Motivation for High Energy Accelerators

CEBAF

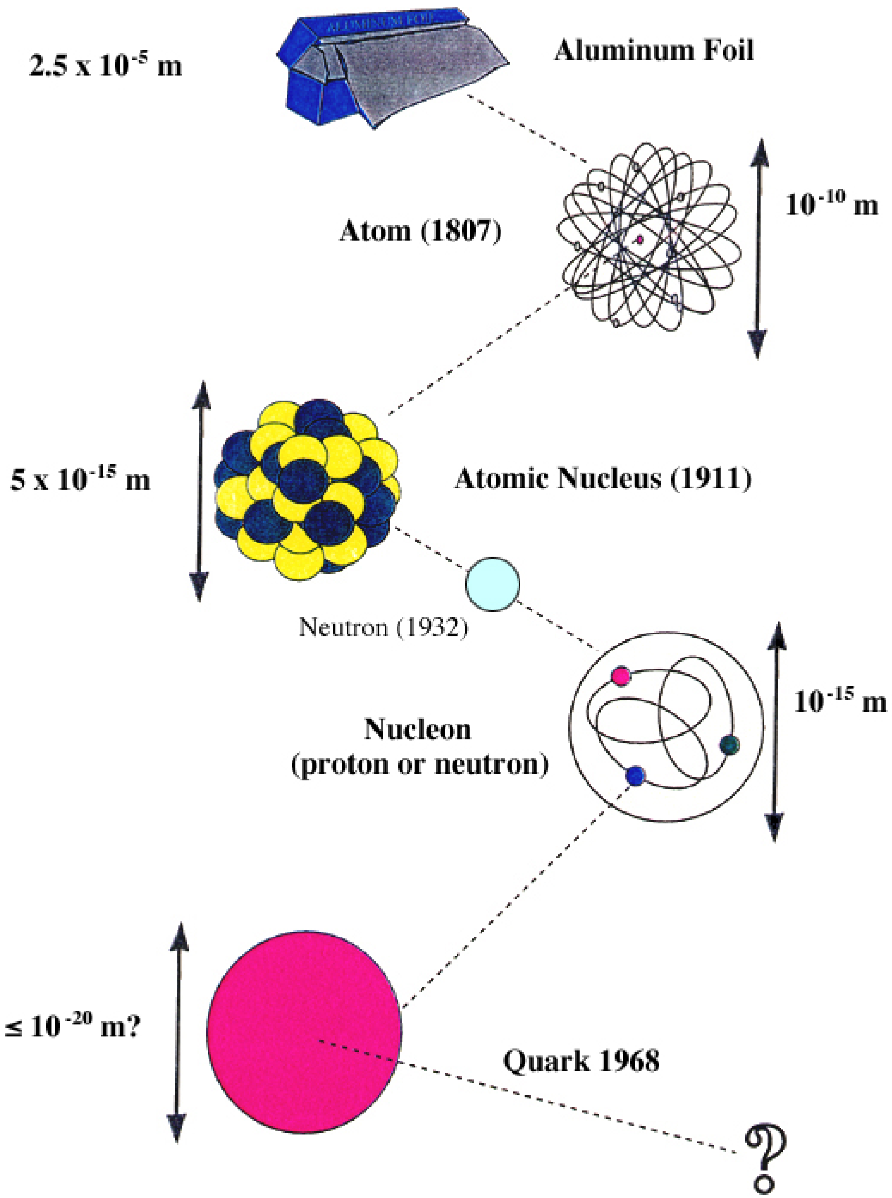
(Continuous Electron Beam Accelerator Facility)

at

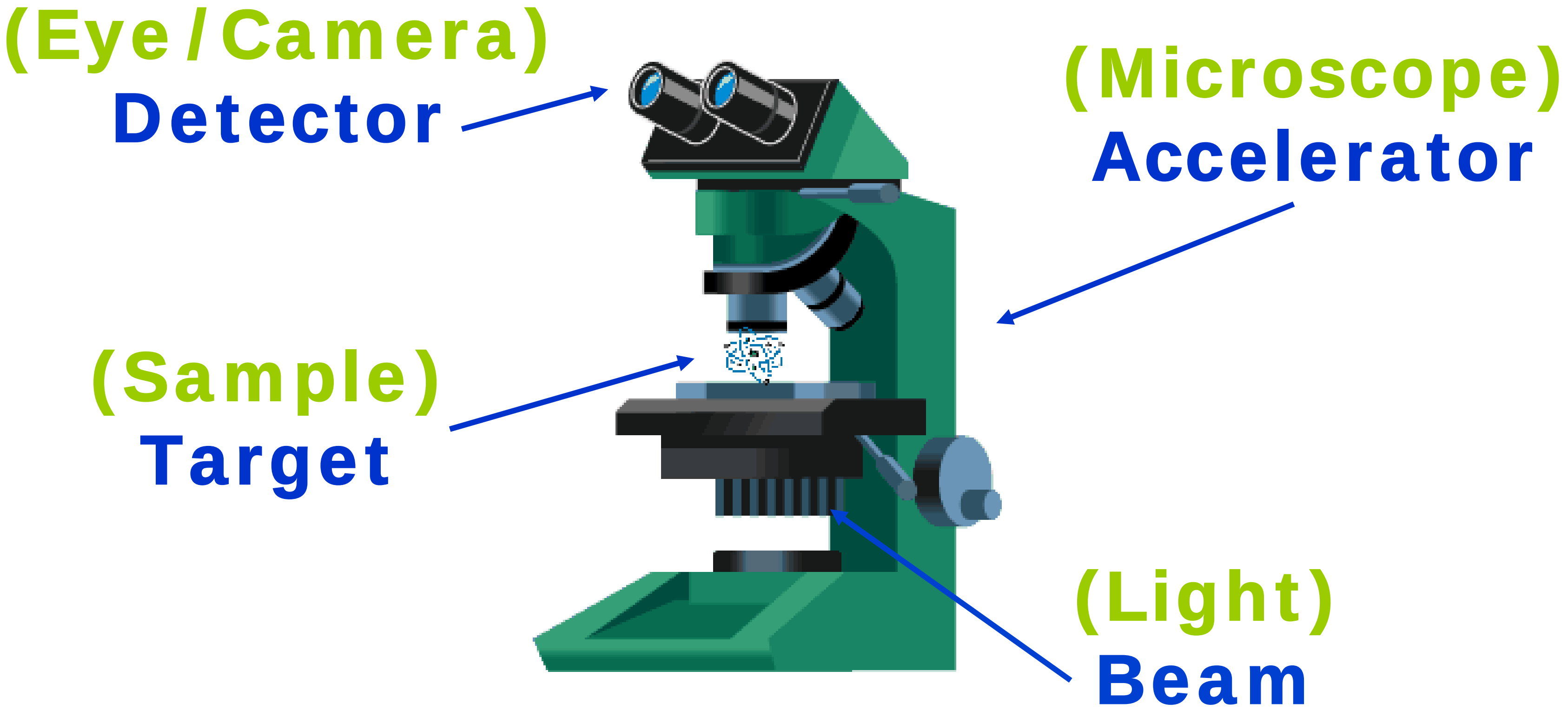
Jefferson Lab

(Thomas Jefferson National Accelerator Facility)

Structure of Matter



How Do We Inspect Nuclei?

