# The Control Room

Operators use video monitors and computer terminals in the control room to monitor and operate the cyclotrons and beam lines.

The control room contains networked computers and programs that allow NSCL operations staff to remotely monitor and control the ion sources, cyclotrons, beam lines, and auxiliary equipment in the laboratory. Because of the radiation levels within the shielded rooms when a particle beam is present, the accelerators, beam transport lines, and particle detectors must be operated by remote control. In the control room, operators can safely adjust or tune the settings of equipment to ensure the delivery of a desired particle beam to an experimental vault. There are more than 20,000 device channels in the control system.

The control room is equipped with computer terminals and video monitors that enable staff to monitor and operate the cyclotrons and beamlines. For example, operations staff can adjust the current in a magnet or the voltage on the cyclotron dees. Staff can also open valves, read beam current, and move slits, probes, and other motorized devices as required to maintain the beam conditions appropriate for the experiment being run.

Video monitors allow operations staff to view the beam by inserting a phosphor screen into one of the many points along the beam's path. A television camera then transmits the glow created by the beam particles' impact on the screen, allowing the operator to adjust beamline magnet currents to focus the beam or measure the beam's size.

The control system is based on the Experimental Physics and Industrial Control System (EPICS) and additional software developed at NSCL. Interfaces have been provided so that products such as National Instrument's LabView® and Microsoft Excel® can access control system channels.


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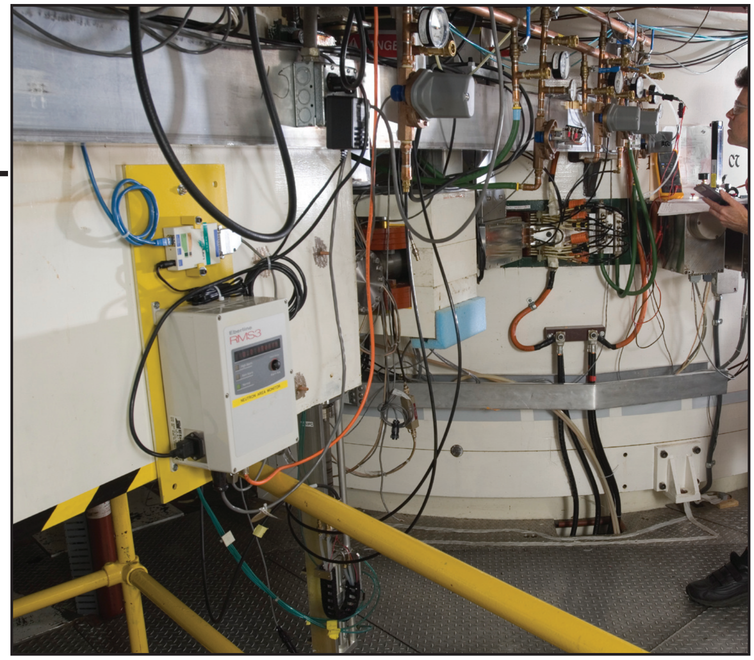
# K500-K1200 Coupled Cyclotrons



View along the beam line from the K500 cyclotron toward the K1200 cyclotron (in the background). The ions pass through a superconducting focusing magnet (large white box in the left half of the picture) and a conventional bending magnet before entering the K1200. The evacuated beam pipe is not visible is this picture.

The K500 Cyclotron is the world's first cyclotron with a superconducting magnet, and the K1200 is the world's highest energy cyclotron. Both operate under the same principles, with the K500 accelerating ions to an energy appropriate for injection into the K1200, which accelerates the ions even further. The energy achieved in the K500 is 10 to 20 MeV/nucleon, corresponding to 15 to 20 percent of the speed of light ("c"). Final acceleration, which brings ions to about 150 MeV/nucleon (50 percent of c), occurs in the K1200 before the ions are sent to an experimental area. The coupled cyclotrons accelerate all elements heavier than oxygen, with variable energy (maximum is 200 MeV/nucleon).

Ions are transported from the ion source to the K500, where they are injected from below on the center axis of the K500. With another deflection, they are put into horizontal motion between the poles of the cyclotron's magnet. The accelerating force of an electric field and the bending force of the magnetic field move the ions into a spiral orbit of increasing energy with correspondingly increasing radius until they are extracted with an electrostatic deflector and directed through a string of focusing and bending magnets into the K1200.

The accelerating electric field is produced by high voltage applied to three electrodes, the "dees," by radio-frequency transmitters. High-current superconducting coils and the magnet steel comprise an electromagnet that generates the magnetic field. The ions are accelerated in the electric fields of the dees, which are spiral-shaped to fit in valleys between the iron poles, hundreds of times. The spiral shape of the steel provides a vertical focusing force on the ions to keep them close to the midplane as they accelerate on their 1 to 3 kilometer orbit. Superconducting coils are used for the electromagnet because they attain higher fields than conventional room temperature coils. The extraction energy of the accelerated beam is proportional to the square of the magnetic field, the extraction radius of the cyclotron, and the ion charge state. Clearly, increasing the magnetic field yields higher energies. Increasing the extraction radius of the cyclotron is another way to increase energy but requires building a larger cyclotron. Increasing the ion charge state is the goal of coupling the two cyclotrons.

An Electron Cyclotron Resonance ion source produces heavy ions in a variety of charge states. Selecting the highly charged ions would seem to be the obvious way to achieve a beam of high-energy ions. Unfortunately, the abundance of ions in an ion source decreases rapidly with increasing charge, such that the intensity would be too low for many experiments. By coupling two cyclotrons, however, we can have both high energy and high intensity.

After acceleration to a speed of about 20 percent of the speed of light in the K500, the interaction of a low-charged ion with matter will result in electrons being stripped from the ion, i.e., in the production of a highly charged ion. The required interaction with matter occurs in a thin carbon foil that is placed in the path of the low-charged ions inside the K1200, about 30 cm from the center. The transmitted high-intensity, high-charged ion beam is then accelerated to the final energy.

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# The A1900 Fragment Separator

One of eight superconducting quadrupole triplets that are used to focus the beam in the A1900 fragment separator.

The A1900 fragment separator uses superconducting magnets to select individual isotopes from the hundreds or even thousands produced in nuclear reactions. This selection is made as the ions transit the separator in less than one microsecond. The techniques used in the A1900 are so sensitive that even one nucleus out of $10^{18}$ produced during a week of colliding the accelerated beam with a target can be identified and its properties studied.

Technically, the A1900 fragment separator consists of two consecutive high acceptance magnetic spectrometers. Each magnetic spectrometer is composed of a set of superconducting magnets designed and constructed at NSCL. Four large dipoles that bend the beam each filter the fragments according to magnetic rigidity. The 24 quadrupole magnets, arranged in eight sets of three (or triplets), are used to collect and focus the beam. Sixteen of the quadrupoles have additional hexapole and octapole coils to correct for aberrations. The entire fragment separator is about 35 meters long, and the maximum magnetic rigidity the device can be tuned to is 6 Tm.

Although the A1900 is highly selective, it can transmit specific isotopes with very high efficiency. The momentum acceptance of $\Delta p/p = 5\%$ and the solid angular acceptance of $\Delta\Omega = 8$ msr, makes it one of the highest acceptance separators in the world.

Detector systems are placed at the intermediate image and the final focal plane positions to unambiguously identify the individual rare ions as they fly through the A1900 separator. A pair of large-area, position-sensitive, parallel-plate avalanche counters (PPACs) tracks the particles through the central or intermediate image. These detectors can be operated at particle rates of up to one million per second. Another smaller pair of PPAC detectors measures the position and angles of the fragments when they reach the focal plane. Here the particles also pass through a thin silicon wafer (a PIN diode) that provides an energy loss signal to identify the chemical element. A thick plastic scintillator is used to measure the total kinetic energy of the particle and the time it took to fly through the separator. It is possible to use this information to determine the mass and nuclear charge for every single particle that travels through the A1900.



