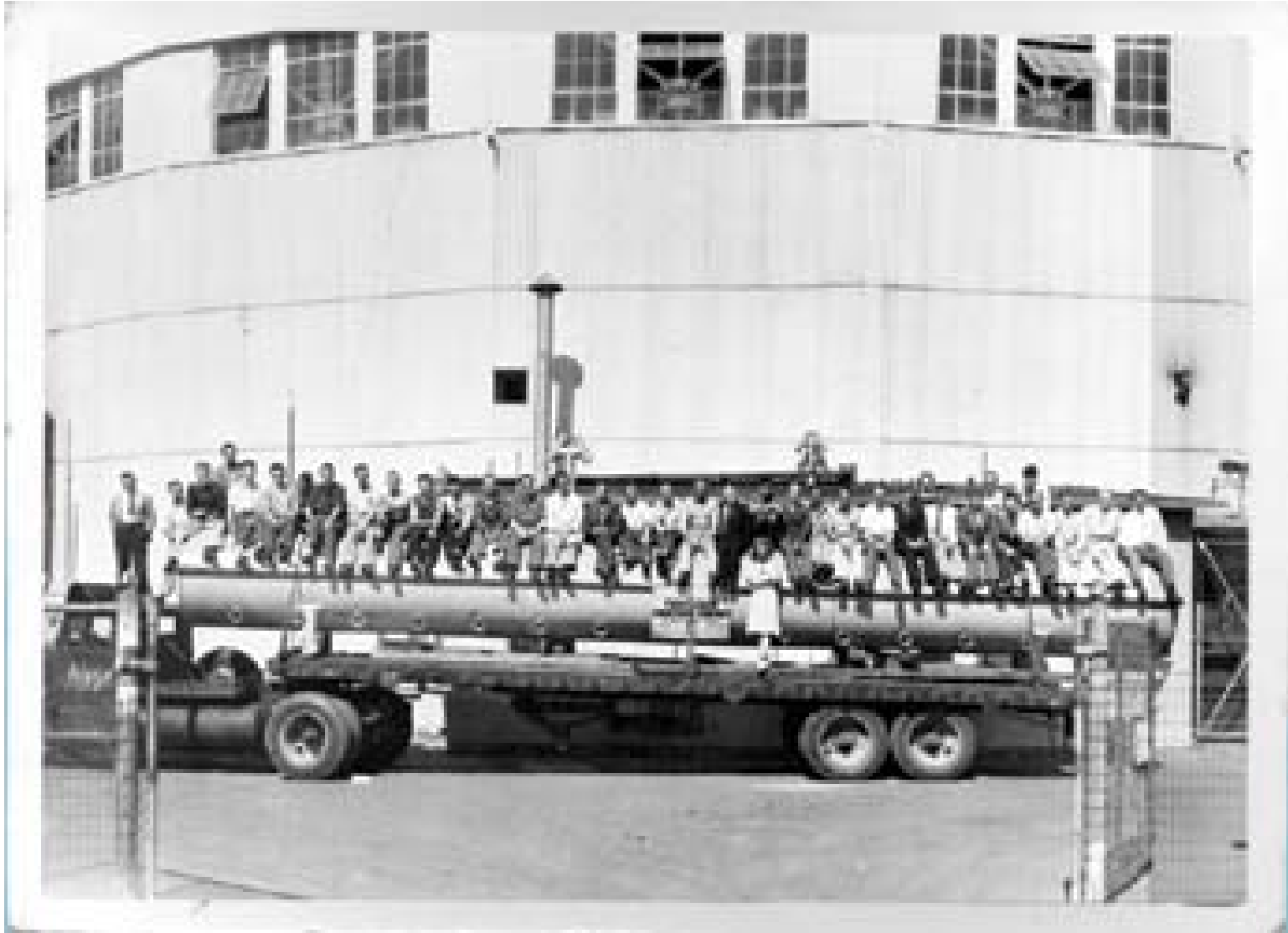


Example of a modern DTL: 402.5MHz, 4.2m, 60-cell drift-tube-linac at the SNS at Oak Ridge.

