2024 OPEN HOUSE ACCELERATOR TOUR POSTERS

WHY STUDY ACCELERATORS?

- Our scientists are constantly inventing new ways to make CEBAF and other particle accelerators more efficient and reliable.
- There are over 40,000 particle accelerator systems used worldwide.*
  - 65% are in industry: non-destructive testing is one use.
  - 30% are in medical settings: cancer therapy is one use.
  - 5% are in research: this includes CEBAF.
- Eventually, we may use particle accelerators to
  - Treat drinking water.
  - Clean up contaminated soil.
  - Increase the efficiency of industrial processes.
- The more we learn about particle accelerators, the more possibilities there are.

*DOE Office of Science: https://science.osti.gov/ardap/Benefits-of-Accelerators

WHY STUDY PARTICLES?

- In "Quantum Universe: The revolution in 21st Century Particle Physics" published by the DOE and NSF, nine fundamental questions are posed:

Questions for the Universe

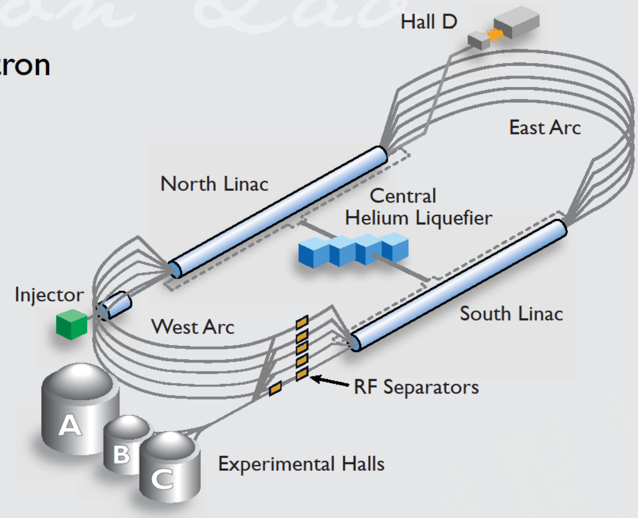
1. Are There Undiscovered Principles of Nature: New Symmetries, New physical Laws? *
2. How Can We Solve the Mystery of Dark Energy? *
3. Are There Extra Dimensions of Space?
4. Do all Forces Become One?
5. Why Are There so Many Kinds of Particles? *
6. What Is Dark Matter, and How Can We Make it in the Laboratory? *
7. What Are Neutrinos Telling Us?
8. How Did the Universe Come to Be? *
9. What Happened to the Antimatter? *

- Investigating these questions not only teaches us a lot about the universe, it pushes us to invent new technologies.

* CEBAF was built to support particle physics experiments exploring these questions.

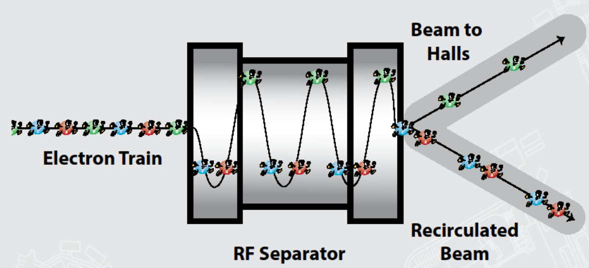
CEBAF BASICS

- CEBAF = Continuous Electron Beam Accelerator Facility
- Our Mission: to continually provide a high-quality electron beam to as many as 4 different experiments (Halls) at the same time.
- The electron beam is produced using lasers to knock electrons free from a gallium arsenide wafer.



Accelerator Overview

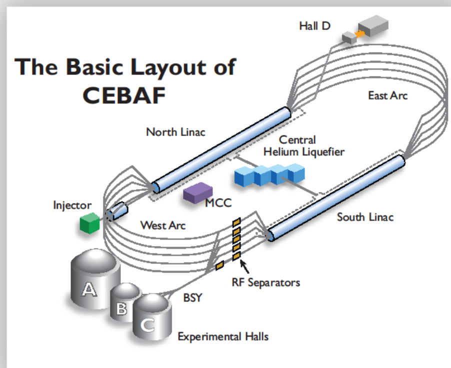
- In the injector, the electrons are formed into bunches. The bunches are lined up and pushed into the accelerator - this train of electron bunches is our beam.
- The bunches are accelerated as it goes through the North Linac. Magnets steer them around the East Arc, then they are accelerated again in the South Linac.



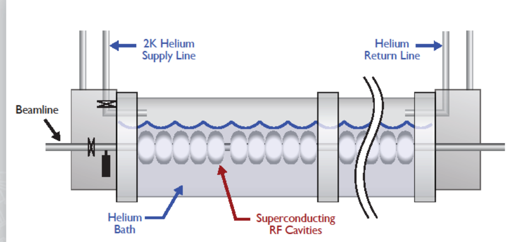
- After accelerating, some bunches may be separated out to go into an experimental Hall, where they will slam into a target. This opens up atoms and lets us look at what they're made of.
- Bunches that do not go into a Hall swing around the West Arc and re-enter the North Linac for more acceleration. They will be joined by more electron bunches coming out of the injector.
- Electron bunches can loop around the accelerator up to 5 times (or 5.5 times if they're going to Hall D) before they go into an experimental Hall.

