National Aeronautics and
Space Administration

NASA EXPLORES

Single-Event Effects (SEE) Testing and the Implications of Semiconductor Technology and Space System Evolution

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To be presented by J. Pellish at the virtual RADSAGA Final Conference and Industrial Event & RADNEXT Public Kick-Off, 17-May-2021

Outline

Origins – why do we need SEE testing?

Evolutions – how are SEE test needs changing?

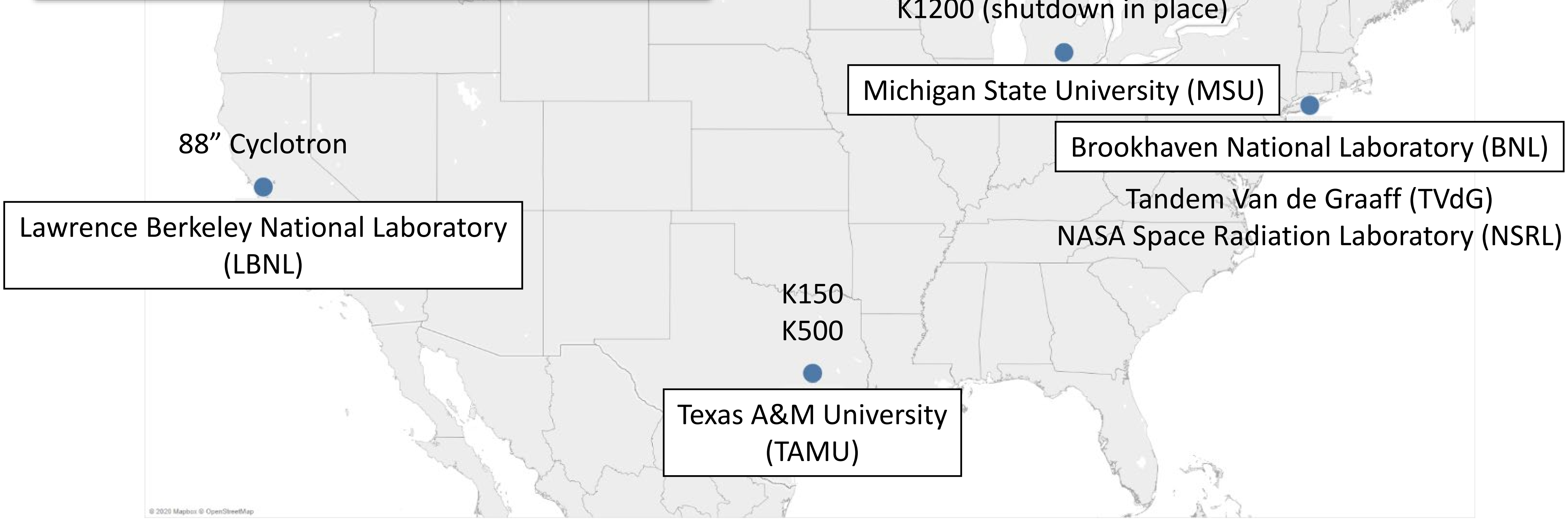
Gaps – do we have access to sufficient capacity and necessary capabilities? (project ahead many years)

Mitigations – what can we do to overcome challenges?

Talk will focus on heavy ion SEE testing in the United States (may generalize)
Large and diverse trade space – just one perspective
SEE test facilities are increasingly critical infrastructure for many economic sectors
…related topics can extend to proton and neutron test facilities too…

U.S. Heavy Ion Test Facilities (*currently*)

- Variety of capabilities, kinetic energy ranges, etc.
- Variety of business models
  - National laboratories
  - Academic institutions



ORIGINS

Why do we need SEE testing?

Space Weather and Climate

<u>Space Weather</u>

Conditions on the Sun and in the solar wind, as well as in Earth's magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.

<u>Space Climate</u>

The historical record and description of average daily and seasonal space weather events that help describe a region. Statistics are usually drawn over several decades.