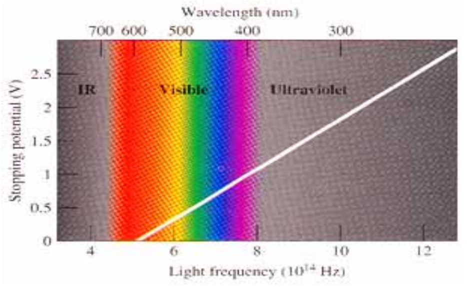


Looking at Small Dimensions

The smallest "detail" we are able to "see" when we "look" is about as small as the size of the wavelength of "light" we use.

e.g. diffraction from slit: $\theta_{min} = \lambda/a$

Wavelength of visible light $\lambda \approx 5 \times 10^{-7}$ m



Size of a living organism	$\approx 1 \times 10^{-6}$ m	Optical microscope works!
Size of an atom	$\approx 1 \times 10^{-10}$ m	" does NOT work!
Size of a nucleus	$\approx 5 \times 10^{-15}$ m	" " "
Size of a proton	$\approx 1 \times 10^{-15}$ m	" " "

<u>CONCLUSION:</u> To look in detail into the interior of atoms and nuclei, a source of "light" is needed whose wavelength is smaller than the wavelength of visible light and comparable to nuclear dimensions!

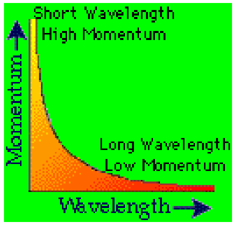
Quantum Mechanics to the Rescue!

- **Albert Einstein** (1905): Waves (light) can have particle-like properties (bundles of energy quanta)

  Energy of quantum: $E = \frac{hc}{\lambda}$ or $E = h\nu$

- **Louis de Broglie** (1923): Particles can behave like waves and have wave-like properties

  De Broglie Wavelength: $\lambda = \frac{h}{p}$



	Energy E (eV)	Wavelength λ (m)	
Visible light:	2.5	5×10^{-7} m	~ our world
Electrons:	10,000	1×10^{-10} m	~ size of an atom
	100,000,000	1×10^{-14} m	~ size of a nucleus
	10,000,000,000	1×10^{-16} m	~ inside a proton

Conclusion #1

- To study details at very small dimensions (atomic or nuclear) we need beams of very fast moving particles
- For viruses to atoms: Use ~100,000 eV electron beams
  - electron microscope
- For nuclei and nucleons: Use multi-million eV beams
  - **High Energy Accelerators**

    (electrons or protons or heavier nuclei)
  - Example: Jefferson Lab (CEBAF)

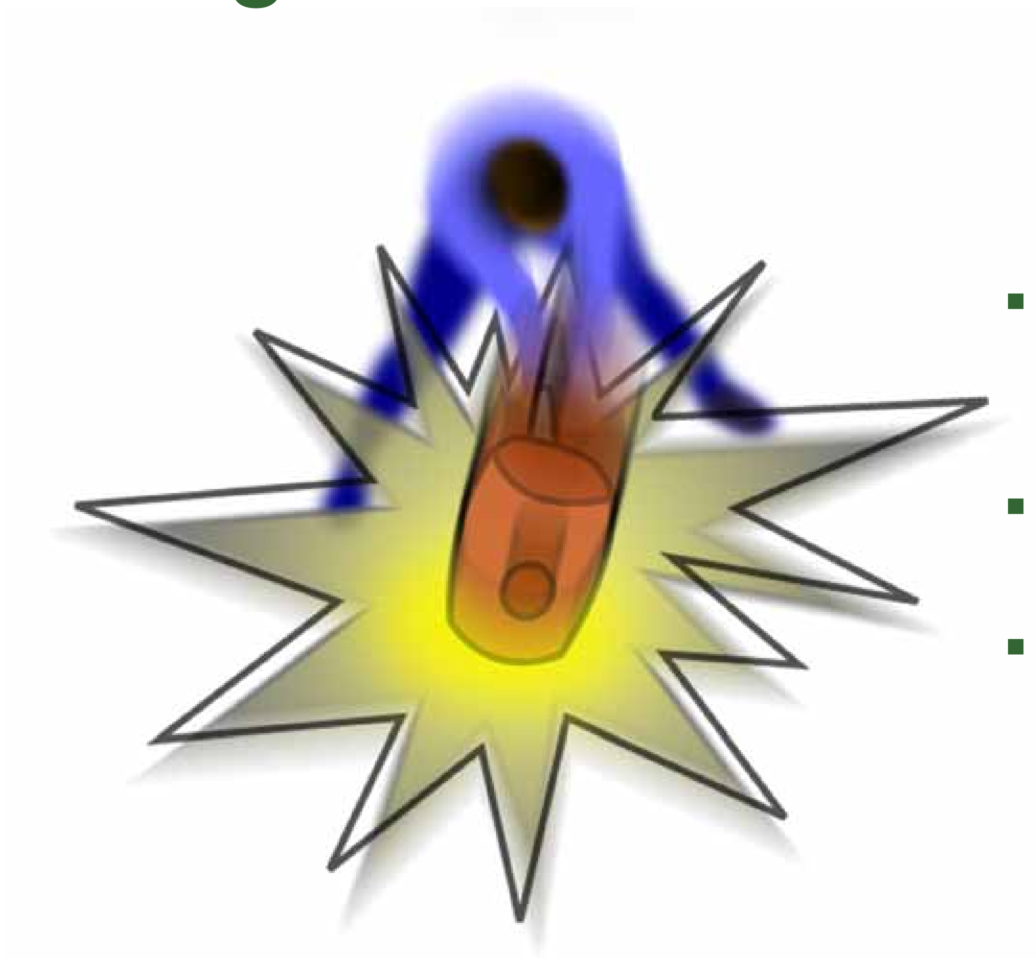
Second Reason for High E Accelerators – Cosmology Connection

