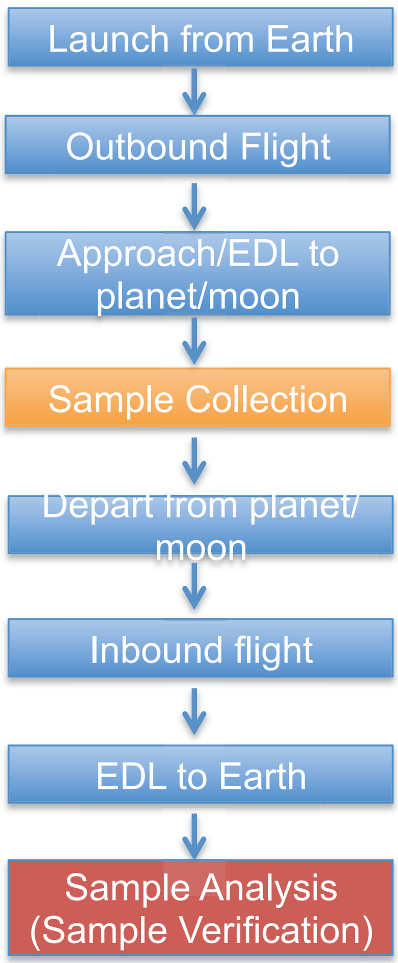
Stardust Aerogel sample collector (Launched 1999)

Genesis solar wind particles collector (Launched 2001)

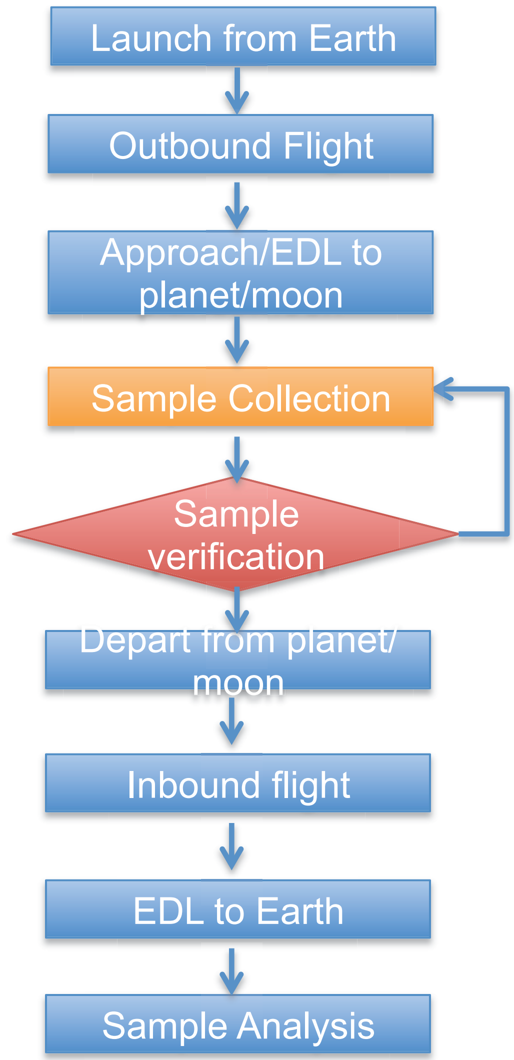
National Aeronautics and Space Administration

NEED: SVS would maximize science return

Previous Unmanned Planetary Sample Return Missions



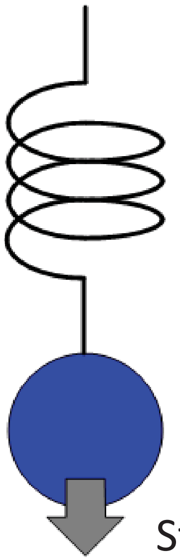
Sample Return Missions with Sample Verification



Re-attempt possible for maximized science return!

