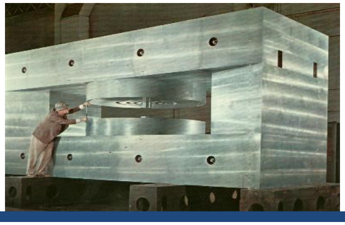
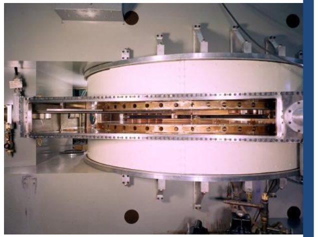
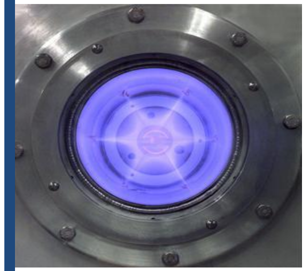
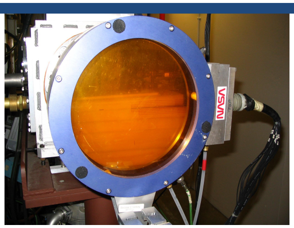
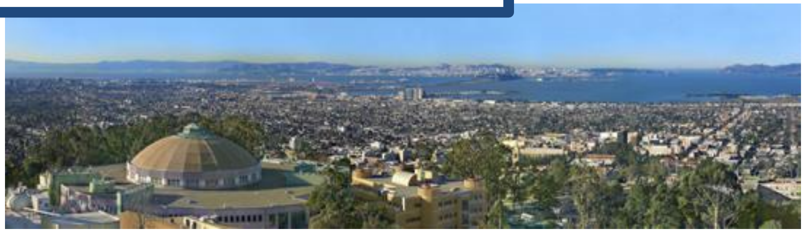
88-Inch Cyclotron







BERKELEY LAB

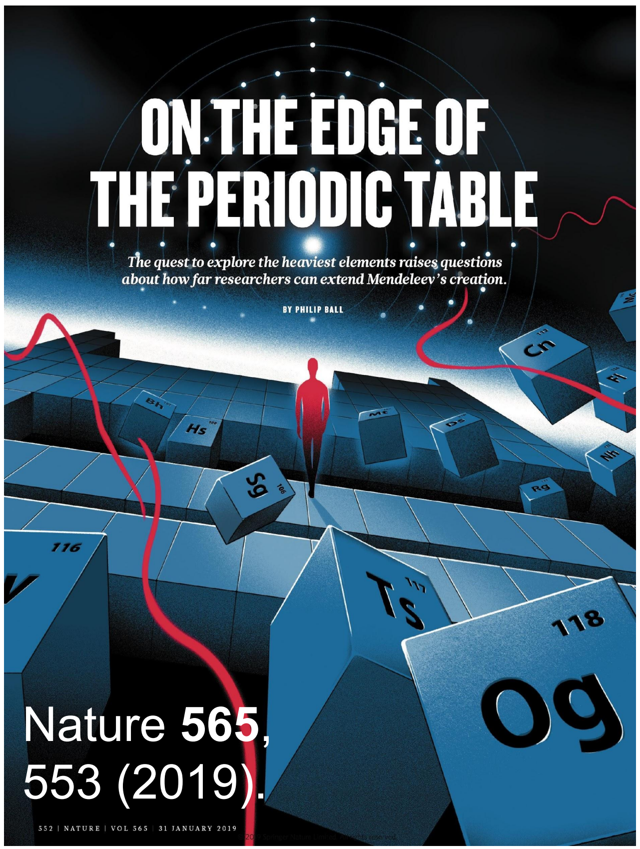
Larry Phair

88-Inch Cyclotron

Lawrence Berkeley National Laboratory

The 88” Cyclotron science opportunities

Super heavy elements



Nuclear Data (experimental needs)

Finding the sweet spot:

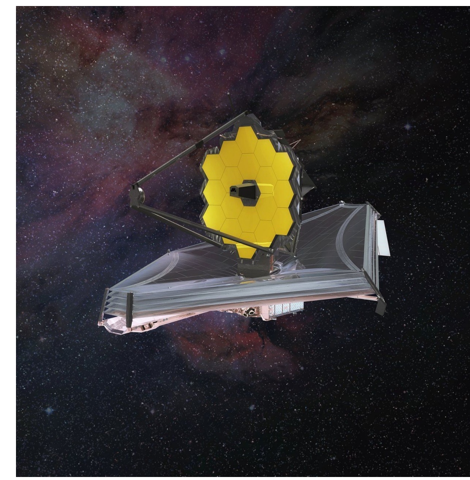
therapeutic radionuclide

^{225}Ac via ^{226}Ra(n,2n)

A 43 g ^{226}Ra target with a 40 MeV deuteron beam would outproduce BNL-BLIP

- Chemical separation efficiency: 91.4 %
- Production rate: 2.1 mCi/mAh/g
- No fission fragments in separated ^{225}Ac.
- No measurable ^{227}Ac (t½=21.8 y)

BASE, SEE testing



- Nearly all American spacecraft have had one or more parts tested at the 88-Inch Cyclotron BASE Facility.

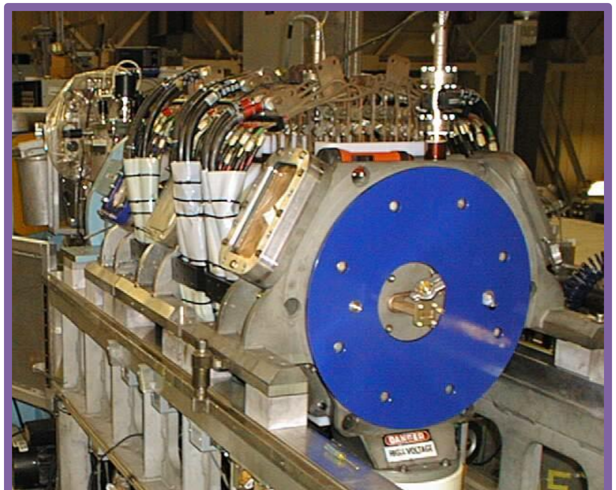
BASE

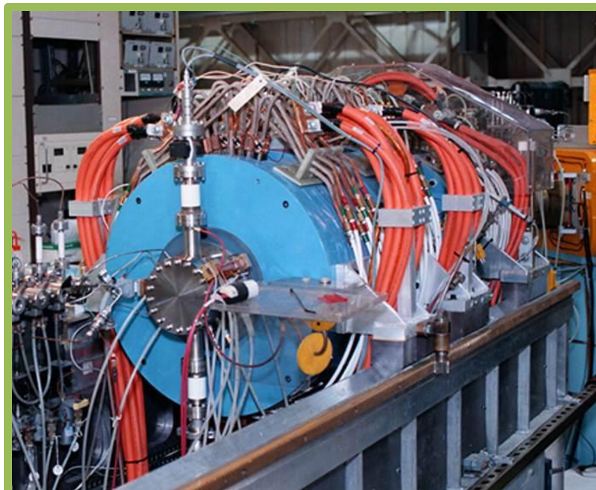
Enabling the science: ECR Ion sources at the 88

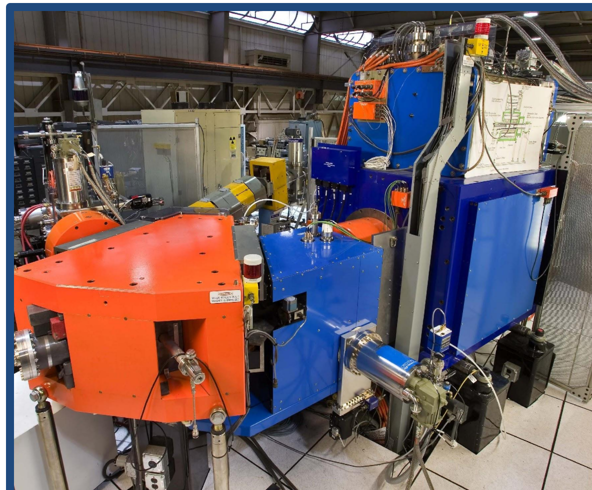
ECR (Gen 1)
1980s
Max B-Field: 0.4 T
Frequencies: 6.4 GHz
Max Power: 0.6 kW

AECR (Gen 2)
1990s
Max B-Field: 1.7 T
Frequencies: 10, 14 GHz
Max Power: 2.6 kW

VENUS (Gen 3)
2000s
Max B-Field: 4.0 T
(superconducting)
Frequencies: 18, 28 GHz
Max Power: 12 kW