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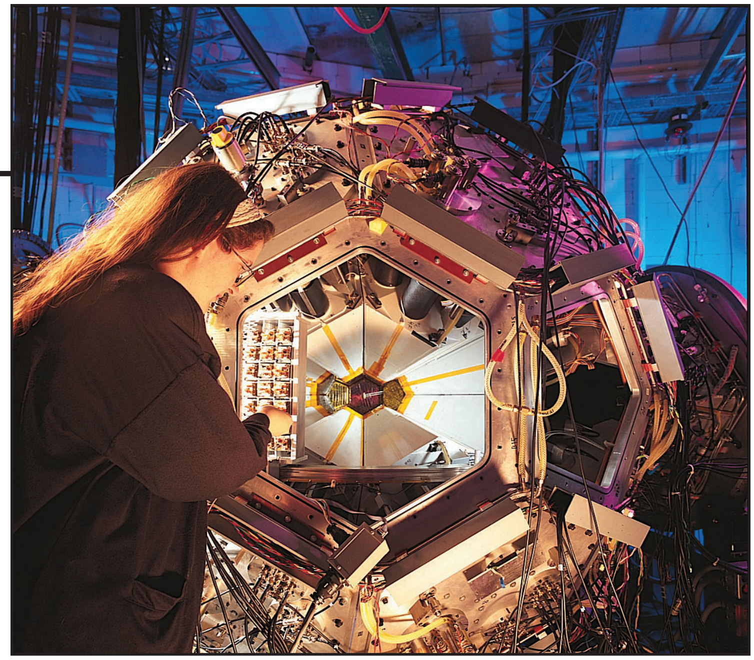
# The 4π Array

The 4π Array is located in the N2 vault. This detector array is designed to study nuclear matter and the dynamics of nuclear collisions, which can produce up to 50 particles (protons, deuterons, alpha particles, and light nuclei); of these, most of the charged particles can be measured by the 4π Array. These measurements tell us how nuclear matter responds to compression and heating. Observations with the 4π Array have been used to extract detailed information about the nuclear equation of state, which is important for understanding neutron stars and supernovae phenomena.

The 4π Array is based on detector systems that respond to the many kinds of charged particles emitted in reactions at energies up to 200 MeV/nucleon. The detectors closest to the target are low-pressure gas counters designed to detect slow moving, highly ionizing particles, such as fission fragments. These fragments stop in the first layer while lighter fragments, such as carbon nuclei, pass through and stop in the second layer, which consists of a gas counter at atmospheric pressure. Fast-moving light particles, such as protons, pass through both layers and are detected in plastic scintillator detectors. These detectors are used to identify and measure the energy of the particles.



An MSU-NSCL graduate student works in the NSCL 4π Array.

Using the 300 detectors in the 4π Array, experimenters can study reactions using target and projectile combinations across the periodic table at projectile energies of 5 to 200 MeV/nucleon.

The 4π Array has been used in various experimental configurations, both as a stand-alone device and coupled with specialized detectors, taking advantage of the 4π Array's high-speed data acquisition and detection capabilities.



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# N4 Vault

Some of the superconducting magnets that deliver beam to the experiments in the N4 vault.

The N4 Vault contains three different permanent experiment stations. The three stations are a user station, the gas stopping station, and the sweeper magnet station. The cryogenic magnets used to deliver the beam to the three experiment stations dominate the floor. The beams enter the room from the right (as you enter) and are directed to each experimental station by a pair of superconducting dipole magnets and a number of superconducting quadrupole magnets.

The user station, which makes up the beam line closest to the doorway, is an area without any dedicated apparatus appropriate for detector tests and irradiations. In a typical irradiation experiment, the beam passes through a diagnostic device to characterize its properties and then exits the beam line into the air through a thin foil. The emerging particles can be used, for example, to irradiate samples for radiation damage studies.

The gas stopping station is connected to the middle beam line. This device can stop and collect all of the beams, including very short-lived rare ions, for transport under precise control at very low energies to the LEBIT ion trap in the N5 vault. The system uses the beam line and degraders to beam the ions to a narrow energy range. Then the ions come to rest in ultrapure helium gas. A series of the largest vacuum pumps at NSCL (seen in the far left from the doorway) remove the buffer gas.

The sweeper magnet and its focal plane detector are connected to the beam line farthest from the doorway. During operation, the large concrete blocks on the east wall are removed to create a path for neutrons created in nuclear collisions to be detected in MoNA, the modular neutron detector array. MoNA sits in the N6 area outside the vault and can make precision measurements of neutrons in coincidence with charged particles detected in the sweeper magnet system. The "sweeper magnet" is so named because it "sweeps" charged particles off to the side and into a large stainless steel box housing position sensitive ion chamber detectors while allowing the neutrons to continue along straight lines. The sweeper magnet is a very strong superconducting dipole magnet constructed at the High Field Magnet Laboratory at Florida State University.



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# The Sweeper Magnet

Designed at NSCL and constructed at the National High Magnetic Field Laboratory (NHMFL) at Florida State University, the sweeper magnet is a compact, large-gap 4 Tm dipole magnet that separates neutrons from charged particles (electrons, protons, and heavier ions) after nuclear reactions that occur when rare isotope beams break up in the target situated in front of the dipole magnet.

The charged particles are deflected in the dipole magnetic field and identified in the focal plane detector box using detectors that measure charge, mass, and momentum. The neutrons are not deflected by the magnetic field and travel a distance of up to 15 meters to the Modular Neutron Array (MoNA). If the charged particles were not separated from the neutrons, the neutron-spectra would be contaminated with charged-particle signals. Measuring both neutrons and charged particles in coincidence allows the complete kinematic reconstruction of the reaction that occurred in the target.

The picture shows the front face of the iron blocks of the sweeper magnet placed above and below the vacuum chamber for the charged particles that are deflected by the magnet. A graduate student is adjusting signals from a detector inside the focal plane detector box.

Complete kinematically reconstructed measurements with the sweeper magnet allow for mass and lifetime measurements as well as spectroscopy measurements of systems that are beyond the limits of particle stability.



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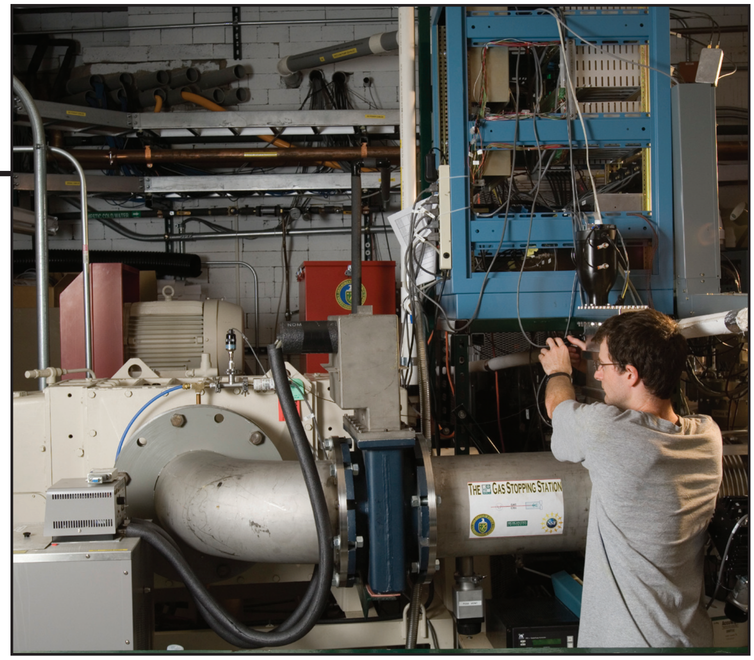
# Gas-stopping Station




A student is shown adjusting a valve on the vacuum line (10″ diameter) that is used to evacuate the gas cell.

The gas-stopping station is a large device designed to slow down and capture the very fast rare ions produced by the A1900 fragment separator. After the ions have been captured (literally, thermalized in helium), they can be studied with new, extremely precise techniques not possible at high energies. Efficient extraction of the ions from the helium gas requires ultrapure (impurities in parts per billion)) gas because impurities interfere with the extraction process.

The photo shows an overhead view of the main features of the collector system. The most apparent parts of the system are the very large pumps used to strip the helium gas from the thermalized ions. The high-energy rare ions prepared in the A1900 separator enter the helium container through the beam line in the center of the N4 vault. Most of the kinetic energy of these ions is removed by passing through polished glass plates of precise thicknesses that range from 0.5 to 5.0 mm. The gas cell (approximately 50 cm long) contains helium at a pressure of approximately one atmosphere in the first metal cross, shown on the right side of the photograph. Once thermalized in the gas cell, the ions are pulled forward by a static electric field and pushed from the high-pressure gas cell by the gas flow through a supersonic nozzle. Virtually all of the helium gas is pumped from right to left through the 10-inch diameter pipe connected to the large vacuum pump. Two additional pumps below the expansion chambers (after the nozzle chamber) remove any residual helium while the ions remain captured in the center of the vacuum by an rf quadrupole ion-guide.