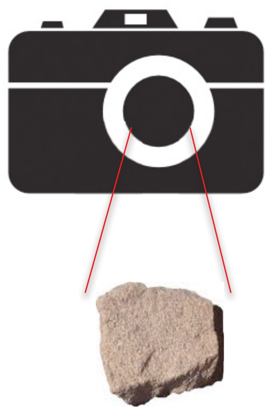
Possible Sample Verification Methods

Spring-Mass Method



- Relatively simple
- Requires gravity (not applicable to Asteroid

Optical Imaging Method

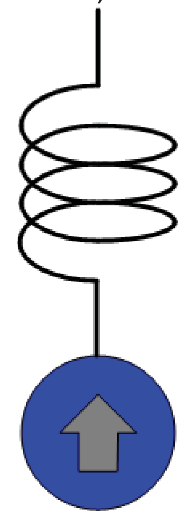


- Color and shape observed
- Lens may be obscured by dust
- Mass not measurable

Inertia Method (Newton's 2nd law of motion)

$$F = m\frac{dv}{dt}$$

Used on ISS for astronaut weight measurement Space Linear Acceleration Mass Measurement Device (SLAMMD)

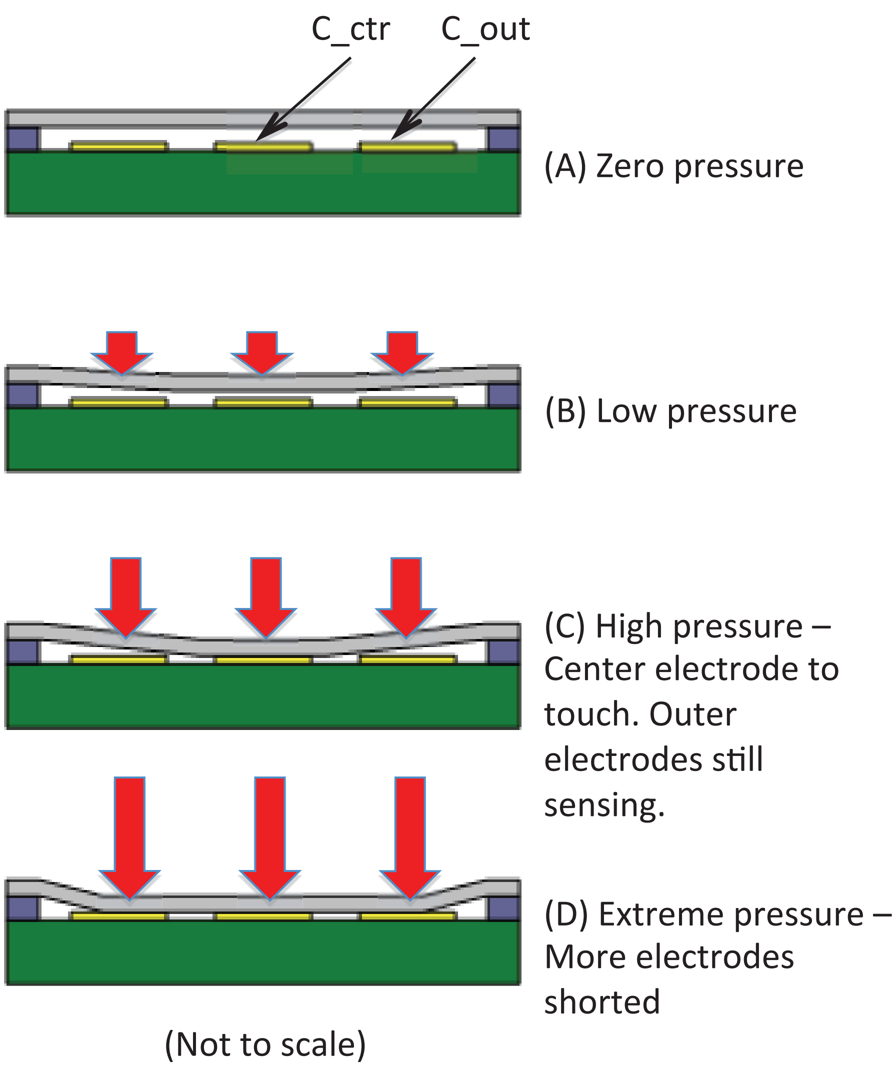


- Applicable to Asteroid (microgravity)
- Requires dynamic thrust

Sample Verification System (SVS) Requirements

- Contamination issues
  - Even small contamination could impact isotopic age determination.
  - All surfaces that may touch sample must be made with proven materials. Only few materials such as SUS304 and AL6061 would be allowed.
- Harsh environment
  - Survival temperature, -95C to +60C on moon.
- Measurement accuracy / range
  - Measure 50g +/-10g in lunar gravity.
  - Range 1000~3000g.
- Robustness
  - Launch and EDL shock tolerance
    - Vibration 10~60G.