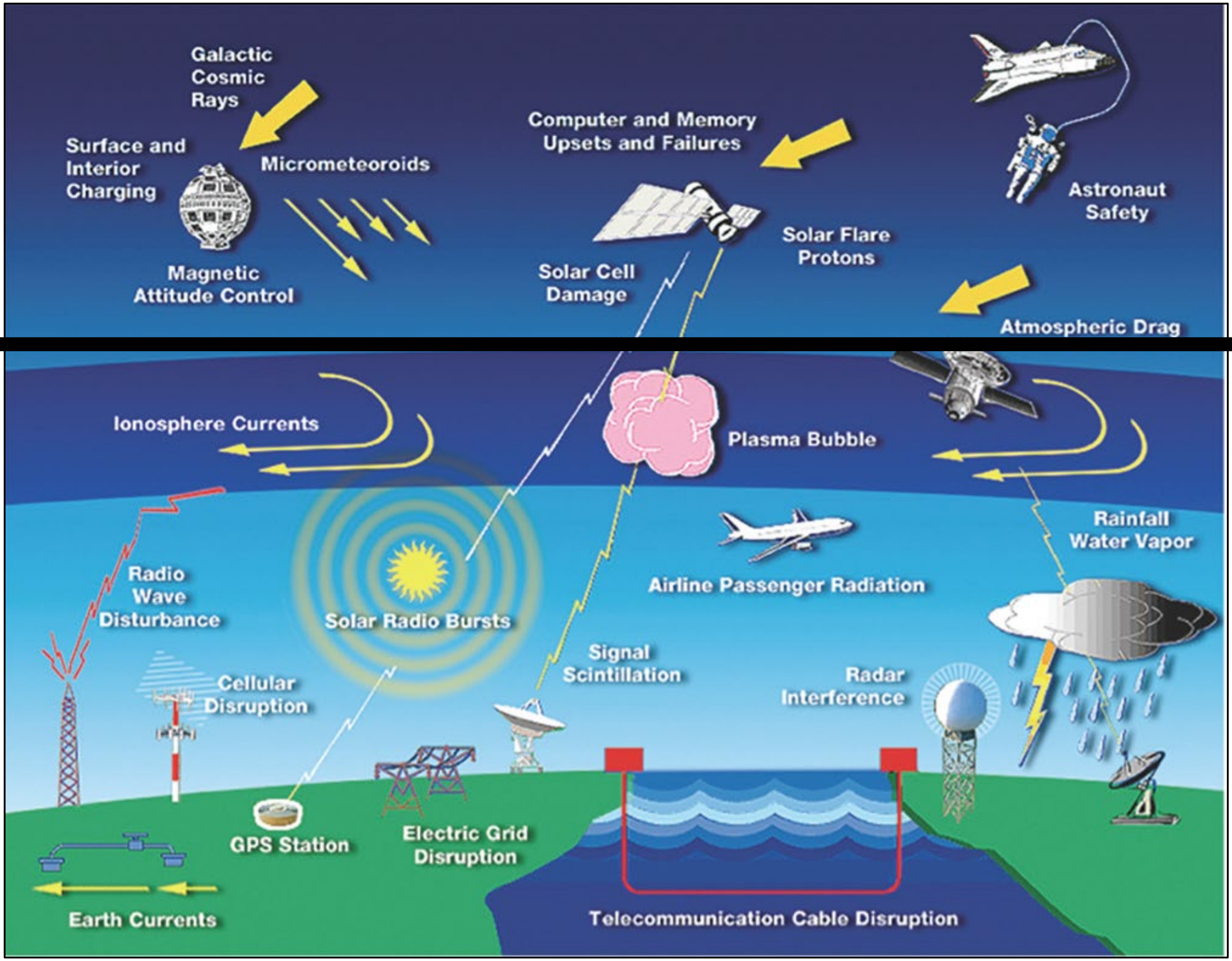
J. Pellish et al., *Cloudy with a Chance of Solar Flares: The Sun as a Natural Hazard*, AAAS Annual Meeting, 2017.

Weather → Operations

Climate → Design

Background image courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

Potential Space Weather Hazards



D. N. Baker, and L. J. Lanzerotti, "Resource Letter SW1: Space Weather," *Am. J. Phys.*, vol. 84, no. 3, pp. 166-180, 2016.

Space-based
&
Ground-based

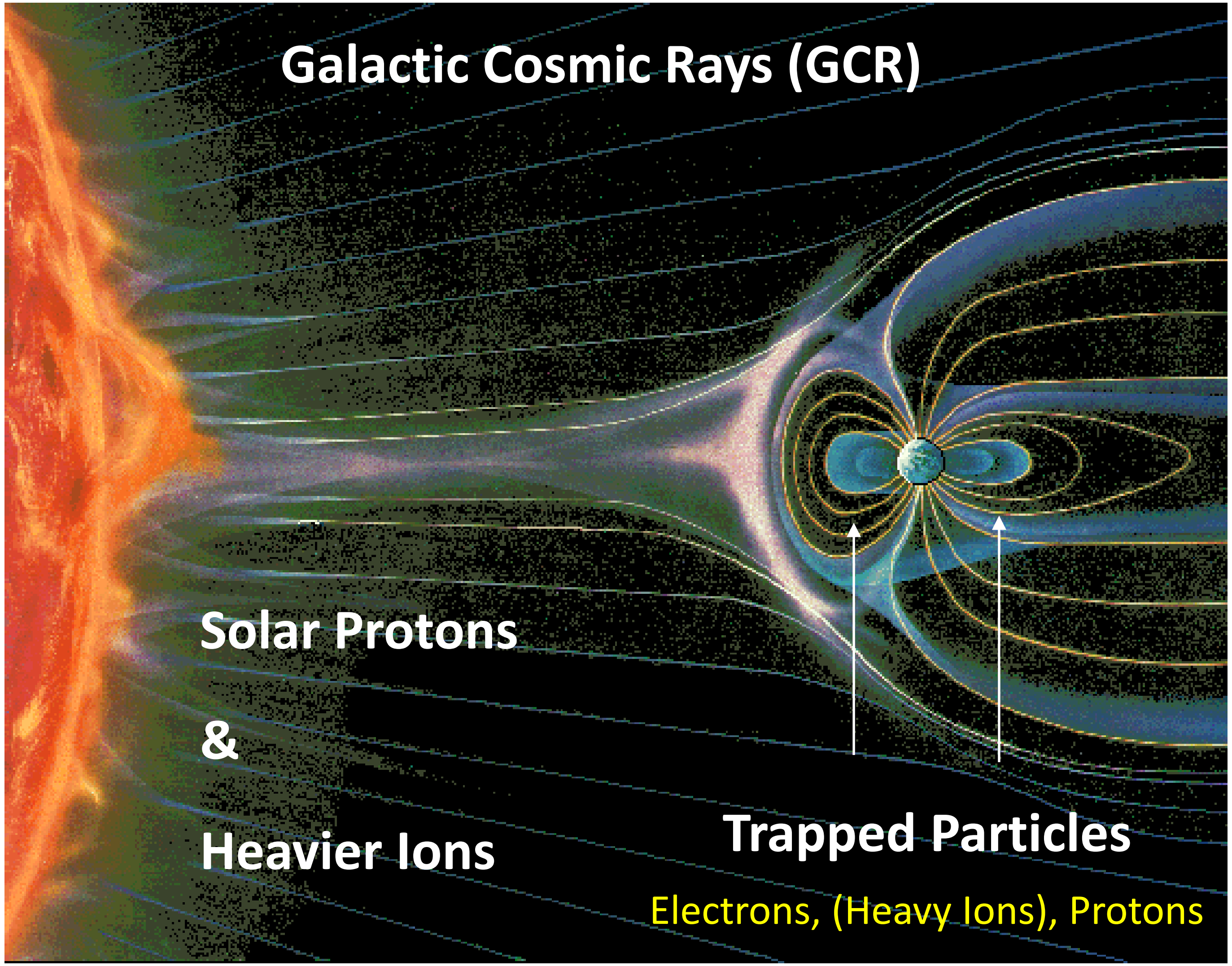
Different communities

Common links

(Earth-Based) Natural Space Radiation Environment

Dynamic

Spatio-temporal Variations



After J. Barth*, 1997 IEEE NSREC Short Course;* K. Endo*, Nikkei Science Inc. of Japan;* and K. LaBel, *private communication.*

