What is a “Cyclotron”?  

A **cyclotron** is a type of particle accelerator consisting of a magnet and a high frequency oscillator, with *ions* travelling in a spiral pattern.

Other types of particle accelerators include:
- Van de Graaff accelerators
- Linear accelerators (“linacs”)
- Synchrotron accelerators
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Accelerators Simplified

- Donut Hole: Van de Graaff
- Churro: Linear Accelerator
- Donut: Synchrotron
- Cinnamon Roll: Cyclotron

This is us!
How does a cyclotron work?

1.) Ions are injected in the center and travel in a curved trajectory due to the magnetic field.

2.) Ions get periodic ‘kicks’ of electromagnetic energy to increase their velocity, causing them to spiral outward.

3.) Once the ions reach the outer orbit, they are pulled out with a high voltage and sent to the experiments.
The 88-Inch Cyclotron

- 300 tons of metal
- First beam in Dec. 1961
- Capable of accelerating hydrogen through uranium
- Ions reach a third of the speed of light and travel 100 to 600 orbits

88-Inch Cyclotron

Cyclotron dee removal

Sitting on top of the RF Tank in the early days
Cyclotron Map & Current Research

Caves 4A & 4B
- BASE Facility
- Heavy ion cocktails and protons for radiation effects testing

Caves 0 & 5
- Nuclear Data Group
- Neutron beams from deuterons

Caves 1 & 2
- Berkeley Gas-filled Separator (BGS)
- Superheavy element research - search for new elements & isotopes, chemistry

Ion Sources

88-Inch Cyclotron
Ion Sources

Why ECR ion sources?

- Higher current beams
- Higher energy beams
- More simultaneous beams
- Improved reliability

\[ m v = q B r \]

- \( m \) = ion mass
- \( v \) = ion velocity
- \( r \) = orbital radius
- \( q \) = ion charge
- \( B \) = magnetic field

We can change this one!

Can’t change these easily

Under development: MARS ion source
Ion Source Evolution

- **MARS**: 5.6 T & up to 45 GHz
- **VENUS**: 4.0 T & up to 28 GHz
- **AECR**: 1.7 T & up to 14 GHz
- **ECR**: 0.4 T & 6.4 GHz
- **PIG**: 0.4 T & 6.4 GHz

Cyclotron beam energy [MeV] vs. Atomic mass [amu]
Elements Accelerated

Periodic Table of the Elements

Most of these elements can’t be accelerated without our ECR ion sources!
Berkeley Accelerator Space Effects (BASE) Facility

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

Help spacecraft survive:
- Galactic cosmic rays
- Solar particles
- Planetary magnetic fields

*Solar Dynamics Observatory (parts tested at BASE)*
Cocktail Beams

Why cocktail beams?

- To efficiently deposit *different amounts of energy* into electronics parts for Single Event Effects (SEE) testing

What is a ‘cocktail’?

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

Standard cocktail beams

- 4.5, 10, 16, 20 MeV/nuc (heavy ion)
- 30 & 32.5 MeV/nuc (light ion)
Bragg Curves - 16 AMeV (in air)
Bragg Curves - 20 AMeV (in air)
Heavy Ion Station Details

- Flux densities 1E2 - 1E7 ions/cm²/sec
- Photomultiplier tube dosimetry
- Remote motion table positioning
- Remote laser alignment
- Vacuum chamber:
  - One-button operation
  - Pumps down in 4 minutes
  - Multiple feedthroughs available
- Cooling/heating plate available
Heavy Ion In-Air Stage

New: In-Air Stage

- Driven by user need for a modern in-air test station
- Versatile:
  - can be used with standard mounting fixtures from other facilities
SEE Software
Microbeam

Main Camera
Used for DUT alignment with beam, measurement of beam size, shape, position, and dispersion

Image Relay Mirrors
Off-axis parabolic mirrors for relaying images from the DUT stage to the main camera

Overview Camera
Provides overall view of DUT motion system

Beam Slit
Provides consistent beam size to focusing magnet

Focusing Magnet
Quadrupole doublet magnet for beam focusing

DUT Motion
Three-axis motorized stage allows DUTs to be rastered across the beam

DUT Illumination
Remotely controlled LED light for illumination during alignment

Dosimetry System
Beam fluence/flux is measured using electrons generated from an Al foil
Protons

- **In-air**: 10 to 60 MeV
- **Vacuum**: 1 to 10 MeV (performed in Cave 4B next door)
- **Standard flux densities**: 1E6 to 3E8 protons/cm²/sec
- 6-inch, 5-mil kapton window with ion chamber dosimetry and laser alignment
Neutrons

Neutrons & Nuclear Data
- Pulsed, high intensity neutron beams
- Broad spectral range: 50 keV to 62 MeV
- Energy centered at roughly half of the beam energy (deuterons)
- Samples places as little as 1 cm away
- Variable flux density of up to $2.75 \times 10^{12}$ neutrons/sr/s @ 10 uA and 33 MeV

Recent Work
- Scintillator characterization
- Neutron damage studies
- Cross-section measurements
- Medical isotope research
- Fission yield measurements
- Neutron inelastic scattering measurements
Who uses BASE?