These slow, thermalized, and precisely controlled ions are passed through the concrete shielding wall via an evacuated pipe to the extremely precise LEBIT ion-trap, where they undergo detailed studies on their atomic masses. The LEBIT system can then pass these ions to other experimental devices for other studies or for reacceleration.

The concept of reaccelerating thermalized rare ions is also key to the success of the proposed RIA accelerator, and several groups around the world are working on similar collection systems. As part of the RIA R&D funded by DoE, the NSCL has developed a system that works with high pressure helium. Perhaps most importantly, the ions produced and studied at NSCL are the closest to those that will be produced by RIA.



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# LEBIT

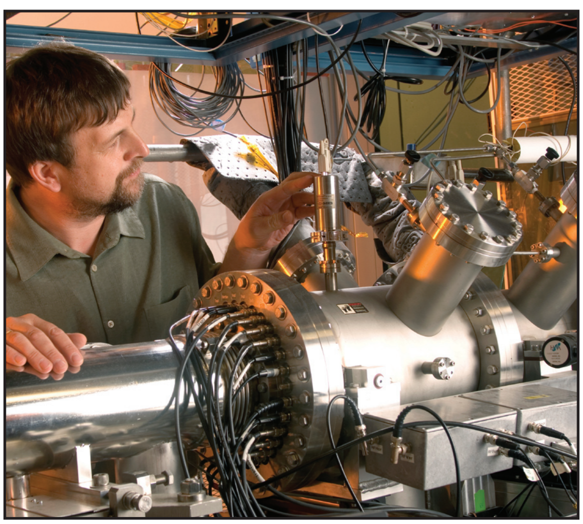
The N5 vault houses the Low Energy Beam and Ion Trap (LEBIT) project. With LEBIT, experiments with slow rare isotope beams are possible. Slow rare isotope beams are the key to such high precision experiments as accurate mass determination, techniques using laser spectroscopy, detailed observation of the decay of a nucleus, and more.

Bringing rare isotopes delivered by the A1900 Fragment Separator at close to half the speed of light to rest in the gas-stopping station in the N4-vault is the start of the low-energy beams for LEBIT. In LEBIT, ions from the gas-stopping station are collected in a device in which electric fields hold them in space. In this ion trap, the ions are brought almost to rest with much reduced random motion and eventually released as rapid, high quality bunches. These ion bunches can then be used for experiments, for example, high precision atomic mass measurements.

For high precision atomic mass measurements, the ions are sent into another ion trap, called a Penning trap. The Penning trap is a balance for weighing single atoms. In addition to an electric field for trapping atoms, the Penning trap uses a very strong magnetic field—about 300,000 times stronger than the Earth's magnetic field in East Lansing and a factor of approximately 10 stronger than the strongest permanent magnets that can be purchased. In the Penning trap, the precise measurement of the circular motion that an ion performs in the magnetic field (cyclotron motion) allows us to determine its mass with a precision down to 10 parts per billion. This is a precision comparable to that of weighing a 100-ton railway engine and being able to tell if a one-dollar bill was left inside or not. With LEBIT, this measurement precision can even be reached for rare isotopes that live less than one second.

Accurate mass measurements are important for learning how strongly neutrons and protons are bound together in a nucleus, for discovering subtle changes in the strength of this nuclear binding, and for delivering key data for fundamental tests and a better understanding of the synthesis of the elements.

A planned extension of the experimental program of LEBIT is laser spectroscopy, which allows scientists to probe the shape and size of a nucleus. NSCL is also considering experiments with beams that are reaccelerated to energies at which nuclei react in the cosmos.



This device is one of LEBIT's ion traps. Ions arriving from the gas-stopping station are collected in this trap and held in space. On demand, the ions can be released as high-quality ion pulses.

The high-precision and gold-plated electrode system of the LEBIT Penning trap which is located inside the large 9.4 Tesla magnet system of LEBIT. The ions are captured inside this trap and their mass is measured here



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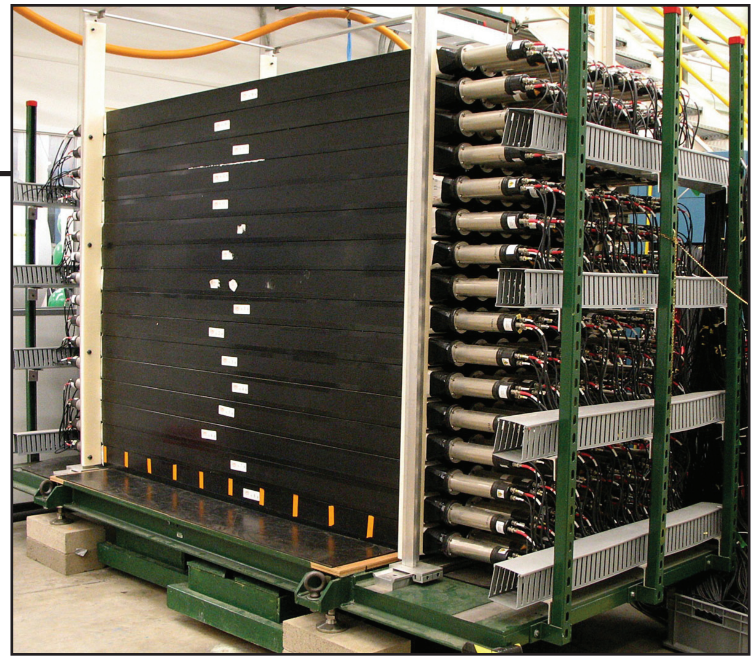
# The Modular Neutron Array (MoNA)



The Modular Neutron Array. This picture shows the 144 detector elements stacked in 9 planes of 16 each, with the photo-multiplier tubes visible at the left and right sides.

MoNA (the Modular Neutron Array) is a detector array specialized in detecting high-energy neutrons from the nuclear breakup reactions that occur when a rare isotope beam strikes a target placed upstream from the detector. A powerful dipole magnet, the Sweeper, is placed between the target and MoNA, deflecting all charged particles away from MoNA and into another detector system. Although the neutrons are moving at 30% to 60% of the speed of light, the detector is designed to detect 70% of all the neutrons that reach the detector.

MoNA measures the neutrons leaving the target, calculating the number of neutrons detected, their position, and their velocity (neutrons travel a distance of approximately 10 meters in less than 100 nanoseconds) in coincidence. All this information can be used to reconstruct a picture of the interior of rare neutron-rich nuclei, providing a deeper understanding of 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, such as supernovae and x-ray bursters. To determine the origin of the universe, understanding how nuclei behave on the edge of stability is essential—and MoNA is an an essential tool in this quest.

Since neutrons are not charged, they cannot be directly detected. Instead, they must react with a nucleus, for instance, by scattering off of it. The active detector material that MoNA utilizes, plastic scintillators, facilitates this reaction. The recoiling nucleus, charged from the collision, excites atoms as it moves through the scintillator. The excited atoms give off light, called scintillation, as they return to their ground state.

Because of the relatively long distance the neutron will travel in matter before it scatters, an efficient neutron detector requires a large volume of detector material. The detector array consists of 144 individual bars of clear plastic scintillator. The bars are stacked 16 high and 9 deep to form a large array. Each of these bars measures $10 \times 10\ cm^2$ and is 2 m wide. The ends of each detector bar are equipped with photo-multipliers to detect the faint scintillation light and amplify its initial signal by a factor of 30 million. The MoNA electronics enables us to determine the position of the light emission along the bar within a few centimeters by measuring the time difference of the signals at the left and right ends. This time difference must be known to within 250 picoseconds. With the precise timing information, we also can calculate the velocity of the neutrons from their flight time.