Breaking Down Radiation Effects

Ionizing Radiation Effects

- Total Ionizing Dose (TID)
- Total Non-Ionizing Dose (TNID)
- Single-Event Effects (SEE)
  - Non-Destructive
  - Destructive

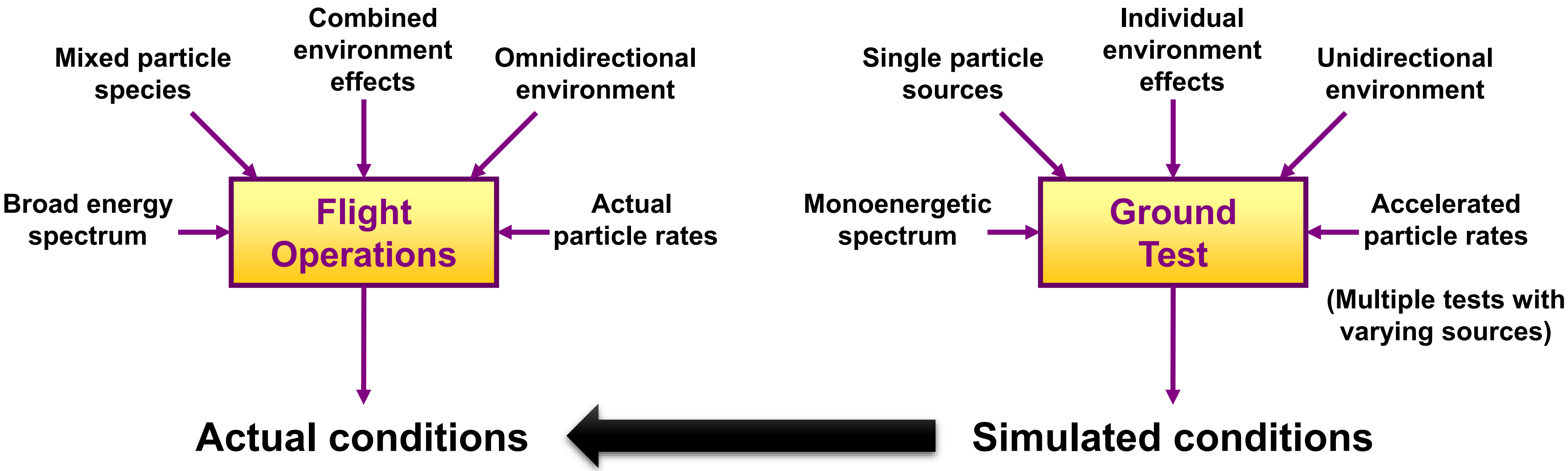
Primarily high-energy protons and **heavy ions**

SEE Testing

- Why do testing? (two primary goals)
  1. To determine the presence and characteristics of single events
     - Destructive or non-destructive?
     - Voltage- and/or temperature-dependent?
     - *List goes on for a quite a while…*
  2. To calculate bounding SEE rates for a given mission, environment, application, and lifetime – this is what matters to designers, system engineers, etc.
- SEE testing is usually performed at particle accelerator facilities, which irradiate an electronic device target (or board or box) with ions

SEE Testing Fidelity

Ground ≠ space – as radiation effects practitioners, we need to understand and account for the differences



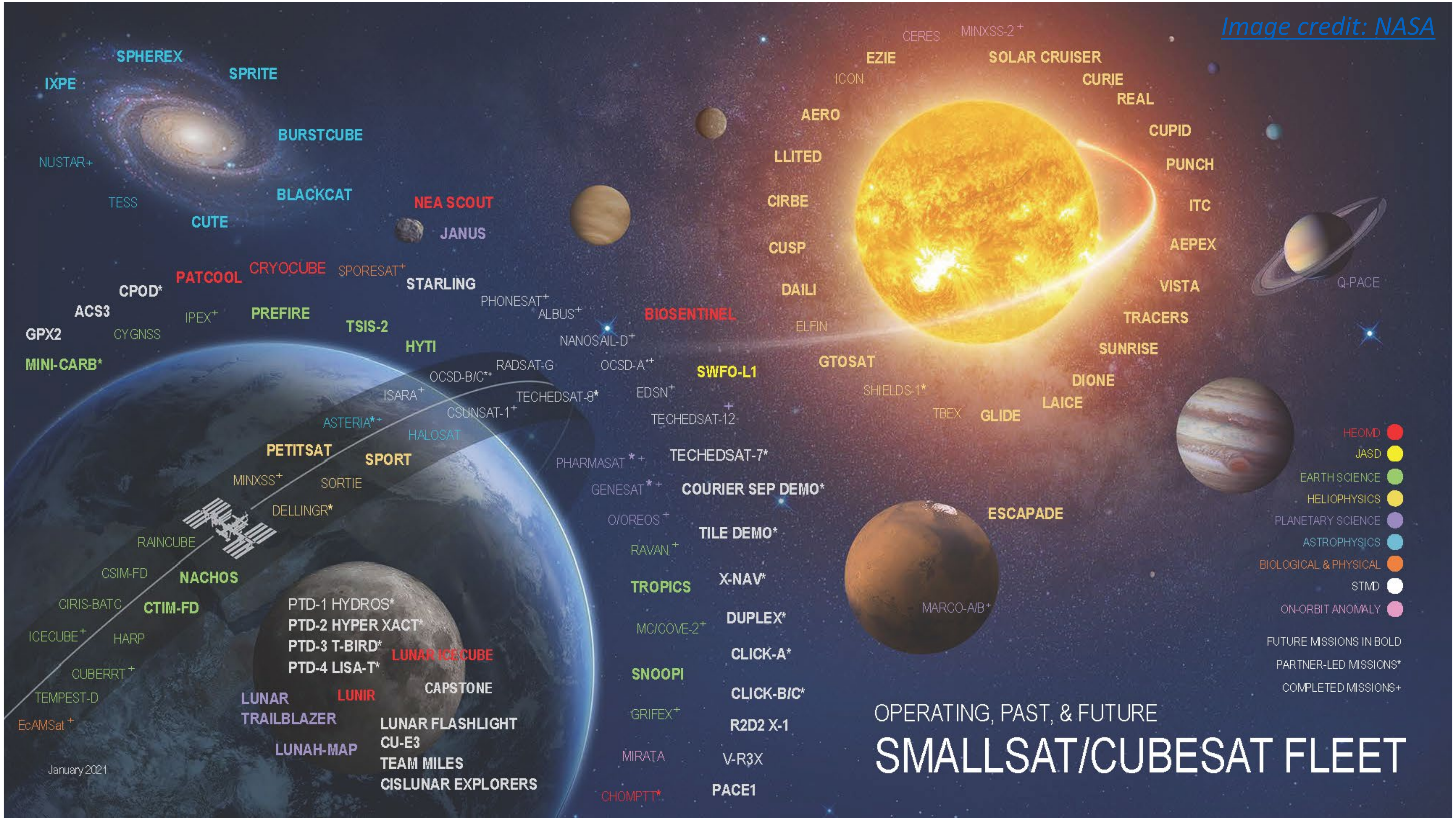
Graphic prepared by K. A. LaBel, NASA GSFC, 2008.

