Domestic Heavy Ion Facilities for Science, Engineering, and Medicine*

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- *Based on electronics single event effects (SEE) test sites and excludes research sites such as the Relativistic Heavy Ion Collider (RHIC) and new Facility for Rare Isotope Beams (FRIB)*

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Acronyms

- Alternate Gradient Synchrotron (AGS)
- Association for Research at University Nuclear Accelerators (ARUNA)
- Atomic Mass Unit (amu)
- Brookhaven National Laboratories (BNL)
- Complementary Metal Oxide Semiconductor (CMOS)
- Department of Defense (DoD)
- Department of Energy (DOE)
- Facility for Rare Isotope Beams (FRIB)
- FRIB Single Event Effects Facility (FSEE)
- Giga Electron Volts (GeV)
- Lawrence Berkeley National Laboratories (LBNL)
- Los Alamos Neutron Science Center (LANSCE)
- Massachusetts General Hospital (MGH)
- Mega Electron Volts (MeV)
- Michigan State University (MSU)
- Not-AND (NAND) Flash Memory
- National Aeronautics and Space Administration (NASA)
- NASA Space Radiation Laboratory (NSRL)
- National Superconducting Cyclotron Laboratory (NSCL)
- Oak Ridge National Laboratories (ORNL)
- Relativistic Heavy Ion Collider (RHIC)
- Single Event Effects (SEE)
- Single Event Upset Test Facility (SEUTF)
- Tandem van de Graaff (TvdG) Accelerator
- Texas A&M University (TAMU)
- Tri-University Meson Facility (TRIUMF)
- University of Alabama at Birmingham (UAB)

Outline

- Abstract
- Facility Overviews
  - Texas A&M University (TAMU)
    - K500 and K150 cyclotrons
  - Lawrence Berkeley National Laboratory (LBNL)
    - 88-in cyclotron
  - Brookhaven National Laboratories (BNL)
    - NASA Space Radiation Laboratory (NSRL) synchrotron
    - Tandem van de Graaff (TvdG) accelerator
  - Michigan State University (MSU)
    - FRIB SEE (FSEE) – Linear accelerator (LINAC) Segment 1
  - Association for Research at University Nuclear Accelerators (ARUNA)
- Gap 1: Capacity – not enough available beam-hours
- Gap 2: Capability
  - Energy range
  - Beam spot size
- Summary and Comments
- Appendix: Protons >50 MeV, Protons >200 MeV

Partial List of Extinct Domestic Heavy Ion Accelerators

- National Superconducting Cyclotron Laboratory (NSCL)
- Lawrence Berkeley National Laboratory (LBNL) Bevalac
- Chalk River Tandem Accelerator Superconducting Cyclotron (Canada)
- Holifield Radioactive Ion Beam Facility at ORNL

Abstract

- This presentation provides a representative list of domestic U.S. heavy ion facilities used for applied research purposes.
  - Basic capabilities and accessibility will be included.
- Current high-level gaps for capacity/access and capability needs to applied electronics research will be discussed.
- Note: “pure” science facilities such as the RHIC and FRIB are out-of-scope for this presentation

Heavy Ion Facility – Texas A&M University (TAMU) Cyclotron Facility

- Type of Source: Cyclotrons (K500/K150)
- Energies:
  - K500 – 15 to 40 MeV/amu; K150 – 15 MeV/amu only
- Test constraint: In-air
- Accessibility: Oversubscribed (K500). Totals for K500 and K150:
  - DOE for internal science: ~6000 hours/year
  - >4000 hours/year for SEE electronics testing (pay to play model)
  - SEE gap is >2000 hours/year at TAMU alone!
- Comments
  - Wide SEE user base
  - Cost ~$1000/hr
  - Protons to ~ 50 MeV
  - K150 underutilized for electronics tests due to limited ion availability (need to add Xe at a minimum for space environment coverage)
  - Upgrades needed for new ion sources (both cyclotrons) and improved K150 vacuum system for improved intensity, ion selection, and efficiency
- Website: https://cyclotron.tamu.edu/