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# The S800 Spectrograph

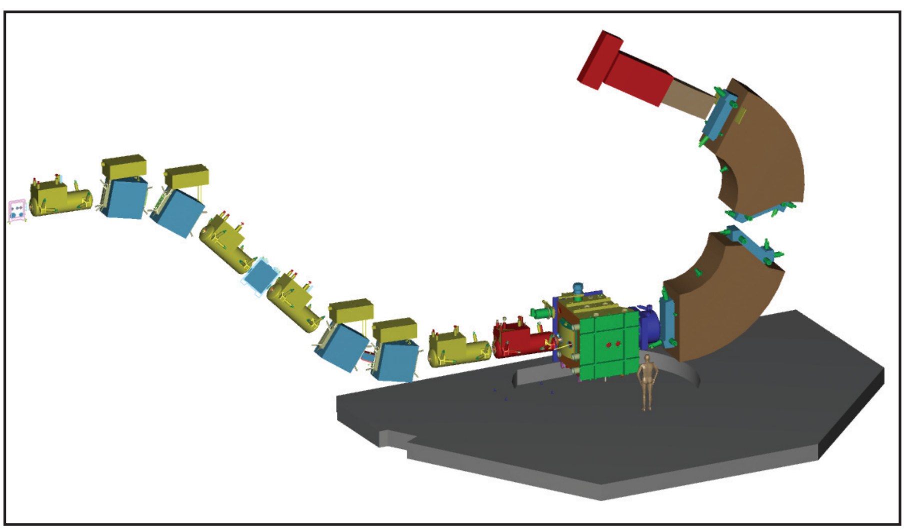
In this photo, the S800 spectrograph has been rotated almost 90° from the beam direction (the analysis line back toward the cyclotrons goes into the picture, behind the man). On the lower left and bottom is the track on which the carriage rolls. The spectrograph curves up to the detector box (with an MSU "S" on the side) on the second level.

The S800 superconducting spectrograph and its analysis beam line are used to measure the energy spectrum of charged particles with high precision.

The S800 spectrograph combines both high resolution and high acceptance in a single device and is specially designed for reaction studies with radioactive beams. Its large acceptances both in solid angle (20 msr) and momentum ($\Delta p/p=5\%$) are well adapted to the large emittances (coordinates of the particles in size and divergence) of secondary beams produced by projectile fragmentation. The high resolution is achieved via an analytical reconstruction method in which aberrations are calculated a priori using data based on measured magnetic fields and used directly to correct the raw data.

The S800 is installed vertically on a carriage that can rotate from 0° to 150°. Its maximum rigidity is limited to 4 Tesla-meters. The analysis line is an essential part of the device since it provides a measurement of the energy and angles of the incoming radioactive beam on an event-by-event basis. This feature is particularly important when using radioactive beams that have both large momentum spreads and emittances.

The S800 is the workhorse of the coupled cyclotron facility, with more than one-third of experiments performed using it.



Schematic layout of the S800 device, from the analysis line on the left, the scattering chamber in the middle where the reaction target is located, to the large acceptance spectrograph with its focal plane on the right.

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# The SRF Clean Room

A superconducting radiofrequency cavity made from niobium is being assembled in preparation for testing.

The superconducting radio frequency (SRF) class 100 and class 10,000 (number of 0.5 µm particles per cubic foot of air) clean rooms provide an environment free of contaminants to enable the development of superconducting cavity technology. An ultrapure (UP) water system (resistivity >17.5 MΩ·cm) is brought into the clean room to supply water for the ultrasonic cleaning and high pressure rinsing of parts.

Superconducting cavities allow scientists to accelerate beams of heavy ions to high energies with very high efficiency (Q0 = 1x1010). To do this, very high electric fields must be established on the metal (niobium) surfaces on the inside of the cavity. The high field produces a high voltage across the gaps inside the cavity, which gives the beam a large accelerating kick. In order to sustain the high field without losing the high efficiency, the surfaces must be very clean and free of dust particles. So the superconducting cavities are rinsed with high-pressure UP water at 1200 psi, sealed, and evacuated (vacuum 1x10-8 torr). The steps take place inside the clean room before being cooled to cryogenic temperatures (about –456° F).

To maintain the clean room quality, the air coming into the room is sent through HEPA (High Efficiency Particulate Air) filters in the ceiling and travels toward the floor. The flow is laminar, meaning that the air currents are very gentle, with almost no mixing within the flow. This traps contaminant particles in the downward flow instead of upward or sideways, which prevents dust from spreading.

The main challenge in operating the clean room is to minimize the dust brought in or produced inside. Parts must be thoroughly cleaned with acetone and methanol before they are brought into the clean areas. People working in the clean room must wear special clothing, including coveralls, hoods, face masks, and gloves. The room itself must be cleaned regularly.

Superconducting cavity research is part of NSCL's involvement in developing technology and design for the proposed Rare Isotope Accelerator (RIA). RIA will use a large number of superconducting cavities to accelerate heavy ions to high energies. With RIA, scientists will carry out a new generation of experiments in nuclear physics and laboratory astrophysics.

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# The Cryogenics Plant

Many of the magnets used at NSCL are superconducting. The NSCL operates its own cryogenics plant to supply the magnets with liquid helium. The plant consists of the following equipment:

- A main helium liquefier with a capacity of 800 liters/hr. (2 kW of cooling capacity at 4 K) sustains the day-to-day operations of the laboratory. This liquefier was installed in 1999.
- A 260 liter/hr. liquefier (1980 vintage), which operated in the laboratory before the coupled cyclotron was built and used for research, is configured to act as a gas purifier and is needed only occasionally.
- A 240 liter/hr. liquefier is only used to keep select magnets cold when the main liquefier is down for maintenance.
- The cryogen distribution network, which includes a distribution box and the rest of the transfer lines and valves. The distribution system transports liquid helium to every device in the lab and returns both cold gas (at approximately 5 K) to be reliquified and room-temperature helium to be compressed and liquefied. Liquid nitrogen is also transported to the magnets through these transfer lines.

To increase the efficiency of the liquefiers, liquid nitrogen is used to cool the compressed gas during the early stages in the plant until the gas is below 80 K. Since the lab does not produce its own liquid nitrogen, tanker trucks deliver it into storage Dewars from which it is dispensed as needed. Liquid nitrogen is used to cool intermediate-temperature shields, which reduce the heat load on the superconducting magnets by intercepting thermal radiation and conduction from the 300° K outer surfaces of the devices.

Programmable logic controllers (PLC) are used to control the operation of the liquefier and the filling of the individual magnet cryostats with liquid helium and liquid nitrogen. The higher level code "EPICS" is used to interact with these computers. Display, logging, some control of plant functions, and all control of magnet-filling cycles is carried out with conventional PCs.

The total 4.5 K cold mass of superconducting magnets is 109 tons and is contained in approximately 70 individual cryostats, These magnets require, on average, an inventory of almost 20,000 liters of liquid helium to keep them superconducting.

Two views of the main distribution box. This is the center point for sending cryogens to the rest of the lab.

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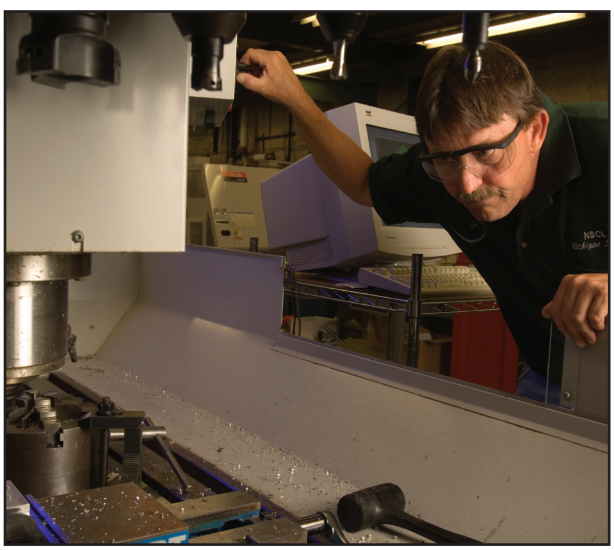
# The Machine Shop

A machine shop capable of producing and modifying complicated parts is essential to the operation and the experimental programs at NSCL. In 1985, the first computer numerical control (CNC) milling machine was purchased to allow the transfer of computer aided design (CAD) files directly to the machining center for fabrication. Since then, the machine shop has replaced older conventional milling machines with new CNC milling centers.