Distributed Capacitance (DisC) Sensor Concept

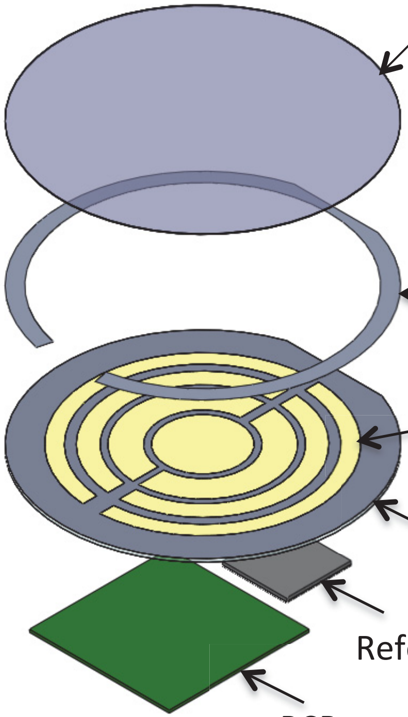


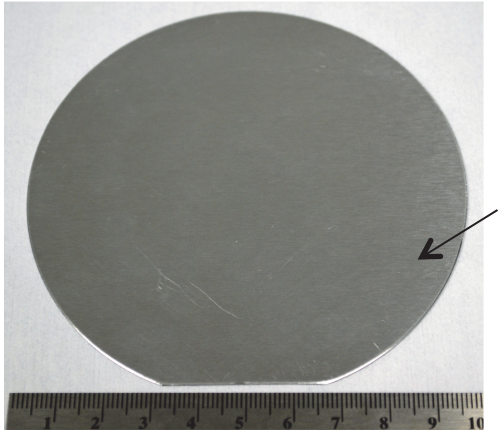
- Elastic membrane and rigid substrate forms variable (semi-) parallel plate capacitor.
- Capacitance is inversely proportional to gap distance.

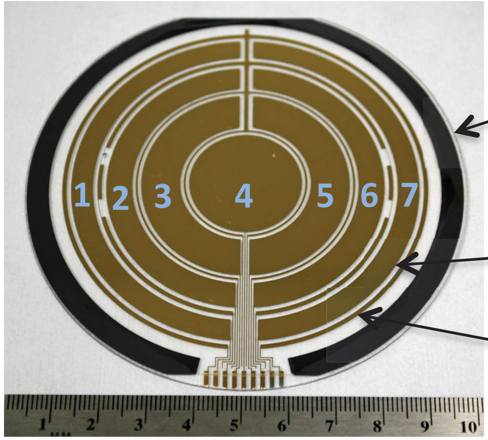
$$C = \varepsilon \frac{A}{d}$$

- As sample accumulates, elastic membrane deform and capacitance increases.
- Robustness: When excessive weight/shock is applied, elastic membrane is stopped/protected by rigid substrate

