Location: General interest – point these out when you see a good example or need to fill time

These are interesting statistics and info about sites that the tour does not visit

Approval:

Content on subsequent pages is divided into three audiences. **General audience**: best for adults/high school students. **Young students**: best for youth in elementary/middle school, though general audience might appreciate it as well. **HS/College Science students**: extra detail that specialized groups may enjoy.

For all audiences

- In nuclear science, we build large instruments to study tiny particles to understand giant stars.
- The original building was occupied in 1964, we've added on 18 times (thru chip testing bldg, 2025)!
- The electronics: most built right here at FRIB designed to do high-speed, high-volume data acquisition.
- Pipes around the building carry cooling water (Low-Conductivity Water, or LCW, reduces corrosion in copper equipment) and liquid nitrogen (LN). We consume ~200 gallons (800 liters) of liquid nitrogen every hour, costing only 26 cents per gallon (7 cents/liter). We make liquid helium on-site in the country's largest LHe cryoplant maintains our 70,000 liters, delivered @ 4.5K or 2K.
- Power supplies and power cables: FRIB is powered by MSU power plant, Consumers Energy in East Lansing, and Lansing's Board of Water and Light. While running, FRIB consumes ~14 MW, or the equivalent of more than 30,000 houses. We have our own substation! If power fails, we have on-site generators to keep the pumps running. MSU power plant gives us priority when power returns. (from Andreas) Our power budget is ~$10 million/year.
- Ethernet cables: carry commands/feedback to/from the control room and experimental data to Data-U.
- Walls: The concrete blocks are stacked around instruments to prevent radiation from escaping. Walls around the transfer hall are at least 6 feet thick, based on calculations that show 200 MeV neutrons produced would still result in less than 10 mRem exposure per year even if we ran experiments 24/7. The wall blocks are not mortared together so they can be easily removed and re-stacked (like big LEGOs), completely changing the layout of the laboratory as needed! Science and technology change quickly, so the laboratory can change to accommodate new technology or techniques.

For all audiences

- The vault-seal alarm: in order to run beam in a vault, hit the red button that informs everyone to leave with lights and sound (music from Close Encounters of the Third Kind), then you seal the door. Unsealing the door automatically cuts off the beam to that vault.
- Vault doors: when we're ready to seal a vault to run beam through it, you must hold the button to close (safety feature!). The doors are solid concrete, 10-15 tons, about as thick as the walls to contain the radiation. When they close fully, switches at the top are tripped to inform the operators in the control room that the vault is sealed.
- We have many bridge cranes that can lift 30, 40, or 50 tons. The cranes could lift one 3-5 Tyrannosaurs (<10 tons each). The vaults are built of concrete blocks with concrete beams (10+ tons) for roofs.
- Noise in the vaults is usually vacuum pumps like the "roughing pumps" found on the floors next to beamlines. We also have diffusion pumps (compresses the air with an oil cascade before pumping out) and cryopumps (literally freeze the air out of the pipe). We need to remove the atmosphere from the beam line so the air molecules don't interfere with the motion of the beam nuclei. Pressures are commonly one-billionth of an atmosphere (10^{-6} Torr) or lower.
- Even when running, the radiation levels are small. You are far more likely to be hurt in a car accident than by radiation in our lab. FRIB does not exceed regulatory radiation exposure limits (from Andreas). Industrial hazards (falling, tripping, etc.) are more common.
- The black disks on the walls (some covered by red caps) & silver disks on the floor serve as lab's "GPS", known points in space, used with a laser surveyor to position instruments within 0.001".
- (from HR) Of > 800 employees, ~30% are students (UG/grad) and ~20% are from other countries.

For all audiences

- Magnet quenching: there are failsafes/pressure release valves to protect superconductors from an uncontrolled switch to normal conduction. In the event of a large release of boiled-off LN, the Oxygen Deficiency alarms in each vault will alert if the percentage goes below 19.5%.
- Annual FRIB operating budget is above $100 million from the US DOE Office of Science
- FRIB was finished 5 months early and on budget!
- NSCL discovered 77 isotopes in three decades. FRIB is designed to discover at least 1000 new isotopes (Discovery of first 5 new isotopes with FRIB)
- FRIB is designed to have ~800x the beam intensity of NSCL's Coupled Cyclotron facility (400 kW vs 0.5 kW)
- 500 m long linear accelerator folded to fit inside the 150-meter-long tunnel that is 10 m underground
- We have the largest liquid helium plant in the U.S. (70,000 L), recovering 100% of the gas for reliquifying
- FRIB has 10 gas storage tanks on top of the SRF bldg that can hold the equivalent of 18,000 liters of liquid helium at 4.5 K. 8 tanks manage the inventory, one for SRF operations, & one for cryomodule tuner gas.
- 300 kW of beam will be unreacted, so it can go to the isotope harvesting station to make other isotopes for medical/agricultural research as a side-effect!
- Harvesting is a new technology we invented, resulting isotopes also useful for security & energy research
- FRIB is designed to slam 50 trillion uranium ions per second into its target.
- We know the neutron dripline up to element 10, neon. FRIB is designed to determine the neutron drip line up to the 30th element, zinc, maybe even farther!
- FRIB is designed to access about 5,000 different isotopes.
- FRIB is designed to identify 80 percent of possible isotopes for all elements up through uranium

Location: Data-U (#1 on the tour locations map) The area where users (researchers) monitor data from their experiments		**Approval**: Daniel Bazin
Safety/Notes: If there are users in the Data-U, avoid disturbing them and give your speech in a different section.		
General audiences	**Young students (revised language)**	**HS/College science students (extra info)**

• Researchers (users) are here 24 hours a day during their experiment, observing data coming to one of the computer banks from whichever detector they're using. There is one Data-U paired with each vault.
• FRIB serves over 1800 users from over 50 countries.
• The cost of research time at FRIB is effectively \$20,000/hr. Operations funded by the U.S. Department of Energy Office of Science.
• Beam time is free to the user provided that they publish their results so their discoveries are shared with the scientific community.
• The average experiment runs for about one week, twenty-four hours per day. Researchers must staff three shifts of 8 hours in this space (like a factory), including a midnight shift.
• The average experiment produces about 100 terabytes of information, the equivalent of about 50,000 hours of HD video. Researchers will take that data home for analysis, filtering out "background noise" and comparing detected signals with model predictions, and eventually publishing their results in a publically-available journal.
• FRIB is like a factory, but instead of cars, we produce new knowledge for humanity.
• Example proposal process: The first call for experiment proposals was due in February 2021, review was completed in August 2021. 30% of requested time was approved. The 401 researchers on the first round of proposals represented 25 countries, 24 states, and 88 institutions.
• The computer monitor displays the current experiment, who's on call, operations status, etc.
	• Researchers (users) are here 24 hours a day during their experiment, observing data coming to one of the computer banks from whichever detector they're using. There is one Data-U paired with each vault.
	• FRIB serves over 1800 users from over 50 countries.
	• Any of those scientists worldwide can ask for research time here. The best experiment ideas are chosen.
	• We don't charge them to do an experiment because it would cost \$20,000/hr, which they probably could not afford! The U.S. Department of Energy Office of Science pays for research to happen here.
	• The average experiment runs for about one week, twenty-four hours per day. Researchers must staff three shifts of 8 hours in this space (like a factory), including a midnight shift.
	• We're like a factory that makes knowledge!
	• If you were on-shift to watch the experiment, what snacks would you make sure were on this table?
	
		• The racks of electronics are connected to the vaults with many cables so experimenters can make changes without having to stop the beam and open the vault door.
		• Data-U sometimes contains the complex electronics required to rapidly collect, process and store data, but most instruments are located remotely and computer-controlled.
		• Running an experiment requires that you apply for beamtime, set up about one month in advance, have group monitoring in Data-U for length of experiment (average 120 hours, about one week), then spend months analyzing the data with the goal of publishing, and writing Ph.D. dissertations.
		• Anyone in the user community can propose an experiment, and those proposals are reviewed by a committee (PAC) featuring some of the nation's top nuclear scientists. (Note: FRIB representatives on that committee are non-voting) The PAC selects the most critical and achievable research and approves beam time. They can only accept about 1/3 of the proposals (~40 experiments/year)!
		• (from Dean Lee presentation) Artificial Intelligence (AI) and Machine Learning (ML) are used for:
		    • Simulating nuclear structure & reactions to accelerate computation of models
		    • Beam tuning and diagnostics to increase operational performance and efficiency
		    • Particle ID and event selection in experimental data, leading to rapid analysis
		• (from Steve Lidia) Linac tuning has reduced from 24 hrs to 2 hrs with AI/ML tools! We run many different beams, repeated tuning makes these tools valuable!

Location: Control Room (#2 on the tour locations map)
Where on-shift operators manage the accelerator and deliver beam to the experiment.