How accurate is ground-based SEE testing in predicting space-based performance?
Increasingly important considerations for new technologies

EVOLUTIONS

How are SEE test needs changing?

Space Community Growth and Diversification



Space Community Growth and Diversification

Human Landing System

Commercial Crew Program

Space Community Growth and Diversification

https://www.defense.gov/

https://www.defense.gov/

Defense Applications

Technology Back Then…

Content courtesy of K. LaBel, *Radiation Effects Boot Camp,* 2021.

- Devices were simple
  - Transistors
  - Memory Arrays (4 kb SRAM!), 8-bit CPUs, etc.
  - High speed was 10 MHz operation
- Technologies were large and mostly silicon
  - >0.5 µm (some >2.0 µm) CMOS feature size
  - GaAs was emerging; rad-hard was silicon on sapphire
- Device packaging
  - Planar
  - Ceramic and a little plastic
  - Through-hole packages (e.g., Dual Inline Packages (DIPs))…

650x Processor

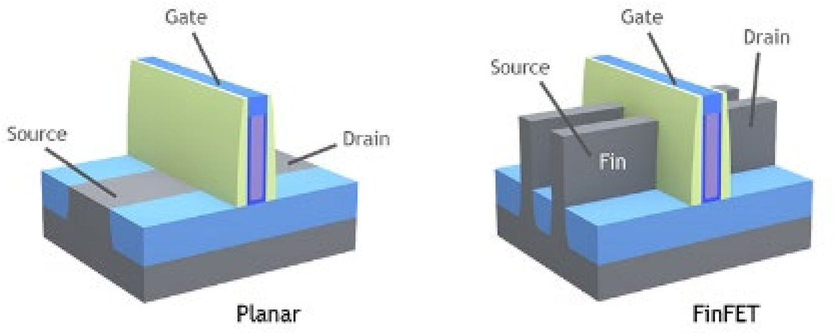
- 8 um feature size (not a typo) – ~1975
- 8-bit CPU
- Up to 14 MHz
- 64 KB RAM
- 256 bytes stack
- No I/O ports
- 28 or 40-pin DIP

For SEE testing – it was easy to access to the die (delidding) with limited SEE signatures (homogeneous devices)

…and Now

Content courtesy of K. LaBel, *Radiation Effects Boot Camp,* 2021.

- Devices are not simple (though “glue” is still needed)
  - FPGAs, multi-core SoCs
  - >>Gbit Memories (with built-in voltage conversion and microcontrollers)
  - Extreme resolution or operating speeds and integration (single devices replacing a whole card of devices from a decade or two earlier)
- Technologies are
  - <10nm CMOS feature size
  - Proliferation of wide bandgap (power, RF)
  - Fins and silicon-on-insulator (SOI) are in!
    - Rad-hard = by design (RHBD)
- Device packaging
  - Mix of planar (old school) and multi-dimensional (2.5/3D) packaging



Courtesy Lam Research Corp.
https://blog.lamresearch.com/tech-brief-finfet-fundamentals/