SVS DisC Sensor: First Prototype







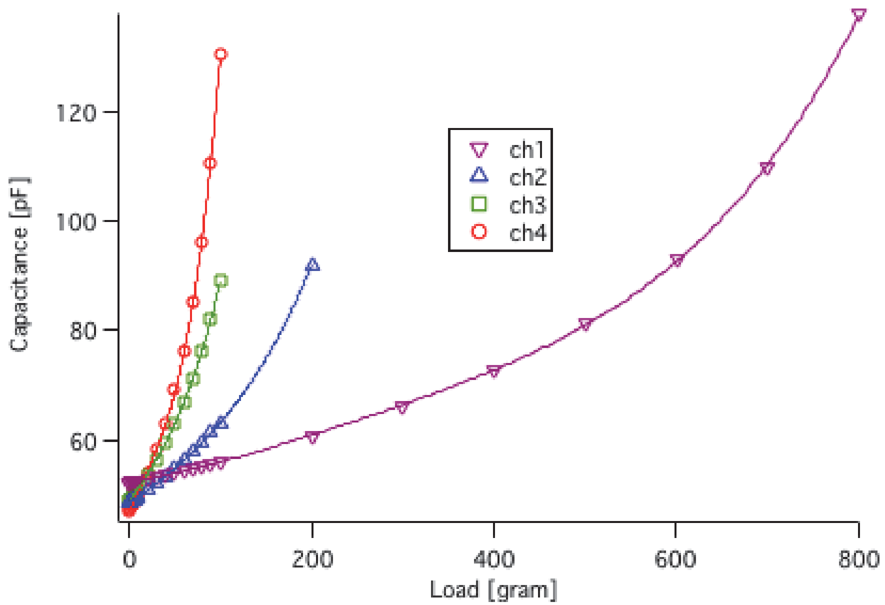
Issues with first prototype:

- Observed thermal drift due to CTE mismatch.
- Front-to-back wiring deemed weak.