Approval: Andreas Stolz

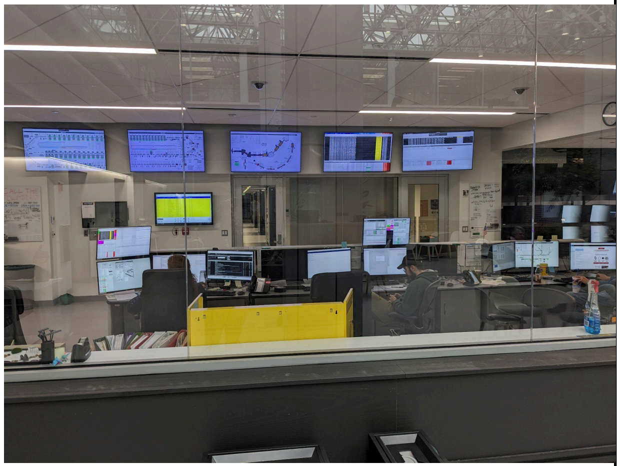
Safety/Notes: No safety issues. This is a good location to visit when many vaults are closed, or you're waiting for another group to move on

General audiences

- While FRIB is running an experimental program, operators are here 24 hours a day monitoring systems and maintaining beam output. We generally have three shifts, like a "nucleus factory"!
- Operating the accelerator is done remotely from the control room. Operators maintain the beam by "tuning" devices to produce quality beams that satisfy the users' needs.
- Expect to run experiments 4000-5000 hours per year
- Maintenance shutdowns and tests make up the rest of the year, which puts the operators other skills to use.
- Operators typically have a bachelor's or master's degree in physics or engineering, and also possess skills in fields such as programming, maintenance, fabrication and electronics.
- Operators are highly-skilled and trained. In many cases they are the only people with working knowledge of how to control and repair a particular instrument. It takes ~9 months to qualify as an operator-in-charge.
- Some monitors show video feeds from points where operators can insert a fluorescent screen to "see" the beam (bright spot) while adjusting its position, size, and shape. This works like old TV picture tubes.
- Our availability (reliability) is generally > 90%, which is great for a lab our size. When our new accelerator was turned on for the first time, we aimed for 80% reliability in the first experiments (expected 20% breakdown while learning), but achieved 93%!
- 2025: 4069 operating hrs, 93% availability
- Operating the controls is similar to a pilot flying (operating) a 747. Just as a pilot is not an expert in aeronautics, operators are not experts in particle physics. Both need a deep understanding of all the systems at their disposal and confidence to operate them successfully.
- Linac started at 1kW in 2022, ramping up to 400kW beam power in the first few years (break more nuclei!)

Young students (revised language)

- Our workers are in here 24 hours every day to keep the accelerator running. We generally have three shifts, like a "nucleus factory"!
- From here, they can run all of the instruments without having to be near them.
- We run experiments for about 10 months out of the year, spending the other 2 months for maintenance and upgrades.
- Our workers come from many backgrounds with many different skills. We need all kinds of people working together to make FRIB successful. Science is a team sport.
- What we do is so unusual, these people train for 9 months before they can run the accelerator.
- Even though our laboratory is full of complicated and sensitive instruments, our workers keep it running well nearly all of the time!
- We don't play any games on these computers. They're not even connected to the internet.
- Accelerator map is on the two left monitors in the row near the ceiling! Green boxes are currently on.



HS/College science students (extra info)

- An example primary beam current (for Ca-48 at 242 MeV per nucleon): 11 trillion particles per second, ~1700 pnA, ~20 kW.
- An example secondary beam production for Si-34: 482 million particles per second
- The majority of software used by our operators to control the facility is developed here at FRIB and runs on standard PCs running Windows. Operators can adjust settings and turn devices on and off in software (clicking a button or typing a new value) or by adjusting hardware knobs. These computers connect to thousands of sensors for diagnostics.
- Over 30,000 settings and readings from instruments are recorded constantly throughout the day by the FRIB's control system.
- FRIB produced a record 20kW uranium beam in 2025
- Spring 2024: announcement of first isotopes discovered at FRIB (thulium-182 and 183, ytterbium-186 and 187, and lutetium-190)
- FRIB supports U.S. industry by addressing the national shortage of microelectronics testing. Its heavy-ion facilities—FRIB Single Event Effects Facility (FSEE) and K500 Chip Testing Facility (KSEE)—test chips used in spaceflight, wireless tech, and autonomous vehicles.
- FRIB tests reliability under radiation using energetic, penetrating heavy-ion beams to simulate in minutes the decades-long effects of cosmic rays on electronics.
- With existing facilities oversubscribed, FSEE will offer up to 2,000 user hours per year while we change targets for the user program. KSEE will offer up to 6,000 user hours per year.
- The federal government funded MSU to establish KSEE by repurposing the world's first superconducting cyclotron, built at MSU in the 1980s.
- Student opportunities through the MSU Space Electronics Initiative, launched by FRIB and the MSU College of Engineering, position MSU as a national leader in chip design, testing, and workforce development.

Location: K500 wooden model (in the Atrium on the tour locations map)
A 1:1 scale model of the beam chamber inside the world's first superconducting cyclotron

Approval: Jon Bonofiglio

Safety/Notes: No safety issues. This is a good location to visit when many vaults are closed, or you're waiting for another group to move on

General audiences	Young students (revised language)	HS/College science students (extra info)
● The K500 cyclotron was designed long before Computer Aided Design (CAD) was available. A wooden model was constructed first in the 1970s to ensure that the parts would fit correctly! ● It is a full-scale model of the interior shows the fan-shaped Dees (radio-frequency high voltage for acceleration) and Hills (high magnetic field regions between the Dees where acceleration takes place). Dee shape helps focus the beam in the vertical direction. ● The 20-mile long coil of niobium wire would wrap around the outside of this model. This superconducting electromagnet, cooled with liquid helium, confines the beam so it travels in a circle inside of the cyclotron ● When the K500 produced beam in 1982, it became the world's first superconducting cyclotron. Nuclei orbited inside ~250 times before exiting at 0.15c or 30,000 miles/second. ● The K500 was refurbished for a Chip Testing Facility (KSEE) to fire particle beams at electronics to test their capability to keep working while bombarded by cosmic rays in space (e.g. on a satellite). ● KSEE helps address the national shortage of testing capacity for advanced microelectronics used in industries like spaceflight, wireless technology, and autonomous vehicles. ●	● Before we used a linear (straight-line) accelerator, our lab used circular "cyclotrons" to make the nucleus go fast and break. ● This wooden model was built to make sure that all of the parts would fit correctly, since they were designing it in the 1970s and didn't have computers to help. ● Where you're standing would be a 20-mile-long wire cooled to -300 degrees F, making a powerful magnetic field to keep particles trapped inside. ● The old cyclotron is being reused to shoot particles at electronics to test whether they'll still work in space. 	● The black trim coils are like fine tuners to make the magnetic field isochronous (the particles stay in phase with the accelerating electric field) ● The copper Hill liner keeps the RF contained in the beam chamber ● The aluminum Beam probe track resides inside of a Dee and follows its shape. It provides a way to carry a camera or beam current monitor (on a little train of cars) to observe the beam as it moves out in radius (i.e., higher energy)

Location: Low-Energy Area/Precision Measurements/LEBIT (#7a or 7b on the tour locations map)

The **Low Energy Beam Ion Trap (LEBIT)**, a detector for measuring the mass of nuclei

Approval: Ryan Ringle

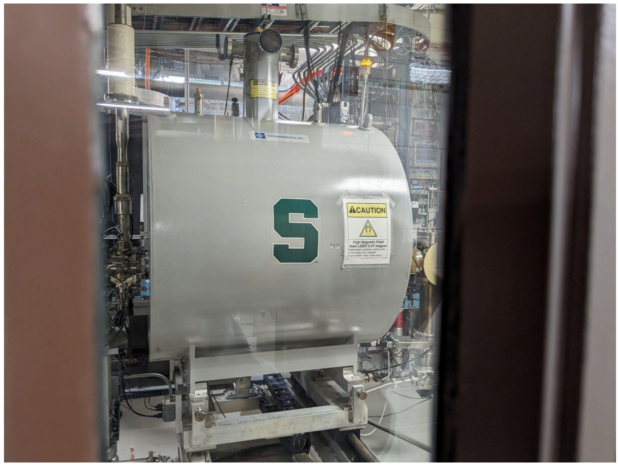
Safety/Notes: View LEBIT by looking in the window on the southern door facing the East High Bay (near "7" on the map)