WHAT DID THEY SAY?

- **JLab ("jay-lab")** - Thomas Jefferson National Accelerator Facility (Jefferson **Lab**oratory) - a U.S. Department of Energy Office of Science national laboratory.
- **CEBAF ("see-baf")** - **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility - the name of JLab's large, racetrack shaped particle accelerator.



- **The MCC** - The **M**achine **C**ontrol **C**enter - the building that houses the Control Room, where Operators control CEBAF.
- **Injector** - Where the electron beam is created and pushed into the first linac.
- **Linac** - **LIN**ear **AC**celerator - A straight part of the CEBAF racetrack, where the electrons accelerate through cryomodules.
- **Arc** - A part of the CEBAF racetrack where magnets steer electrons through a U-turn and into the next linac.
- **Cryomodule** - An insulated tank that contains RF cavities bathed in liquid helium.



Cryomodule Cutaway

- **RF** - **R**adio **F**requency - We use radio frequency microwaves to accelerate electrons through the cryomodules.
- **RF Cavity** - A bumpy looking cylinder made of niobium through which electrons accelerate.
- **RF Separators** - Components that use RF energy to separate the beam into individual, experiment-specific strands.
- **BSY** - **B**eam **S**witch**Y**ard - The area where magnets steer the separated strands of beam into Halls A, B, and C.

Jefferson Lab

VIRGINIA IS FOR SCIENCE LOVERS

CEBAF TIMELINE

WHAT'S NEXT???

- The upcoming MOLLER experiment will push CEBAF to the limit. There are about 150 other experiments planned or in the approval process—with more proposals coming.
- Future upgrades?? Physicists have a lot of ideas—Can we reconfigure CEBAF to produce positrons? Should we go for 22 GeV?—but nothing is settled yet.

2023
Injector upgrade including a new booster.

2018
Simultaneous beam delivery to 4 experimental Halls.

2017
12 GeV upgrade complete

2000
Reaches design energy of 6.07 GeV, 12 GeV upgrade proposed.

2003
12 GeV upgrade named as a DOE priority.

2009
Construction for the 12 GeV upgrade, including Hall D, begins.

1999
2nd polarized electron gun installed.

1997
First 5-pass, 4GeV, 3-beam separation to 3 experimental Halls.

1995
Beginning of physics experiments.

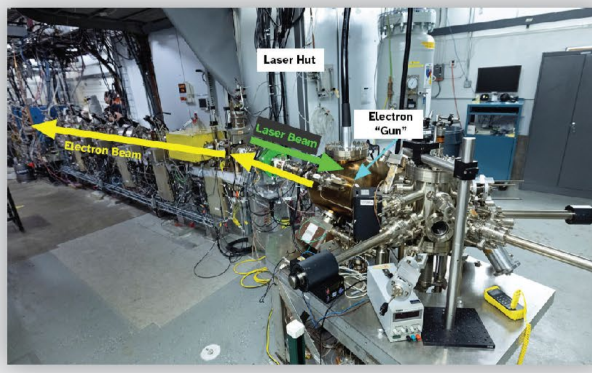
1976
Physicists request facility to study quarks.

1984
Newport News site chosen, CEBAF funding approved.

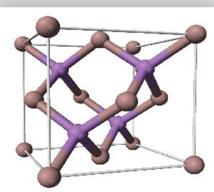
1987
Construction begins.

THE INJECTOR: MAKING BEAM

- The electron beam originates in the Injector.
- Four lasers (one for each experimental Hall) alternately pulse light towards our electron "gun."

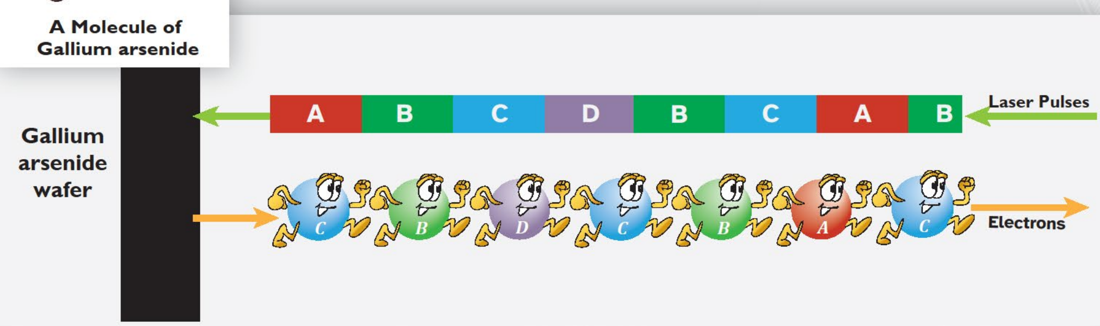


- We can vary the characteristics of the light produced by each laser. This yields electrons that are custom made for each experiment.



A Molecule of Gallium arsenide

- There is a cathode containing a gallium arsenide wafer inside the gun. Laser light hits the wafer, and electrons (photoelectrons, specifically) are emitted.