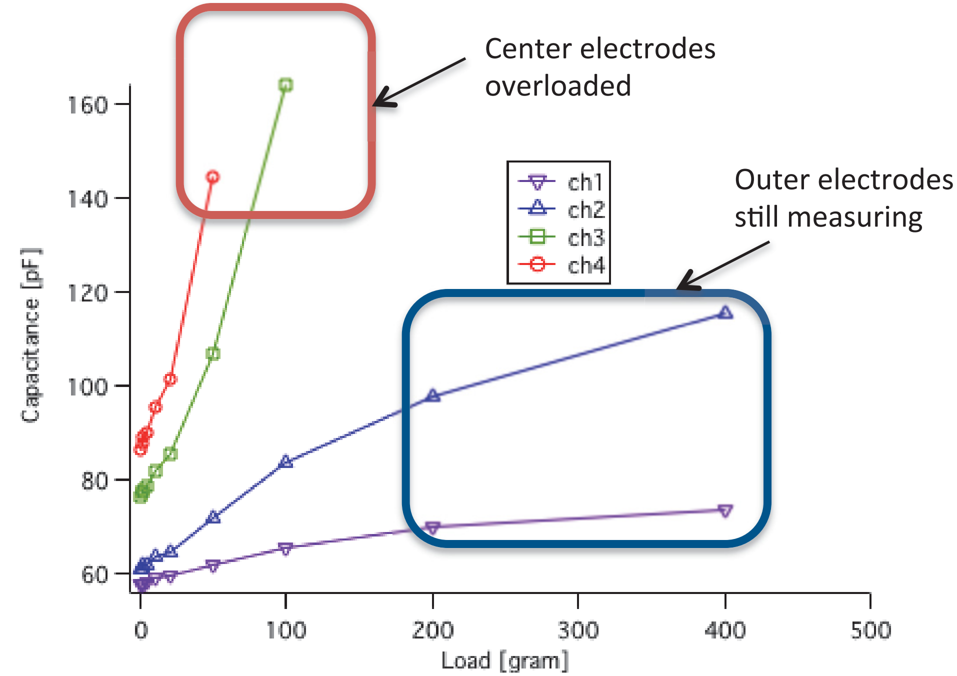
Fabrication method

1. Silicon/glass anodic bonding
2. DRIE Silicon
3. Evaporate electrode pattern

Simulation vs. Experiment



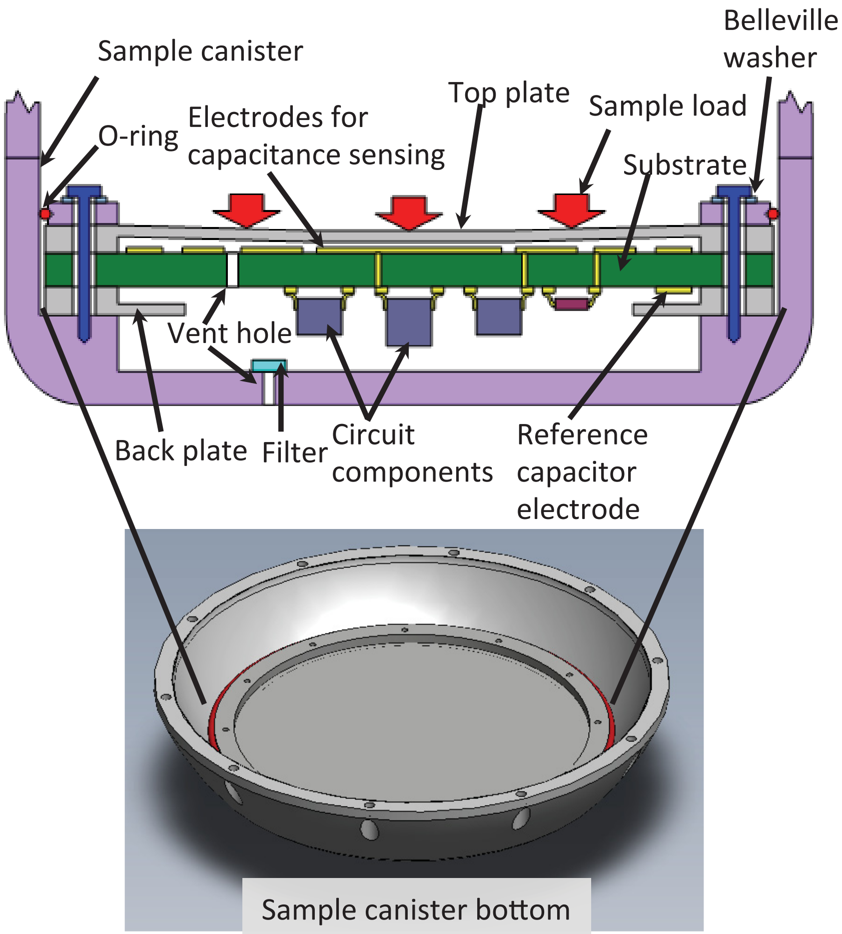
FEM simulation



Experimental result
(Uniform loading with BB pellets)

- Once center channel touch, the rate of increase slows at outer channels.
- This is because top plate and electrode contact is not simulated.
- Otherwise, the behavior looks similar.

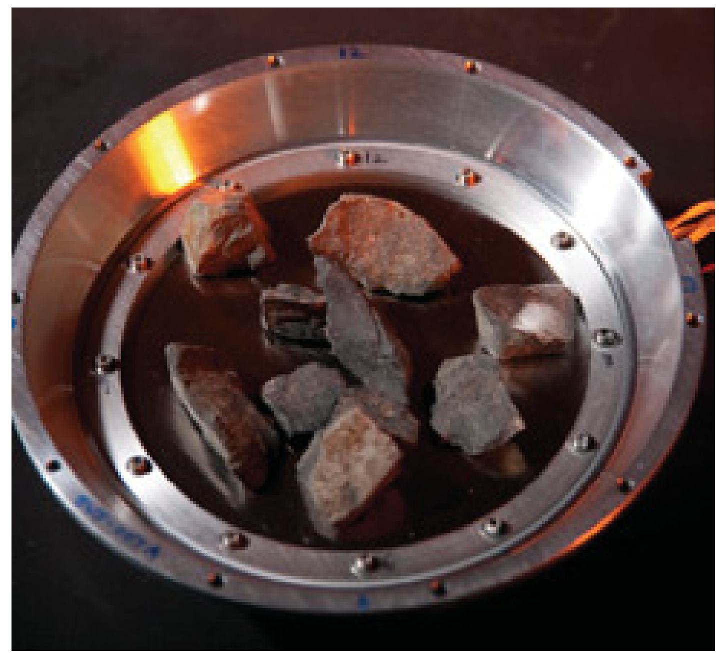
SVS DisC Sensor: Second Prototype



(Cross-sectional view is not to scale)