Heavy Ion Facility – LBNL

- Type of Source: Cyclotron (88-in)
  - Radiation effects at Berkeley Accelerator for Space Effects (BASE) includes SEE testing
- Energies: 10, 16, 20 MeV/amu
  - 20 MeV/amu upgrade for ion selection in discussion along with improved reliability
- Test constraint: Vacuum/Air (depends on penetration range needed)
- Accessibility: Limited
  - DOE facility with ~2500-3000 hours/year science
  - DOE model requires block purchase yearly: very limited "pay to play" option. SEE availability ~1200 hours/year
  - Poor access for industry
- Comments
  - DoD, NASA have blocks purchased in 2022 for SEE
  - Quick ion changes
  - Cost >$2000/hour
  - Protons to ~50 MeV; neutrons as well (talk to Larry Phair or Lee Bernstein)
- Website: https://cyclotron.lbl.gov/

Heavy Ion Facility – NASA Space Radiation Lab (NSRL) at BNL

- Type of Source: Synchrotron
- Energies: wide kinetic energy range from ~30 MeV up to >1GeV/amu (100 MeV-1GeV/amu nominal). Wide range of z ions available.
- Test constraint: Air
- Accessibility: Limited
  - NASA Human Research Program (HRP) is prime customer (1200 hours in FY22)
  - SEE blocks purchase by DoD/NASA – up to 1000 hours/year
  - Commercial space and National Cancer Institute use “several hundred” hours/year (limited pay to play)
  - Additional time requires additional workforce (new shift) and guaranteed DOE model funding
- Comments
  - Cost ~ $4000/hr
  - Beam structure (pulsed spills) has some limitations for SEE testing
  - Upgrades under discussion, but operating model may be “challenging”
- Website: https://www.bnl.gov/nsrl/

Heavy Ion Facility – MSU FSEE

- Type of Source: Tap off of LINAC Beam Segment 1 (FRIB is a 3-stage LINAC system overall)
- Energies: 5-40 MeV/amu
- Currently under DoD contract
  - Electronics test station
  - Beam validation
- Comments
  - This will be a new facility and has a learning curve for providing ions/beam/dosimetry in a manner conducive to SEE testing
  - It will take a while “to get up to speed” on operational efficiency needed such as ion/energy changes, cabling to user test systems, etc… However, may be applicable for other research purposes that use single ion/energy as well
  - Stay tuned…
- Website: none yet

Heavy Ion Facility – Brookhaven National Labs (BNL) Single Event Upset Test Facility (SEUTF)

- Type of Source: TvdG
- Energies: mostly < 10 MeV/amu; up to 29 MeV protons
- Test constraint: Vacuum
- Accessibility: Very Good
  - Unknown current user load, but online schedule show unavailable for next few months, then wide open availability
  - Estimate of 1500 hours/year could be available
- Comments
  - Cost: >$1500/hr
  - Limited use for many electronics due to limited penetration range of ions available
- Website: https://www.bnl.gov/tandem/capabilities/radiobiology-research-facility.php

Brookhaven National Laboratories' Single Event Upset Test Facility (SEUTF)