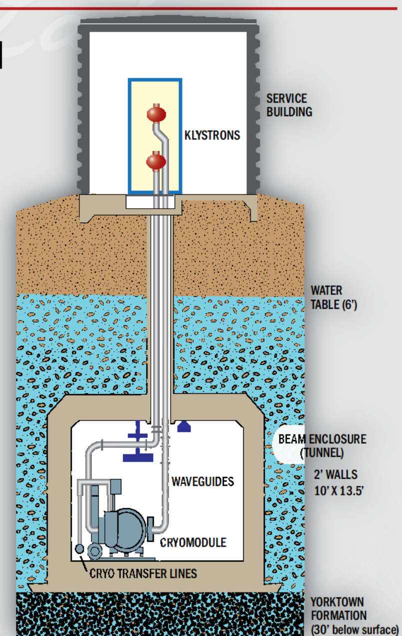
- The electrons are drawn away from the gun at about 50% of the speed of light. We use magnets and RF energy to form & transport the electron bunches that make up our beam.
- The electrons are accelerated first by the Booster, then by two more cryomodules. They reach about 99.99% of the speed of light before they enter the North Linac.

THE TUNNEL

- You are 25' underground and surrounded by water!
- The race-track-shaped tunnel is 7/8 mile around (1.4 km).
- Tunnel dimensions are 10' high by 13.5' wide.

The water table is about 6' below the surface of the ground, so the tunnel is under water.

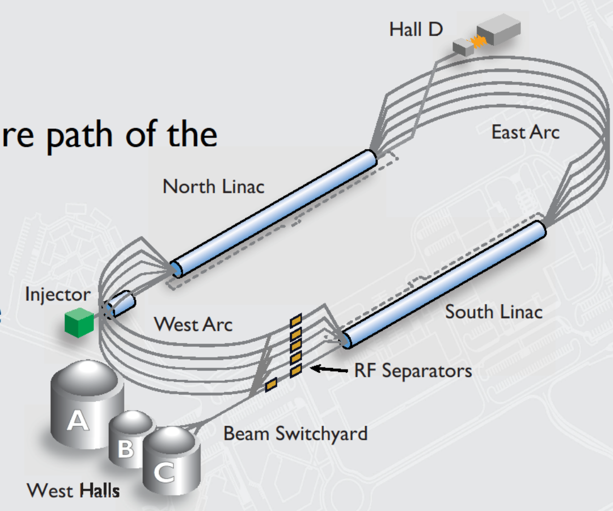
- The base of the tunnel rests on the Yorktown Formation, an old sea bed.
- It has 2' thick walls of steel-reinforced cast concrete.
- ~25,000 cubic yards of concrete were used to build the tunnel, which equals 12 miles of concrete trucks



Tunnel Cross Section

INSIDE THE TUNNEL

- The tunnel contains the entire path of the electron beam including
  - The injector,
  - Two linacs, each ~1/4 mile long,
  - Two arcs, each with five stacked beamlines,
  - The line going to Hall D, and
  - The beam switchyard.

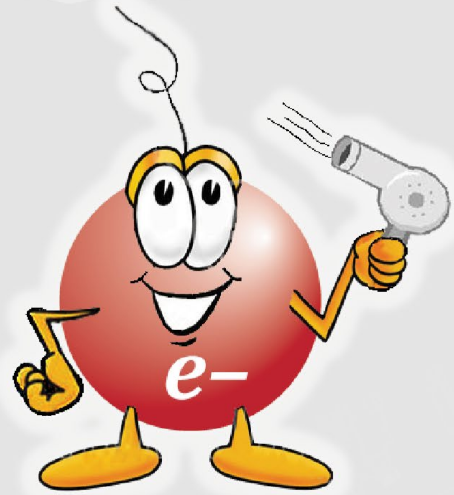


Jefferson Lab

VIRGINIA IS FOR SCIENCE LOVERS

THE ELECTRON BEAM

- The beam size is 200 microns—about the width of a human hair.
- The beam travels at almost (~99.999999998%) the speed of light (186,282 miles/second).
- It could circle the earth in the blink of an eye.
- Out of 20 electrons in our beam, 19 have the same spin (or the same polarity). In nature, electron spins are usually random.



Hair Thin Electron Beam

- Beam energy can reach 12 GeV (12 billion electron-volts).
- The beam will quickly burn through the vacuum tube if missteered. Fast-shutdown safety systems help keep that from happening.

THE BEAMLINE

- When not zinging through a cryomodule, the electron beam goes through a tube made of stainless steel, aluminum, and ceramic segments.

- Vacuum in the beamline is between 1×10^{-6} and 1×10^{-10} torr. The vacuum keeps the beam from hitting air molecules.
- Magnets mounted around the beamline steer and focus the beam.
- Sensors along the beam line help to monitor and troubleshoot beam transmission.
- Precision is important! Beamline elements are aligned to within ±0.5 mm of their design locations.
- The beam will quickly burn through the vacuum tube if mis-steered. Fast-shutdown safety systems help keep that from happening.