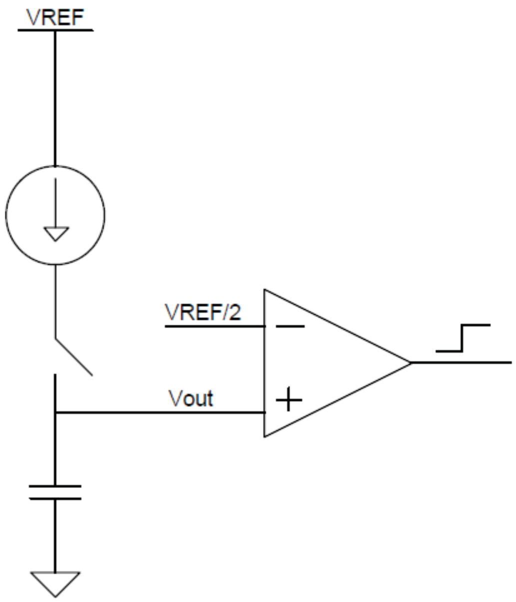
Improvements over first prototype

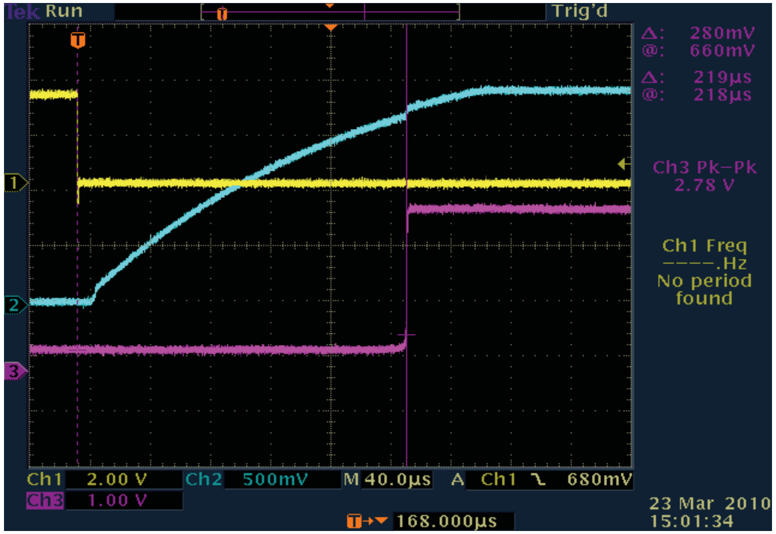
- Use Polyimide PWB as substrate:
  - Distributed capacitor electrodes on top side
  - Circuit components on bottom side
- CTE mismatch absorbed by allowing plates to slip
- Use more flight-approved components



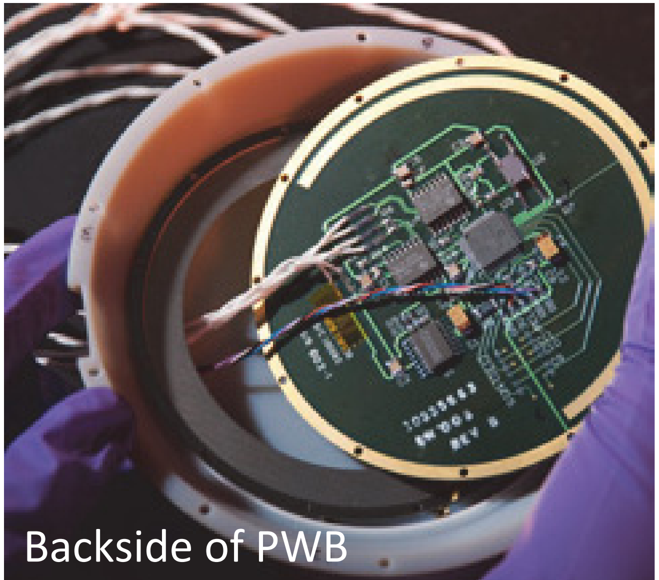
Electronics: How it works

- Current source charges selected SVS capacitive electrode
- Voltage on capacitor compared against reference with comparator
- Microcontroller counts charge time for capacitive measurement