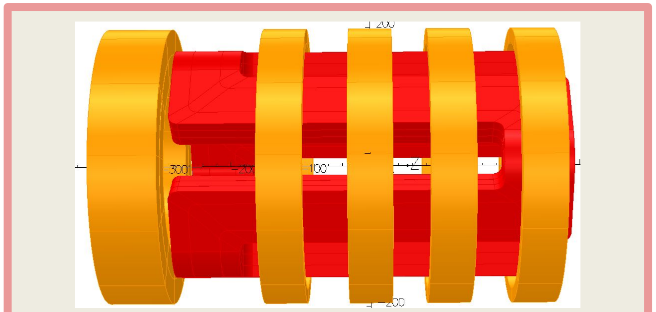




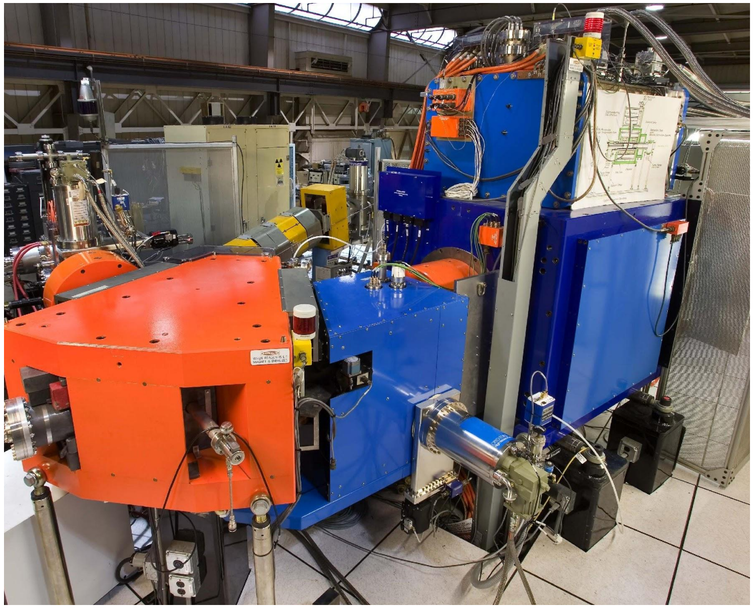


Under development:

MARS (Gen 4)
Max B-Field: 5.7 T
Frequency: 45 GHz
Max Power: 20 kW



VENUS: 3rd generation ECR ion source



VENUS ion source

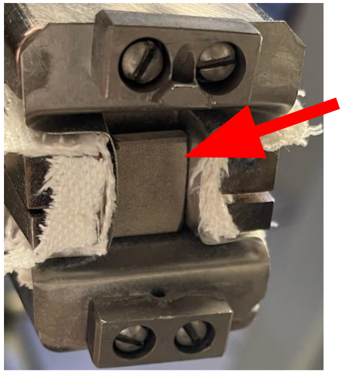
- Remains one of the two top-performing ECRs in the world
- Ti beams for SHE searches
- 5,500 hours envisioned for FY24

Machine Learning with VENUS

- High-performance ECR ion sources have a large operational phase space defined by upwards of 20 control parameters
- This broad space is both difficult and tedious for humans to explore. VENUS still sets world record beams through patient human tuning in new operational regions
- Machine learning is being used with VENUS to maximize ion beam currents through methodical exploration of the operational phase space
- Envision **exporting (new) high performance solutions to FRIB.**

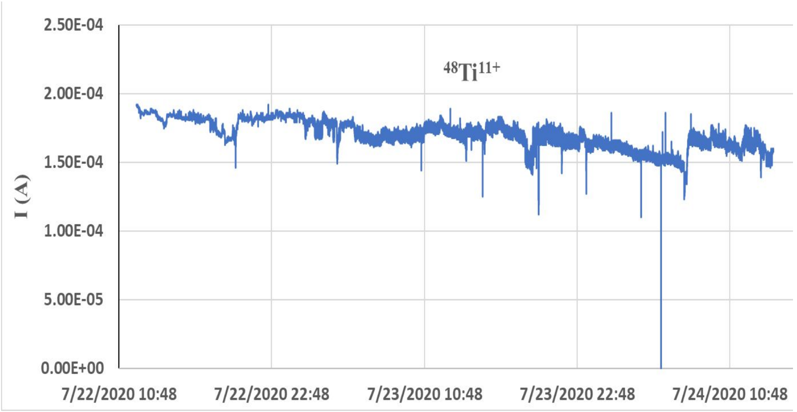
SHE Program (Element 120) needs intense ^{50}Ti beams
Oven technology

Boat Oven

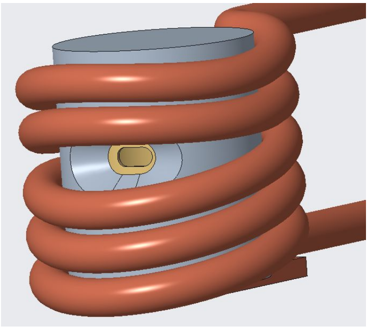


- Produced $^{48}Ti^{11+}$ and $^{51}V^{12+}$ currents in **excess of 150 eμA.**
- Direct loading of Ti and V metals without any crucibles.

- Consumptions of Ti and V in the tests were of 3-4 mg/hr.
- Commercial Ta or W folded-boats (loaded volume ~ 2 cm^3)

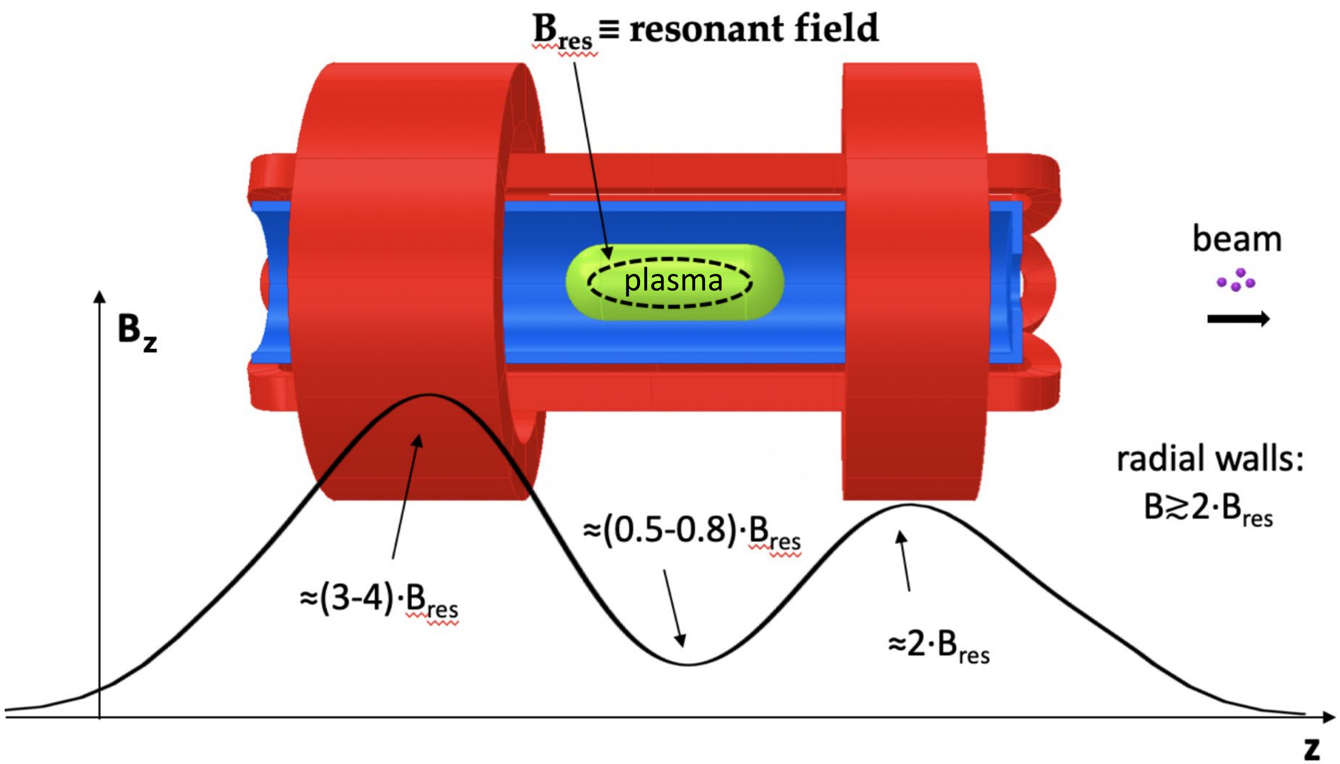


Inductive Oven



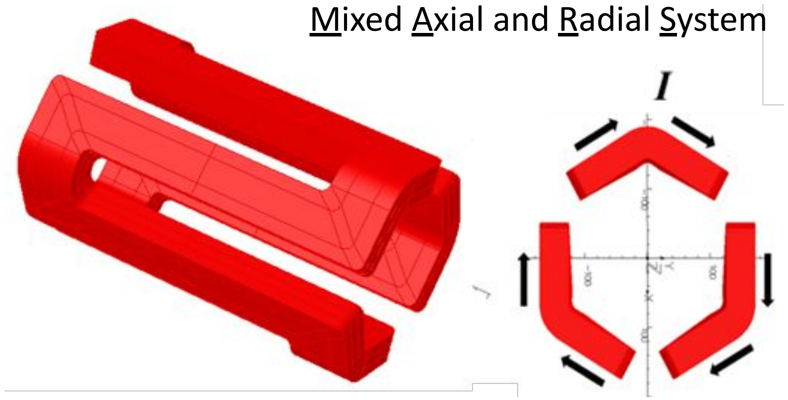
- The high magnetic fields in VENUS make resistive ovens susceptible to failure from strong Lorentz forces
- Inductive ovens experience no net Lorentz force and will be more robust in high-field ECR ion sources