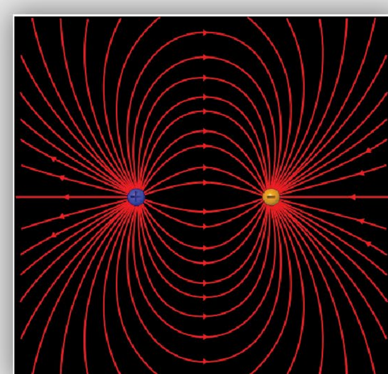
	Pressure in torr
Earth's atmosphere	760.0
Vacuum cleaner	600.0
Light bulb	0.1
Thermos bottle	0.001
JLab beam pipe	0.000001
Outside the ISS	0.000000001
JLab Cryomodule	0.0000000001
Deep space	0.0000000000001
Perfect vacuum	0.000000000000000 . . .

MAGNETS

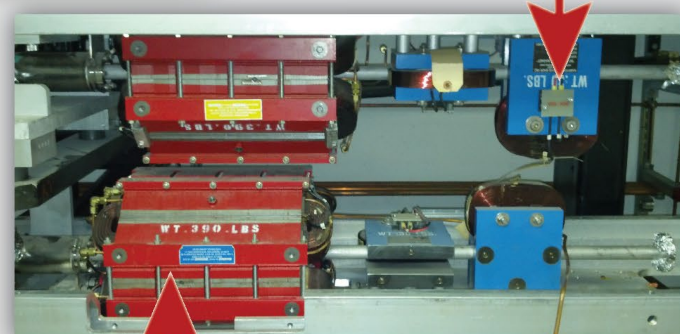
- Magnets steer and focus the beam.
- There are ~2,500 magnets in the accelerator.

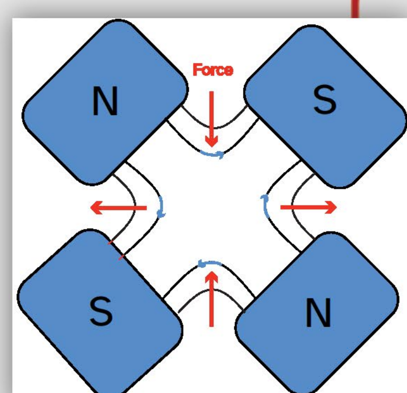
Quadrupoles

- Are usually painted red.
- Are used for focusing the beam.
- They generally work in pairs: one focuses the beam in the horizontal plane, the other in the vertical plane.



Correcting Dipole Forces





Focusing Quadrupole Forces

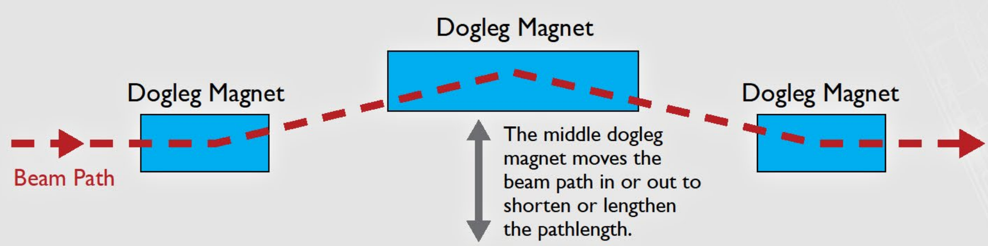
Dipoles

- Are usually painted blue.
- Are used for steering.
- Large dipole magnets bend the beam around the arcs.
- Small ones make fine steering corrections.

DOGLEG MAGNETS

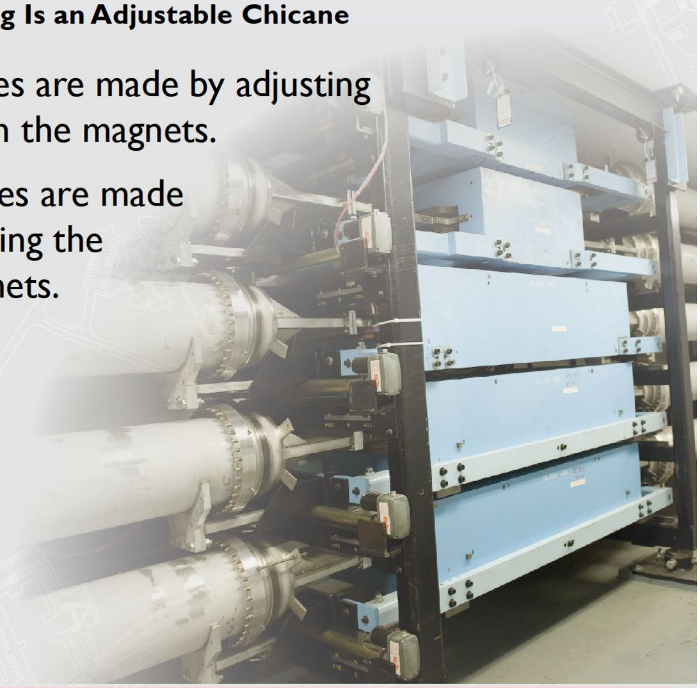
- The beamline expands and contracts as the temperature changes.
- The distance an electron must travel around the loop can vary by as much as one centimeter.

- ANY variation of pathlength means that the electrons will miss the crest of an RF wave and will not accelerate.
- Dogleg magnets are adjustable and let us control the pathlength. There is a set of them after each spreader.