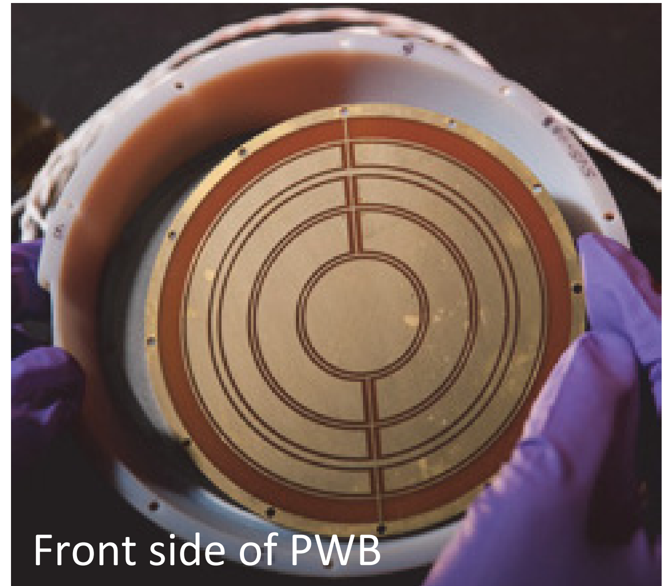




Second Prototype Assembly



Backside of PWB



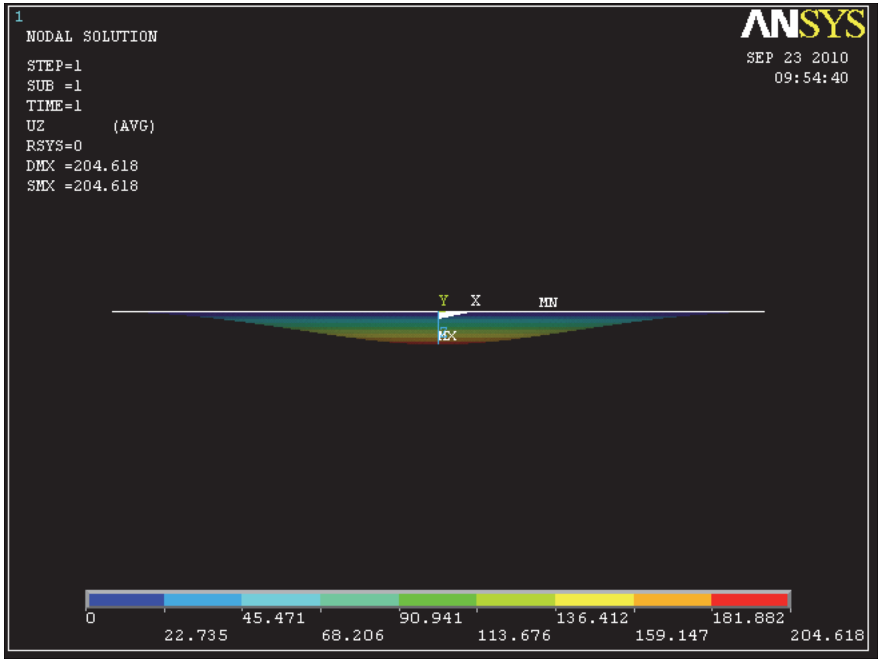
Front side of PWB

SUS304 Top plate is placed

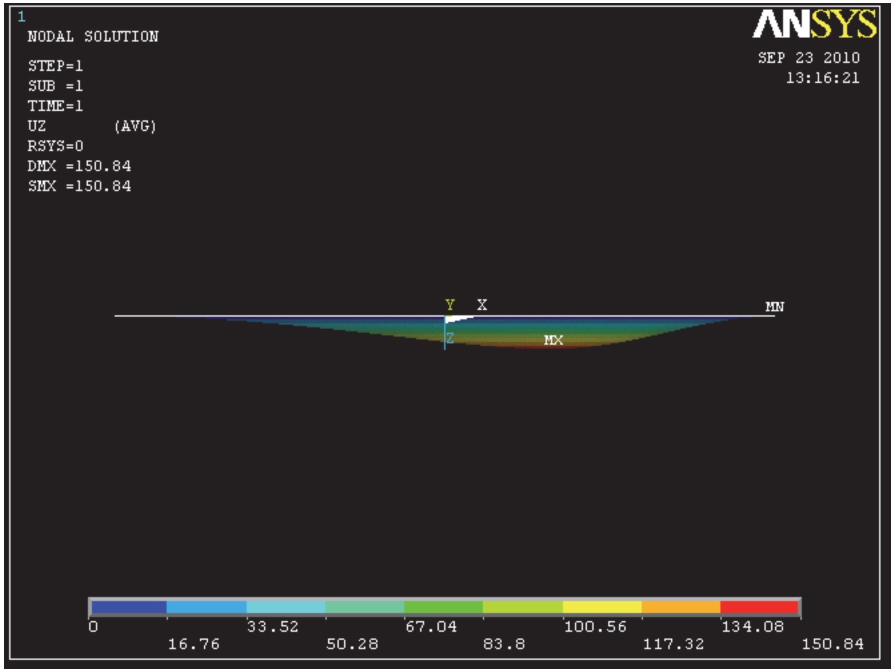
Assembled unit

National
Aeronautics and
Space
Administration

Non-Uniform Loading



100g weight (20mm diameter footprint) placed at center



100g weight (20mm diameter footprint) placed 20mm off-center

(z-axis scaling is exaggerated)

- **Localized load may cause measurement error.**
- **Statistical approach coupled with robotic arm agitation to minimize measurement error (shown next page).**

National