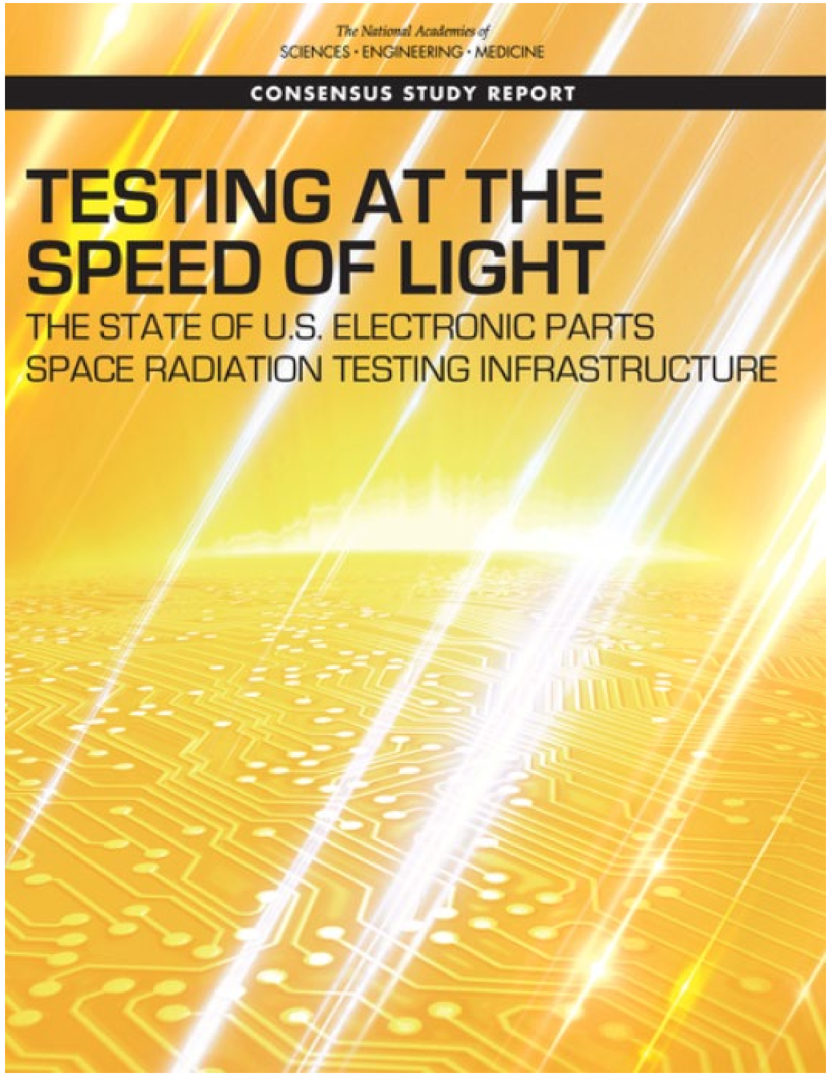
GAPS

Do we have access to sufficient capacity and necessary capabilities?

Recent Assessments (NASEM 2017-2018)

- Key findings
  - Growing use and tightening supply
  - Infrastructure showing signs of strain
  - Aging workforce in a domain that requires specialized training and skills
  - Fast-moving technology
- Points to / needs
  - More organizational coordination
  - Test facility sustainment & new investments
    - Coupled with appropriate research & development
  - Workforce development

At least one detailed assessment pre-dated this work in the 2010s



https://doi.org/10.17226/24993

Recent Assessments (AoA 2019)

- Key findings
  - Existing heavy ion SEE test facilities cannot meet current or future SEE test demand (~5000 hour/year gap)
  - Department of Defense efforts as well as U.S. Government and commercial space are driving significant increases in SEE testing demand
  - Current heavy ion accelerators for SEE testing at U.S. universities and Department of Energy labs have limited capacity and capability
  - More complex electronics (e.g., processors, ASICs, FPGAs) require more test hours
  - More advanced electronics and packaging (3D ICs, flip-chip packages, system-on-a-chip, or system-in-a-package) require higher ion energies >100MeV/n

AoA Findings and Recommendations are <u>Independent and Non-Binding</u>


Strategic Radiation-Hardened (SRH) Electronics Council (SRHEC) Public Summary from Analysis of Alternatives (AoA) for Domestic Single-Event Effects (SEE) Test Facilities

John Franco, DTRA
Jim Ross, NSWC Crane

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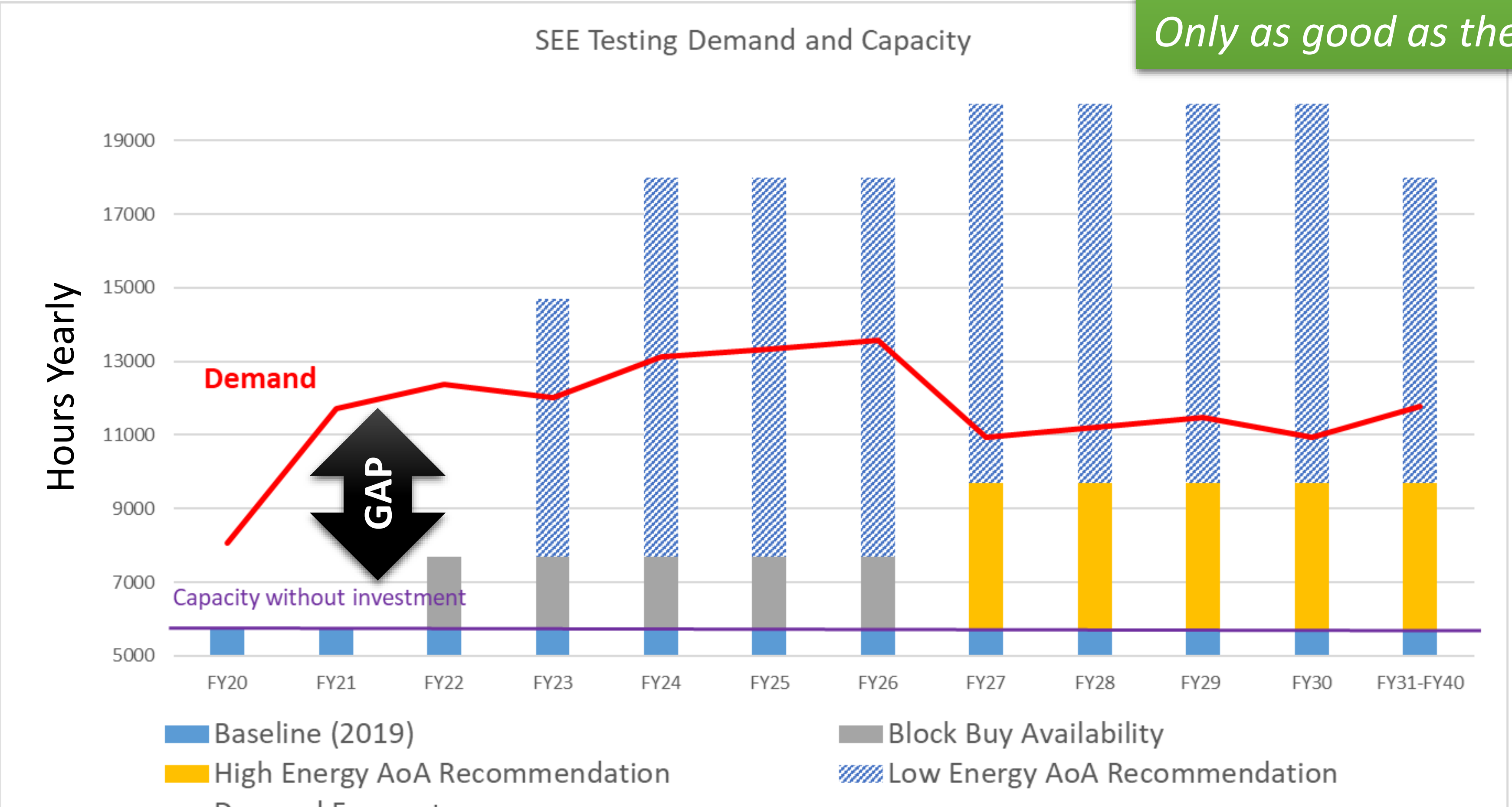
J. Calkins, 2021 High-Energy Single-Event Effects (SEE) Testing Users Meeting (slides)