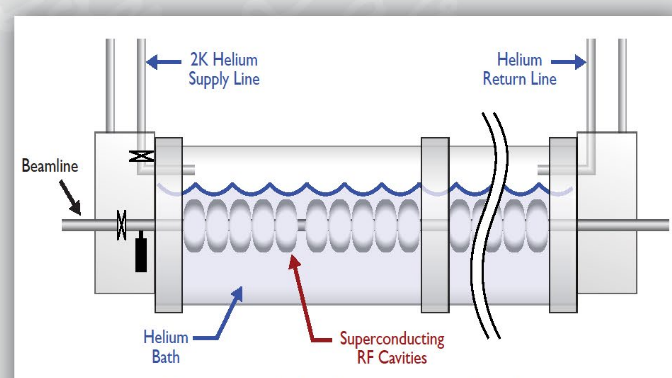


Each Dogleg Is an Adjustable Chicane

- Small pathlength changes are made by adjusting the field strength within the magnets.
- Large pathlength changes are made by physically repositioning the motorized dogleg magnets.



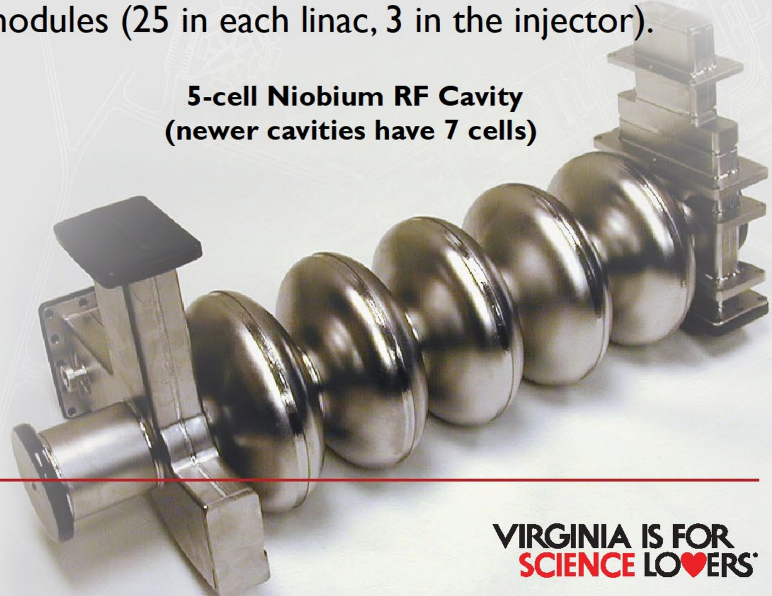
CRYOMODULES



Cryomodule (cutaway view)

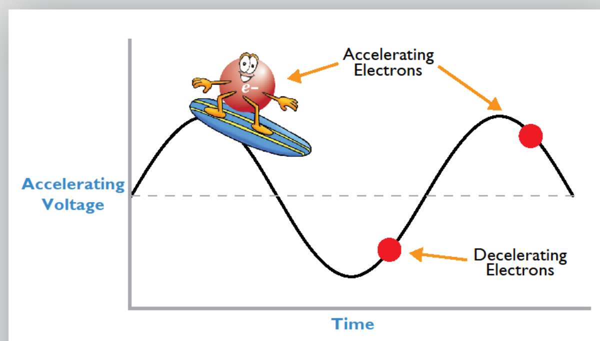
- Cryomodules are like large, super-insulated, stainless-steel thermos bottles.
- The linac cryomodules contain 8 RF cavities in a 400 gallon bath of liquid helium.
- The temperature in the cryomodules is 2 Kelvin (–456°F). Everything except helium is frozen at this temperature.
- The extreme cold makes the niobium cavities superconducting (they don't resist the flow of electrons).
- The vacuum in the cavities is between 1×10^{-10} and 1×10^{-11} torr (deep space is $\times 10^{-13}$ torr). This removes molecules that could freeze to the sides of the cavities, which would reduce their superconductivity.
- It costs ~$1.45 million to build a new cryomodule.
- We have 53 cryomodules (25 in each linac, 3 in the injector).

5-cell Niobium RF Cavity
(newer cavities have 7 cells)