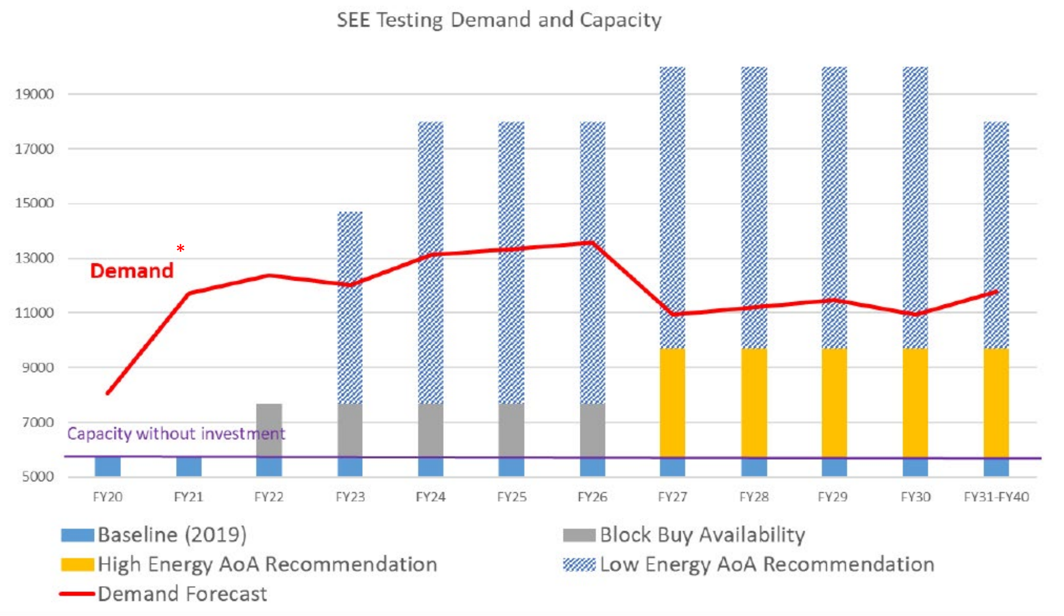
Courtesy NASA

Heavy Ion Facility – ARUNA

- Type of Source: multiple accelerator types
- Energies: varying, but mostly low energy <11 MeV (exception is TAMU described earlier)
  - Note: energy is unsuitable for electronics testing, but of interest for other research
- Association of 10 universities
- Good resource article exists at: http://www.nupecc.org/npn/npn314.pdf
  - Basic facility information, capabilities, and science usage
- Website: http://aruna.physics.fsu.edu/index.html

Gap: Heavy Ion Facility Capacity

- The electronics test community has reached a critical load point where:
  Demand significantly exceeds Supply
- Current facilities are timeshared with prime science (DOE and others) as well as other research communities
  - Additional nuclear data research would need to fit within existing capacity or user blocks (science/electronics/other)