Since the 1950s drift tubes contain quadrupole magnets for strong focusing.

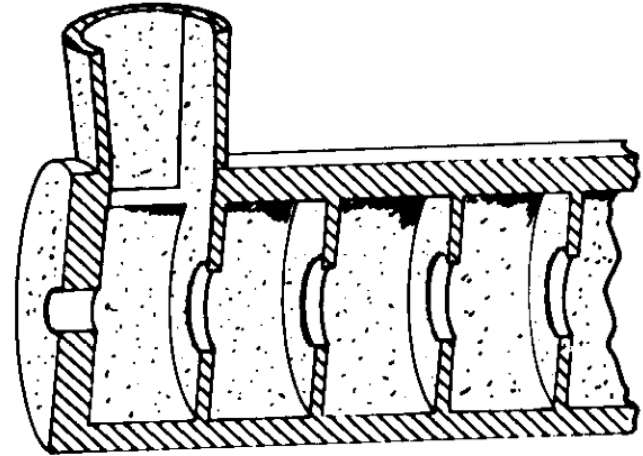


12m Alvarez drift-tube linac with 0.9m diameter at Berkeley (1947)



First electron linac (1947) at Stanford

- RF microwave sources near **3 GHz** were available after WWII.
- Ginzton, Hansen, and Kennedy at Stanford designed the disk-loaded waveguide.
- **This is a stacked array of pillbox cavities** with a central hole for the beam and for cell-to-cell coupling of the electromagnetic wave.



Travelling electromagnetic wave transfers energy to the beam.

Advances in normal-conducting linacs

1960s-1980s

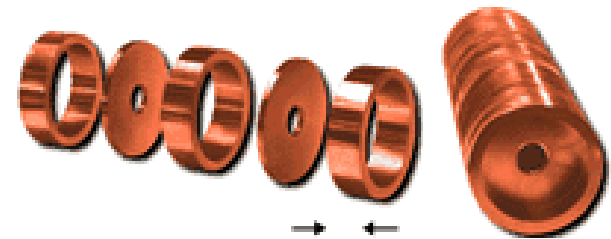
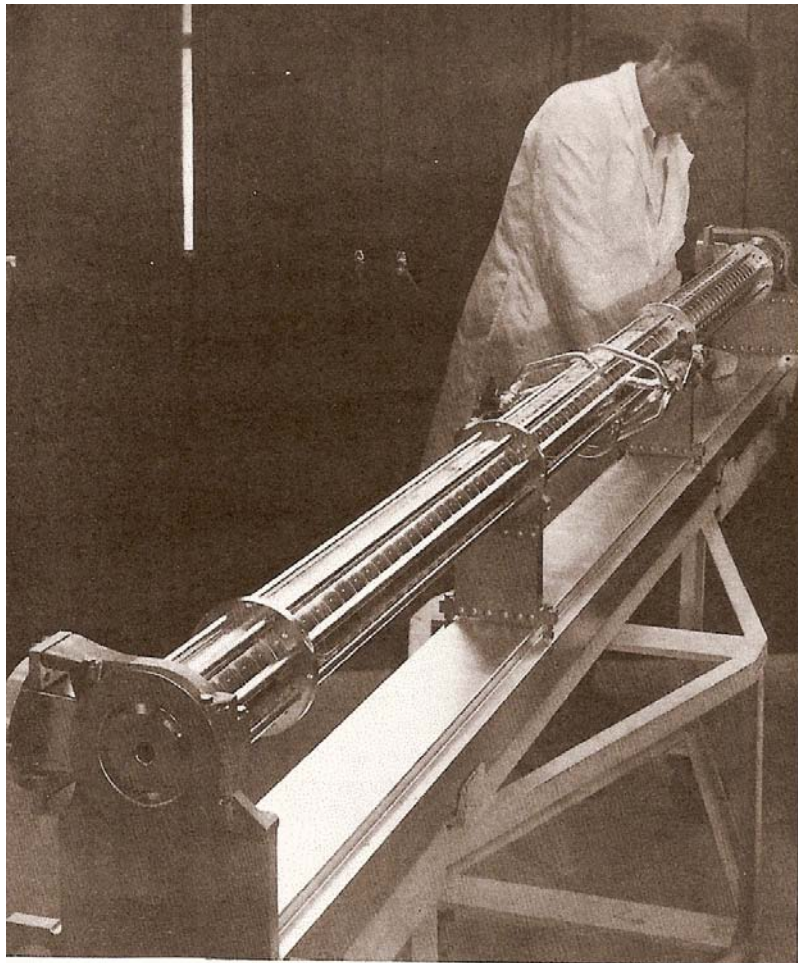
SLAC is the world's longest linac (3-km)