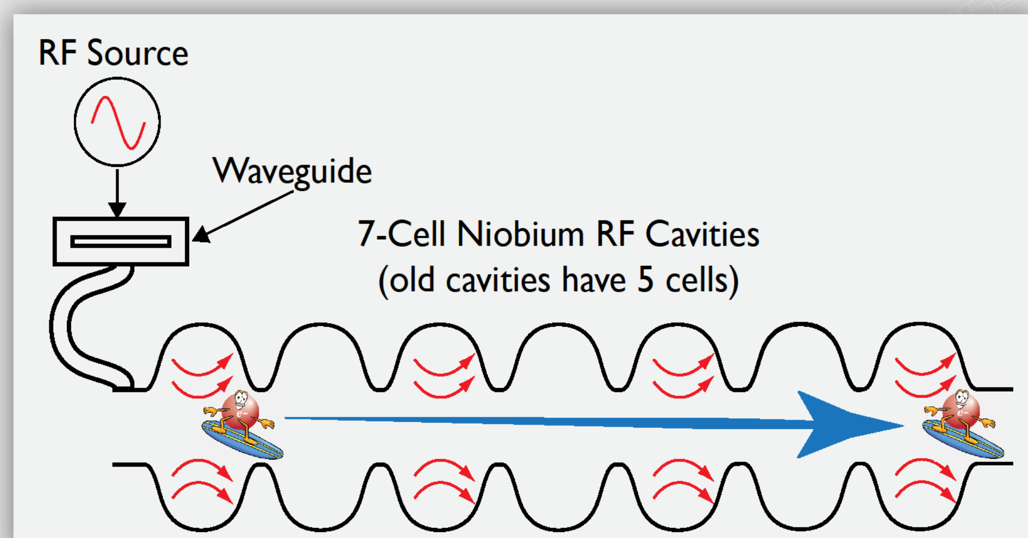
BEAM ACCELERATION

- When the RF waves enter the niobium cavities, strong electromagnetic fields are created within the cavities.
- These electromagnetic fields accelerate the electron beam closer to the speed of light.
- Like a surfer riding a wave, the electrons accelerate only if they arrive at the correct time.



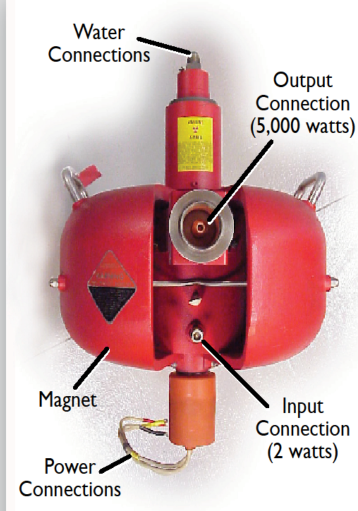
Accelerating Electrons Ride the "Crest"

- Timing is everything! If the timing isn't exactly right, the electrons could miss the accelerating wave and actually decelerate.
- The goal is to keep the electrons tightly bunched and riding the "crest" of the electromagnetic wave.

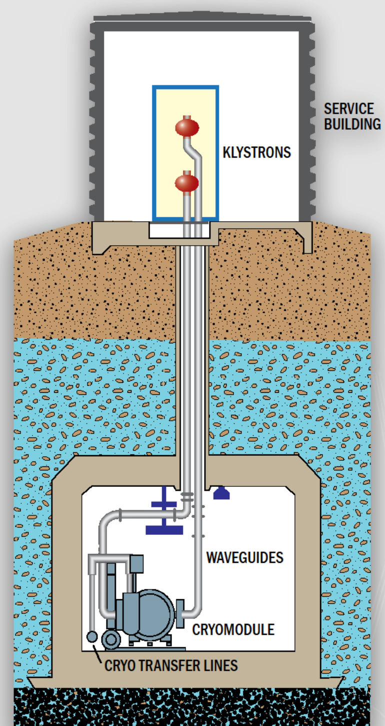


RF POWER FOR ACCELERATION

- RF = Radio Frequency
- SRF = Superconducting Radio Frequency
- 418 klystrons supply the RF power in the accelerator.
- They use velocity modulation to amplify microwaves: each klystron produces about 5 microwave ovens' worth of power. (Microwaves are on the RF spectrum.)
- Waveguides (hollow metal channels) connect the klystrons to the cryomodules and guide the RF energy to the niobium cavities in the cryomodules.

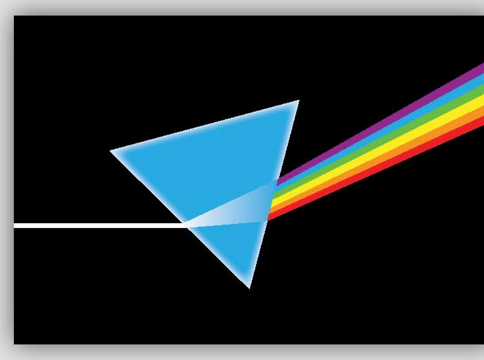


Klystron

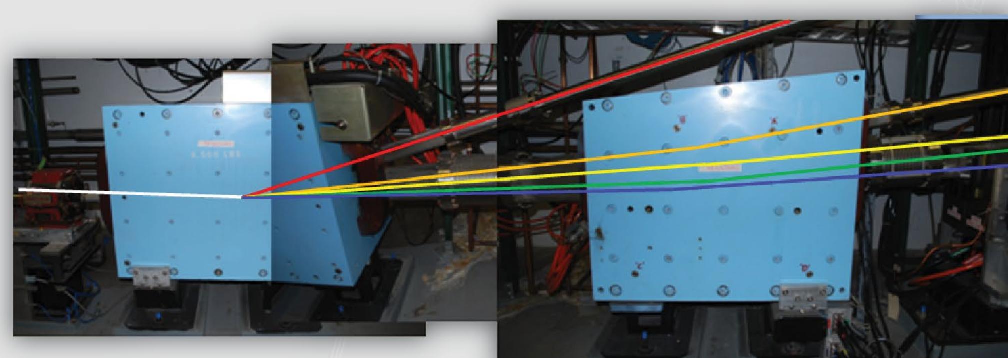


- With 2 watts applied to its input, a klystron can supply up to 5,000 watts of RF power.
- Klystron vital statistics:
  - 1,497 MHz operating frequency
  - 11,600 volts DC operating voltage
  - 1.3 amps DC operating current
  - Water cooled