- Connection between high energies, nuclear physics and cosmology
- Big Bang: Eruption from an infinitely dense point in space-time
- Extremely high temperatures and thermal energies existed
- Profound effect on the nature of matter and the forces of nature during those first instances
  - All matter consisted of a “soup” of free quarks, gluons and leptons
    - As the universe expanded and cooled down, quarks and gluons combined to form nucleons
  - There was only one unified force of nature
    - The present “four” forces were split off from it at later times, as the universe cooled down

Conclusion #2

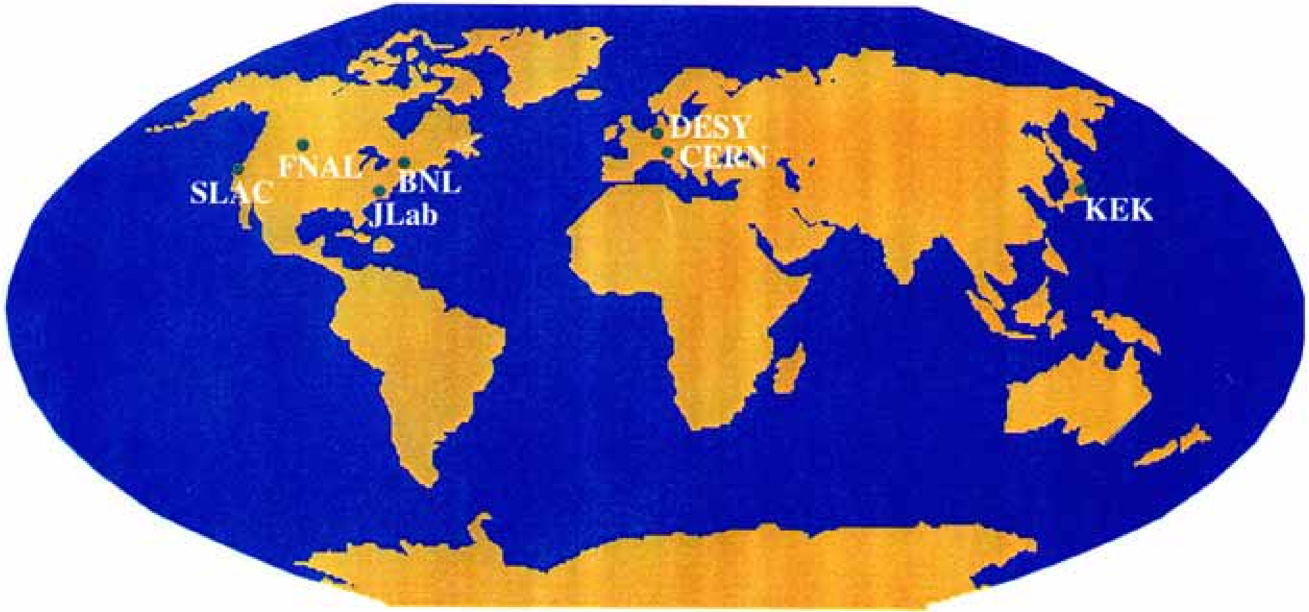
- To study extreme conditions, e.g. those at the beginning of the Universe, we need a laboratory environment of high energies and temperatures
- Use multi-billion eV beams
  - **High Energy Accelerators (Colliders)** (very heavy particles)
  - Example: Brookhaven Lab (RHIC Collider)

Third Reason for High E Accelerators



- Wider choice of parameters for study of nuclear events
- Discovery of new particles requires higher energies
- New frontiers possible