- Stanford Linear Accelerator Center (SLAC), 50 GeV, 2856 MHz room-temperature electron linac
- **Fixed-target facility (SLAC)** beginning in 1966
- **Electron-positron linear collider (SLC)** beginning in 1989, Burt Richter et al.
- **Linac Coherent Light Source (LCLS)** beginning 2009, uses electrons accelerated in the last kilometer of the linac for the world's first X-ray FEL

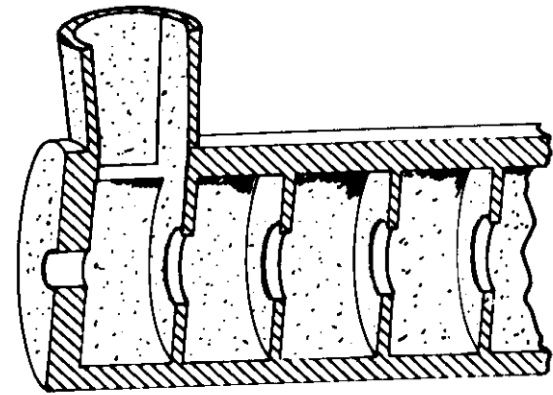


Aerial view of 3-km SLAC Linear Collider

10-foot disk-loaded, 2856 MHz, SLAC accelerating structure, 86 cells per structure, 960 structures make up the SLAC 3-km linac.