General audiences

- LEBIT has a superconducting magnet (gray barrel with spartan "S", note the yellow light on top indicating strong magnetic field) where previously-slowed & *bunched* nuclei are trapped in a circular orbit.
- It's probably the strongest magnet you'll probably ever see (9.4 T, 94000 gauss, about 200,000 times the strength of the Earth's magnetic field), and it's always on (note yellow light above it), but it's well shielded. NOTE: you can feel the field near where the beamline enters the barrel, so beware!
- You can measure mass by measuring the frequency of its orbit (like RPM) inside the magnetic trap: heavy ions are slower.
- LEBIT can measure the mass of a nucleus to one part in 100 million; like weighing an entire jumbo jet and telling how much change is in the pilot's pocket.
- Once staff got the current (about 100 amps) running in the superconducting coil inside, they unplugged it. The current is still going! It's superconducting, so there's no reason for the current to stop as long as the niobium wire is kept cold. LEBIT can operate for several thousand years before recharging. It is essentially the best battery you'll ever see.
- Helium and nitrogen gas pressure release valves allow vaporized LHe and LN2 to escape. Oxygen sensors in the room tell you if too much nitrogen is escaping (because N2 displaces oxygen and creeps along the floor, making it hazardous). Any ice on the LN2 pipes is just humidity in the air freezing onto the cold surface.
- [LEBIT directly measured the mass of copper-56 (half-life 0.1 seconds)](LEBIT directly measured the mass of copper-56)

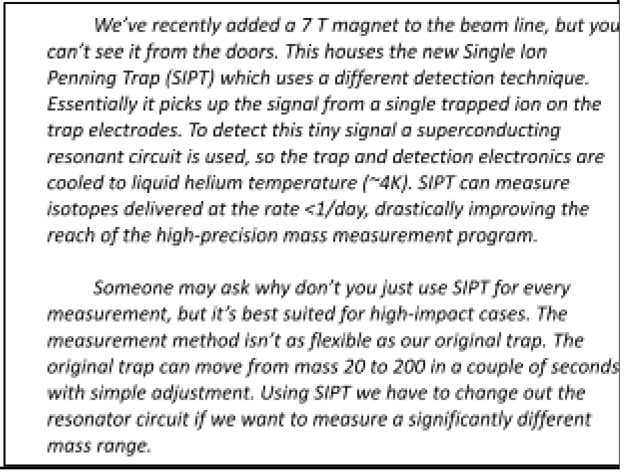
Young students (revised language)

- This incredibly powerful magnet can trap tiny particles inside so scientists can tell how much they weigh.
- The magnetic field is blocked by the metal walls, so it can't really affect you at this distance.
- It's so sensitive, it's like weighing a jumbo jet and telling how much change is in the pilot's pocket.
- This measurement happens FAST because the particles we measure don't last long. It once measured a copper nucleus that existed for about a tenth of a second!
- Because the wire making the magnetic field is kept cold, it stores energy almost perfectly. This will keep its magnetic field for thousands of years before they need to plug it in again! It's like the best battery ever.



HS/College science students (extra info)

- You can measure their mass by measuring the frequency of their orbit (like RPM) inside the magnetic (+electrostatic= Penning) trap: heavy ions are slower. Typical frequencies measured are 1-10 MHz.
- Cyclotron frequency is a simple calculation: ω_c = qB/m (cyclotron frequency is equal to charge*B-field/mass)
- The mass is measured by probing the ions' specific (cyclotron) frequency with a radio frequency electric field, seeking the resonant frequency that will eject it from the trap. This technique works best for single trapped ions.
- Can measure isotopes with half lives down to the ms range. Stopping in the helium gas cell takes 10-100 ms. Cooling/bunching the beam (converting a continuous beam of nuclei to bunches) takes 5-30 ms. Time spent measuring in the Penning trap takes between a few ms to a few s.
- World record for precisely measuring mass of short-lived isotope w/ a Penning Trap like LEBIT at TRIUMF: Lithium-11 (half life 10 ms)!
- Mass measurement results can have implications for astrophysics, the r-process path, nuclear structure and fundamental interactions.
- Helium and nitrogen gas pressure release valves allow vaporized LHe and LN2 to escape. Oxygen sensors in the room tell you if too much nitrogen is escaping (because N2 displaces oxygen and creeps along the floor, making it hazardous). Ice on the LN2 pipes is just humidity in the air freezing onto the cold surface.



We've recently added a 7 T magnet to the beam line, but you can't see it from the doors. This houses the new Single Ion Penning Trap (SIPT) which uses a different detection technique. Essentially it picks up the signal from a single trapped ion on the trap electrodes. To detect this tiny signal a superconducting resonant circuit is used, so the trap and detection electronics are cooled to liquid helium temperature (~4K). SIPT can measure isotopes delivered at the rate <1/day, drastically improving the reach of the high-precision mass measurement program.

Someone may ask why don't you just use SIPT for every measurement, but it's best suited for high-impact cases. The measurement method isn't as flexible as our original trap. The original trap can move from mass 20 to 200 in a couple of seconds with simple adjustment. Using SIPT we have to change out the resonator circuit if we want to measure a significantly different mass range.

Location: Low-Energy Area/Beam Cooler Laser Spectroscopy (BECOLA) (#7a on the tour locations map)

BECOLA performs spectroscopy on rare isotopes with a laser tuned to different energies/colors.

Approval: Kei Minamisono

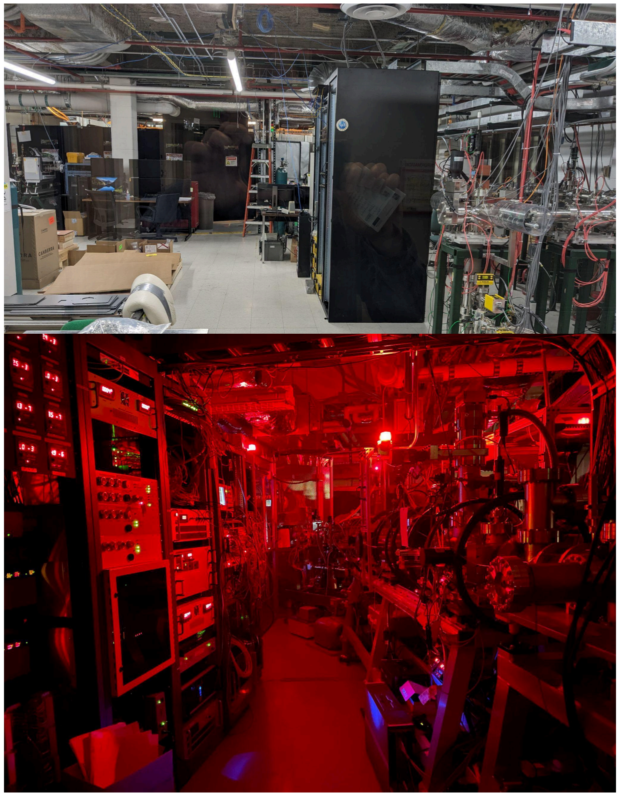
Safety/Notes: View BECOLA by looking in the window from the main hallway (just west of receiving)

General audiences

- BECOLA stands for BEam COoler and LAser spectroscopy. BECOLA shoots laser light into very "cold" beams of nuclei to study the nuclear structure and fundamental symmetries.
- The BECOLA facility measures the size and shape of radioactive isotopes shines laser lights of many different colors on the radioactive beam to give it just the right energy to knock off an electron. The colors of the laser light needed to do that tell us details about the nuclear shape.
- Depending on its electron configuration, an element reacts to a certain color of laser light and fluoresces as a response. The color to which the atom reacts depends on the element (each has a "fingerprint" spectrum) and even among isotopes of an element there is subtle change of the light color absorbed. Researchers use the slight variations of color to deduce information about nuclear structure and fundamental symmetries.
- BECOLA can detect light wavelength change of 0.00001%. The human eye can only detect a change of 0.1%
- BECOLA can measure nuclear structure, such as the "size" of a nucleus; a charge radius. BECOLA can measure a nuclear radius of a few femtometers (10^{-15} m), and distinguish radius variations between isotopes that are hundreds of times smaller.
- The laser system consists of a 15 W green laser to pump a Titanium:Sapphire ring laser (~2 W, 700-1000 nm). The light from the Ti:S laser can be frequency doubled to generate second-harmonic light (~250 mW, 350 – 500 nm). Laser light is transported through an optical fiber or using mirrors about 25 meters to the BECOLA beam line.
- Laser spectroscopy can be applied to very few nuclei entering BECOLA - one or less per second!
- BECOLA found light, radioactive calcium isotopes are surprisingly small

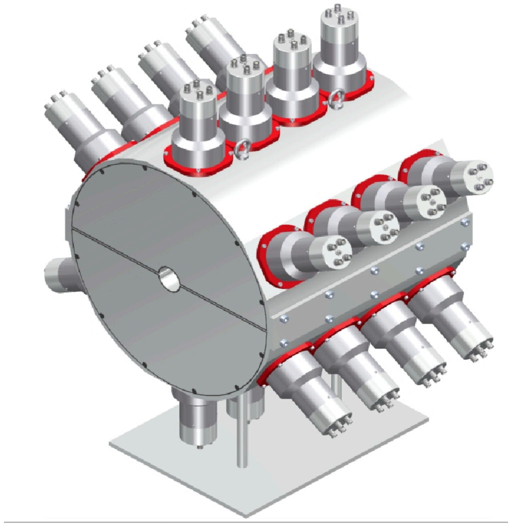
Young students (revised language)

- Behind the black barrier, we can shoot lasers at short-lived radioactive particles. Each kind of tiny nucleus can only absorb specific colors, and it's unique like a fingerprint. By finding what colors are allowed for a specific nucleus helps us figure out its size and shape.
- This detector is ten thousand times more sensitive to color than your eye!