SPREADER MAGNETS



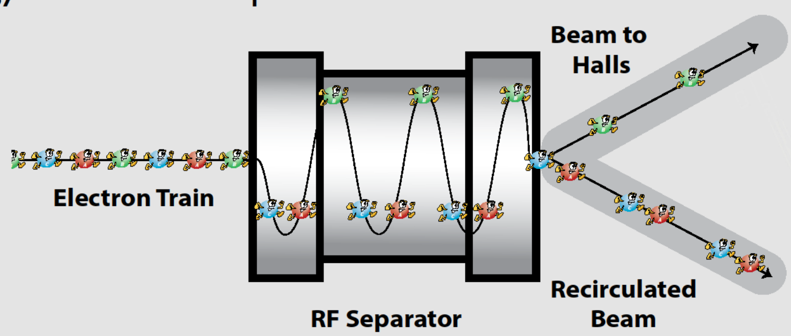
- The beam can contain electrons that have been around the loop 0-5 times - simultaneously.
- When an electron gains energy it gets harder to turn.
- Before the multipass beam can go around an arc, the electrons must be separated based on their energy.
- Large spreader magnets are located at the end of each linac. They act like magnetic prisms to vertically separate the electron beam into the different beam energies.
- After separation, each electron goes through the path best suited for it: lower energy first pass electrons through the top arc, high energy 5th pass electrons through the bottom.
- On the other side of the arc, recombiner magnets put all the electrons, regardless of their energies, back into the same beamline so they can go through a linac for another kick.



A visualization of the spreader magnets in action.

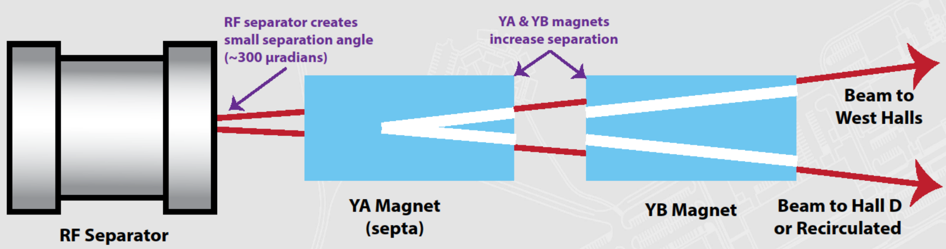
RF BEAM SEPARATION

- CEBAF can deliver electrons to all 4 of JLab's experimental Halls simultaneously. Each Hall requires electrons with unique characteristics.
- The beam is set up in the injector so that the electrons are arranged and lined up in orderly bunches - like train cars - which are pushed through the accelerator in a specific sequence.
- The separators act as time-dependent switches. They use RF energy to sort and separate the individual bunches.



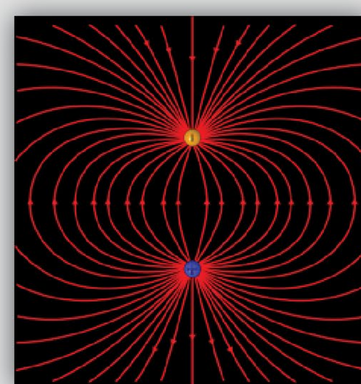
An RF Separator Sending Beam to 3 Halls

- RF Separators can only separate the bunches a tiny amount. The magnets that follow increase the separation and ensure that the right electrons go to the correct Hall - or recirculate around the accelerator again.



- The more energy an electron bunch has, the harder it is to separate it out. Low-energy first pass electrons go through the one separator at the top of the stack. High-energy fifth pass electrons go through the bottom 4 RF separators.

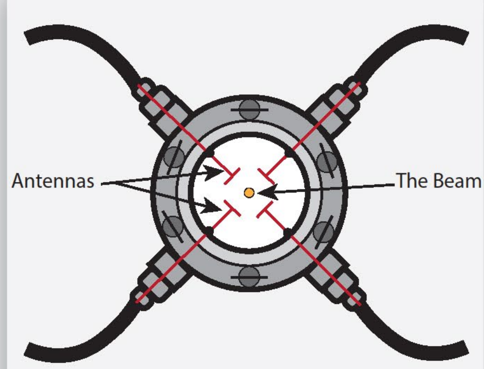
ARC MAGNETS



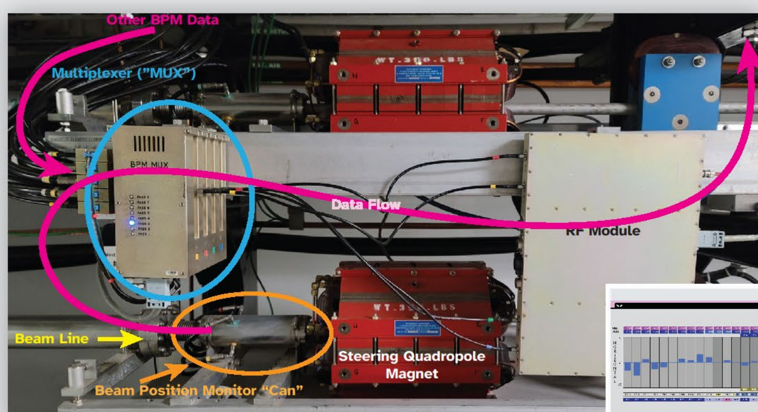
- Large dipole magnets bend the beam around the arcs, connecting one linac to the other.
- Individual dipole magnets can be powered up to 700 amps. (The electric feed to a house is usually rated for 200 amps.)
- Approximate lifting power of a large dipole magnet is ~12,000 pounds.
- First-pass beam is relatively easy to steer: it goes through the smaller magnets at the top of the arc.
- Fifth-pass beam has 5 times the energy of first-pass beam. It is very hard to steer, and goes through the big magnets at the bottom of the arc.