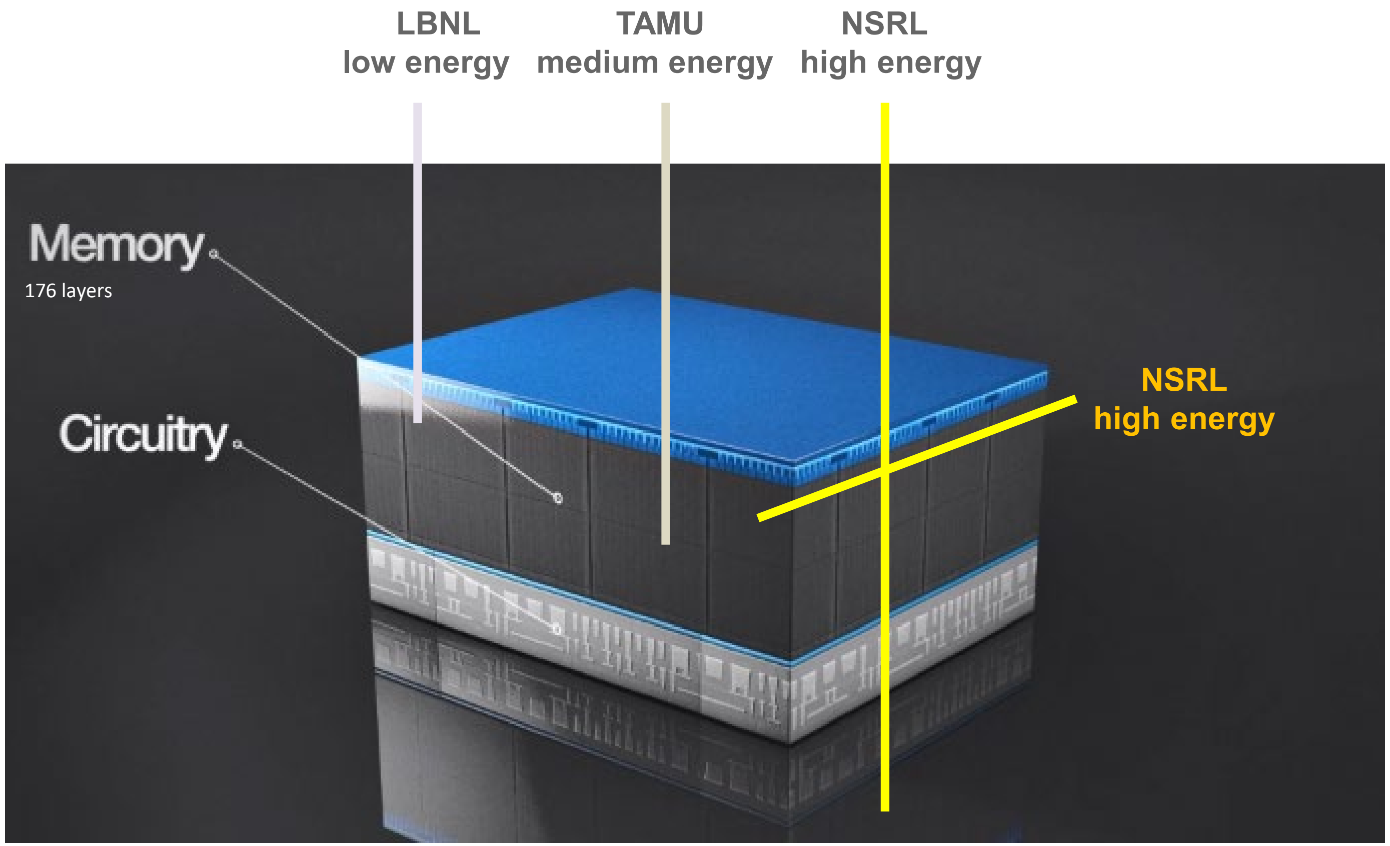


SEE Testing Demand
J. Franco & J. Ross, 2021 High-Energy Single-Event Effects (SEE) Testing Users Meeting (slides) GAP

**-Demand forecast is mostly limited to DoD and doesn't include all possible efforts -- red curve could underestimate demand*
- ***More recent update indicates gap has increased (unpublished)***
- *AoA efforts timeline has moved to the right and high energy efforts have limited funding. Only new SEE test line at Michigan State University (MSU) is currently underway (low energy).*

Gap: Capability – High Energy Range

- Modern complex electronics and their associated packaging require high energy heavy ions in order for the beam to reach sensitive volumes within the device (see figure to the right)
- Currently, NSRL is the only domestic facility available, and access is limited

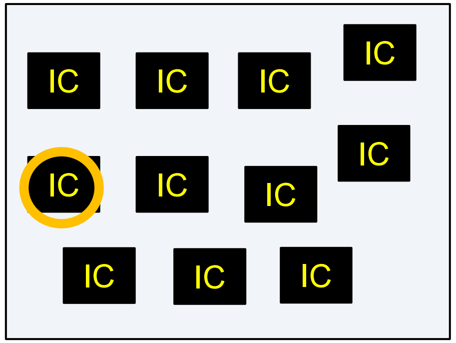


Micron's proprietary CMOS-under-Array technique constructs the multilayered stack over the chip's logic, packing more memory into a tighter space and shrinking 176-layer NAND's die size, yielding more gigabytes per wafer.