All you really need to know about ECRIS in one slide

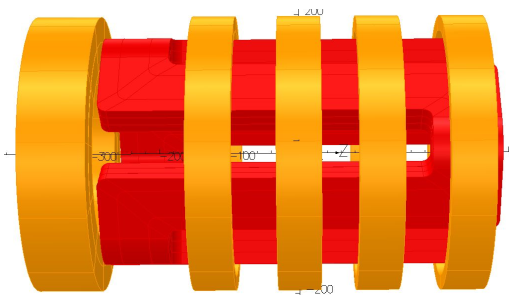


- ECR ion sources producing highly-charged ions have the above properties
- Increasing the resonant fields (and therefore all confining fields) increases performance

MARS-D: 4th generation ECRIS (45 GHz)

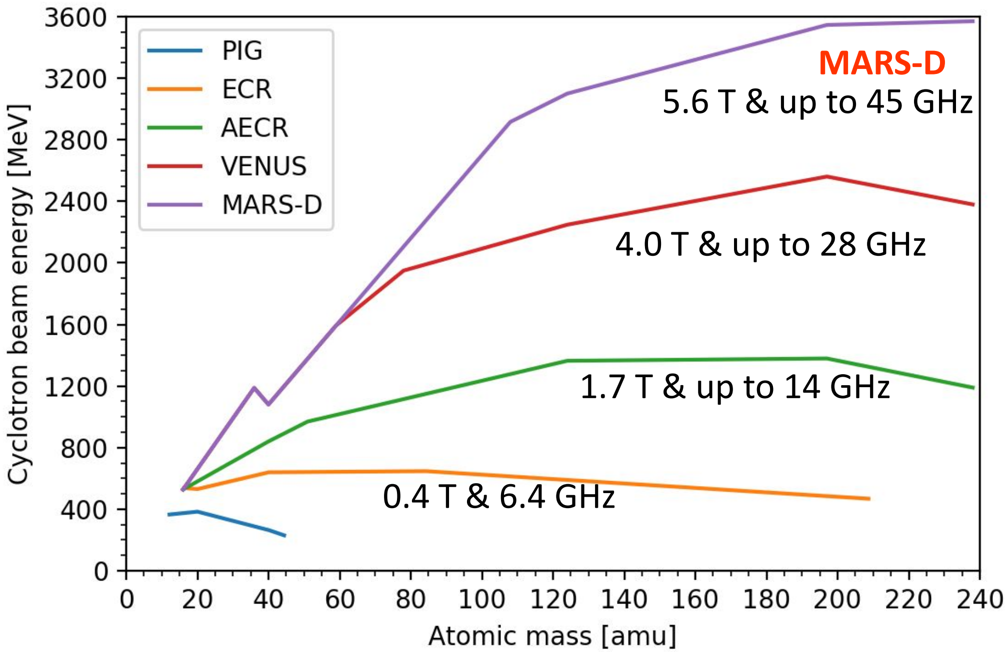


- **A closed-loop-coil alone** provides the necessary sextupole field **and** ~80% of the required solenoid fields



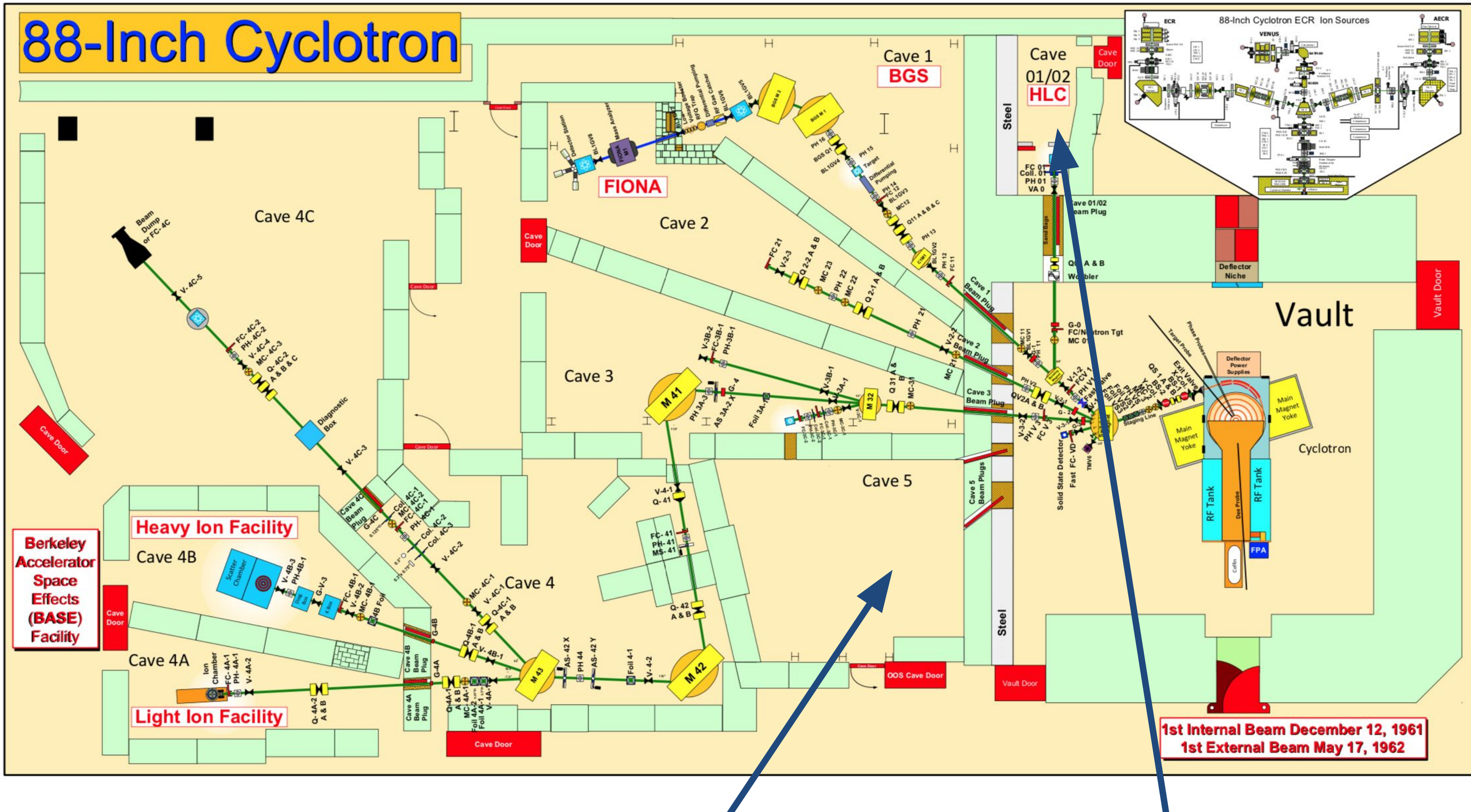
Demonstrator MARS-D will reach fields necessary for 45 GHz operation using the well-tested superconductor material NbTi

Funding in FY23-24 to **wind the magnet**



- Expected x4 beam intensity for superheavy element searches
- Provides a cost-effective **upgrade path for FRIB** by replacing VENUS
- Paves the way for **5th generation, 80 GHz** ECRIS using MARS geometry and higher field materials such as Nb_3Sn

88” Cyclotron application: neutron beams



Cave 5: neutron beams

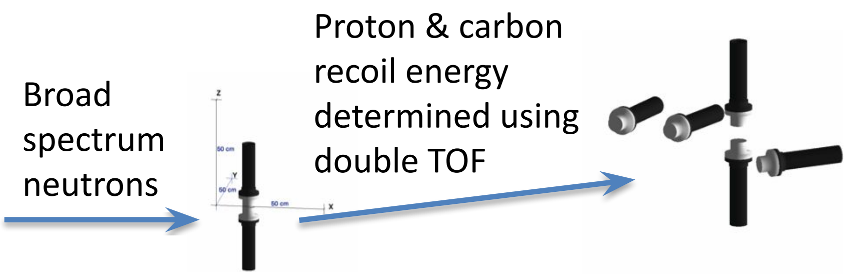
- ~10^9 neutrons/sr/s (from deuterons at 16 MeV)