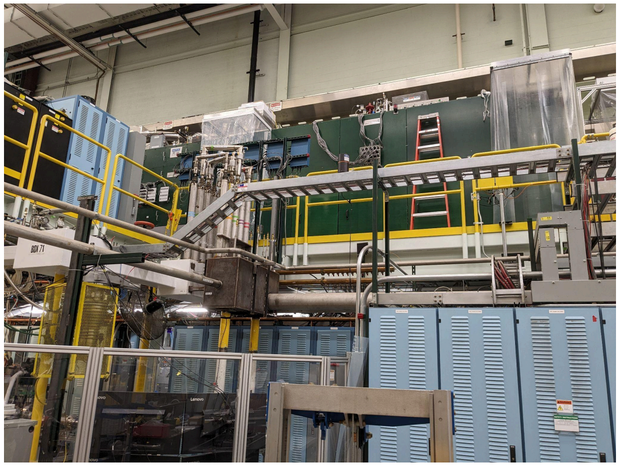
HS/College science students (extra info)

- Beams from the gas stopper are delivered to the BECOLA beam cooler/buncher. The cooler/buncher is a device that improves the quality of a rare isotope beam from the gas stopper, meaning it emits beams with a small energy spread, small divergence, small diameter and so forth.
- Resulting fluorescence is collected with a detection system using an ellipsoidal mirror. The laser light and beam pass through one of the focal points of the ellipse. Any fluorescence emitted at the focal point is re-focused at the other focal point, where a light detector is placed. This is similar to a parabolic antenna for satellite TV, efficiently collecting signals.
- The fluorescence detection system is turned on only when there are beam bunches from the cooler/buncher, increasing signal to noise ratio. The technique makes it possible for experimenters to perform measurements with incoming ion beam rates as low as ~ 100 ions per second, which makes more (and rarer) isotopes accessible to the researcher.
- Experimenters can also produce polarized beams (all spins are pointing in the same direction) using optical pumping technique with circularly polarized laser light. The bike rim coils along the beam line produce a magnetic field to maintain the polarization. The polarized beam is required for the beta-particle-detecting nuclear magnetic resonance (β NMR) technique, which has much higher sensitivity than the conventional NMR due to the polarization and beta particle detection. This technique may be applied to rates as low as ~ 100 ions per second as well.
- The BECOLA facility includes a Penning Ionization Gauge (PIG) offline ion source, a discharge sputtering source that can generate many stable isotopes including refractory elements (transition metals). Experimenters can use beams produced at the PIG source offline to develop the best laser excitation schemes for spectroscopy in future rare isotope experiments.
- The BECOLA facility can perform Collinear Laser Spectroscopy (CLS) and Resonance ionization Spectroscopy Experiments (RiSE). Radioactive beams and laser light are overlapped in the beam line to excite (add energy to) or ionize (remove electrons from) atoms.
- For this type of laser spectroscopy we only need very small laser power of ~ 0.001 W (laser light used to remove an electron non-resonantly requires ~ 1 W of power).

Location: Low-Energy Area/Summing NaI (SuN) detector (#7a on the tour locations map) **SuN** performs total absorption spectroscopy of gamma rays from decaying isotopes.		**Approval**: Artemis Spyrou
Safety/Notes: View SuN by looking in the window from the main hallway (just west of receiving), it may be on the floor		
General audiences	**Young students (revised language)**	**HS/College science students (extra info)**
● The cylindrical detector called SuN is very good at detecting gamma rays, or high energy light that you can't see with your eye. Nuclei that are excited or running into each other often release extra energy as gamma rays. In this way, SuN studies decays and reactions that happen inside of stars. ● The crystals inside SuN absorb gamma rays and pass a lower-energy light into the tubes, which send a signal to be recorded by the computer through wires (that may not be connected). ● Even though the nucleus might emit several gamma rays before reaching its lowest energy (ground state), this detector can sum up all of those energies to discover how much total energy the nucleus had before emitting gamma rays. ● There is an upgrade called SuN++ which makes SuN bigger and more sensitive. ● SuN is usually combined with other detectors which detect other particles, like SuNSPOT and SuNFlower which detect electrons. ● A tape that runs through the center hole is called SuNTAN, and another detector that can go overtop called SuNscreen. ● SuN detects cosmic rays (radiation from space) as well, creating noise and a lot of useless data. SuNscreen can also pick up the cosmic rays to help identify which data are relevant and which can be ignored. ● As nuclei pass through the center hole, the detector covers almost every direction that a gamma ray might escape, so it will catch nearly all of them!	● The SuN detector is round with tubes sticking out in many directions… it kind of looks like how you might draw a sun! ● The crystals inside contain sodium (like in salt). When nuclei go into the center hole, they sometimes shine a very high-energy light that you can't see, but the crystals absorb it and send a signal out through the tubes to a computer. This is one way that scientists can "see" what is happening to a nucleus without ever looking at it. ● This detector can be partnered with lots of other ones, like SuNscreen, SuNflower, and SuNTAN. 	● SuN is a γ-Total Absorption Spectrometer. It is a cylindrical shape NaI(Tl) detector, 16-inch in diameter and 16-inch in height. ● It is segmented in eight optically separated segments, which are positioned above and below the beam axis. Each segment is being read by three photomultiplier tubes (PMT) resulting in a total of 24 signals coming out of the detector. The PMT signals are then fed into the Digital Data Acquisition System (DDAS). ● SuN is used with auxiliary detectors depending on the type of experiment. A mini-DSSD implantation station was developed for fast-beam decay studies, while the SuNTAN tape transport system is typically used with low-energy beams to study longer-lived isotopes. Finally, an MCP detector and hydrogen gas cell are used for capture-reaction measurements at ReA3. ● Measurements with SuN discovered that a very small change in nuclear energy could lead to a large change in nuclear shape. Cobalt-70 exhibited both spherical and deformed states. ● SuN used the beta-Oslo method to find that massive stars likely produce twice as much iron-60 (neutron caption from iron-59) as predicted by models. This experiment showed it is possible to test these reactions on short-lived isotopes. ● Sodium iodide crystals are highly efficient and cost-effective detectors. Germanium crystals have much better energy resolution, but detect fewer gamma rays and cost much more. ● SuN also detects cosmic rays from space… those signals are background noise that interfere with the measurements we are trying to make. SuNSCREEN is made of nine long plastic scintillator bars that cover SuN like a roof. Any events detected in SuNSCREEN and SuN at the same time are likely cosmic rays travelling vertically, so they can be rejected!

Location: East High Bay (#12 on the tour locations map) The **ReA3 Reaccelerator** brings “stopped” nuclei up to stellar energies for experiments	**Approval**: Antonio Villari

Safety/Notes: Watch for bridge crane operation.

General audiences	Young students (revised language)	HS/College science students (extra info)
• The ReAccelerator (ReA) linear accelerator (linac) is a compact version of the FRIB driver linac. It was originally designed for rare isotope beams, but can also accelerate stable ion beams. • The ion beam is first accelerated in the ReA radio frequency quadrupole and then through three cryomodules (cold boxes) located inside the green lead shielding plates. Parts of the accelerator charge to over one million volts to push the nucleus faster and faster. • This linear accelerator is a prototype of the FRIB accelerator, proving that the new design could work. ReA3 contains 15 accelerating cavities, compared to 324 in the FRIB linac. • Some experiments can’t be done while the nuclei are traveling at half the speed of light. This upgrade lets us stop the beams (in the gas stopper), ionize them (strip them of electrons to high charge states in EBIT, the Electron Beam Ion Trap), and reaccelerate them to about 8% of the speed of light. This is approximately the speed of nuclei you’d find in a star, so this reaccelerated beam lets you do nuclear astrophysics experiments that reproduce nuclear reactions found in stars. • ReA3 makes FRIB the only facility of our kind (fast-beam fragmentation) with this capability. Researchers have been asking for this world-unique science capability! • First experiments with rare-isotope beams began in September 2015.	• This short accelerator was built before the big FRIB accelerator underground. This new kind of accelerator was invented here and this is the first one ever built. • Parts of the accelerator charge over one million volts to push the nucleus faster and faster. • Not only did it show that our new technology worked, but it can also make nuclei go about as fast as they would in a star! When they run into our detectors, those nuclei act like they would in a star so we can reproduce what stars do (like the fusion that makes them shine). • Usually we have six-foot-thick walls of concrete to block radiation, but they wouldn’t fit up on that platform, so we’re using a thin green lead shell. • This room is 1.5 football fields long. The yellow bridge crane (like you’d see in a factory) can roll that entire length and move heavy instruments. 	• The ReA3 accelerator has 15 superconducting cavities made of pure niobium. These next-generation accelerators are of a brand-new design, developed in collaboration with some other labs around the country, and we’ve built the first ones ever. As nuclei pass through, the center part is charged to +/- one million volts, shooting the nuclei out the other side. There are different sizes/shapes of cavities, all operating at 80.5 MHz, each optimized to operate at either 4.1% or 8.5% of the speed of light. • Resulting beam energies from ReA3 will be variable and relatively low (from 0.3 MeV/u to 6 MeV/u), 3.2 MeV/u (8% of c), appropriate for astrophysics-type experiments. By comparison, FRIB achieves 200 MeV/u for uranium beam (over half the speed of light). • FRIB uses similar cavity technology, incorporating 324 cavities in 4 designs to make up the 400-yard-long accelerator. • Cavity parts can be formed by FRIB or a contractor. FRIB now has an electron beam welder to melt niobium seams together, since standard welding would introduce other metals that are not superconducting. • ReA3 showed that selenium-72 is more like a football, while selenium-70 flattens out into a Frisbee • ReA3 tested fusion reactions that may heat the surface of a neutron star