- NASA
- Dept. of Defense
- Defense Contractors
- Semiconductor Manufacturers
- Private Space Companies
- Telecom & Satellite Companies
- Universities
- National Laboratories
- Small Businesses

What type of work is performed?

- Chip testing
- Detector characterization
- Materials & shielding studies
- Biomed research
“Instead of an attic with a few test tubes, bits of wire and odds and ends, the attack on the atomic nucleus has required the development and construction of great instruments on an engineering scale.”

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

“Let us cherish the hope that the day is not far distant when we will be in the midst of this next adventure.”

- Ernest Lawrence

cyclotron.lbl.gov
**Single Event Effects**

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

**Examples of Single Event Effects:**

**Single-Event Upset (SEU):** A soft error caused by a single ionizing particle striking a sensitive node.

**Single-Event Latchup (SEL):** An abnormal high-current state with loss of device functionality; requires cycling power to restore operation.

**Single-Event Burnout (SEB):** High-current state in a device that results in catastrophic failure.

**Single-Event Functional Interrupt (SEFI):** A soft error affecting a device’s internal control signals that causes it to reset, lock-up, or otherwise malfunction.

**Causes of SEE’s:**
- Cosmic rays
- Solar
- Van Allen belts
- Nuclear weapons
- Natural isotopes

**Sampling of Upsets, Unclassified (1970s & 80s):**

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelsat IV</td>
<td>TTL Flip-Flop</td>
</tr>
<tr>
<td>Voyager</td>
<td>CMOS Memory</td>
</tr>
<tr>
<td>Pioneer VENUS</td>
<td>TL RAM, PMOS Shift Register</td>
</tr>
<tr>
<td>TIROS-N</td>
<td>Potential CMOS RAM SEL</td>
</tr>
<tr>
<td>DMSP</td>
<td>NMOS Memory</td>
</tr>
<tr>
<td>SDS</td>
<td>64-bit TTL Schottky RAM</td>
</tr>
<tr>
<td>GPS</td>
<td>NMOS Memory</td>
</tr>
<tr>
<td>SMM</td>
<td>Fast Bipolar Memory</td>
</tr>
<tr>
<td>Landsat D</td>
<td>Memory &amp; possible CMOS SEL</td>
</tr>
<tr>
<td>Galileo</td>
<td>Possible CMOS PROM SEL</td>
</tr>
<tr>
<td>LES 8 &amp; LES 9</td>
<td>TTL Flip-Flop</td>
</tr>
</tbody>
</table>

**Courtesy of COTS Journal**
88-Inch Contributions to Space Exploration

Apollo 17 (experiment with lunar soil sample)
Solar Terrestrial Relations Observatory (STEREO)
Solar Dynamics Observatory (SDO)
Parker Solar Probe
Genesis (Solar Wind Sample Return)
Messenger (Mercury)
Pioneer Venus
Van Allen Probes
IMAGE/Explorer 78
Landsat
Global Positioning System (GPS)
Lunar Reconnaissance Orbiter (LRO)
Mars Pathfinder
Mars Polar Lander
Mars Climate Orbiter
Mars Exploration Rover (MER) / Spirit & Opportunity
Mars Science Laboratory (MSL) / Curiosity Rover
Mars Atmosphere & Volatile Evolution (MAVEN)
Mars 2020 / Perseverance & Ingenuity
Mars Odyssey
Phoenix (Mars)
ExoMars
InSight (Mars) Lander
Dawn (Asteroid Belt)
Galileo (Jupiter)
Juno (Jupiter)
Europa Clipper (Jupiter)
Cassini-Huygens (Saturn)
Voyager (Jupiter, Saturn, Uranus, Neptune)
New Horizons (Pluto)
Space Shuttle
Orion Multi-Purpose Crew Vehicle
International Space Station (ISS)
James Webb Space Telescope
Spitzer Infrared Telescope Facility
Swift Gamma-Ray Burst Mission
Stardust (Comet Sample Return)
Deep Space 1
Atlas Launch Vehicles
Delta Launch Vehicles
xEMU Space Suit
...and many more!