Major World Laboratories in Nuclear and Particle Physics

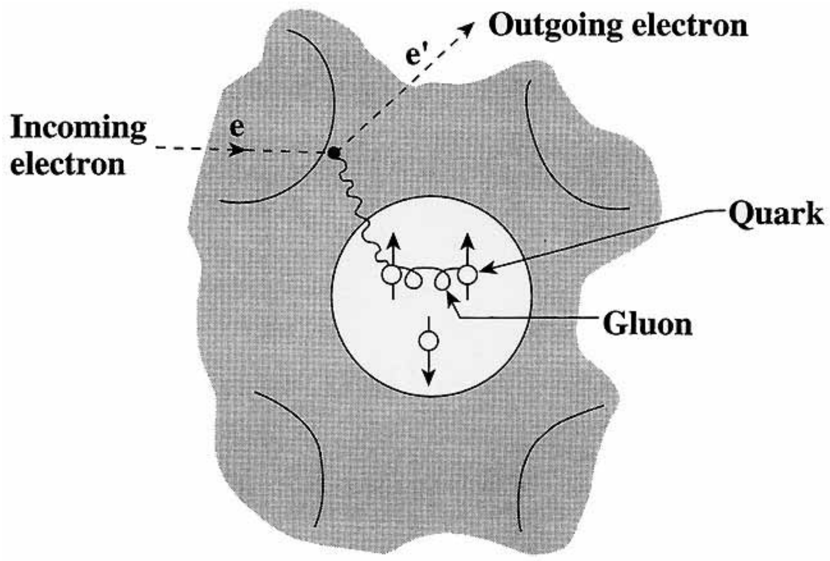


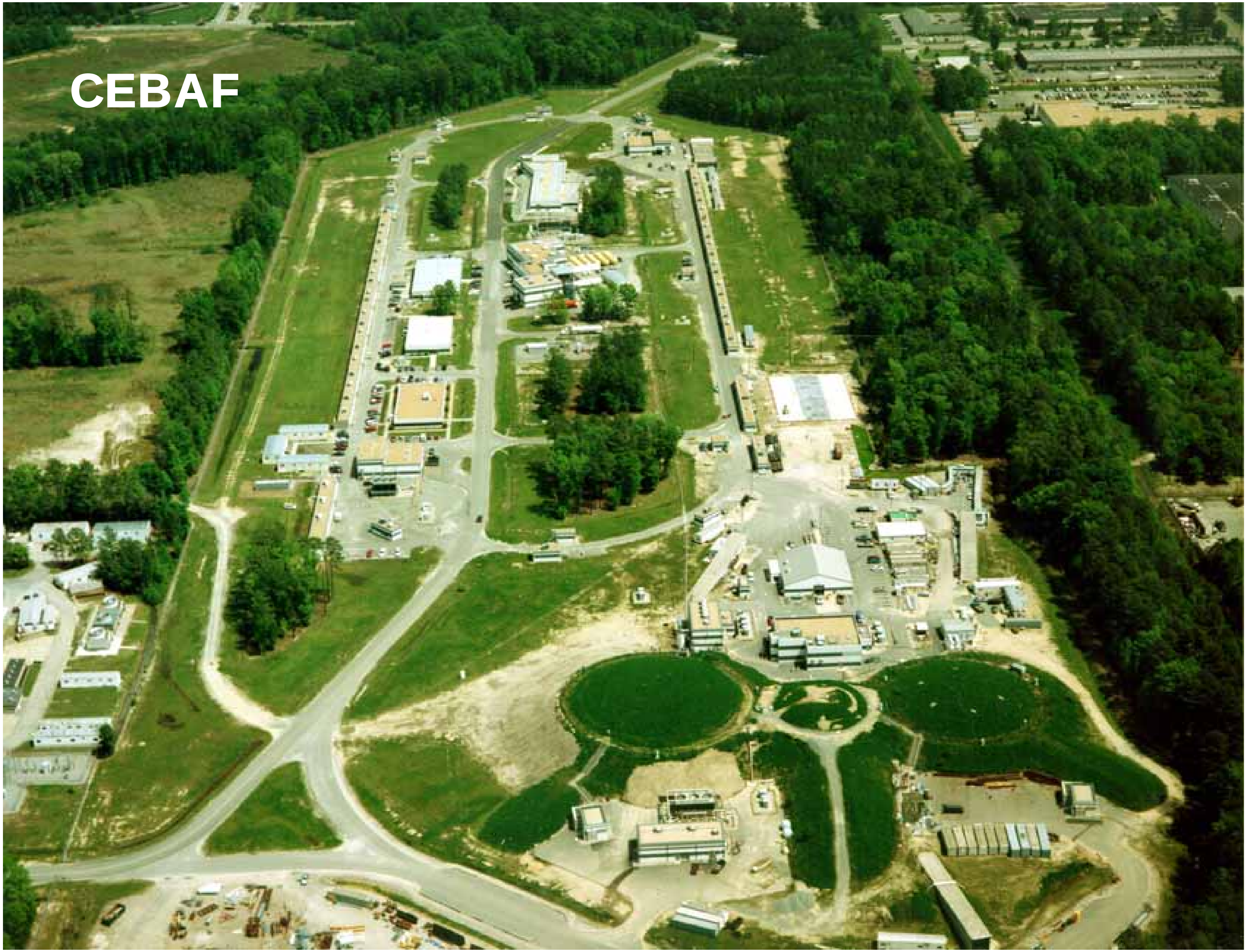
Role of CEBAF/Jefferson Lab

- At lower energies we understand nuclear physics in terms of protons and neutrons interacting via the exchange of mesons and we have a rudimentary theory using models.
- An very high energies we understand particle physics and their interactions in terms of quarks and gluons and have an exact and tested theory of the strong interaction (QCD)
- **CEBAF explores transition region between the low energy regime where this "standard picture" of nucleus applies and the high energy regime where QCD applies and quarks and gluons must be included explicitly**
- Understanding this transition is one of the last frontiers in our understanding of ordinary matter

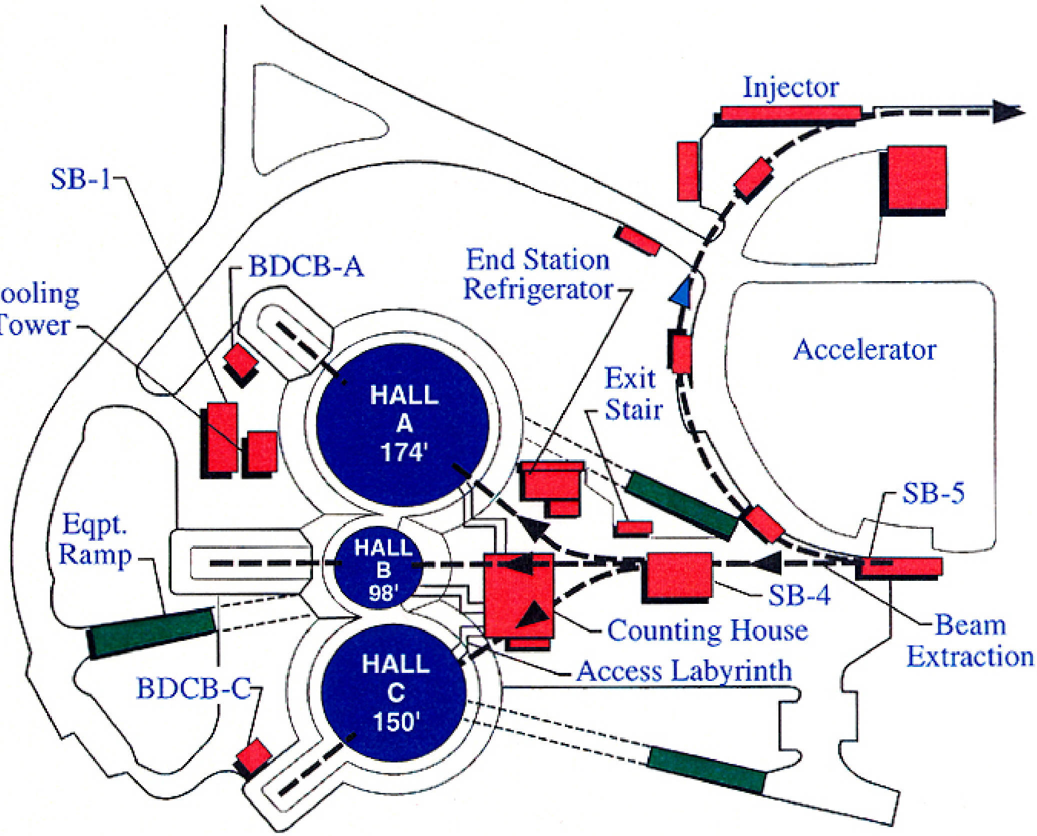
Why an Electron Probe?

- Electrons have no internal structure
- Electromagnetic interaction well understood
- Electrons penetrate deep inside a nucleus
- Probe distances down to 1/10 size of proton