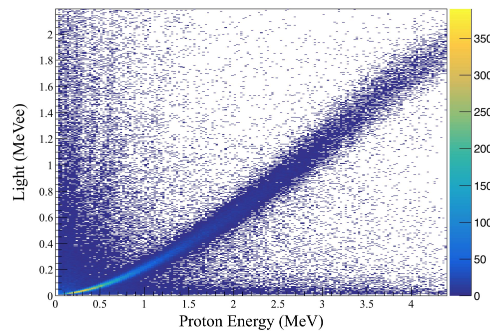
Cave 0: neutron dose

- few x 10^{12} neutrons/sr/s @ 10 uA of 33 MeV deuterons

Light Yield Measurements – UCB/LBNL Approach

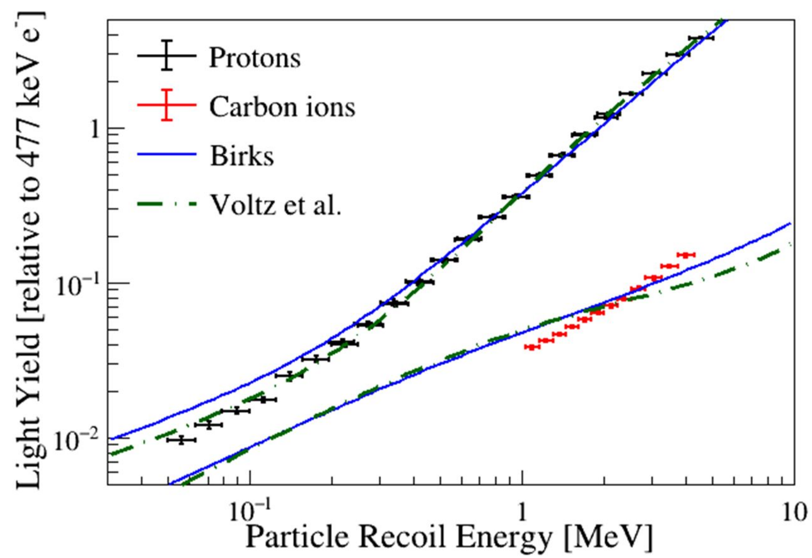
New model-independent method developed at the 88-Inch to obtain scintillator response to recoil nuclei using broad spectrum neutron source





Each detector pair results in a continuous light yield measurement over a broad energy range

- ***Advances basic understanding of scintillation physics***—Exploration of physical mechanisms for ionization quenching ⇒ tailored scintillating media
- ***Applications for advanced nuclear energy systems, nuclear security and safeguards, fusion diagnostics, and more***
  - Enables accurate simulation of neutron detection systems
  - Neutron image reconstruction
  - Next-generation neutron detector material prospecting



Consistent LY measurements from 10s of keV to 20 MeV with full UQ

BASE Facility Mission

Mission:

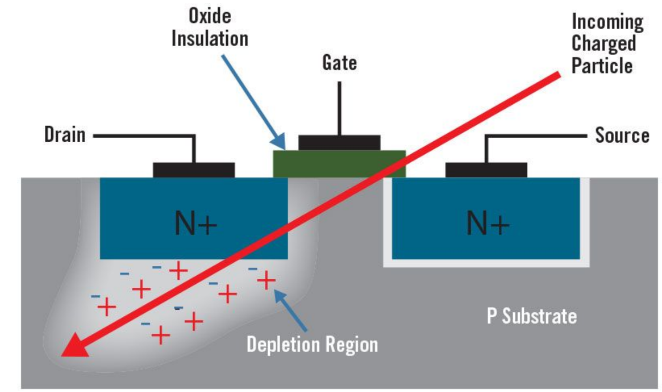
Support national security and other US space programs in the area of radiation effects testing.

*Left: Recent images captured by NASA's **James Webb Space Telescope**. Right: **Artemis-1** on the launch pad. All of these had parts at the BASE Facility.*

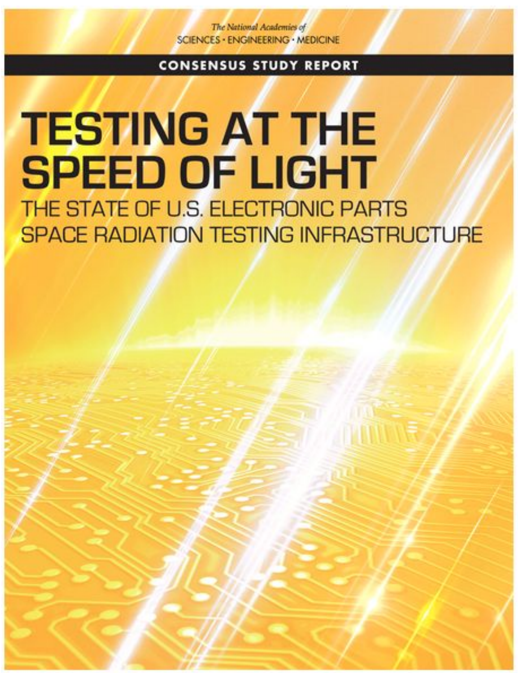
Single Event Effects

Single-Event Effect (SEE): Any measurable or observable change in state or performance of a microelectronic device, component, subsystem, or system (digital or analog) resulting from a single energetic-particle strike.

Causes of SEE's: Galactic cosmic rays, solar particle events, particles trapped in planetary magnetic fields, natural isotopes in chip packaging, and nuclear weapons.



Courtesy of COTS Journal



National Academies study from 2018

Recommendation: *"… define the usage needs for parts radiation testing and **assure the adequacy and viability of radiation test facilities out to 2030**."*

Primary locations for SEE testing: **TAMU, 88, MSU, BNL**

TRMC: dedicated to ensuring the DoD Components have the right Test and Evaluation (T&E) Infrastructure to accomplish the T&E mission.

Funding:

- $2.3M of improvement funding in FY23-24 for a 20 MeV cocktail at the 88" Cyclotron
- Block buys of beam time for SEE testing

NP Community: Contributions to Space Exploration*

Solar Terrestrial Relations Observatory (STEREO)

Genesis (Solar Wind Sample Return)

Messenger (Mercury)

Parker Solar Probe

Pioneer Venus

Van Allen Probes

IMAGE/Explorer 78

Solar Dynamics Observatory (SDO)

Landsat

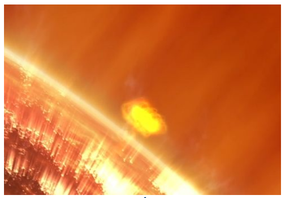
GPS

Mars Pathfinder

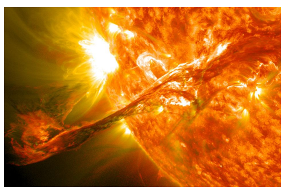
Mars Polar Lander

Orion Crew Vehicle

Mars Climate Orbiter



Parker



SDO

GPS

Orion

Mars Exploration Rover (MER) / Spirit & Opportunity

Mars Science Laboratory (MSL) / Curiosity Rover

Mars Atmosphere & Volatile Evolution (MAVEN)

Mars Odyssey

Phoenix (Mars)

ExoMars

Mars 2020 (Perseverance & Ingenuity)

InSight (Mars) Lander

Dawn (Asteroid Belt)

Juno (Jupiter)

Galileo (Jupiter)

Cassini-Huygens (Saturn)

Europa Clipper (Jupiter)

Voyager (Jupiter, Saturn, Uranus, Neptune)

New Horizons (Pluto)

Ingenuity

Juno

Europa

Space Shuttle

Lunar Reconnaissance Orbiter

International Space Station (ISS)

James Webb Space Telescope

Spitzer Infrared Telescope Facility

Swift Gamma-Ray Burst Mission

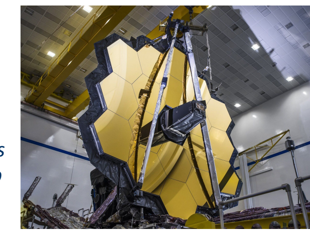
Stardust (Comet Sample Return)

Deep Space 1

xEMU Space Suit

Atlas Launch Vehicles

Delta Launch Vehicles



James Webb

xEMU

*Tested at the 88" Cyclotron

MARS - Perseverance

Summary

Next 5-10 years

- Deliver intense A~50 beams for national and international studies of heavy and super-heavy element research
- MARS-D ECR Ion Source, optimized magnet geometry
  - Winding a NbTi magnet now (2 years)
  - Magnet → ECRIS (5 years)
  - Then use newer high field materials (Nb_3Sn, high T superconductors) → MARS-80GHz (10 years, magnet)
- Provide beam for nuclear data needed to enable and support national activities in energy, medicine, and security
- BASE Facility for space effects measurements that are needed to support the US government and commercial space and aeronautics communities.
- Train students in nuclear science and accelerator technology

Questions?

"No individual is alone responsible for a single stepping stone along the path of progress, and where the path is smooth, progress is most rapid."

-E.O. Lawrence

xEMU Space Suit tested at BASE

Why BASE?

1859: The "Carrington Event" destroys telegraph stations and injures operators.

1962: "Starfish Prime" was conducted in space over the Pacific Ocean. The explosion damages Hawaii electrical grid components and cripples satellites. Test 184 destroys Soviet power plant. Single Event Upsets (SEU) first predicted by Wallmark & Marcus.