Location: East High Bay (#12 on the tour locations map) The **Clean Room** is a place to assemble sensitive and high-voltage instruments.		**Approval**: Brandon Ewert
Safety/Notes: Watch for bridge crane operation.		
General audiences	**Young students (revised language)**	**HS/College science students (extra info)**
● The cleanroom is where FRIB can build instruments that must meet very high cleanliness specifications in order to operate at high accelerating voltages (because dust or bumps on the surface would cause sparking). ● Occupants of the cleanroom are required to wear “bunny suits” to keep body contaminants from escaping into the clean environment. ● A newer clean room for preparing accelerator parts is located in the building next door. ● The components being prepared and assembled here are the vacuum chambers, beam pipes, and diagnostic devices that are being installed in the FRIB beamline. ● Many components prepared in this cleanroom have been installed adjacent to superconducting coldmasses, the “engine” of the new FRIB linear accelerator. These coldmasses (prepared in the other cleanroom) contain “cavities” made of niobium, a metal used for its superconducting properties. The cavities are energized with large electric fields (over one million volts) on the internal surfaces to accelerate ions. Any surface contamination (dust, hair, lint) and oils or films can spoil the vacuum and result in sparking and performance degradation, which is why our cleanrooms and clean assembly processes are so important!	● This room is incredibly clean so when we put together parts, they won’t have any dust on them. At the high voltages we use, that dust would act as a lightning bolt! ● To go inside you’d need to wear the white “bunny suits” that keep your dust from getting into the air. 	● The cleanroom is separated into two rooms of different classes, a Class 100 and Class 10,000. “Class” refers to a measure of the cleanliness of the room. To certify a Class 100, there must be less than 100, 0.5 µm particles, per cubic foot of area. In comparison, the air in the East High Bay (where you’re standing) measures at over 350,000, 0.5µm particles, per cubic foot. ● The 27,000-square-foot SRF Highbay (east side of the building, by Wharton) includes more than 370 square meters of class-100 clean room and chemistry facilities, automated resonator-etch tools, ultrapure water systems, a component inspection area, and a high-temperature vacuum furnace. ● The SRF cleanroom was the facility where FRIB staff processed and tested 324 superconducting resonators of four different types. The team then assembled them into 46 cold-mass strings of six different cryomodule types.

Location: HRS Vault (#10 on the tour locations map)

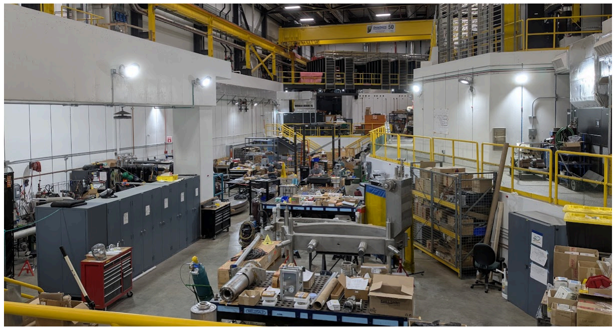
The **High Rigidity Spectrometer (HRS)** can measure mass and structure of many r-process isotopes

Approval: Ting Xu

Safety/Notes: Watch for overhead crane operation. You can take groups west along the catwalk as far as the fire extinguisher on the right-hand wall.

General audiences

- The bending power of the proposed HRS (like a mass spectrometer) will be able to direct all rare isotopes produced at FRIB, even with the envisioned FRIB upgrade to 400 MeV/u. This will enable the most sensitive experiments across the entire chart of nuclei, thereby enabling experiments with the most neutron-rich nuclei available at FRIB. In combination with the ability to use thicker reaction targets experiments will have 2 to 100 times as many desired nuclei for over 90% of experiments with neutron-rich isotopes
- These gains are over what will be possible with existing spectrometers at FRIB (S800 and Sweeper) that have half of the rigidity (steering power) and can't capture/direct all of the isotopes that FRIB can produce. This new detector will be able to measure the structure and mass of many more nuclei, including ones that are important to how stars make heavier elements.
- HRS is designed to accommodate FRIB's scientific program after the envisioned upgrade that will double FRIB's beam energy to 400 MeV/nucleon. Having the HRS available will help realize the full potential of FRIB!
- The critical Sweeper dipole magnet will be 15 ft tall, 20 ft wide, and 9 ft deep, weighing over 1.3 million pounds (650 tons, ~600,000 kg). The magnets can bend nuclei that travel at velocities of up to 70% of the speed of light or 130,000 miles per second (~210,000 km per second).
- DOE Office of Science awarded $115 million in 2023 to establish and operate HRS over seven years.
- In February 2025, DOE approved ~$50 million to build the High-Transmission Beam Line linking the ARIS fragment separator into the HRS vault

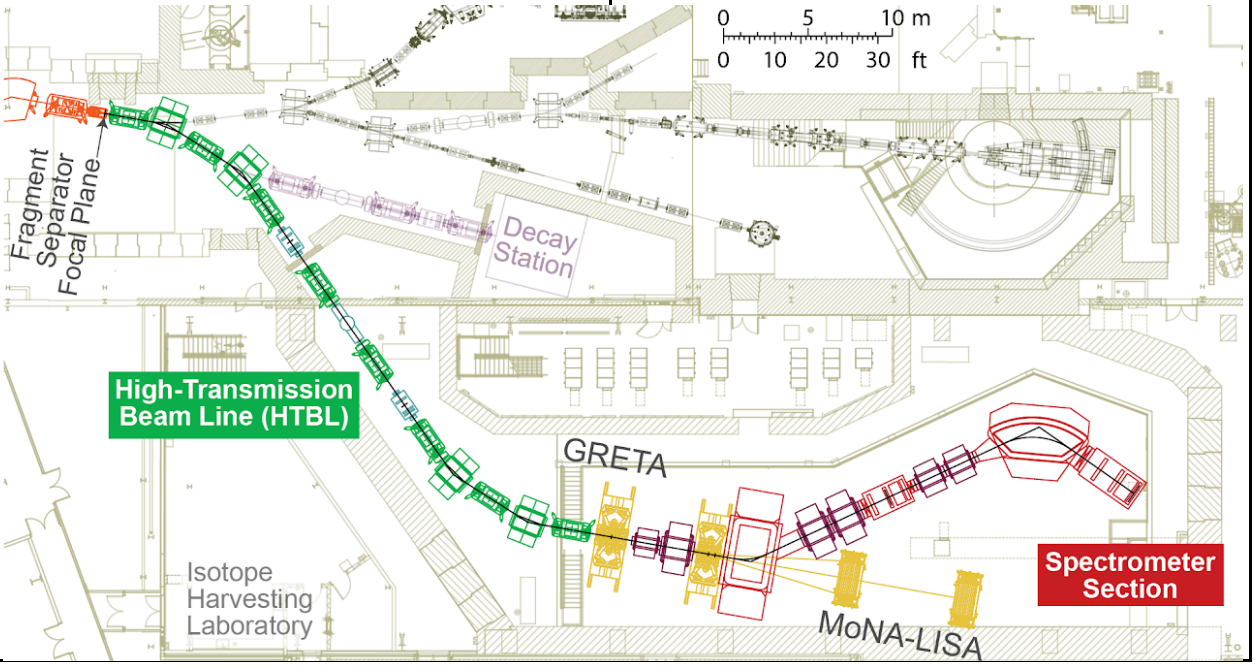


Young students (revised language)

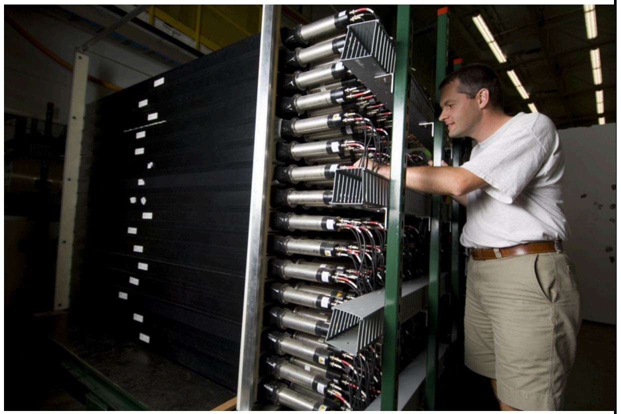
- The S800 Spectrograph on the other side of the wall is a three-story, 300-ton detector. But it was built in the 1990s and can't measure all of the particles that FRIB can make!
- Thus, we need a bigger and better detector! This room will have a long series of magnets stretching from one end to the other, allowing it to measure the size and shape and weight of the nucleus. It will help us learn how nuclei work and how stars use them to create heavy elements like gold!
- The yellow bridge crane can lift 50 tons, which is enough to pick up 5 Tyrannosaurs. We use it to move heavy instruments and wall blocks.