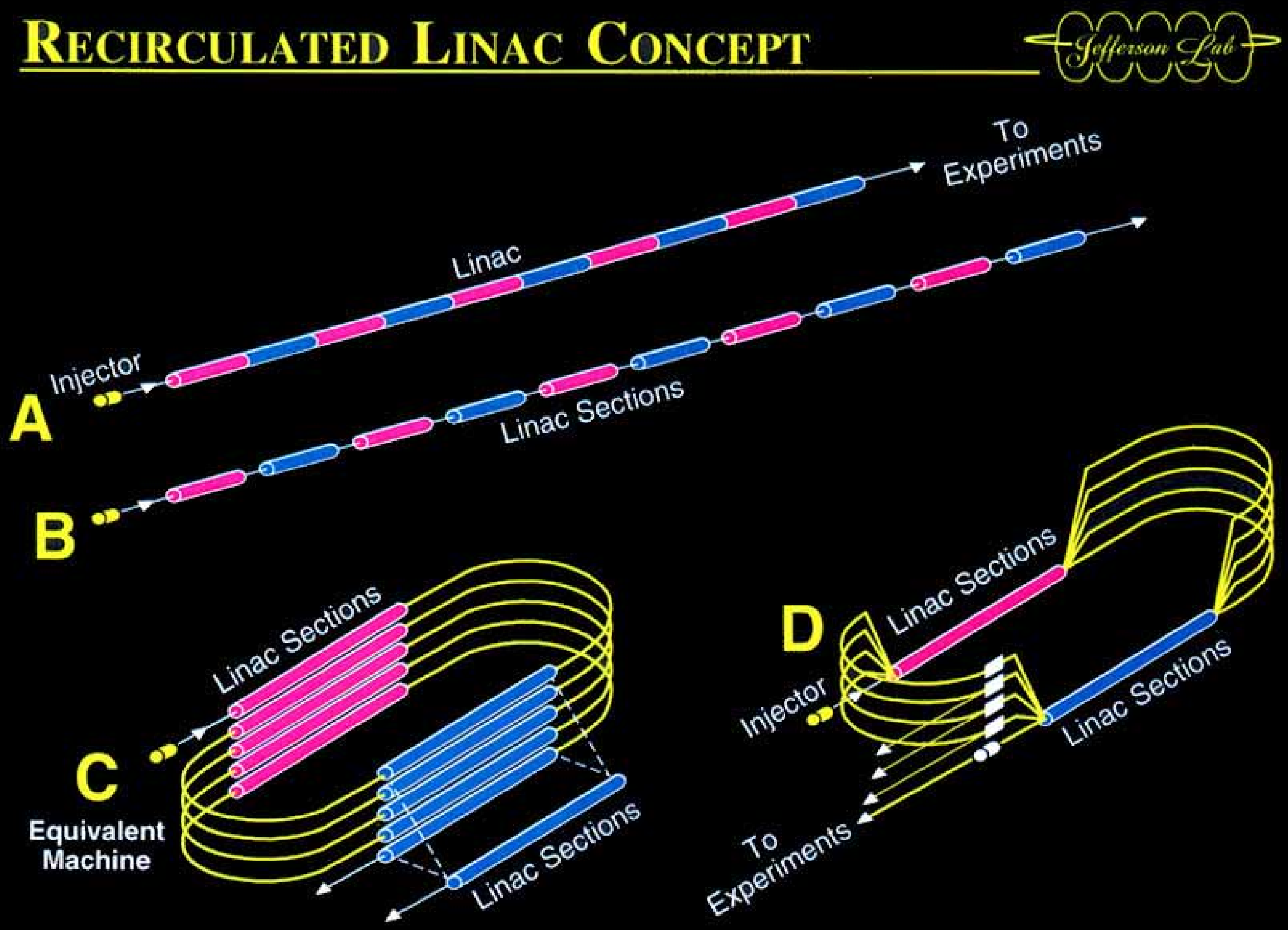

CEBAF

End Station Site Plan



Jefferson Lab

Recirculated Linac Concept

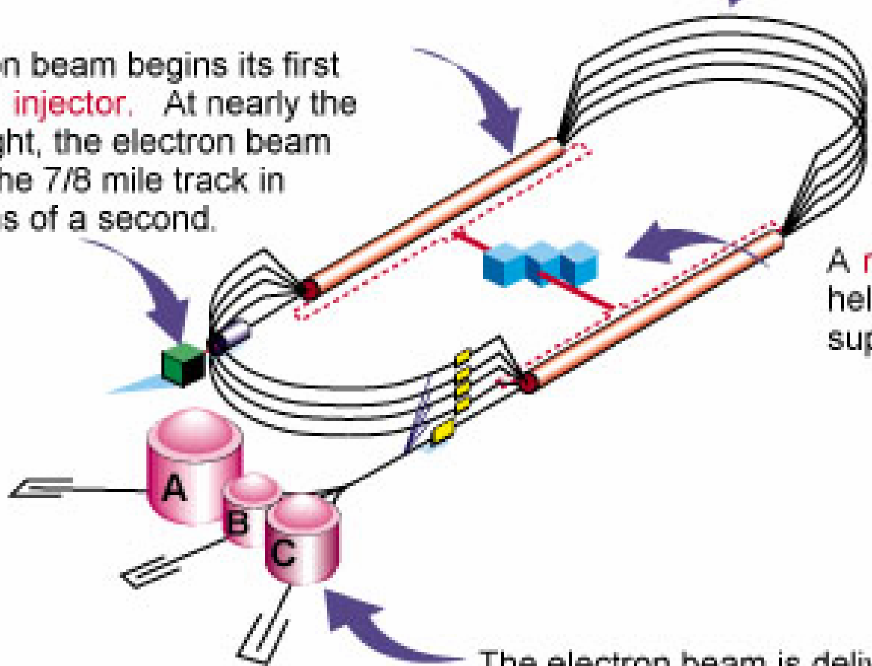


How CEBAF Works

Each linear accelerator uses superconducting technology to drive electrons to higher and higher energies.

Magnets in the arcs steer the electror beam from one straight section of the tunnel to the next for up to five orbits.

The electron beam begins its first orbit at the injector. At nearly the speed of light, the electron beam circulates the 7/8 mile track in 20 millionths of a second.



A refrigeration plant provides liquid helium for ultra-low-temperature, superconducting operation.

The electron beam is delivered to the experimental halls for simultaneous research by three teams of physicists.

Needs of Coincidence Experiments

- Reaction experiments prefer (need) continuous electron beams.
  - Need to distinguish particles emerging from a single collision (real coincident events) from those that are products of more than one collisions occurring at different, though nearby, times (accidentals).
- “Pulsed” (not continuous) accelerators produce beams with fairly intense average currents but with particles bunched in brief, recurring bursts (“duty factor” of 1%) of very high instantaneous currents.
  - Very high concentration of particles in the short time of these bursts produces too many accidental coincidences.
  - Need to spread these bunches out.
- “Continuous wave” accelerators accelerate particles continuously, not in bunches, achieving average currents equal to their instantaneous currents (duty factor nearly 100%).
- Conventional (non-superconducting) electron linacs use RF power to produce accelerating E fields (E gradients) in copper cavities.
- These E fields produce enormous heating (300 kW/m) in the electrical resistance of these cavities and, if operated “continuously” ordinary cooling would not be sufficient to maintain the structural integrity of the copper cavities.
  - This necessitates “pulsed” operation.