Recent Assessments (AoA 2019)

Only a snapshot in time

Only as good as the data collected



Adapted from J. Calkins, 2021 High-Energy Single-Event Effects (SEE) Testing Users Meeting (slides)

Demand forecast is based on Fiscal Year 2020 projections of Defense programs (other contributors too!)
Demand input from integrators, manufacturers, and suppliers would improve fidelity of demand forecast

Recent Assessments (AoA 2019)

- Demand for high-energy SEE testing is growing (projections only)

Low Energy SEE Test

2020

- 90% of SEE test is Low Energy
  - 10-50 MeV/n (Mega-Electron Volts /n)

2030

- 60% of SEE test is Low Energy
  - Economical test for monolithic integrated circuits
  - Issues for flip-chip, stacked die, 2.5/3D packaging, and assemblies
- Access assured with low energy investments
- TAMU K500 & K150, LBNL, FRIB Lin Seg 1, and MSU K500 meet Low Energy demand

High Energy SEE Test

2020

- 10% of SEE test is High Energy
  - >100 MeV/n

2030

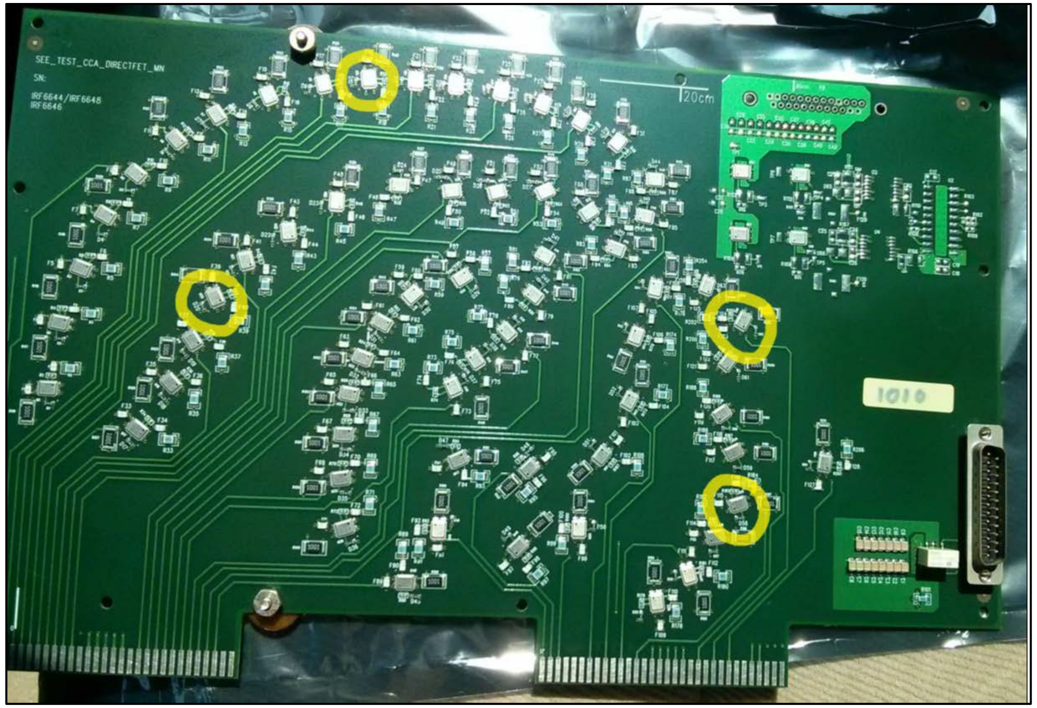
- 40% of SEE test is High Energy
  - New technology and CCA level testing will demand high energy
  - Economical for new technology
- Access assured by high energy investment
- 40% is ~4000 hours/yr
  - BNL AGS or MSU K1200 meets High Energy demand

J. Calkins, 2021 High-Energy Single-Event Effects (SEE) Testing Users Meeting (slides)

Likely High-Energy SEE Testing "Killer Applications"

- Improving space environment simulation fidelity
- Overcoming semiconductor, packaging, and system technology testing challenges
- Increasing test efficiency / throughput
  - Multiple devices simultaneously
  - Improved return on investment
- Enabling card-, box-, and system-level testing