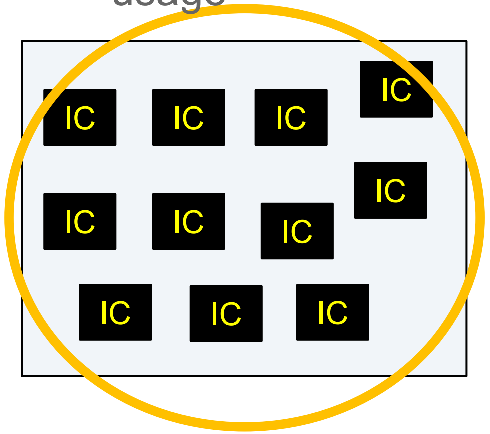
Courtesy of Micron , https://www.eetimes.com/micron-leapfrogs-to-176-layer-3d-nand-flash-memory/#

Gap: Capability – Large Diameter Beam Spot (non-rastered)

- Traditional SEE Testing
  - Irradiate one device at a time



- Batch Device Irradiation
  - Irradiate large number of devices simultaneously
  - Economical beam usage



- System Irradiation
  - Irradiate entire card or system simultaneously
  - **Growing trend**

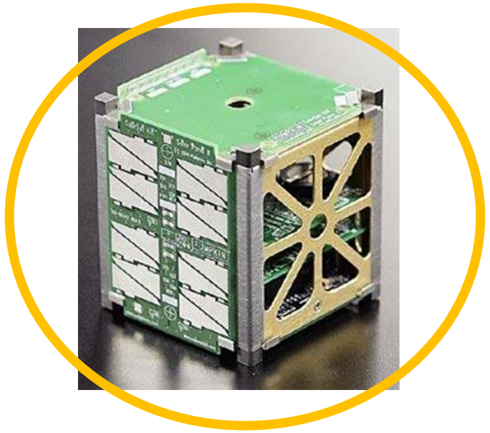


Image courtesy of Vanderbilt University

High energy allows an option for a large irradiation area due to the kinematics of the accelerator designs
- **NSRL is only current facility with this capability.**

Summary and Comments

- Presented herein has been a brief overview of existing domestic heavy ion facilities
- Infrastructure challenges exist for both capacity and capability
- Additional access for new nuclear data experiments may be difficult to find
- Year-round access: Operational constraints such as facility maintenance periods drive periods of time throughout the year where beam is **unavailable** (e.g., January or prime user conflicts)
- Additional facility investments such as NSCL accelerators (K500 and K1200) reutilization, BNL Alternate Gradient Synchrotron (AGS), and other options are in review and discussion
- Biggest challenge: getting ALL the user needs across all fields and coordination of organizations

Appendix: Protons >50 MeV

- Proton sites due to medical treatment usage are more plentiful, but not always accessible (medical load, perceived risk, business model)
  - Business side is VERY dynamic and access (or not) changes on a regular basis for medical treatment centers
  - Access is often on a purely non-interference basis with medical treatments and/or research in many case: nights and weekends, only
- The following list a representative **snapshot** of currently accessible locations in two parts: 50-60 MeV regime, >200 MeV regime (with 1 exception)
  - 50-60 MeV
    - University of California at Crocker Nuclear Lab
    - University of Washington
    - LBNL
    - TAMU

Appendix: Protons >200 MeV

- >200 MeV(highest energy available) – currently providing proton access for research
  - James M. Slater MD Proton Treatment & Research Center
  - Mayo Clinic Proton Beam Facility - Phoenix
  - Mayo Clinic Proton Beam facility - Rochester
  - Massachusetts General Hospital (MGH) Francis H. Burr Proton Beam Therapy Center
  - Northwestern Medicine Chicago Proton Center
  - Provision CARES Proton Therapy Center*
  - Tri-University Meson Facility (TRIUMF) Proton Irradiation Facility
  - Johns Hopkins University Proton Therapy Center
  - Proton International at UAB
- * Provision Knoxville
  - Due to new management, facility will be closed as of 1 Feb 2022.
  - Discussions underway on options for accelerator and a new dedicated research facility
  - This was the U.S. site with most access for electronics testing
- Other potential facilities exist such at ORNL, LANSCE, etc…
- Spreadsheet tracking electronics testing access updated quarterly
- No guaranteed access facility exists domestically