Coincidence Time Spectrum at CEBAF

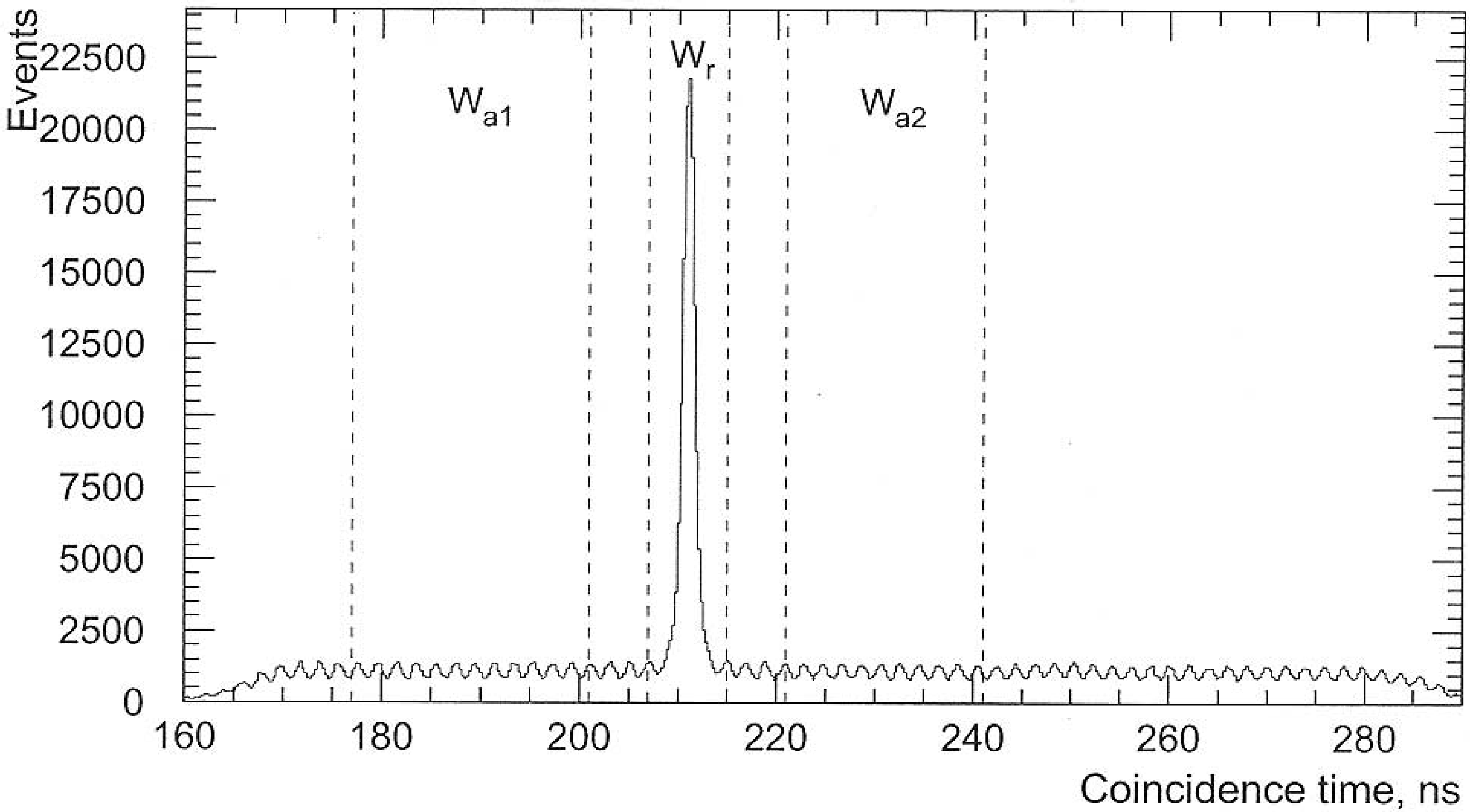


Figure 5-9: Coincidence time between particles detected in the two spectrometers, corrected for time of flight to the focal planes.

Superconducting RF Technology

- If cavities could be made with essentially zero electrical resistance, the heating produced by the RF power used to produce accelerating electric fields would be very small. This would make possible:
  - Beams of continuously accelerated electrons (100% duty factor)
  - Meaningful coincidence experiments of low-counting (small cross section) reactions, with low accidentals.
- CEBAF design uses such superconducting RF technology
  - Niobium RF cavities cooled to 2 K so that Niobium becomes a superconducting metal (zero resistance).
  - Excellent beam quality is possible
  - Simultaneous independent beams in Halls A, B, and C (and D in 2011?) through beam recirculation.
  - Upgradeable beam energy (to 12 GeV in 2011?)
  - Appreciable savings in the cost of electric power.