1972: Hughes satellite temporary failure. It is identified as an SEU by Smith, Holman, and Binder.

1978: Intel (May & Woods) discovers that alpha particles from naturally occurring isotopes in computer chip packaging cause upsets.

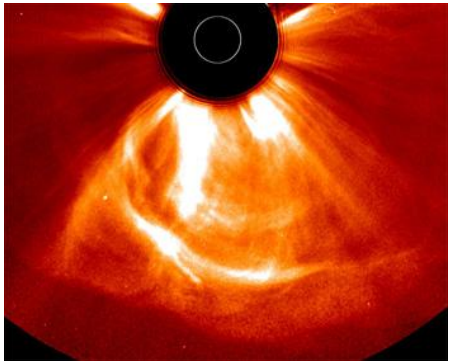
1989: Two different solar events destroy satellites, take down the Quebec power grid and Toronto Stock Exchange, and interfere with the Space Shuttle Discovery.

2003: Largest solar flare ever recorded. Measured as X-28 prior to sensors being lost, later estimated to have been as high as X-50.

2012: A Carrington-class coronal mass ejection narrowly misses Earth. Had it hit, according to studies conducted both before and after, it would have been *globally catastrophic*.

2015 to Present: Significant increase in priority due to National Space Weather Action Plan & Strategy, Presidential Executive Orders, National Academies Study, a changing global military paradigm, and the "center of the chessboard" moving to space.

Starfish Prime explosion as seen from Honolulu in 1962.



23 July 2012 CME as viewed by the STEREO spacecraft.

Radiation Effects at the 88

1979: The *world's first* heavy ion single event effects test is performed at Berkeley Lab's 88-Inch Cyclotron and the former Bevatron (just up the hill from the 88).

1984: The first U.S.-based Electron Cyclotron Resonance (ECR) ion source begins operation at the 88-Inch Cyclotron, leading to the development of "cocktail" beams.

1990: A second ion source, the AECR, comes online at the 88-Inch Cyclotron.

2004: USAF and NRO begin partial support of the 88-Inch operating budget, resulting in an Interagency Agreement.

2008: VENUS ion source comes online at the 88-Inch and begins delivering beam to BASE users.

2016: NRO withdraws from the Interagency Agreement.

2018: National Academies study "Testing at the Speed of Light" is published. NASA joins USAF in providing partial funding support for the 88-Inch Cyclotron.

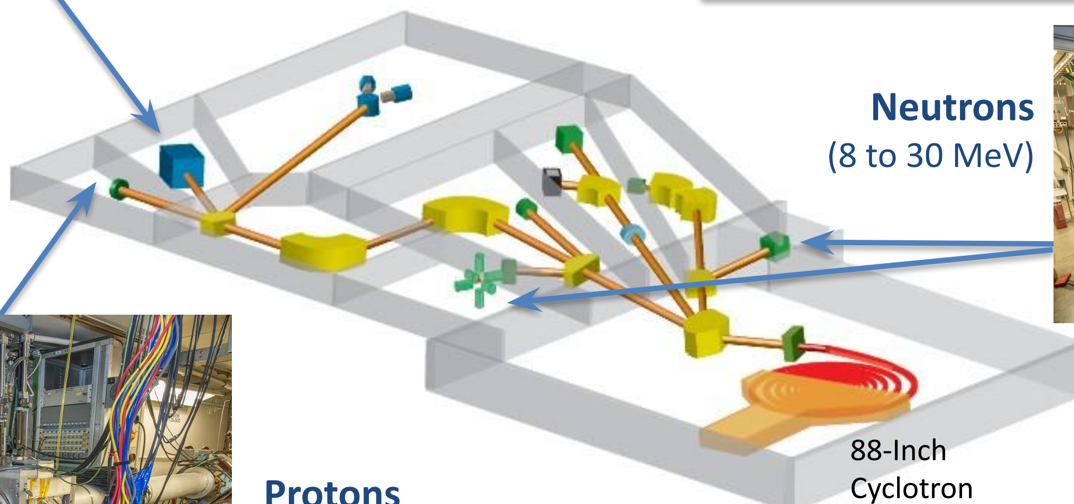
2020: USAF withdraws from the Interagency Agreement. MDA begins using the newly-available beam time. COVID-19 and a cooling tower failure force the 88-Inch into two extended shutdowns.

2021-2022: Returned to normal operation with new cooling tower. Sharpest ramp-up in beam hours in cyclotron history. For the first time, BASE Facility hours outnumber DOE research hours.

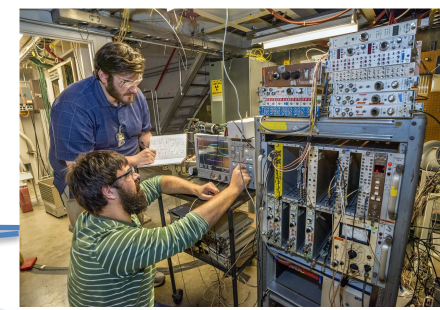
BASE Facility Layout & Capabilities

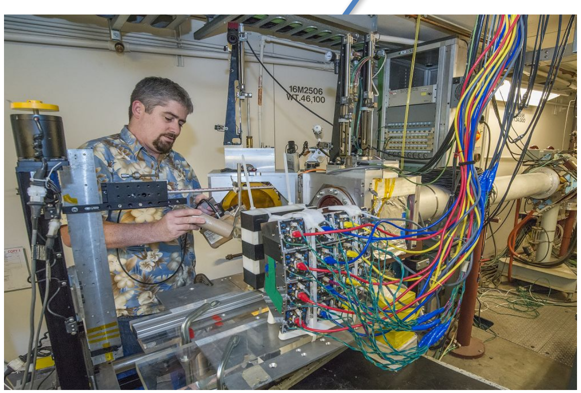
Heavy Ion "Cocktails"
(4.5 to 20 AMeV)
Low Energy Protons
(1 to 10 MeV)
Microbeams

"One-stop" facility for radiation effects testing
- Heavy Ions (in-air & vacuum)
- Light Ions
- Protons
- Low Energy Protons
- Neutrons
- Microbeams



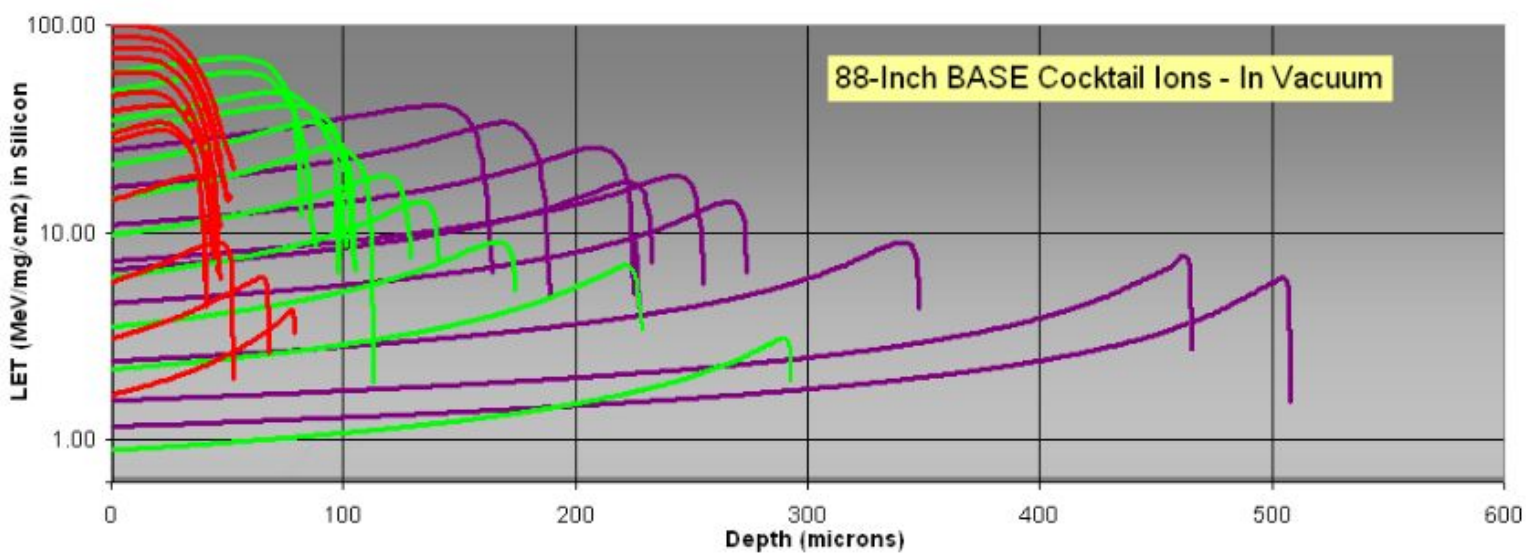
Neutrons
(8 to 30 MeV)