HS/College science students (extra info)

- The HRS consists of two main elements: the High-Transmission Beam Line (HTBL) and the Spectrometer Section. Rare isotopes beams are transported from the FRIB fragment separator through the HTBL to the target position at the HRS. The first element of the HRS after the target station is the sweeper dipole, which diverts charged particles toward a focusing beam line that transports particles to the spectrometer dipoles and the focal plane detectors. The spectrometer dipoles provide the precise exit channel characterization with momentum and particle identification resolutions required for the broad scientific program with the HRS.
- Also shown in the figure are the Gamma-Ray Energy Tracking Array (GRETA) and the Modular Neutron Array (MoNA-LISA). There are many other state-of-the-art detectors that have been developed by the User Community that will be used in combination with the HRS to achieve the scientific objectives of FRIB.
-



Location: HRS (#10 on the tour locations map) This detector may be set up in different places. **MoNA-LISA** is a major student project to create sensitive neutron detectors for neutron-rich nuclei.	**Approval**: Thomas Baumann
Safety/Notes:	

General audiences	**Young students (revised language)**	**HS/College science students (extra info)**
● The Modular Neutron Array (MoNA) and Large multi-Institution Scintillator Array (LISA) were built by college students in a collaboration of 12+ colleges and universities (funded by $2 million from NSF), and they come to FRIB regularly to conduct experiments. College students can do world-leading research! ● From the measured parameters we can calculate where neutrons hit, what direction they were travelling, and how fast. Information from MoNA-LISA can be used to reconstruct a picture of the interior of rare neutron-rich nuclei, their structure and, ultimately, answers to astrophysical questions because rare neutron-rich nuclei play a key role in the synthesis of the heavy elements and help drive tremendous stellar explosions, like supernovae and x-ray bursts. ● When not detecting neutrons from a beam, MoNA-LISA can still count cosmic rays, which is useful data. ● The total length of all cables for MoNA is 5 miles (8 km), and LISA's cables stretch 7 miles (11 km). With the large number of detector modules, cabling is a significant cost with each cable costing about $50. The cabling weighs about 1 ton. ● 2012: MoNA-LISA were used to discover di-neutron decay (new type of decay) of oxygen-26 and beryllium-14. ● Research opportunities at FRIB like by MoNA-LISA is a major reason MSU is a top-ranked nuclear science graduate school in USA! More than 25% of all U.S. Nuclear Physics graduate students receive part of their training at FRIB. Our ~150 grad students finish nearly one year faster than the national average. About one-quarter are women. ●	● Until HRS is constructed, this room is being used to put together useful instruments like accelerator parts and magnets for steering. ● The MoNA-LISA detector is a set of black bars with silvery circles on the ends in the far left corner . ● MoNA-LISA is a collaboration of more than a dozen schools (MSU, CMU, WMU, Hope College, Florida State, Indiana University, etc.) funded by the National Science Foundation.. ● While professors at those schools designed it, college students a bit older than you built it, assembled it, and did their own experiments. It's a $2 million student project! ● The clear plastic inside will glow when a particle hits it, so it's possible to "see" invisible things as they go through! ● The black bars are normally connected to the computer (blue rack) with 12 miles of cables. 	● Operation: after secondary collision between rare isotopes and a target, the sweeper magnet diverts all charged particles from the beam into the attached detector box, allowing just neutrons to bombard MoNA and LISA. Note that the neutrons pass right through metal and air - while nuclei require a vacuum for transport, neutral neutrons rarely interact with matter. 6-foot walls of concrete are required to contain the neutrons. ● Each bar of plastic scintillator (like acrylic glass) is wrapped in a black covering so no light can enter. As neutrons pass through, the only way they interact is rarely scattering off a nucleus in the material (which is tiny compared to the size of the atom). The plastic is hydrogen-rich because when neutrons hit a proton (H nucleus), their similar mass makes for a large effect. The jostled proton will excite electrons to emit light, which travels to the ends of the bar where photo-multiplier tubes (PMTs) amplify it up to 30 million times for detection. ● The PMTs (kind of like night vision goggles) also detect when the light arrives very precisely, so the position of the light emission along the bar can be determined within a few cm by measuring the time difference of the signals at the left and the right end. This difference has to be known to less than one ns (billionth of a second). Additional spatial tracking of neutrons comes from identification of which of 288 bars gave the signal.

Location: Rack Room (#11a on the tour locations map)

These **power supplies** and other systems support the linear accelerator underground.

Approval: Dan Morris

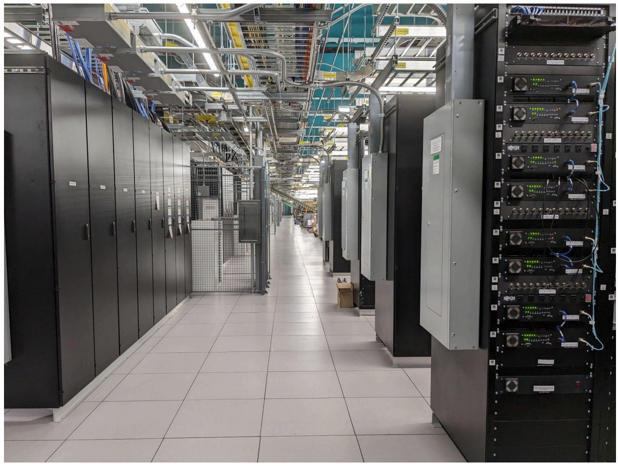
Safety/Notes: Watch for trip hazards! There may be cables on the floor.

General audiences

- The FRIB rack room contains controls, diagnostics, power supplies, and safety systems needed to operate FRIB's linear accelerator.
- The FRIB rack room is approximately 500 feet long, includes 800 instrument racks, and contains over 23,000 individual cables. The total length of the cables is over 500 miles.
- Power supplies provide direct-current (DC) power for the room-temperature and superconducting magnets.
- Electricity comes from three utilities: MSU, Consumers Energy, and Lansing Board of Water & Light. Operation takes 14 MW, costing $10 million/year.
- Copper coaxial transmission lines transfer power from the RF amplifiers in the rack room to the accelerator in the tunnel. RF energy is used to excite large electric fields that accelerate the charged particles.
- The power supplies end a short distance away… we left a large "empty space" (just pipe) so we could add more cryomodules in a future upgrade. That's why our lab has been here for 60+ years - always looking ahead
- The linac is ~10 meters below you. At the far west end of this room is where it turns to hit the carbon target ~15 meters underground. The target is a graphite disc about 30cm wide and 2-8 mm thick. It rotates to spread the heat over larger area and is water-cooled.
- The cables in trays above are well-organized and documented so it's easier to find and fix an issue.
- Racks are water-cooled via pipes underneath the raised floor
- *(from Brad Bull)* The tunnel underneath you is ~570 feet long and 70 feet wide (173m by 21 m). When they dug up the dirt, the original plan was to temporarily pile it between FRIB and the Wharton Center. That pile (called Mt. FRIB) would have been the tallest building on campus! The dirt has been spread on a field near the corner of Farm Lane and Mount Hope, making it obviously a few feet higher.

Young students (revised language)

- This may look like a server farm, but it's not computers, it's all power supplies! These create the high voltage that the accelerator needs to push nuclei.
- Copper conduits on the top of each set of racks carry the high voltage down a ten-meter shaft to power the cryomodule (cold accelerator box) below that rack. If you look at where the racks are, you can see the accelerator lined up!
- Our lab needs the same amount of power as 30,000 homes, costing $14 million per year.
- The accelerator goes from the front end/ion source to the far end of this room, turns around to come back, then turns around for the third "leg".
- It's one long accelerator, but it's folded twice and looks like a paper clip. This way it could fit in our lab's old parking lot. The original design would have had the 500-meter long tunnel stretching between residence halls and in front of the Wharton Center.