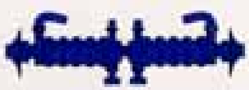
ACCELERATOR PRODUCTION

Thomas Jefferson National Accelerator Facility

ACCELERATOR COMPONENT

CAVITY

- Cavities developed at Cornell and CEBAF and produced by industry

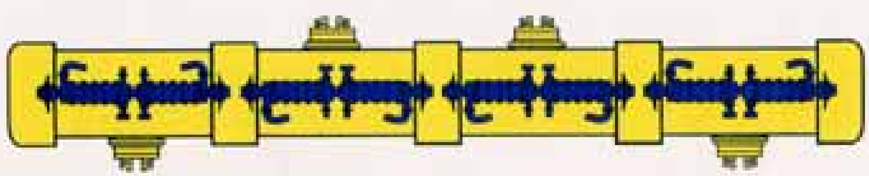


CAVITY PAIR

- Pairs assembled and tested at CEBAF

CRYOUNIT

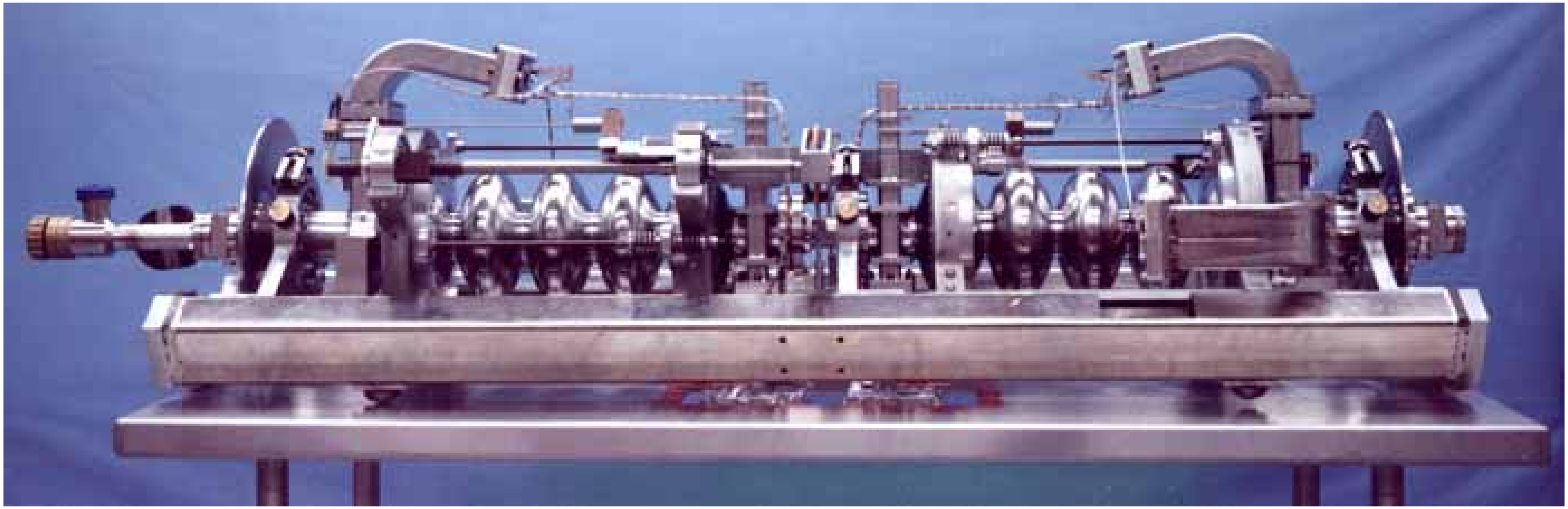
- Cryounits fabricated at CEBAF



FULL CRYOMODULE

- Production cryomodules assembled, tested, and installed in tunnel

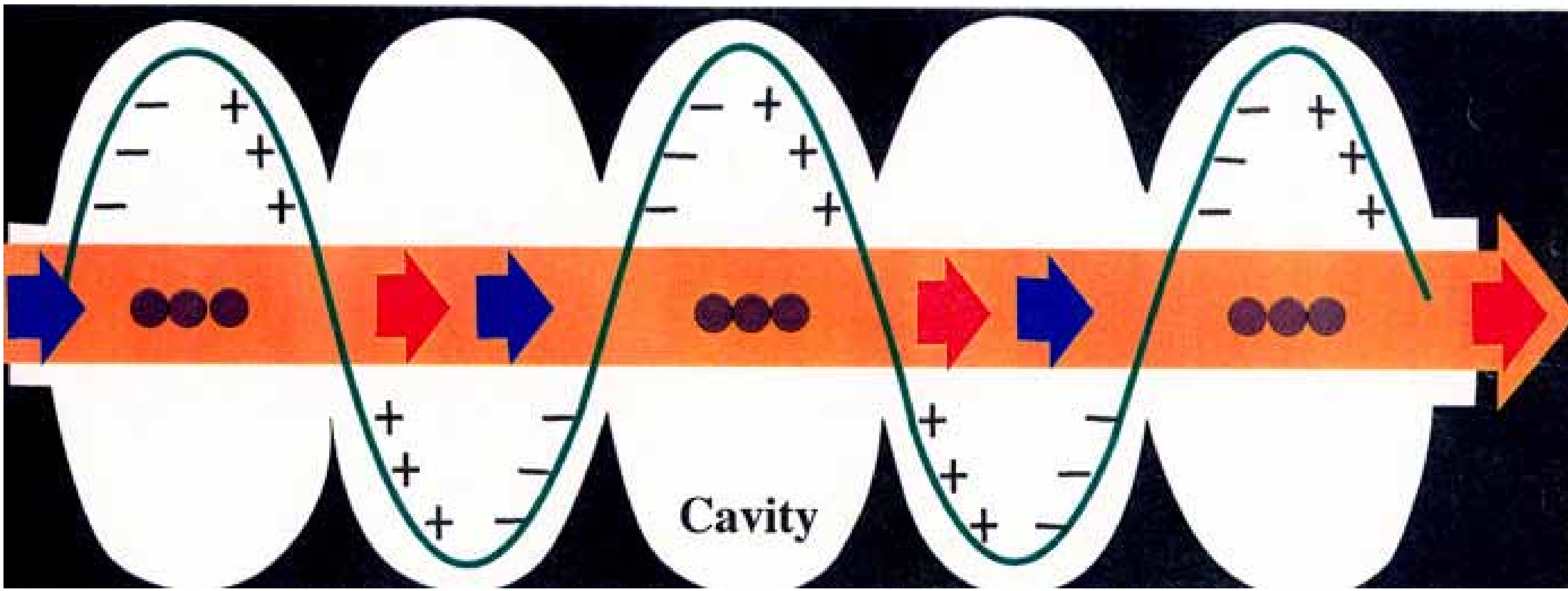
Niobium Cavity Pair



Issues Limiting Success of Superconducting Cavities Solved

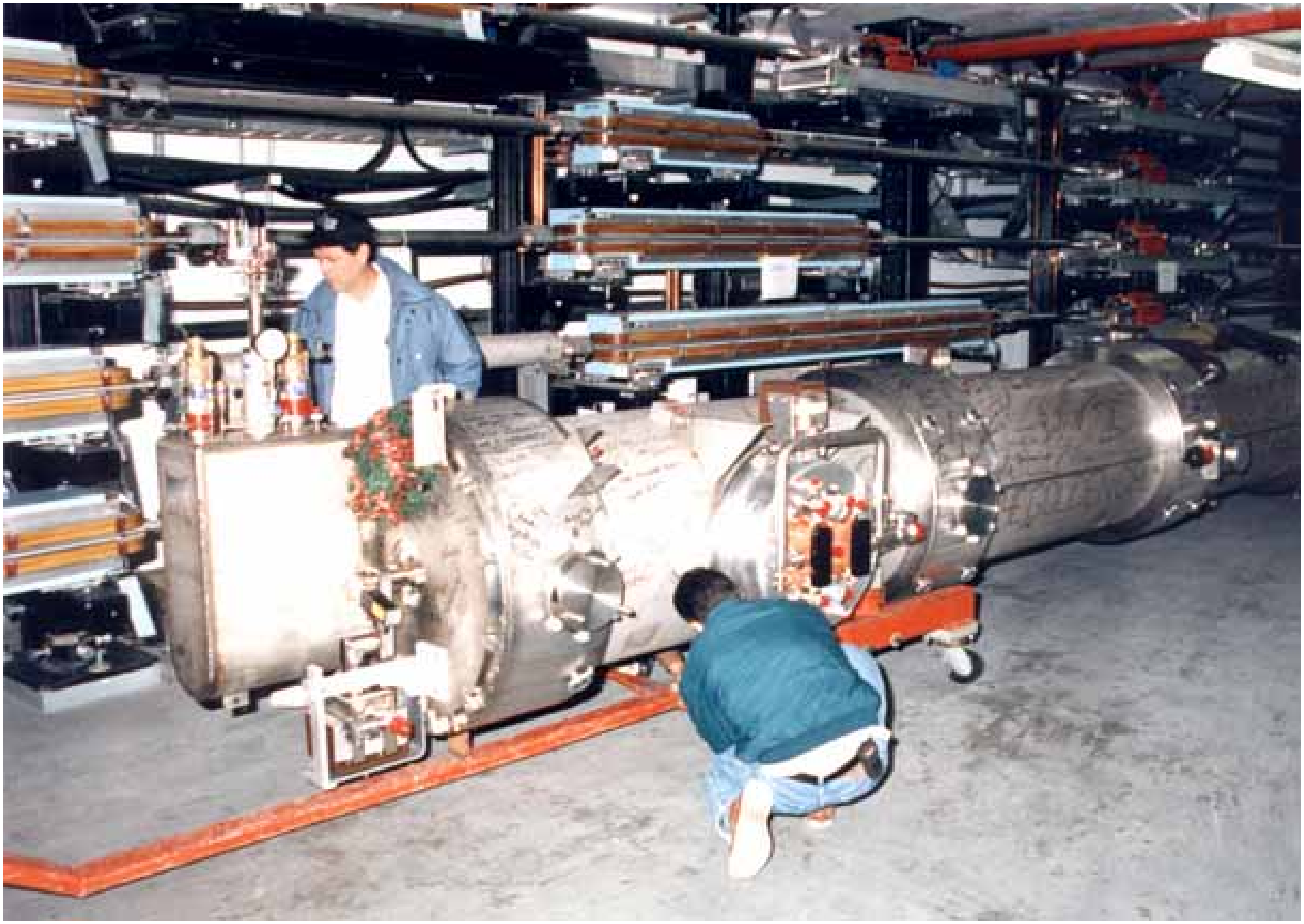
- **Multipacting** (acceleration and multiplication of stray electrons hitting cavity walls and depositing energy) limits E gradient and deposits heat on cavity wall, threatening superconductivity.
  - **Solution:** Elliptical shape cavities