The current shop configuration consists of three Hurco CNC Milling Centers, one Milltronics CNC Milling Center, one Milltronics CNC Mini Mill with fourth axis capability, and two CNC controlled lathes, one of these with live axis tooling. All of the new machines are equipped with PC-based controllers. We have three Bridgeport mills, two with CNC controllers and the other with standard XYZ readout. CAD and CAM software is used to generate tool paths from 2D and 3D solid modeled parts designed in Mechanical Engineering. These tool paths are then electronically transferred to the machining center for fabrication. Keeping a modern machine shop enhances the capabilities of NSCL and also benefits outside users.

Highly skilled welders capable of performing vacuum-tight and cryogenic welds are essential to the cyclotrons and the diagnostic and beam delivery systems. Technical support personnel assemble, maintain, and repair equipment dedicated to running the cyclotrons and their related devices. The teamwork and dedication of the fabrication and assembly group is a major contributor to the successful experimental program at NSCL.



Precision machining on a CNC Milltronics Milling Center.


CNC programming of a lathe with live tooling.

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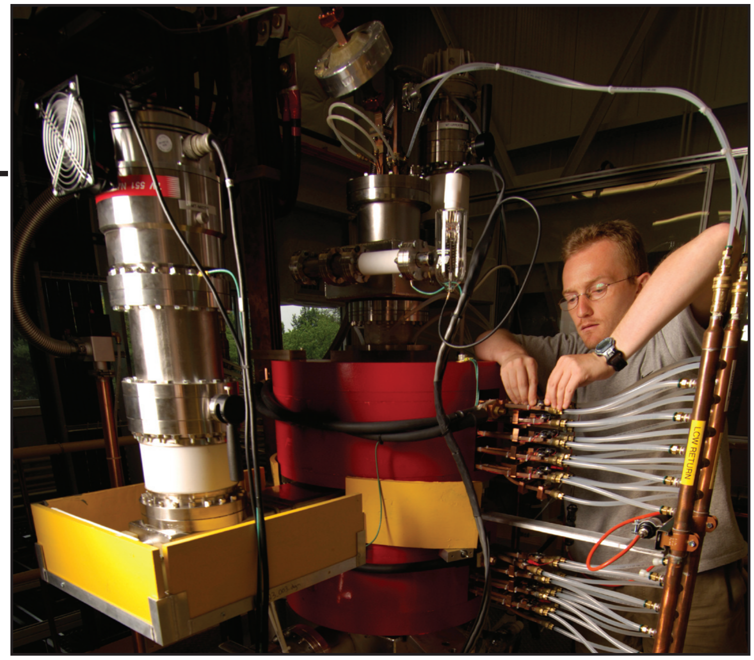
# Electron Cyclotron Resonance Ion Source Area

In the ion source area, two Electron Cyclotron Resonance (ECR) ion sources are available to produce the ions that are injected into the cyclotrons.

In an ECR source, the gas or vapor of the desired element is held in a specially designed magnetic field (a “magnetic bottle”). The elemental atoms are ionized through collisions with electrons kept in motion by microwaves. Circular coils at the top and bottom of the source chamber and a hexapole magnet produce the magnetic bottle around the sides. The transmitters of the microwaves that heat the electrons run at several times the frequency of a household microwave oven, which has a typical frequency of 2.45 GHz. A gas or vapor of the desired element enters at the top of the magnetic bottle. The corresponding ions are continuously extracted from the bottom and then sent to the cyclotron. A tiny oven is available to heat metals and other solid elements into a gaseous state.

NSCL has three ECR ion sources:

- The Superconducting-ECR (SC-ECR) uses superconducting magnets.
- Two copies of the Advanced Room TEMperature Ion Source (ARTEMIS) utilize normal conductor circular coils and permanent magnets arranged to make a hexapole. ARTEMIS-A is used as an injector in the cyclotrons. ARTEMIS-B is an off-line ion source with an associated beam line and is used for tests and new ion beam development. It is located in the South High Bay area.



Final adjustments being made to ARTEMIS-B, the research and development ECR ion source, located in the South High Bay.

The nuclear physics experiments performed at NSCL require the production of increasingly intense particle beams. When the transmission efficiency of the accelerators and beam lines reaches the maximum possible value, the only way to further increase the beam intensity is to increase the ion source output. The current worldwide trend in the field of ECR ion sources is to design and build new sources that operate at even higher microwave frequencies and with correspondingly higher magnetic fields. NSCL is in the process of constructing a new ECR ion source—Superconducting Source for Ions (SuSI) - that will operate with two frequencies (18 GHz and 14.5 GHz) and will use superconducting coils to produce the necessary magnetic field.



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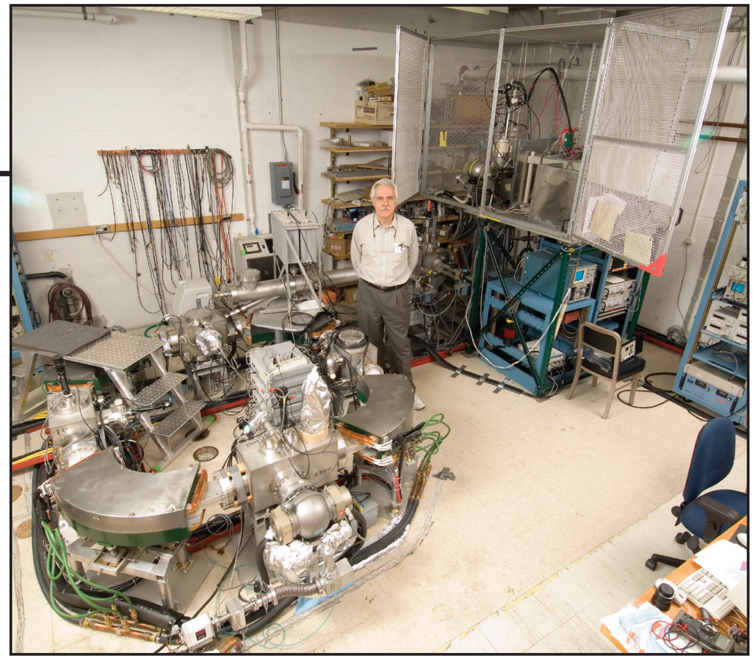
# The Small Isochronous Ring (SIR)



Photograph of the Small Isochronous Ring. The ion source (inside the cage in the upper right) produces ions that are injected into the four-sided storage ring. These ions are stored for a variable number of turns to study the evolution of the bunches due to space charge forces within the bunches.

The Small Isochronous Ring (SIR) was built to study the effect of the internal forces within the bunch of particles being accelerated in a cyclotron. Since access to the cyclotron is limited, the Small Isochronous Ring (SIR) makes it possible to perform long-term and detailed studies.

The Hydrogen ions are produced in the ion source (upper right of the photo inside the cage). Because the ion source produces more than one type of ion, they must be separated with a selecting magnet. The ions are then transported in the horizontal beam pipe and periodically injected in the ring. There is a slanted beam pipe that brings the ions to the lower horizontal plane where the ring is situated. The ring is composed of four ninety-degree bending magnets. In the four straight sections are an injection region, an extraction region (opposite to the injection region in the foreground) and two diagnostics regions (lying between the injection and extraction regions).

The dominant forces on the cyclotron beam are magnetic. They keep the beam focused and rotating in approximately circular orbits and the electric forces provided by the acceleration system. As the ions gain energy on each pass through the acceleration system, their orbits increase in radius and separate from the previous orbit.

At the extraction radius, a very thin plate of metal is inserted between orbits and an electric field is applied to redirect the last orbit toward the experimental area.

In a simple approximation, we look at the cyclotron as accelerating individual particles that do not interact among themselves. But when the number of ions being accelerated is significant, the charges in the beam produce an electric field that affects the other ions in the bunch and the single particle model is not valid any more.

The ions that are at the head of the bunch receive an electric force from the rest of the bunch that comes behind them. This is a repulsive force that tends to accelerate the particles in front of the bunch, which will gain more energy than the ions in the middle. Similarly, the ions at the tail of the bunch will receive a force that pushes them back, loosing energy.

The radius of the ion orbits in the cyclotron is determined by their energies. The energy spread introduced by the intra-beam forces generates an increase in the radial width of the bunches in each turn. This effect will reduce (and sometimes eliminate) the separation between turns at extraction. This reduced turn separation will prevent the extraction of the beam without losses. For intense beams (many kW or even 1 MW), this is a fatal problem.