Aeronautics and
Space
Administration

Sensor Calibration with Rock

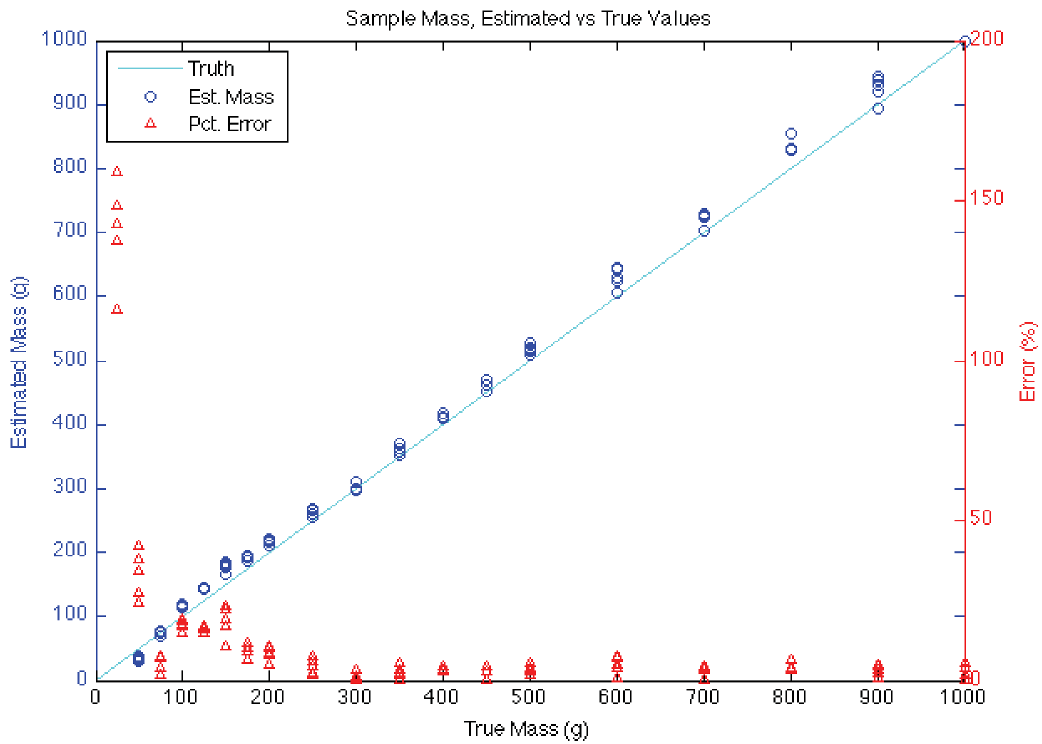


Plate thickness 300um
Initial gap width 200um

- Repeated test with canister agitation provides improved measurement accuracy.

Summary

- Proof-of-principle sample verification system (DisC sensor) developed for Lunar sample return missions.
- Sensor designed for harsh environment and robustness.
- Sensitivity depends on plate thickness and initial gap width: typ. 0.1~1pF/gram
- Calibration with rock sample showed good statistical accuracy.
- Environmental tests (Thermal vacuum, shock, etc.) planned.

Thank You!