HS/College science students (extra info)

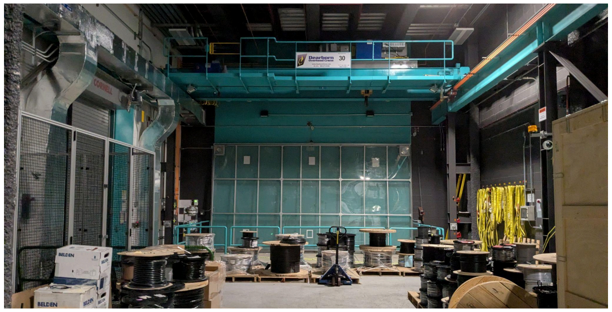
- Solid-state radio-frequency (RF) amplifiers, driven by low-level RF controllers, excite the superconducting radio-frequency cavities (niobium at 4.5K or 2K) at 80.5 or 322 MHz.
- The quarter-wave resonators operate at 80.5 MHz, with a maximum amplifier power of 2 kW to 4 kW. The transmission lines are 7/8 inch to 1-5/8 inches in diameter.
- The half-wave resonators operate at 322 MHz, with a maximum amplifier power of 4 kW to 8 kW. The transmission lines are 3-1/8 inches to 4-1/16 inches in diameter.
- The controls racks include instrumentation for cryogenics (temperature and helium levels), power supplies, superconducting magnets, and vacuum systems (pressure and valve control).
- Diagnostics instruments monitor the health of the beam and protects the instruments. This ensures the beam is delivered with the expected power to the target. A number of intercepting and non-intercepting devices monitor beam position and beam current.
- The beam of many different nuclei then passes thru two 120-ton and two 180-ton dipole magnets to steer the fast-moving beam up to ground level while also separating the isotopes in the beam to be studied. A few more magnets on this floor complete the filtering, so the fragment separator is 90 meters long.
- *(from Brad Bull)* The floor of the tunnel is close to the water table. To make sure that water couldn't seep in, construction crews ran pillars (caissons) down to bedrock and poured a 5-foot-thick slab on top. For 36 hours, every concrete mixer in mid-Michigan was here continuously pouring 3500 cubic yards of concrete. There are no seams in the tunnel floor, so there's nowhere for water to enter!

Location: East Loading Bay (also known as truck bay) (#11 on the tour locations map)

Front End (ground level) is where stable nuclei start, **Crane above** can move cryomodules down shaft!

Approval: Tomofumi Maruta, Laura Popielarski

Safety/Notes: You can open the door and look into the Front End, but do not take groups inside!

General audiences	**Young students (revised language)**	**HS/College science students (extra info)**
• The heavy-ion beam from FRIB begins in the front end. Two different Electron cyclotron resonance (ECR) ion sources remove electrons from atomic nuclei. Only one ion source is used at a time for an experiment, while the other is prepared for another experiment. • In the ion source, neutral atoms from an element (chosen to maximize chance to produce the rare isotope) are vaporized into a hot plasma, which knocks electrons off the atoms and ionizes them. The resulting ions are contained with electric and magnetic fields. Once ions of appropriate charge are produced, they are extracted into the FRIB accelerator. • The ion source can strip all electrons from elements lighter than calcium. Heavier elements have some left (U ~ 76+) • Each ion source is installed on a 100,000-volt platform (insulated from the ground) that provides the energy boost to push ions down a 10-meter shaft to be injected into the linear accelerator. • FRIB has the highest-power and highest-energy superconducting heavy-ion linac in the world! It consists of 46 cryomodules (green boxes) of six different types. • One cryomodule weighs 13 tons and costs about $3 million. When they're moved in here on a flatbed truck, the crane above can pick them up and lower them down the shaft (currently filled with 20-ton concrete blocks). When the cryomodule reaches the tunnel floor, it's rolled into place. We can attach giant wheels/casters onto cryomodules. • The cryomodules contain superconducting radio-frequency (SRF) resonators and superconducting solenoid magnets. Operating at cryogenic temperatures of 2 kelvin and 4.5 kelvin, the SRF resonators accelerate the beam, and the solenoids steer and focus it. • The 46 cryomodules are assembled in three linac segments in the shape of a paper clip in order to fit the 1,500-foot-long accelerator into the 500-foot-long tunnel. The cryomodules accelerate any ions from hydrogen to uranium, with calcium-48 being most common (it's neutron-rich). • Different types of cryomodules are tuned to efficiently accelerate beams that are traveling at different speeds.	• You are standing on top of the accelerator right now! There actually is a window to look down, but it's full of 20-ton concrete blocks to stop radiation from coming up here. • The blue crane above you can take those out to open a ten-meter-deep shaft straight to the tunnel. You could even see the accelerator! • The crane can lower a cryomodule (green accelerator box) down to the bottom, and we attach wheels onto the box so it can be rolled into place. That's how the instruments got into the tunnel originally. • The front end is where we knock electrons off of atoms so we can push them through the accelerator with over one million volts. • Seeing the front end is a great reminder of why we need more than 800 people to make the lab work. No one can do it all on their own! We need a team to make the accelerator, a team to cool it all, a team for feeding nuclei into it… science is a team sport!  	• The Low Energy Beam Transport line, the radio-frequency quadrupole (RFQ), and the Medium Energy Beam Transport line speed the heavy ion beams up to 0.5 percent of the speed of light. • ARTEMIS, the Advanced Room-TEMperature Ion Source, is one of two electron cyclotron resonance (ECR) ion sources that FRIB uses to produce ions from atomic nuclei. ARTEMIS supports general-purpose operations. • FRIB's second ion source, the superconducting ECR (SC-ECR) ion source, was built in collaboration with Lawrence Berkeley National Laboratory. It provides high intensity for all elements, including heavy ion beams like uranium. It operates at 28 gigahertz (GHz). Exciting the plasma at a higher frequency helps ions with higher charge states reach higher intensity. • An ion source does not create just one desired ion; it creates many. The first magnet sorts out the desired ions. Most of the ions stop in the magnet wall; only the desired ones make it out. • The large features extending from the beamline are beam profile monitors. The orange structures are solenoids, which focus the beam. The silver structure is an electrostatic dipole to bend the beam down toward the linac tunnel. • The cryomodules accelerate all ions from hydrogen to uranium to at least 200 MeV/nucleon to create rare isotopes. Future upgrade plans to achieve 400 MeV/u. • Six different cryomodule types that comprise the linac are beta=0.041, beta=0.085, beta=0.085 matching, beta=0.29, beta=0.53, and beta=0.53 matching. • The beam-delivery-system is at the end of linac segment 3. It is also where additional cryomodules will be added in a future energy upgrade of FRIB to 400 MeV/u. • The liquid lithium charge stripper (world's first!) helps FRIB achieve design-goal beam energies beyond 200 MeV/u and beam power up to 400 kilowatts. Conventional charge-stripping foil would only last seconds under FRIB's beam power. The lithium doesn't react with the argon atmosphere in the chamber. • SRF cavities were built by a family-owned airplane parts shop in Indiana, we taught them how!

Location: ReA3 High Bay (#13 on the tour locations map) Detectors for reaccelerated beams; nuclear astrophysics experiments; JENSA and SECAR	**Approval**: Hendrik Schatz

Safety/Notes: Stop in walkway north of shielding wall (try to leave a path for thru foot traffic) or look thru west-facing door near LEBIT. No real safety issues.