By scaling down the parameters such as energy and beam current, the experimental setup of SIR allows us to study these effects and benchmark the computer codes used to design the accelerators using just a small fraction of the power of the big cyclotrons and with much simpler diagnostics.



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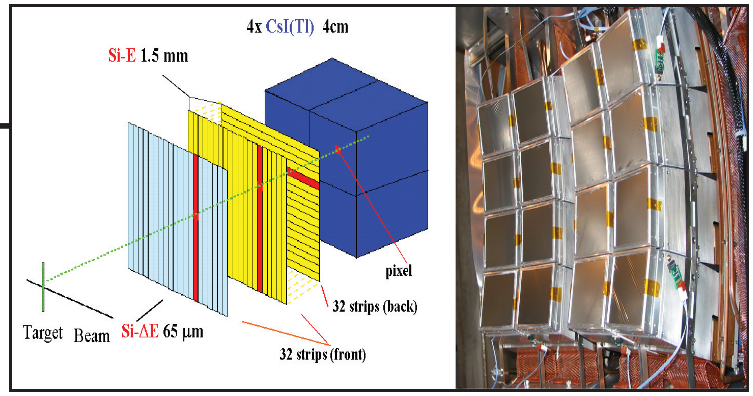
# The HiRA Strip Detector Array

The High Resolution Array (HiRA) is a state-of-the-art detection array capable of detecting charged particles produced in nuclear collisions. In addition to measuring their energy and identifying their mass and charge, the array provides the precise positions of detected particles. To allow flexibility to configure the arrays in different geometries, HiRA consists of 20 modules, called "telescopes," that have individual active surface areas of 64 mm x 64 mm. Further information can be found at http://groups.nscl.msu.edu/hira

Each telescope has three layers of detector material. The first two layers are made from high-purity silicon. Charged particles that enter these detectors create a short-lived pulse of current, which is collected on electrodes on the front and back surfaces of the detectors. These electrodes are subdivided into 2 mm wide strips; each electronic pulse in a strip indicates that a charged particle has passed through it. By arranging the front strips vertically and the back strips horizontally, the front and back strips can be correlated to localize the trajectory of the particle to a point (called a pixel) on the detector 2 mm x 2 mm in area.

Lower energy particles typically penetrate the first silicon detector and stop in the second. Higher energy particles penetrate both and stop in a Cesium iodide (Thallium doped) (CsI (Tl)) crystal that emits light when hit by a charged particle. The charge detected in the silicon detectors and, if availiable, the light in the CsI (Tl) are analyzed to obtain the energy, charge, and mass of the particle.

One technological advance in the HiRA detector is the Application Specific Integrated Circuit (ASIC), developed at Washington University, to process the signals produced in the first two layers of the silicon detectors by the passage of charged particles. Compared to the electronic modules used in previous nuclear physics experiments, ASIC decreased the size of the electronics needed from that of a small suitcase to that of a postage stamp. It also reduced the cost by approximately a factor of ten.




The photo shows one arrangement of 16 HiRA telescopes in an actual experimental setup. Each element in the array is a compactly packaged HiRA telescope. The schematic diagram on the left shows the layout of one HiRA telescope, which consists of 3 detectors—a very thin silicon wafer divided into 32 vertical strips, a thicker silicon wafer with the front side divided into 32 vertical strips, and a back side divided into 32 horizontal strips backed by four CsI (Tl) scintillator detectors. Each telescope requires 100 channels of electronics to process the detected signals. During the experiment, the front of each HiRA telescope is covered by a very thin mylar foil to protect the detector from light. The compact design requires that all the electronics be channeled to the back of the detectors beyond the view of the photograph.

HiRA was commissioned in the summer of 2005. In its first year of operation, it was used in four experiments to study the structure of unstable nuclei and the reaction mechanisms that produce them. Other experiments have been performed to measure the masses of nuclei that may be important to rapid hydrogen burning on the surfaces of neutron stars. Such burning processes are believed to be the likely source of astronomical X-ray bursts. Future experiments will expand the scientific agenda for HiRA.

HiRA was built by a collaboration of scientists at NSCL, Washington University in St. Louis, Indiana University, Western Michigan University, Southern Illinois University at Edwardville, and INFN in Milan, Italy.



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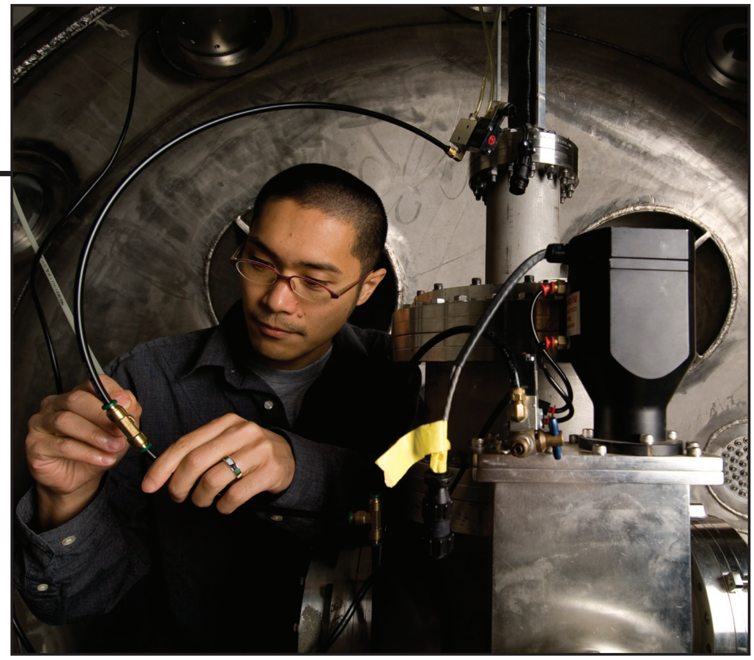
# N3 Vault


An experimenter sets up a self-contained beam line inside the 92″ scattering chamber.

The N3 vault is the most general purpose experimental area in the laboratory. The primary device in this vault is the 92″ scattering chamber, a cylindrical stainless steel vessel 92″ in diameter and approximately 120″ long, designed to house complex detector arrays in vacuum.

Two types of experiments are carried out in this vault—those in which the experimental apparatus is inside the large vacuum chamber and those in which the chamber vessel is removed and a small self-contained beam line is built. In a typical chamber experiment, the vacuum vessel is evacuated in about 45 minutes to about 3 x 10-6 Torr using two large turbo pumps and a liquid nitrogen cold trap.

Beams from the coupled cyclotrons enter the N3 Vault from the west wall and are focused by the superconducting quadrupole magnets in the large white box onto the experiment target. The coupled cyclotron beam then strikes a thin foil target in the center of the vacuum chamber. The detector apparatus can be rotated about the target by remote control using a motorized turntable and arm systems. After passing through the detection system, the beam is deposited in a shielded beam dump in the east wall of the vault. Electrical signals from the experiment are passed out of the chamber through hermetically sealed BNC, SHV, and Lemo feedthroughs mounted on the circular ports of the chamber.

Typically, experiments at the NSCL use racks of electronics just outside the chamber to process the signals from the detectors. Once processed, the information is passed to computers in the data rooms using Ethernet connections.

The HIRA detector was commissioned in the N3 vault. This is one of the setups that uses the entire vacuum vessel. If an experiment does not require the large vacuum vessel, the back two-thirds of the chamber and the turntable system can be removed from the vault and a self-contained beam line constructed. These beam lines are built for experiments using gamma ray or neutron detectors. If an experiment needs liquid nitrogen, a supply tap is available. If a piece of experimental apparatus is too large for the door, the N3 vault roof is opened so that the laboratory's 40-ton crane can lower it into place. In this configuration, experiments have been carried out with the SEGA detectors, APEX, and β-decay setups.