Protons
(10 to 60 MeV)
Light Ions
(30 to 32.5 MeV)

BASE Cocktails



Legend:
4.5 AMeV
10 AMeV
16 AMeV

All three are refined and running smoothly

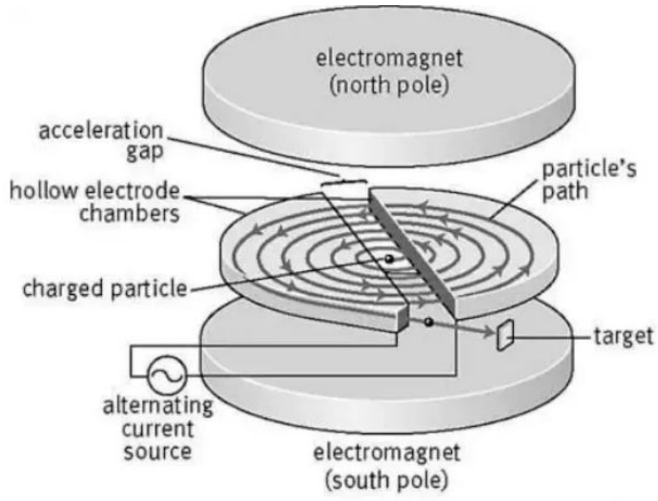
NEW:
20 AMeV

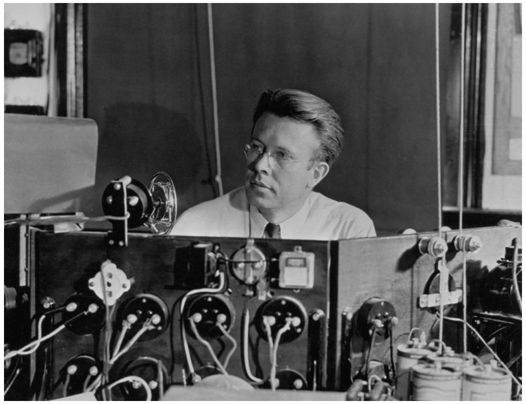
Still a few growing pains

- The correct cocktail for a given test is the one that will deposit the required amount of energy at the proper penetration depth.
- High LET ions are the most difficult to tune out of the machine, but thanks to ion source and Cyclotron improvements, we can achieve very high fluxes for even our heaviest ions.

Useful Cyclotron Equations

Berkeley Lab's 184-Inch Cyclotron, the largest single-magnet cyclotron ever built.





Ernest O. Lawrence at the controls of the 37-Inch Cyclotron.

$$E/A = k\,(q/A)^2$$

E = energy

A = atomic mass of ion

k = "k-value" (maximum rigidity)

q = ion charge

$$m\,v = q\,B\,r$$

LBNL → q

UC Davis → r

Texas A&M → B

m = ion mass

v = ion velocity

r = orbital radius

q = ion charge

B = magnetic field

$$f = \frac{q\,B}{2\,\pi\,m}$$

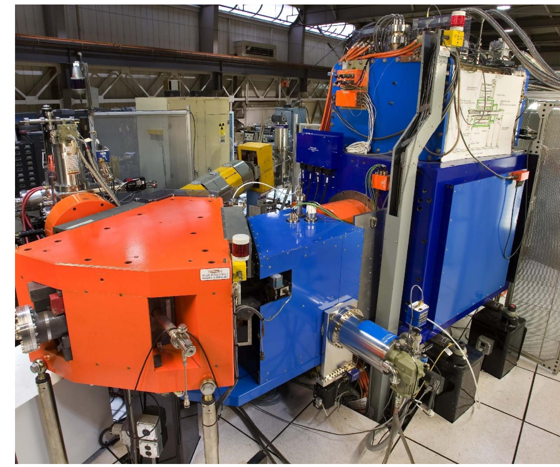
f = cyclotron resonance frequency

q = ion charge

B = magnetic field

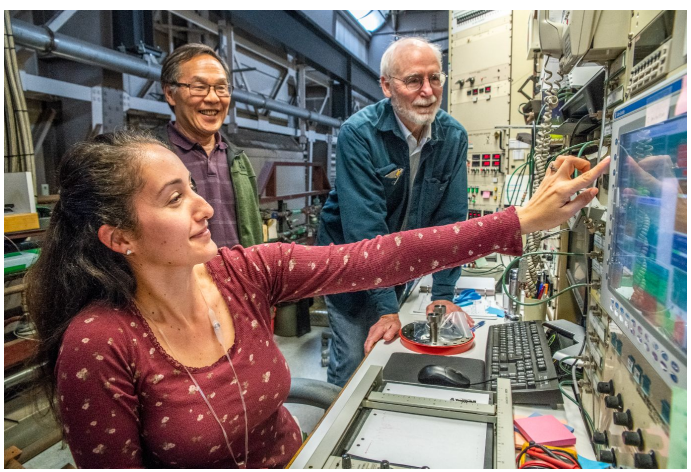
m = ion mass

Importance of Ion Sources to BASE



<u>Example</u>: GOLD in the 10 AMeV Cocktail

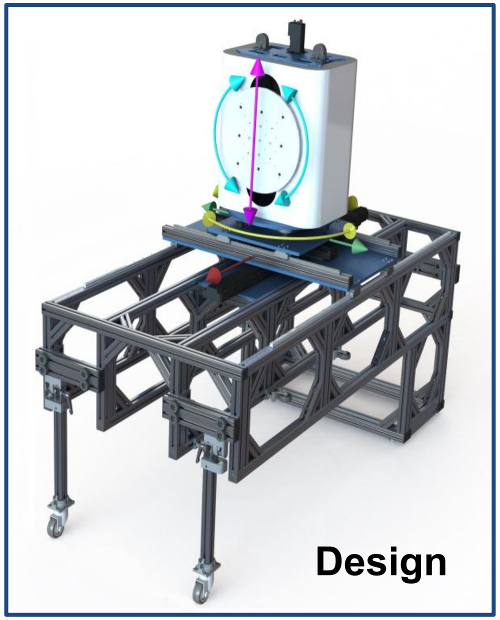
- Au-197, charge state of +52
- Generated by both oven and sputter probe
- LET = 85.76 MeV/mg/cm^2, range = 105.9 microns
- Made possible thanks to VENUS ion source

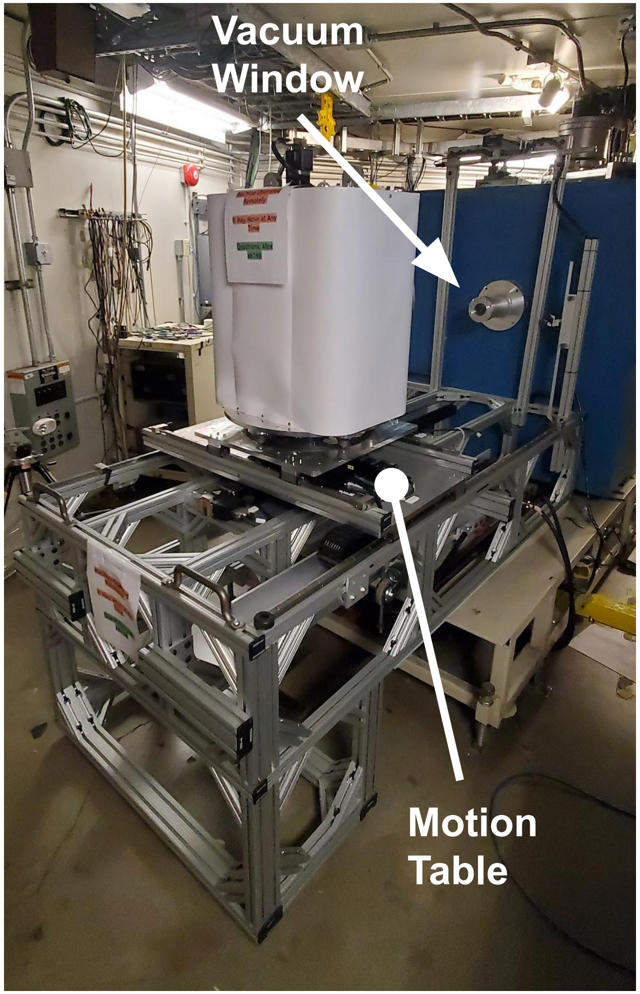


Other BASE beams made possible due to VENUS:

- 16 & 20 AMeV xenon
- Most of the 20 AMeV cocktail
- Higher energy cocktail beams? (MARS)