Cells are stacked pillbox cavities



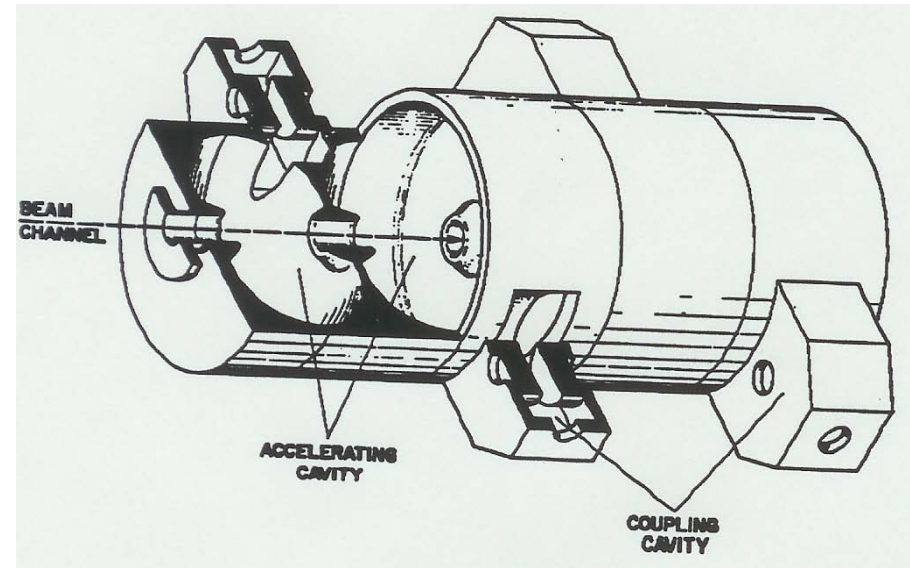
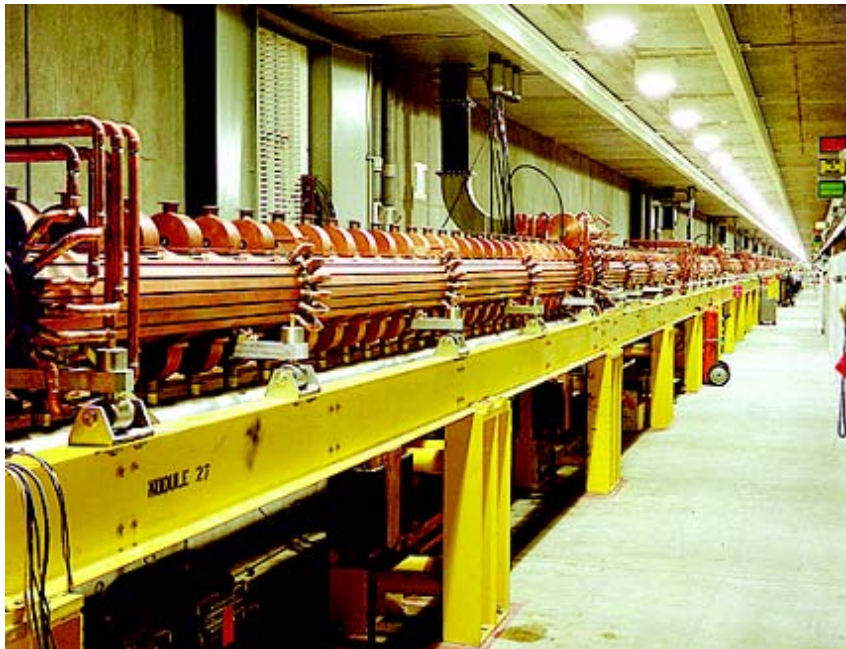
800-MeV, ½ mile LAMPF proton linac at Los Alamos

- Began operation in 1972 as LAMPF, a high-current pion factory.
- Now, its **Los Alamos Neutron Science Center (LANSCE)**, a spallation-neutron source and proton radiography facility.

The major innovation for LAMPF was the invention of the side-coupled linac for acceleration of the high energy protons (100 to 800 MeV)

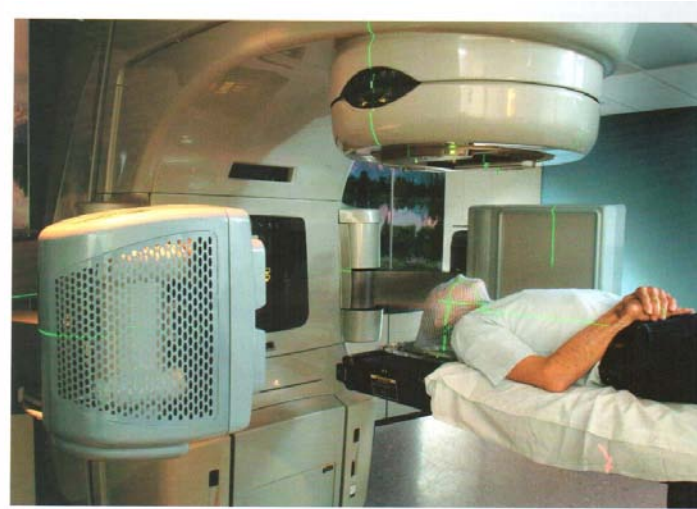


Side cavities provide the cell-to-cell electromagnetic coupling permitting on-axis accelerating cells to be designed for maximum efficiency.