Testing 63 DUTs in Parallel



T. Turflinger, 2021 High-Energy Single-Event Effects (SEE) Testing Users Meeting (slides)

Low-energy testing is not going away, but expect to see high-energy SEE needs grow as these applications have to be invoked more frequently

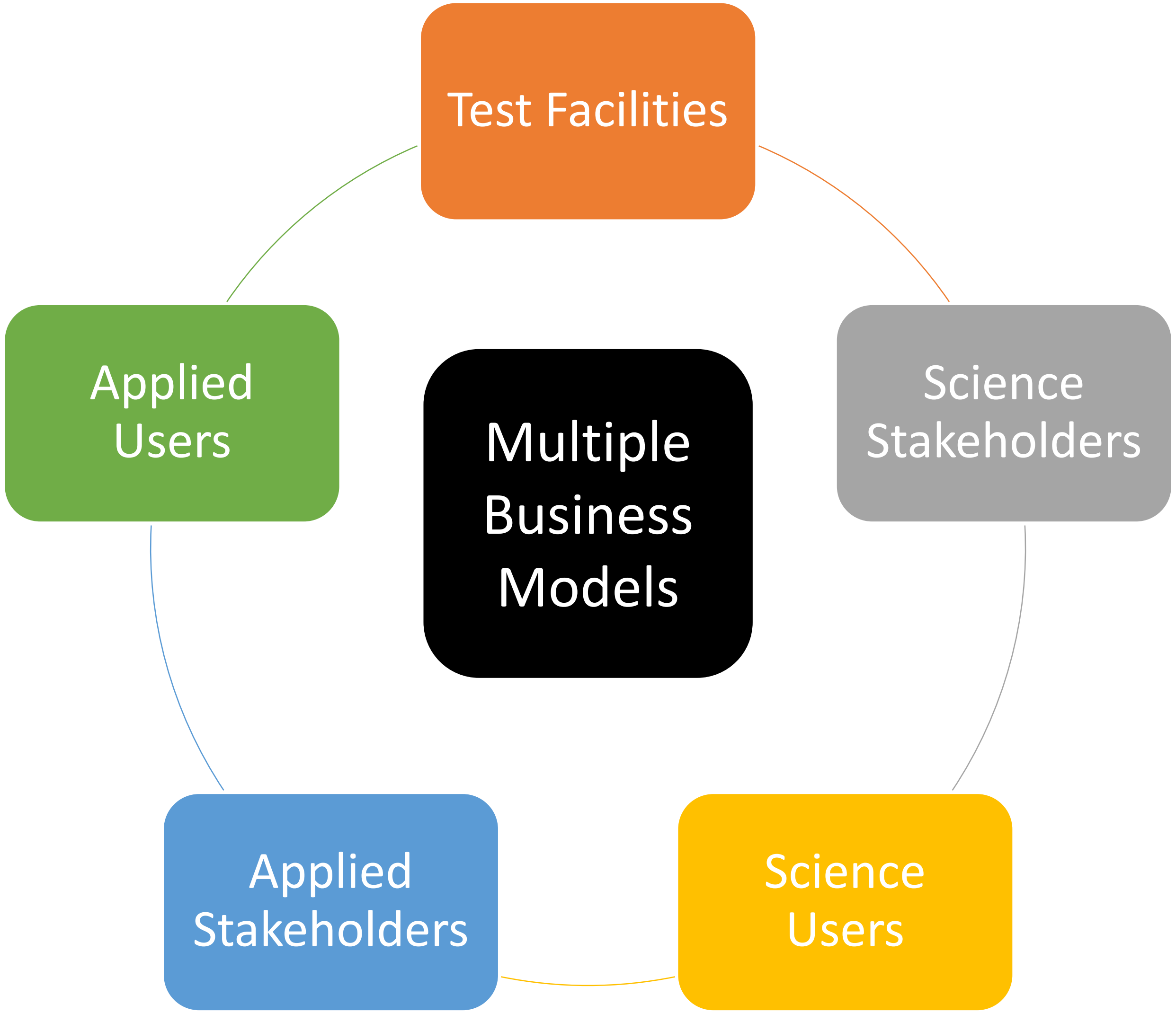
MITIGATIONS

What can we do to overcome challenges?

