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)

To be presented by Kenneth A. LaBel at the Workshop on Applied Nuclear Data Activities (WANDA) 28 February – 4 March 2021.
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
  o Texas A&M University (TAMU)
    » K500 and K150 cyclotrons
  o Lawrence Berkeley National Laboratory (LBNL)
    » 88-in cyclotron
  o Brookhaven National Laboratories (BNL)
    » NASA Space Radiation Laboratory (NSRL) synchrotron
    » Tandem van de Graaff (TvG) accelerator
  o Michigan State University (MSU)
    » FRIB SEE (FSEE) – Linear accelerator (LINAC) Segment 1
  o Association for Research at University Nuclear Accelerators (ARUNA)
• Gap 1: Capacity – not enough available beam-hours
• Gap 2: Capability
  o Energy range
  o 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

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Abstract

• This presentation provides a representative list of domestic U.S. heavy ion facilities used for applied research purposes.
  o 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:
  o K500 – 15 to 40 MeV/amu; K150 – 15 MeV/amu only
• Test constraint: In-air
• Accessibility: Oversubscribed (K500). Totals for K500 and K150:
  o DOE for internal science: ~6000 hours/year
  o >4000 hours/year for SEE electronics testing (pay to play model)
  o SEE gap is >2000 hours/year at TAMU alone!
• Comments
  o Wide SEE user base
  o Cost ~$1000/hr
  o Protons to ~ 50 MeV
  o K150 underutilized for electronics tests due to limited ion availability (need to add Xe at a minimum for space environment coverage)
  o 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/](https://cyclotron.tamu.edu/)

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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/](https://cyclotron.lbl.gov/)

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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/](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](https://www.bnl.gov/tandem/capabilities/radiobiology-research-facility.php)
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](http://www.nupecc.org/npn/npn314.pdf)
  - Basic facility information, capabilities, and science usage
- **Website:** [http://aruna.physics.fsu.edu/index.html](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
  
  o Additional nuclear data research would need to fit within existing capacity or user blocks (science/electronics/other)

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*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.

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

• Traditional SEE Testing
  o Irradiate one device at a time

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

• System Irradiation
  o Irradiate entire card or system simultaneously
  o Growing trend

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
  o James M. Slater MD Proton Treatment & Research Center
  o Mayo Clinic Proton Beam Facility - Phoenix
  o Mayo Clinic Proton Beam facility - Rochester
  o Massachusetts General Hospital (MGH) Francis H. Burr Proton Beam Therapy Center
  o Northwestern Medicine Chicago Proton Center
  o Provision CARES Proton Therapy Center*
  o Tri-University Meson Facility (TRIUMF) Proton Irradiation Facility
  o Johns Hopkins University Proton Therapy Center
  o Proton International at UAB
• * Provision Knoxville
  o Due to new management, facility will be closed as of 1 Feb 2022.
  o Discussions underway on options for accelerator and a new dedicated research facility
  o 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