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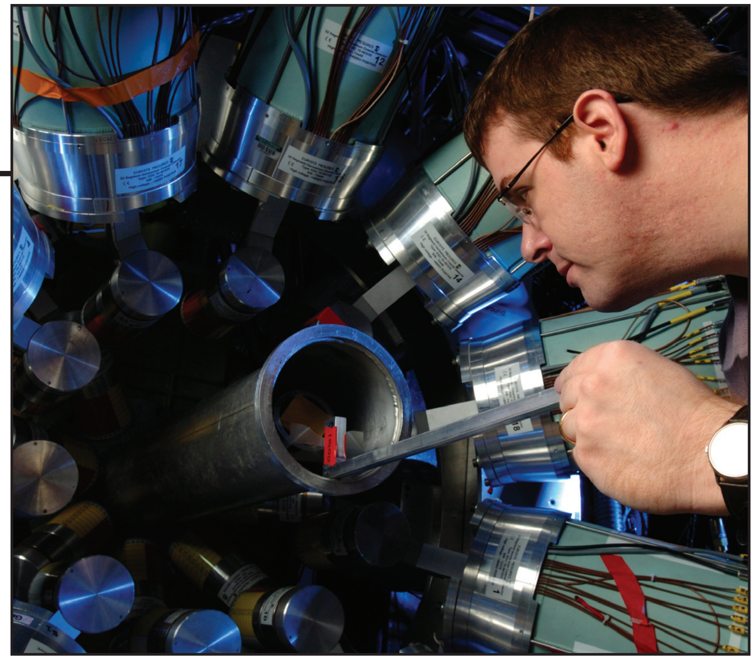
# Segmented Germanium Array (SeGA)



A graduate student inserts a target into the vacuum pipe at the center of the SeGA array.

The Segmented Germanium Array (SeGA) is a γ-ray detector with up to eighteen 32-fold segmented germanium detectors that are used primarily for the efficient detection of gamma rays from in-flight nuclear reactions. The high degree of segmentation facilitates the precise determination of the interaction point in the germanium crystal. Together with the knowledge about the emission point of the γ-ray, the γ-ray energy emitted from the fast-moving particles can be reconstructed.

A few examples of reactions studied are intermediate-energy Coulomb excitation, which probes the charge distribution of a nucleus; inelastic proton scattering, which yields information about the matter distribution within a nucleus; and one- and two-nucleon knockout reactions that provide information on the single-particle structure of a nucleus is studied. Because of the efficiency of the array and the sensitivity of these techniques, the structure of many, or very exotic, nuclei (some produced at rates of less than 100 particles/sec) can be studied at NSCL.

SeGA represents the first large-scale implementation of highly-segmented germanium detectors for use in intermediate-energy in-beam studies. Because of the high velocities of the beams from the Coupled Cyclotron Facility (typically greater than 30 percent of the speed of light) the study of inbeam gamma-ray decays had been hampered by the fact that the minimum opening angle (and hence the ability to correct for the Doppler shift of the gamma ray) of existing detectors was limited by the size of the detector. This meant that it was impractical to utilize the superior energy resolution of germanium (compared to other gamma-ray spectrometers) because of the large size of these detectors. With the development of the 32-fold segmented SeGA detectors, it is now possible to localize the interaction of gamma rays within the individual counters and consequently know the angle of emission of a gamma ray to a precision that is much smaller than the size of the detector.

SeGA is designed as a multifunctional tool to be used in conjunction with the other permanent devices at NSCL, such as the S800 spectrograph, the Beta Counting System, and the Sweeper Magnet. SeGA has also been used for g-factor measurements and to tag isomeric beams. SeGa has been used in more than 20 Ph.D. experiments since 2003.



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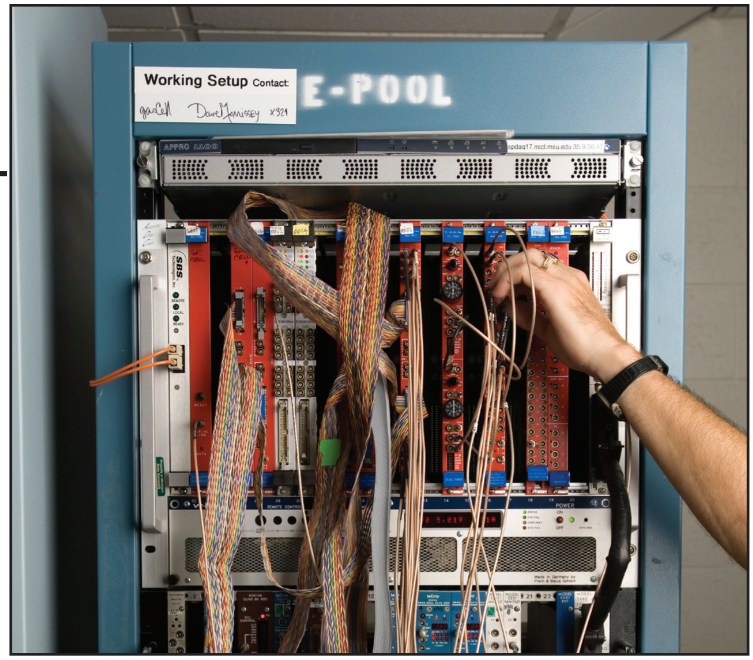
# Data Acquisition




Parts that comprise the beginning of the acquisition station.

Experiments at NSCL produce enormous amounts of data for analysis. Computers systematically acquire, record, and analyze these data. To be manipulated by computers, the raw pulses that come from a detector must be turned into numbers representing many different quantities, such as the height of a pulse, the charge in a pulse, or the timing of a pulse, relative to the accelerator rf or to pulses from other detectors.

The picture on this page shows the parts that comprise a typical data acquisition station. Signals from the detectors are cabled to Analog Electronics. Here, various modules shape and amplify the weak signal amplitudes (on the order of millivolts) and fast (nanoseconds) signals into more manageable pulses (volts and microseconds).

Specialized discriminator modules are also used to create logic signals that indicate the presence or absence of a usable signal from a segment of the detector array. The purpose of these logic signals is to determine if, on the whole, an interesting event has occurred that should be recorded. If an interesting event has occurred, signals are sent to the digitizers that turn the pulses into numbers for the computer. A "master trigger" signal is sent to the computer to tell it to read out the digitized data. The acquired data are then made available to standard PCs in the online data analysis area (Data U's) over a standard local area network and are also recorded to a disk for more detailed analysis later.

The experimental software group at NSCL is a recognized leader in the field of data acquisition and analysis in nuclear physics at the scale performed at NSCL. Nearly 25 other institutions have expressed interest in using the NSCL data acquisition and analysis system at their own institutions. The MSU Board of Trustees has allowed NSCL to release software as an open source project to all interested parties. Both the analysis and acquisition components are now hosted at sourceforge.net, an open source community development hosting service.



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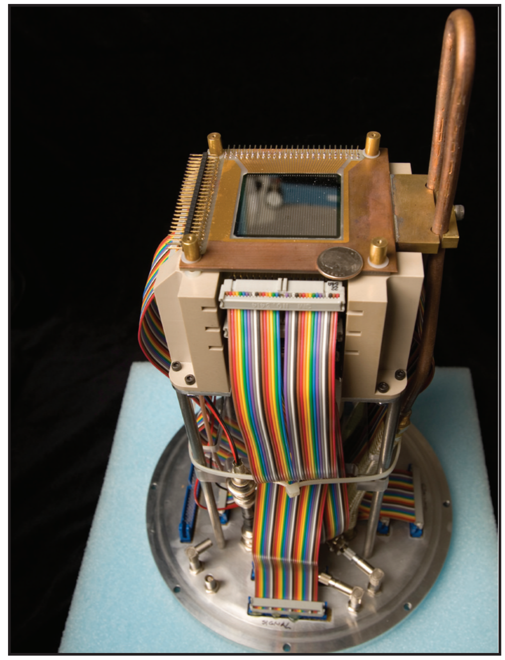
# Beta Counting System (BCS)



The Beta Counting System detector stack. The detector in view is the DSSD implantation detector.

The beta counting system (BCS) is used to obtain data on lifetimes of nuclei far from the line of beta stability, where experimental data are very limited. The most probable decay pathway for such exotic nuclei is beta decay, where a proton (neutron) transforms to a neutron (proton) with a corresponding release of energy that is carried off by two particles: an electron (positron) and antineutrino (neutrino). Beta decay lifetimes of nuclei far from stability are important to characterizing nuclear structure and to defining the mass-processing path of the rapid-neutron capture process in the cosmos responsible for the production of more than 60 percent of the heavy, stable isotopes found in nature.

The BCS consists of a series of silicon semiconductor detectors that are used to measure the energy-loss signals of both low-energy beta particles and high-energy implantation events. The centerpiece detector of the BCS is a double-sided silicon microstrip detector (DSSD) that has 40 strips in each of the horizontal and vertical directions, thus providing 1600 pixels for position correlations.