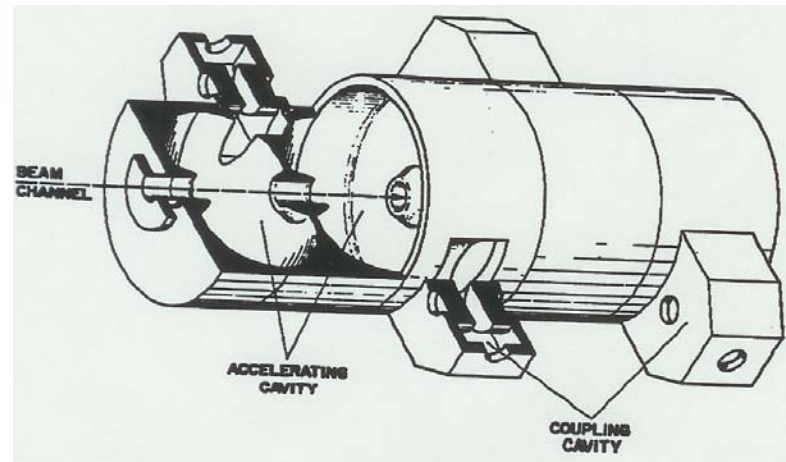


Side-coupled linacs are used for commercial electron-linac x-ray generators for cancer therapy

(delivering 4 to 25 MeV electrons)

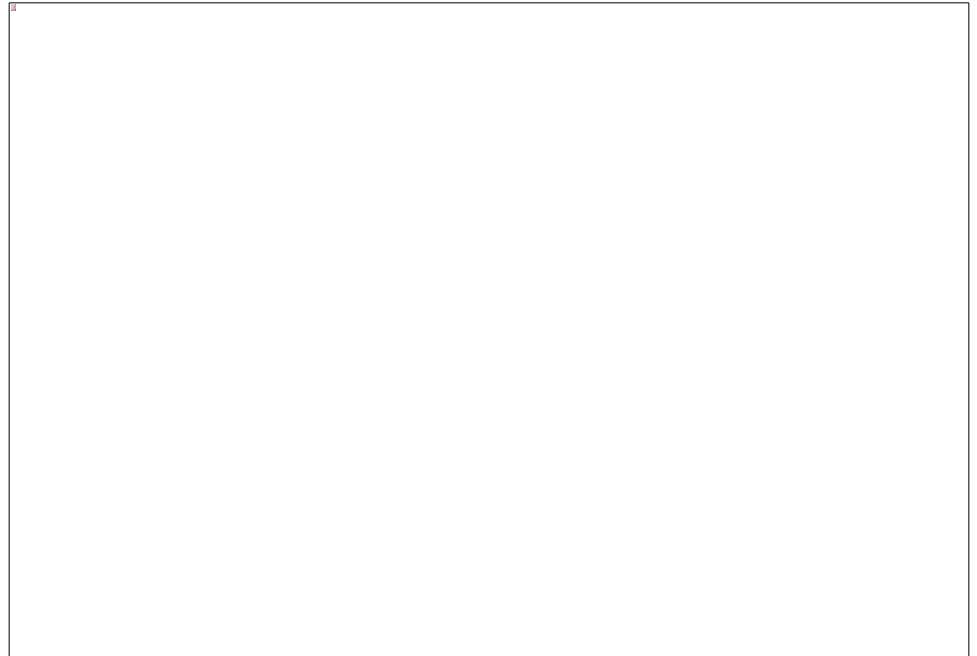


About 5000 side-coupled linacs are used in hospitals worldwide because of their high efficiency.



A major innovation was invention of radiofrequency quadrupole (RFQ) by Kapchinskii and Tepliakov.