More Organizational Coordination

Most facilities have multiple user and stakeholder communities

SEE testers are often guests in facilities designed and built for science



Need to invest in facilities is clear, but the trade space is complex

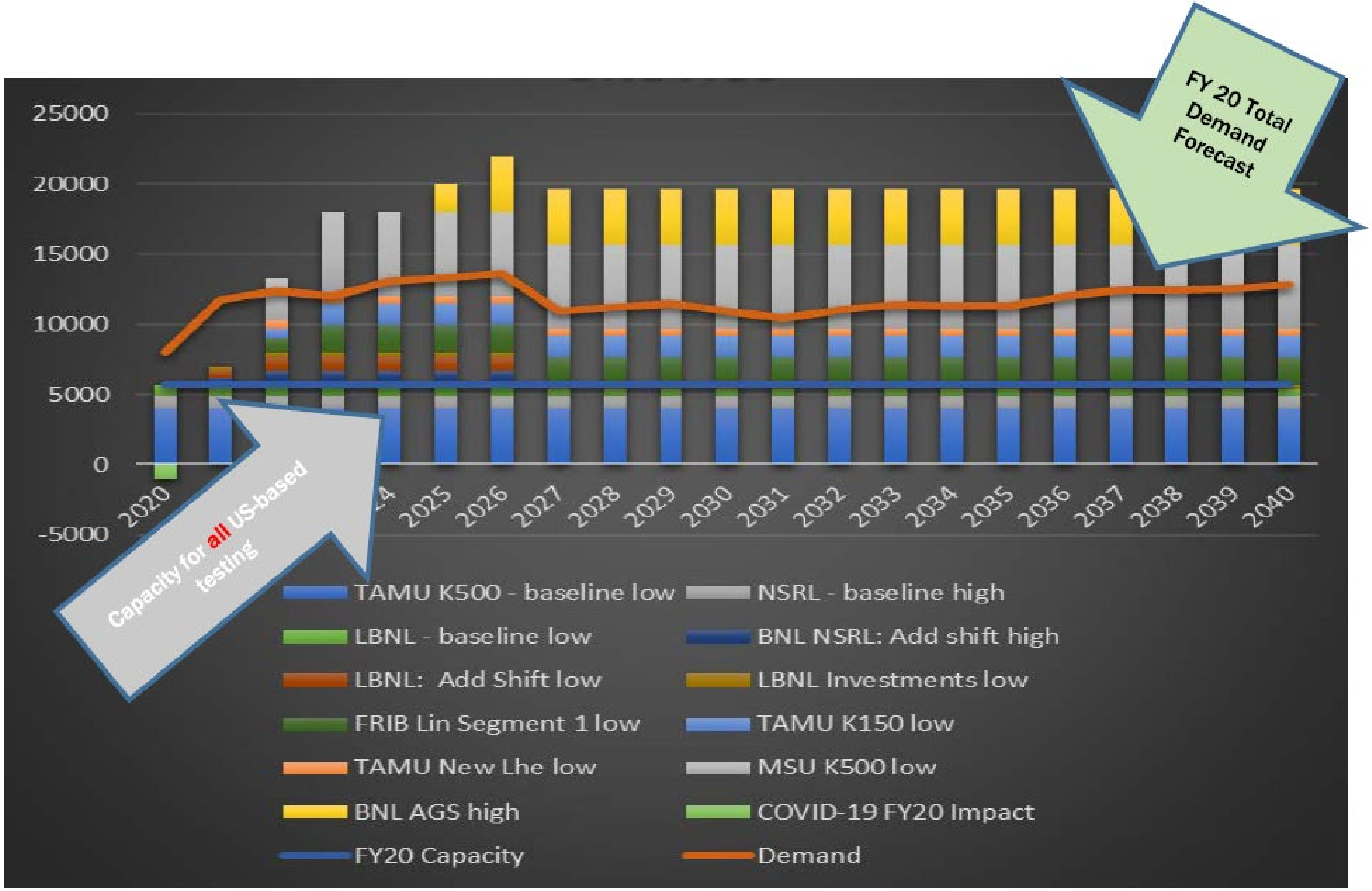
Unique time in the radiation effects community given planned investments & possibilities

Test Facility Sustainment & New Investments

- Utilize existing infrastructure to expand low-energy capacity
  - Repurpose available accelerator systems and leverage workforce, possibly gaining facilities more dedicated to SEE testing
  - Consider reliability investment for current accelerator systems to increase availability through better efficiency and less downtime
  - *Needs are immediate and investment proposals are forthcoming*
- Continue and accelerate studies for new high-energy capabilities
  - Understand demand evolution for high-energy SEE – harder to predict, but know it is coming
    - Development and utilization phasing are stretched out relative to low-energy investments
    - Requires more funding up front (vs. low-energy) and careful consideration of long-term operation and sustainment costs
  - *Needs are growing and proposals are being considered*

Capacity vs. Demand with Recommendations (AoA 2019)

- Solutions exist!
  - Range of paths to cover low- and high-energy gaps
- Likely that not all recommendations will be pursued
- Investments in capacity and capabilities are evolving quickly and will play out over next several years



J. Calkins, 2021 High-Energy Single-Event Effects (SEE) Testing Users Meeting (slides)

Workforce Development

Students, faculty, facilities, and employees

Grow New Community Members

Two-Fold Needs

Train Existing Community Members

Workforce Development

- Provide clear demand signals and adequate resources
- Develop necessary skills
- Acquire diverse talent
- Retain personnel in the community with robust growth opportunities

- Leverage existing programs, resources, and collaborations with greater coordination
- Develop new programs as needed to support knowledge transfer and enable graceful workforce succession

Develop a sustainable workforce model with acceptable baseline capabilities – strive to be practitioner-independent and maintain subject matter expertise

Summary

- Heavy ion SEE testing is essential for robust space exploration, science, and technology capabilities
  - Essential part of the space industrial base
- Growing space economy and expanding mission objectives are driving demand and have created gaps in both capacity and capabilities
- Mitigations exist and require sustained funding and coordination to execute successfully

- *Same thoughts might be applicable to other SEE testing infrastructure*
- *While specifics may differ, general themes appear outside the U.S. too*

THANK YOU FOR YOUR ATTENTION

Acronyms

Abbreviation	Definition
AAAS	American Association for the Advancement of Science
AGS	Alternating Gradient Synchrotron
AoA	Analysis of Alternatives
ASIC	Application-Specific Integrated Circuit
BNL	Brookhaven National Laboratory
CCA	Circuit-Card Assembly
CMOS	Complementary Metal Oxide Semiconductor
COVID	Coronavirus / SARS-CoV-2
CPU	Central Processing Unit
DIP	Dual In-line Package
FPGA	Field Programmable Gate Array
FRIB	Facility for Rare Isotope Beams
GaAs	Gallium Arsenide
GCR	Galactic Cosmic Rays
GPS	Global Positioning System
JPL	Jet Propulsion Laboratory
LBNL	Lawrence Berkeley National Laboratory

Abbreviation	Definition
MSU	Michigan State University
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NSRL	NASA Space Radiation Laboratory
RAM	Random Access Memory
RF	Radio Frequency
RHBD	Radiation-Hardened By Design
SEE	Single-Event Effects
SoC	System on a Chip
SOI	Silicon On Insulator
SRAM	Static Random Access Memory
SRH	Strategic Radiation-Hardened
SRHEC	Strategic Radiation-Hardened Electronics Council
TAMU	Texas A&M University
TID	Total Ionizing Dose
TNID	Total Non-Ionizing Dose
TVdG	Tandem Van de Graaff
U.S.	United States