The fast fragmentation beams from the A1900 are stopped in the DSSD, and information (energy-loss, time-of-flight, total kinetic energy) corresponding to each implantation event is recorded. These implantation events are then correlated with beta decays on an event-by-event basis, where both position and time information is used to uniquely assign a low-energy beta-decay event with a high-event implantation event. The decay lifetime is derived from the difference in the absolute time stamps that are also recorded for both implantation and decay events.

The BCS serves as the main trigger detector for delayed spectroscopy experiments that utilize the Segmented Germanium Array (SeGA) and the Neutron Emission Ratio Observer (NERO). A beta calorimeter system is also available to measure the total energies of the fast electrons emitted during beta decay, which provides direct information on the masses of short-lived nuclei.

The combination of BCS and NERO has been successful in determining the beta decay half-lives of several neutron-rich nuclides that lie near and along the astrophysics rapid-neutron capture process (r-process). Modeling the r-process can be markedly enhanced with improved experimental data, including information on beta lifetimes, masses, and delayed neutron branching ratios for nuclei far from stability, all of which can be achieved using the BCS.

Beta-delayed gamma-ray spectroscopy completed using the BCS-SeGA combination has revealed important new information on the transitioning between spherical and deformed shapes for neutron-rich nuclei. Such transitions can be used to understand why certain proton and neutron numbers become favored as one reaches the limits of stability. For example, the appearance of a new subshell closure at N=32 for neutron-rich ${}_{24}Cr$, ${}_{22}Ti$, and ${}_{20}Ca$ nuclides was inferred based on beta-decay half-lives and the low-energy quantum structure of the beta-decay daughter nuclides collected using the BCS coupled with SeGA. Continued exploration of the neutron-rich region of the chart of the nuclides can help improve on the theoretical description of the nuclear system.

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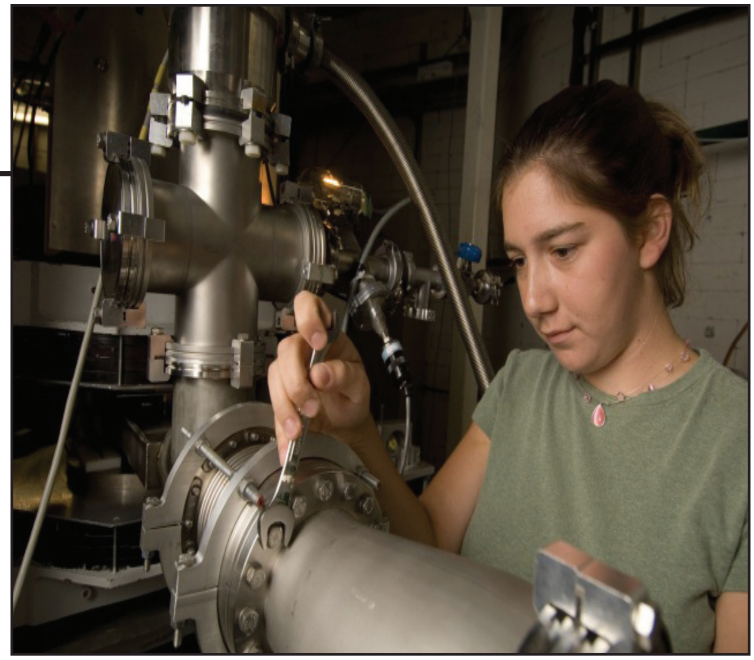
# beta-Nuclear Magnetic Resonance (beta-NMR)


Student adjusting diagnostic chamber upstream of beta-NMR magnet.

The beta-Nuclear Magnetic Resonance (beta-NMR) apparatus is used to measure ground state dipole and quadrupole moments of radioactive nuclei having very short half-lives. The ground state magnetic dipole moment carries information on the orbital contribution to the state wavefunction, while the electric quadrupole moment is a direct measure of the nuclear charge distribution away from spherical symmetry. Knowledge of nuclear dipole and quadrupole moments provides a sensitive test for theoretical models, since the electromagnetic operator has a well-known form.

The beta-NMR consists of a small electromagnet with a foil at its center to catch the fast moving radioactive beam from the A1900 fragment separator. Surrounding the foil is a pair of plastic scintillator telescopes to detect beta particles emitted from the stopped radioactive beam. Small, multiturn copper coils around the implantation foil introduce a continuous wave radiofrequency signal into the sample.

A beta-NMR spectrum is obtained by determining the ratio of the beta counting rates in the two beta telescopes as a function of the incoming frequency of the radio waves. At resonance, a deviation of this counting ratio is observed. For a magnetic dipole moment measurement, the frequency of absorbed radiation required to reach resonance is directly related to the magnetic dipole moment divided by the nuclear spin. Multiple resonances are observed during a quadrupole moment measurement due to the additional interaction of the nuclear quadrupole moment with the inherent electric field gradient of the implantation foil.

The beta-NMR is operated under the same physical principles as the Magnetic Resonance Imaging (MRI) method for medical diagnostics. Typical magnetic resonance experiments, like MRI or NMR for organic molecule characterization, require large sample sizes for successful measurements; however, by detecting the emitted beta particles from the sample, a gain in sensitivity of 14 orders of magnitude is realized by beta-NMR measurements compared to conventional NMR and MRI.

One area of focus at NSCL has been the measurement of the magnetic moments of mirror nuclei, which differ only by the exchange of proton and neutron numbers. The summed magnetic moments of mirror nuclei provide an important framework for testing isospin symmetry in nuclei. Ground-state magnetic moment data are limited for short-lived radionuclides above mass 30, where the stronger Coulomb fields (due to larger Z value) and small proton separation energies may affect isospin symmetry. We have extended the known magnetic moments for isospin 1/2 and 3/2 mirror systems to mass 57 and 35, respectively, and observed no significant deviations from theoretical predictions.

For a successful beta-NMR measurement, the radioactive beams from the A1900 must be spin-polarized. Recently, we have demonstrated that secondary beam polarization can be achieved via nucleon pick-up reactions onto projectiles traveling at intermediate energies. Beams of polarized nuclei have applications beyond nuclear physics. The availability of polarized radioactive beams at the NSCL will offer new opportunities for multidisciplinary research, ranging from studies of fundamental interactions to materials science.

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# Deflector Test Stand

The purposes of the deflector test stand are to test operational deflectors before installation in the cyclotrons and to test how to improve deflector performance.

The deflectors are high voltage devices residing at the extraction radius of the cyclotrons. Each cyclotron has two of them. Their purpose is to provide an electric field on the order of 100 kV/cm that accelerates the particles in the radial direction, deflecting them into the extraction channel at the start of the extraction orbit. Each deflector has a negatively charged, high voltage electrode, up to one meter in length and powered by a high voltage power supply. An electric field exists between the electrode and a 0.010-inch thick grounded plate. The particles pass between the plate and the electrode, bending their paths into the extraction channel.

Deflectors must be periodically removed, disassembled, and cleaned. After this process they are put in the test stand to run for one to four days in a conditioning process. A deflector can not usually operate at required voltages upon installation but must go through a period of slowly improving performance. Conducting a conditioning procedure in the test stand shortens the time required to condition the deflectors. It also verifies that the deflector is not seriously flawed. In the test stand, a vacuum is obtained by means of a roughing pump and a cryo-pump, a magnetic field is supplied, and a high voltage is supplied through a K1200 cyclotron-style feedthrough from a high voltage power supply. By injecting small amounts of oxygen into the deflector, the capability of holding high voltage is improved. A computer program ramps and monitors the voltage, turning the voltage up when possible and lowering it when the current is excessive. The ramp rate, current limit, turn down rate, and oxygen flow rate are controllable through the program. The computer also allows for efficient, long-term conditioning.

We use the test stand to test modifications to components, different materials, and effects on high voltage. Insulators may be tested independently; feedthroughs may be tested alone; and conditioning techniques may be investigated. We have short pseudo-deflectors that simulate small deflectors. In these we test combinations of materials, types of insulators, and conditioning techniques.

The Deflector Test Stand. It is placed inside a magnetic field. The long tube at the bottom of the picture is the high voltage feedthrough.

On the bench is a deflector for the K1200 cyclotron, called the E2 deflector. The septum is removed and one can see the high voltage electrode.

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