- **Surface defects** on Nb cavities become conducting spots. Need to contain them locally by increasing thermal conductivity of Nb metal to prevent cavity quenching.
  - **Solution:** Slow, repeated, melting of Nb releases embedded gas; Yttrium on deposited on Nb surface captures O_2 from bulk Nb.
- **Vacuum bubbles** in Nb created through electron beam welding reduce heat conduction, and cause surface roughness limiting E intensity.
  - **Solution:** Replace normally focused electron beam by rastered beam.
- **Design of couplers** transferring RF power to cavities produced stray magnetic fields induces quenching and exacerbate electron multipacting
  - **Solution:** Coupling holes were moved away from cavity walls to beam pipes at end of cavities.

Electron Acceleration in RF Cavity

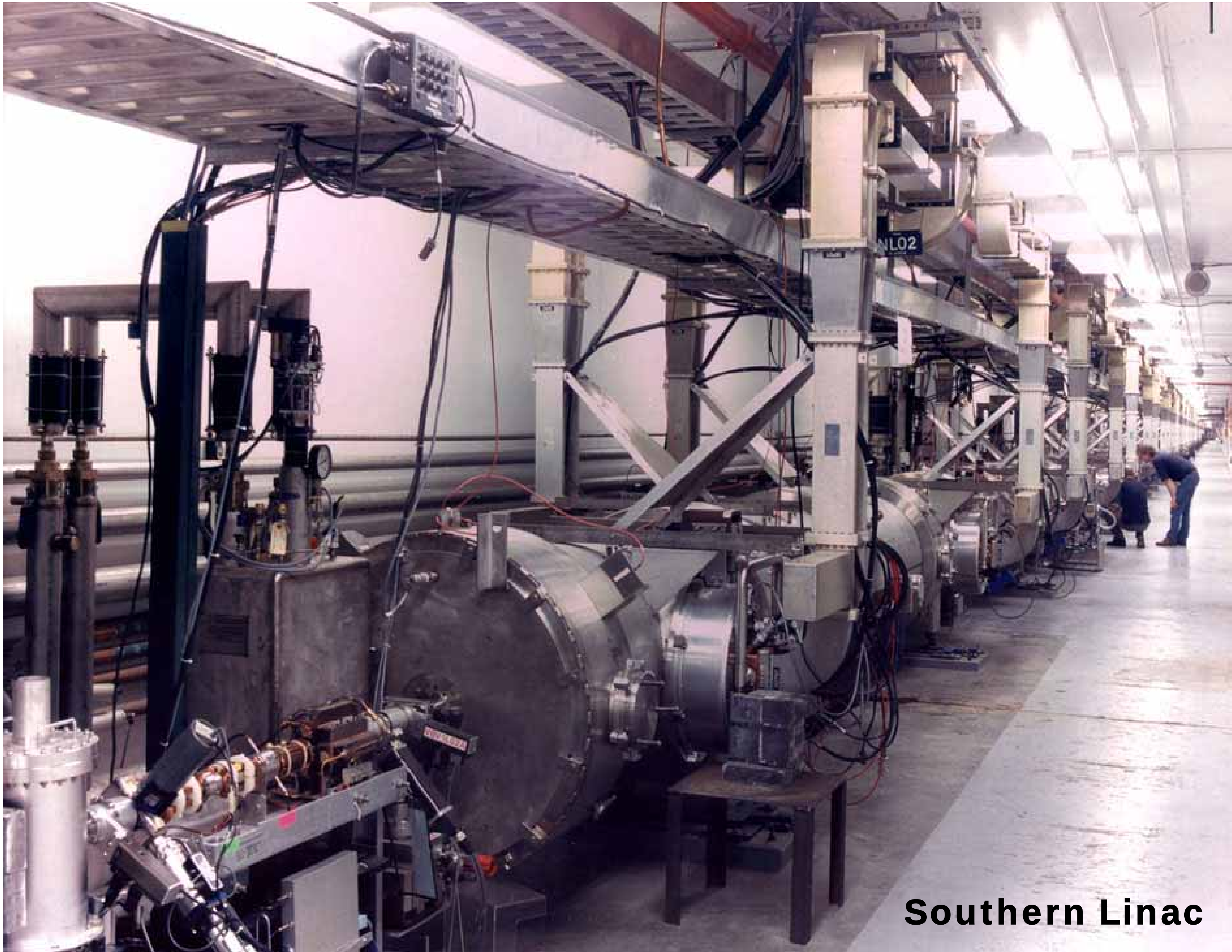


Assembly of Cavity Pairs

Last Cryomodule Installed



Central Helium Liquifier (CHL)



Southern Linac

Steering Magnets

CEBAF Switch Yard

CEBAF Machine Control Center (MCC)

CEBAF Center