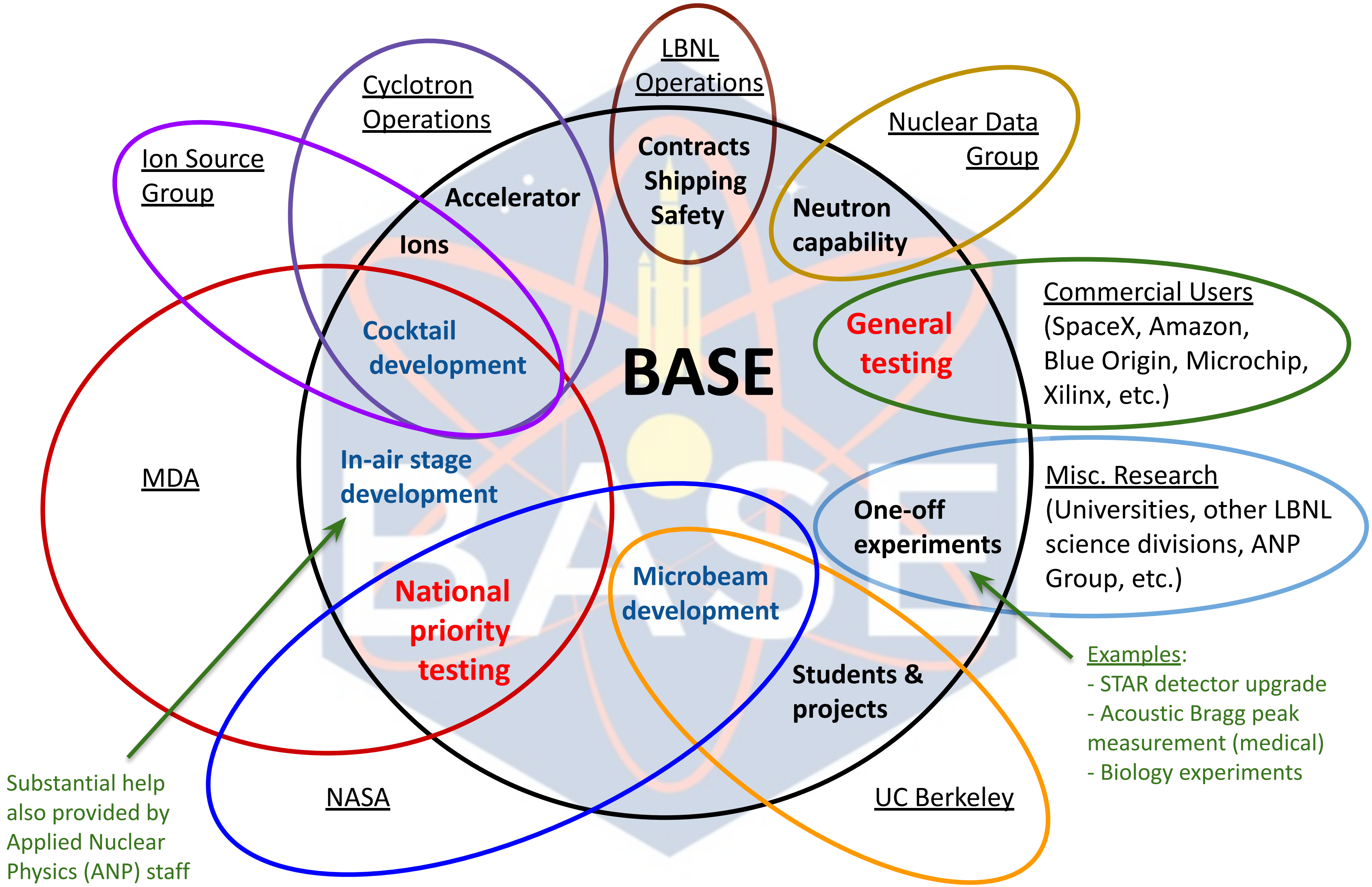
NEW: In-Air Stage





- Driven by user need for a modern in-air test station
- <u>Versatile</u>: can be used with circuit board mounting fixtures from other facilities (NSRL & TAMU)
- <u>Efficient</u>: Can be installed or removed in 10 minutes
- New compact window designed for improved positioning of devices under test at different incident angles
- In use now in Cave 4B

Strategic Partnerships



Organizations Using BASE

Lawrence Berkeley Natl. Lab
Lawrence Livermore Natl. Lab
Los Alamos Natl. Lab
Sandia National Labs
Johns Hopkins - Applied Physics Lab
Naval Research Lab
Fifth Gait Technologies
Radiation Test Solutions (RTS)
Cobham / Aeroflex
Micro-RDC
Honeywell
Microchip / Microsemi
Silicon Space Technology
Xilinx
Linear Technology
Moog, Inc.
International Rectifier
Xsis Electronics
Save, Inc.
Raytheon
Semicoa
The Aerospace Corp.

Missile Defense Agency
Lockheed Martin
Cypress Semiconductor
Texas Instruments
Space Micro
Exelis
Broadcom
Georgia Tech
Rochester Inst. of Technology
MIT – Lincoln Laboratory
Caltech
University of Colorado
Robust Chip
JD Instruments
ThermoFisher Scientific
3D Plus
L-3 Communications
ITT
University of Wisconsin
Intel
European Space Agency (ESA)
Japanese Space Agency (JAXA)

NASA Ames
NASA Johnson
NASA Goddard
NASA Jet Propulsion Lab
SpaceX
Blue Origin
Google
Amazon
United Launch Alliance
Northrop Grumman
Vanderbilt University
Boeing
Ball Aerospace
SEAKR
Peregrine Semiconductor
National Semiconductor
Semicoa
ST Electronics
NAVSEA Crane
LaRosa Engineering
Space Vector Corp.
Viasat

Beam Time Allocation

1. Determine the total beam time hours for the fiscal year from "Tier 1" primary funding agencies (DOE, NASA, MDA).

2. Determine if there are any large maintenance items requiring more time (cooling tower replacement).

3. Layout the draft calendar with run and shutdown slots.

4. Determine the number of hours of allocated beam time for each primary funding agency & their priorities.

5. Adjust calendar layout for researchers needing extended runs (Ex: 2-month continuous runs for BGS).

6. Obtain buy-in from all funding agency stakeholders.

7. Sell any remaining available beam time to "Tier 2" WFO users.

Tier 1:

Commit to a minimum number of hours for each fiscal year and have high priority.

Tier 2:

Work For Others (WFO) users utilizing available beam time if and when it becomes available.

Beam Requests

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Beam Request Form

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Title or Type of Experiment/Proposal/Test:

Abstract of Experiment/Proposal (attach to email or provide links to documents if desired):

Desired Start Date of Run:

Alternate Start Date of Run:

Location of Experiment, if known (i.e. Cave):

Total Tune + Run Hours Needed:

Type of Beam Desired (cocktails, pr

Beam Request Form:

The request for beam time is initiated by submitting a Beam Request Form from our website at **cyclotron.lbl.gov**.

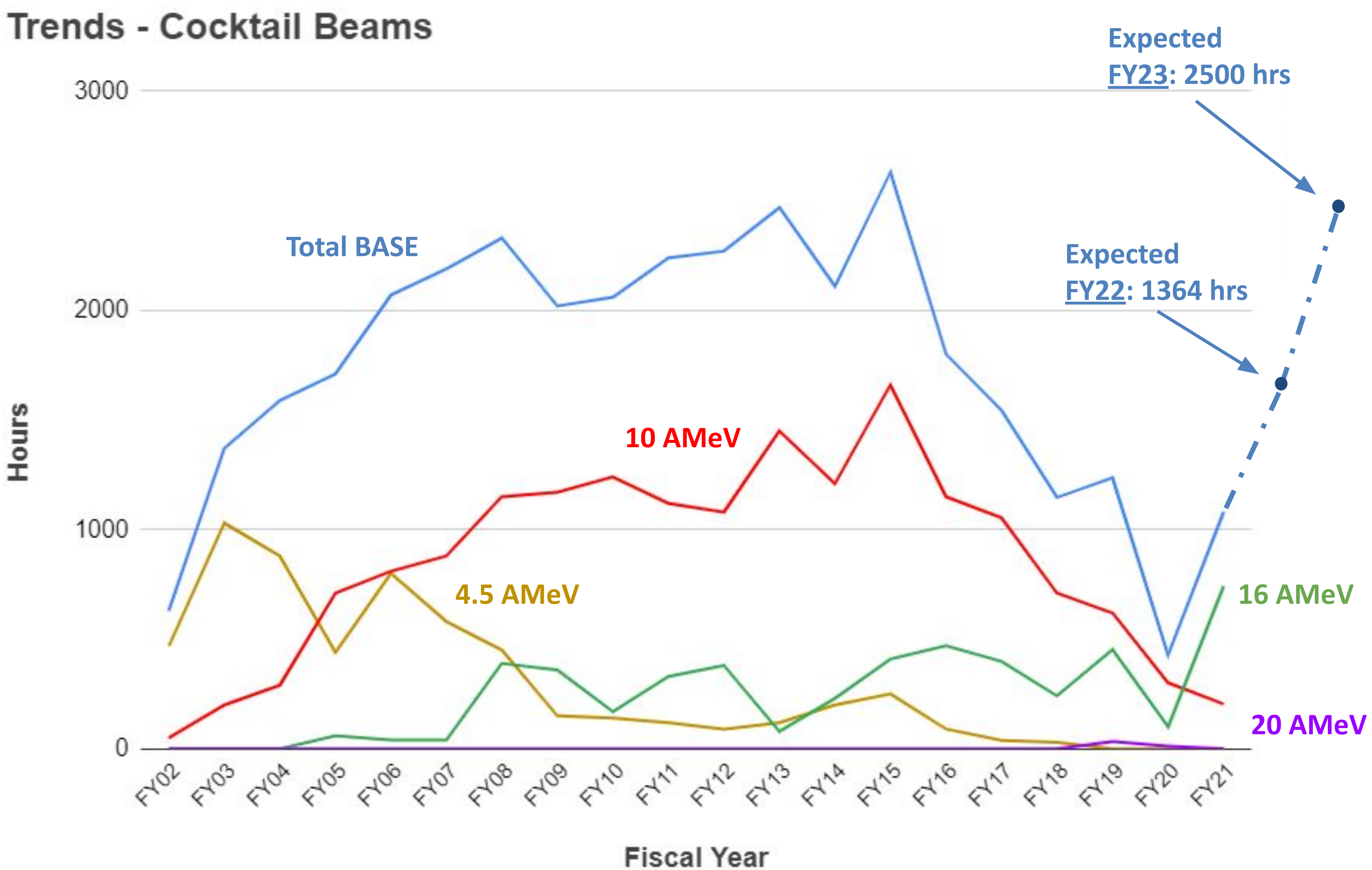
Proposal Evaluation Form:

Incoming requests for pay-per-hour users are evaluated based on weighted criteria.

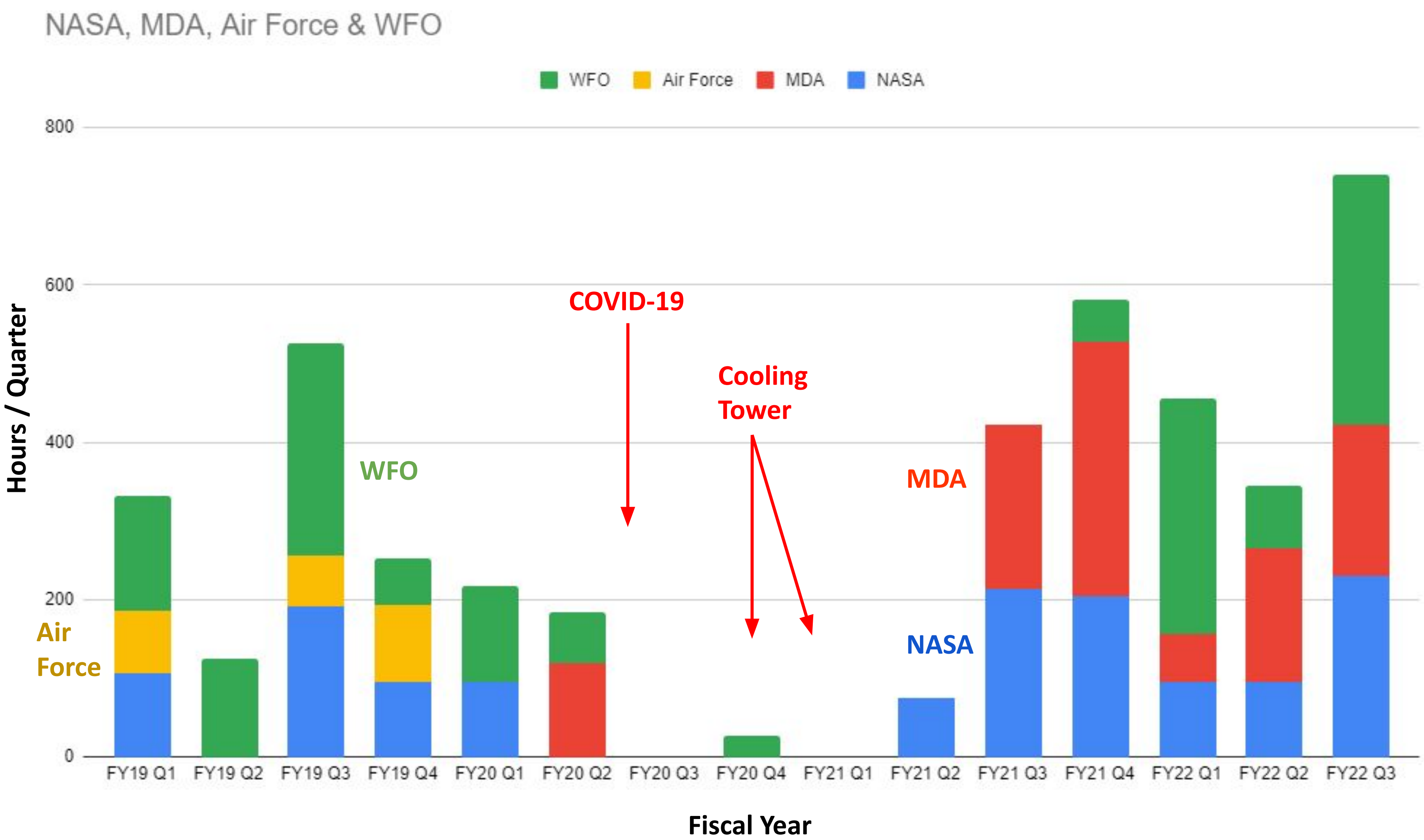
(Not applicable to Tier 1 funding agencies).

Proposal has clear, achievable objectives	3	1	5	3			
Principal Investigator has necessary knowledge/skills to lead experiment	4	2	10	8			
Principal Investigator has sufficient support staff/students to complete experiment successfully	4	1	5	4			
All experimenters will follow designated safety requirements	3	3	15	9			
Principal Investigator and requesting organization likely to use all beam time	1	3	15	3			
Cyclotron has material and staff resources to support experiment	3	1	5	3			
Previous experiments have been conducted without significant technical, administrative, financial, or personnel issues	1	1	5	1			
Experiment has potential for continued work	3	1	5	3			
Experiment has potential to produce results that are scientifically significant	1	1	5	1			
				35	out of	70	50%

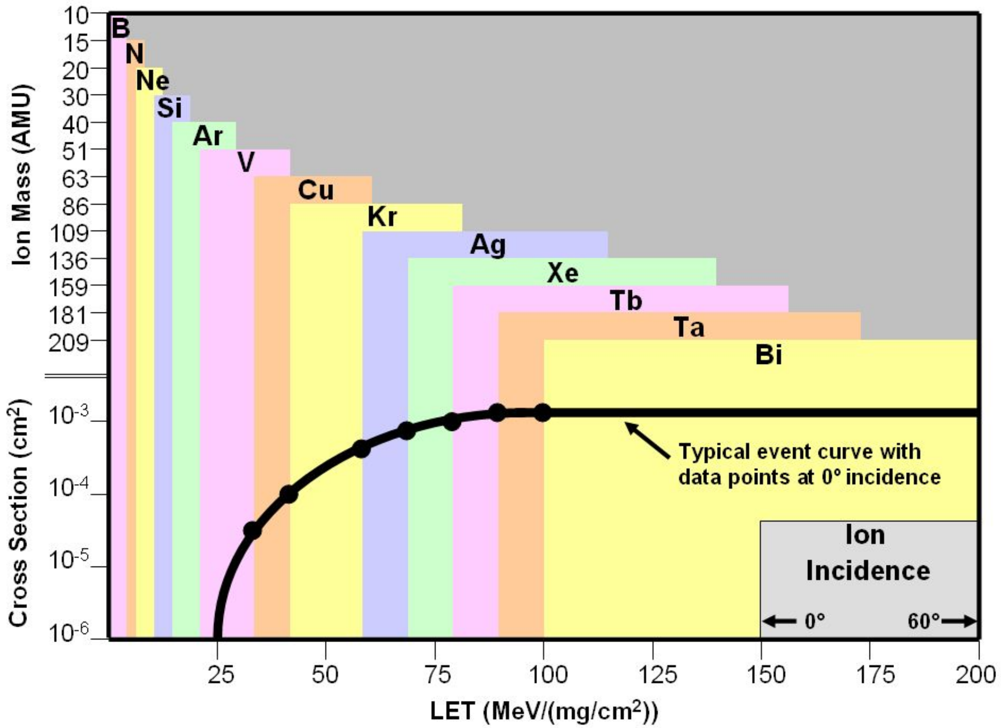
BASE Facility Trends



BASE Facility Trends



What is a ‘Cocktail’?



Standard cocktail energies

- 4.5, 10, 16, & 20 MeV/nucleon

What is a ‘Cocktail’?

- Unique to cyclotrons with ion sources
- Multiple ions injected simultaneously
- Ions are selected and separated by simply changing cyclotron frequency
- Cyclotron + ion sources = **3 minutes** to change ions (instead of 4 hours)

Why do we do this?

- To *efficiently* deposit different amounts of energy into electronics parts
- Allows us to see how the parts will react *before* we send them up to space