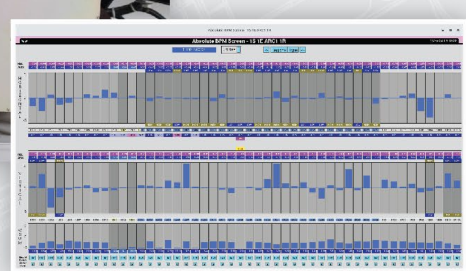
Measuring Beam Position

- The electron beam should be centered in the beam line at all times. If it goes off-center, it could hit a component of the machine and damage it.
- Beam Position Monitors ("BPMs") use 4 antennas that pick up the beam's RF signature to gauge the location of the beam within the beam line.
- Data from the BPM goes into a multiplexer, which reads the signals from several BPMs, one at a time. The blue lights indicate which BPM it's reading at the moment.
- The multiplexer sends the signal to an RF module, which cleans up the signal, calculates the X and Y positions of the beam, and sends the data to a computer in a service building upstairs.
- The computer converts the signal into information that an Operator can view on their monitor.



BPM "Can" Cross-Section



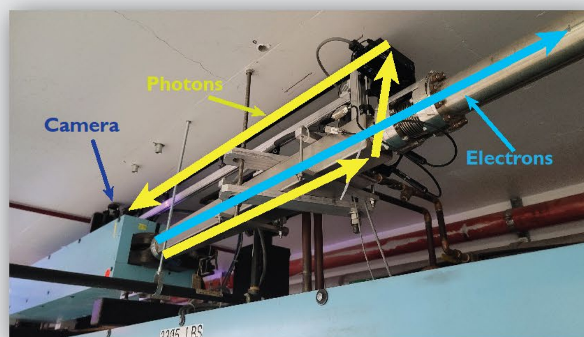


Jefferson Lab

VIRGINIA IS FOR SCIENCE LOVERS

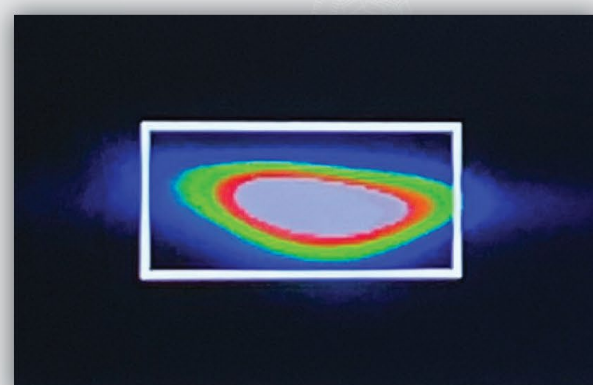
SYNCHROTRON LIGHT MONITOR

- When an electron beam is bent by a magnet, it gives off synchrotron radiation in the form of photons, or light.
- Photons are not bent by magnets. They fly straight ahead —and at strategic locations in CEBAF, into a Synchrotron Light Monitor (SLM).



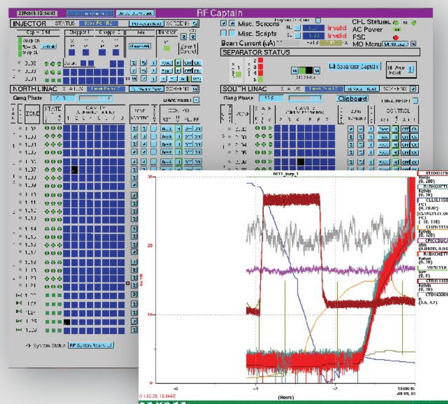
Synchrotron Light Monitor

- Inside the SLM are mirrors that send the photons into a camera.
- The camera displays a live image on the display wall in the MCC Control Room.
- Operators use that image to see what the electron beam is doing at this point. For example:
  - Is the horizontal position bad? The beam energy is not correct.
  - Is the image a horizontal stripe? The energy is very unstable.
  - Is there more than one spot? The beam for a Hall isn't aligned.


SLM Display

MACHINE CONTROL CENTER

- The Machine Control Center (MCC) is staffed around the clock during accelerator operations.
- There are three eight-hour shifts per day.
- A control room crew consists of a Crew Chief and two operators.
- Crew Chiefs and operators typically have some physics background or a very strong technical aptitude.
- The crew runs the accelerator, performs radiation surveys, operates the Personnel Safety System, and responds to emergencies.
- Principal Investigators (technical experts) may help perform special tests or troubleshoot specific problems.
- The four experimental halls have their own control rooms, as do the Central Helium Liquefier and the Low Energy Recirculator Facility.



Control Screens