General audiences	Young students (revised language)	HS/College science students (extra info)
• Low-energy (star-like) beams feed into this room from ReA3 on the other side of the far wall. The many experimental stations here study nuclear astrophysics (how nuclei behave in stars). • Jet Experiments in Nuclear Structure and Astrophysics (JENSA) contains the world's densest He gas jet with 10^{19} nuclei/cm^2. • JENSA experiments will directly measure astrophysical reactions of radioactive nuclei with hydrogen or helium at the same collision energy that particles have inside stellar explosions e.g. X-ray bursts and Novae (10^8 - 10^9 degrees) • Jet inlet pressure is maintained by a large compressor of up to 40 Atmospheres. The connection to the high vacuum beamlines is made with a series of differential pumping stages where 13 large pumps (each named after a dwarf in The Hobbit) bring the pressure stepwise down to high vacuum. All gas is recirculated in a closed system so we can use expensive gases like ^{3}He (filling the system is about $100k) • SEparator for CApture Reactions (SECAR) can directly measure astrophysical reactions where a radioactive nucleus captures either a proton or a helium nucleus, emitting a gamma ray. • The purpose of SECAR is to separate the beam from the capture reaction product, which can then be counted in detectors at the far end of SECAR. SECAR is expected to detect reactions that occur with rates as slow as one per day. • SECAR will be sensitive to extremely weak reactions in the rp process that are important to understand X-ray bursts, Novae, Supernovae, Supermassive Stars, and other more exotic phenomena, especially how some heavy elements are made!	• Exploding stars can make nuclei do very rare and surprising things, which just might be how they can make heavy elements like gold. • In this room, we take nuclei moving like they would in a star and run them into the world's densest spray of helium (coming out of a needle). The ways that the nuclei react with the helium can help us understand how it works in stars. • This room is loud because of many pumps, as usual. But to make the world's densest helium jet, we have 13 pumps pushing the gas through a tiny needle! Each one of those pumps is named after a dwarf in the Hobbit: Thorni, Ori, Nori, Dori, Bifur, Bofur, Bombur, Kili, Fili, Balin, Dwalin, Oin, Gloin	• **Jet Experiments in Nuclear Structure and Astrophysics (JENSA)** is designed by Colorado School of Mines and Oak Ridge Nat Lab, funded by DOE and JINA. JENSA contains the world's densest He gas jet with 10^{19} nuclei/cm^2. • The radioactive beam from ReA3 hits a 4mm stream of gas (the jet), and reaction products such as protons or helium nuclei are detected by surrounding Si detectors. Reactions that emit only gamma-rays need a gamma ray detection array and the SECAR recoil separator. • The radioactive beam passes through JENSA's gas jet. Both the unreacted beam and the few heavier nuclei produced by capture reactions in the target enter SECAR. The purpose of SECAR is to separate the beam from the capture reaction product, which can then be counted in detectors at the far end of SECAR. • SECAR consists of four separation stages – the first and last separate charge states using dipole magnets, while the middle two use a Velocity Filter to separate by velocity. • All magnets operate at room temperature • The primary projectile rejection components of SECAR are the two Velocity Filters, also known as Wien Filters (large blue boxes). They include a vertical magnet field B and a horizontal electric field E that together serve to deflect the trajectory of any particles with a velocity different than E/B (balances F=qE in one direction with F=qvxB in the other direction). By appropriately tuning these fields, the unreacted beam particles (10^{13} - 10^{17} times higher intensity) can be deflected away while the reaction products of interest (recoils) are passed through to eventually reach the focal plane for identification. • SECAR was designed by JINA-CEE scientists at Notre Dame, then built by a collaboration with funding from the DOE Office of Science and the NSF.

Location: Re6 Vault/SOLARIS (#14 on the tour locations map)

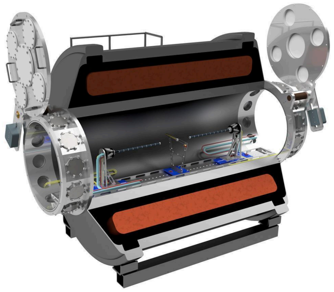
A detector for measuring nuclei exiting the ReA6 reaccelerator

Approval: Ana Henriques

Safety/Notes: Watch for crane operation! Gates require card activation, which requires ReA6 access training. Flashing yellow light next to the cylindrical magnet indicates magnetic field on - do not enter if it is flashing!

General audiences

- SOLARIS is a big cylindrical magnet, much like an MRI you would find in a hospital (because we bought it from one).
- Typical field strength can vary from 2-4 Tesla (50,000x the Earth's magnetic field) uniformly spread over large volume.
- SOLARIS is designed to explore the structure of rare isotopes using "simple" nuclear reactions that occur between the rare isotope beam and a light target nucleus such as proton, deuteron (hydrogen-2), triton (hydrogen-3), alpha (helium-4) or helium-3.
- Research here allows better understanding of nuclear reactions in stars and nuclear energy levels.
- Researchers can put different containers inside the magnet to measure what nuclei do when they hit each other.
    - First mode: arrays of silicon detectors placed around the beam axis catch scattered particles emitted from nuclear reactions in the target
    - Second mode (AT-TPC): when fast nuclei come from the accelerator into a tube of helium inside, they bounce off of the helium and knock off electrons. Catching those electrons as they hit wires inside (creating electric current) lets the detector track nuclei in 3D!
- The AT-TPC is 1000 times more sensitive than before, so physicists will be able to perform experiments that were previously impossible
- This detector was produced through a collaboration with Argonne National Laboratory, just outside of Chicago. Researchers from many labs/schools planned for over a decade to produce a new and useful tool that would let them do these measurements at FRIB!



Conceptual design of the vacuum-mode silicon array setup inside SOLARIS

Young students (revised language)

- SOLARIS is a big cylindrical magnet. It's actually an MRI machine we bought from a hospital!
- Typical field strength can be varied from 2-4 Tesla (50,000x the Earth's magnetic field) uniformly spread over large volume.
- Researchers can put different containers inside the magnet to measure the various things that nuclei do when they hit each other.
- Sometimes they put a tube of helium inside, and when fast nuclei come in from the accelerator, they bounce off of the helium and knock off electrons. Catching those electrons on wires inside (creating electricity) lets the detector track nuclei in 3D!
- Research here allows better understanding of nuclear reactions in stars and nuclear energy levels.
- The AT-TPC discovered an incredibly rare radioactive decay: a nucleus with very few protons actually released one of them, which shouldn't happen!

The SOLARIS solenoid magnet set up in ReA6 High Bay

HS/College science students (extra info)

- SOLARIS has two modes of operation:
    - Vacuum chamber inside, uses on-axis array of silicon detectors for hi-res study of reactions. Various targets and detectors can be inserted in the middle of the solenoid magnet.
    - AT-TPC mode uses a gas chamber as a target and detection material - as star-like nuclei enter, they react with target gas (usually helium, as they would in a star). The products ionize many electrons, which drift under a voltage difference until they strike the detector pad at the end of the cylinder. Using location and time of electron arrivals, this tracks particles in 3D! The strong magnetic field causes those particles to travel in a helix/spiral which is distinct for each different type of particle, so they're easy to identify!
- The total volume of this "target" is 250 liters, in a cylinder 1 meter long by about 50 cm diameter, just enough to fit inside a MRI solenoid
- Even though the target is a gas, its thickness is up to 1,000 times larger than traditional solid targets
- Single-nucleon transfer reactions (trading one proton or neutron between nuclei) measured here will help us understand nuclear structure and each particle energy.
- These "capture" reactions could create heavy elements.
- The AT-TPC discovered an incredibly rare radioactive decay: proton emission after a beta-minus decay in beryllium-11. Neutron-rich nuclei don't usually emit protons!
- The maximum magnetic field of this MRI machine is 40,000 Gauss (Earth's magnetic field is 0.25-0.65 Gauss).
- This superconducting magnet is cooled by a reservoir of 3,300 liters of liquid helium keeping the temperature at 4.2°K (-452°F)
- Once the magnet is energized, its power supply is disconnected and a current of about 300 Amps flows in the superconducting coil indefinitely.
- The plastic enclosure is there to keep ferromagnetic objects from getting too close to the bore of the magnet.
- The GRETA (Gamma-Ray Energy Tracking Array) detector is now installed in this vault. It uses high-purity germanium crystals to capture gamma rays in a full sphere around the target. 10-100 times more sensitive than previous systems with incredible tracking precision. 30 quad modules

<table>
<tr><td colspan="2">Location: FRIB scale model (between the Auditorium and Seminar Room on the tour locations map)
These two models (one of the entire building, one of the linac addition) are a great way to orient visitors</td><td>Approval:</td></tr>
<tr><td colspan="3">Safety/Notes: No safety issues. This is a good location to visit when many vaults are closed, or you’re waiting for another group to move on</td></tr>
<tr><td>General audiences</td><td>Young students (revised language)</td><td>HS/College science students (extra info)</td></tr>
<tr><td>Full building model
● Point out where visitors entered the lobby and tower 3 where they are standing.
● Trace the beam from the ion source (back left corner) to the target (back right corner) to the experimental areas (tall building in center).
● Identify the SRF High Bay (left side, near the Wharton Center) where accelerating cavities are cleaned, conditioned, tested, and assembled into cold masses for installation in a cryomodule.
Linac building model
● Again, you can trace the beam from the ion source, through three linac segments deep underground, to the target, then up through the preseparator to the experimental areas.
● Point out the surface-level loading bay next to the ion source at the left end - this is where groups can visit (and may have).
● Note the black “dirt” between surface building (where the racks are) and the linac tunnel. This provides radiation shielding, along with the concrete of the structure. RF power is carried from the rack room through tubes to the tunnel.
●</td><td>● You can see that the particle accelerator is buried deep underground - the black stripe here is dirt, and there is concrete above and below. This all blocks radiation from coming up.
● See the orange box on the right - that’s where the nuclei smash into a target at half the speed of light. This spot is even deeper: 15 meters underground.
● The orange pipe and shapes coming out at the right are the magnets used to filter out the nuclei we don’t want, which is most of them. The wedge-shaped magnets are 180 tons apiece (that’s one blue whale each)!</td><td>● Point out the cryomodule boxes in the linac. There are 46 cryomodules containing 324 SRF cavities in four types.
● The final FRIB building is over 500,000 sq. ft., double the size of NSCL before it.
● Planning for a next-gen accelerator lab started in 1999, we won the $730 million project from US Department of Energy in 2008, construction started in 2014, and operation began in May 2022 (finished early and on-budget)!
● The original building was finished in 1964, and we’ve added on 18 times since.</td></tr>
</table>