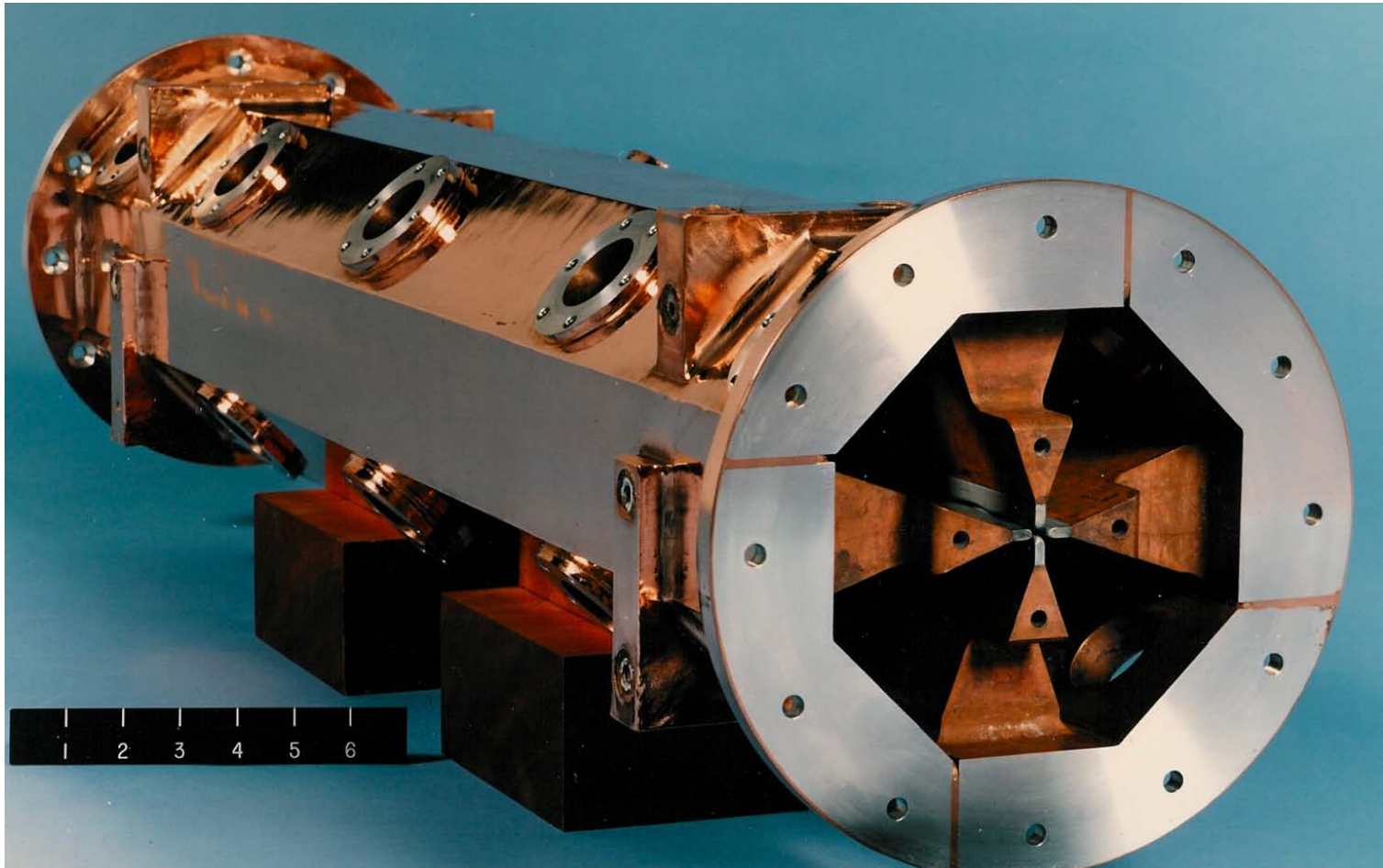
- Consists of four vanes in a cylindrical cavity. No drift tubes needed.
- Uses RF electric fields for **bunching, acceleration, and strong transverse focusing** for low velocity ions.
- Accelerating fields are obtained from modulation pattern on the four vanetips.
- **The strong electric focusing produces large increases the beam-current limit for ion linacs.**



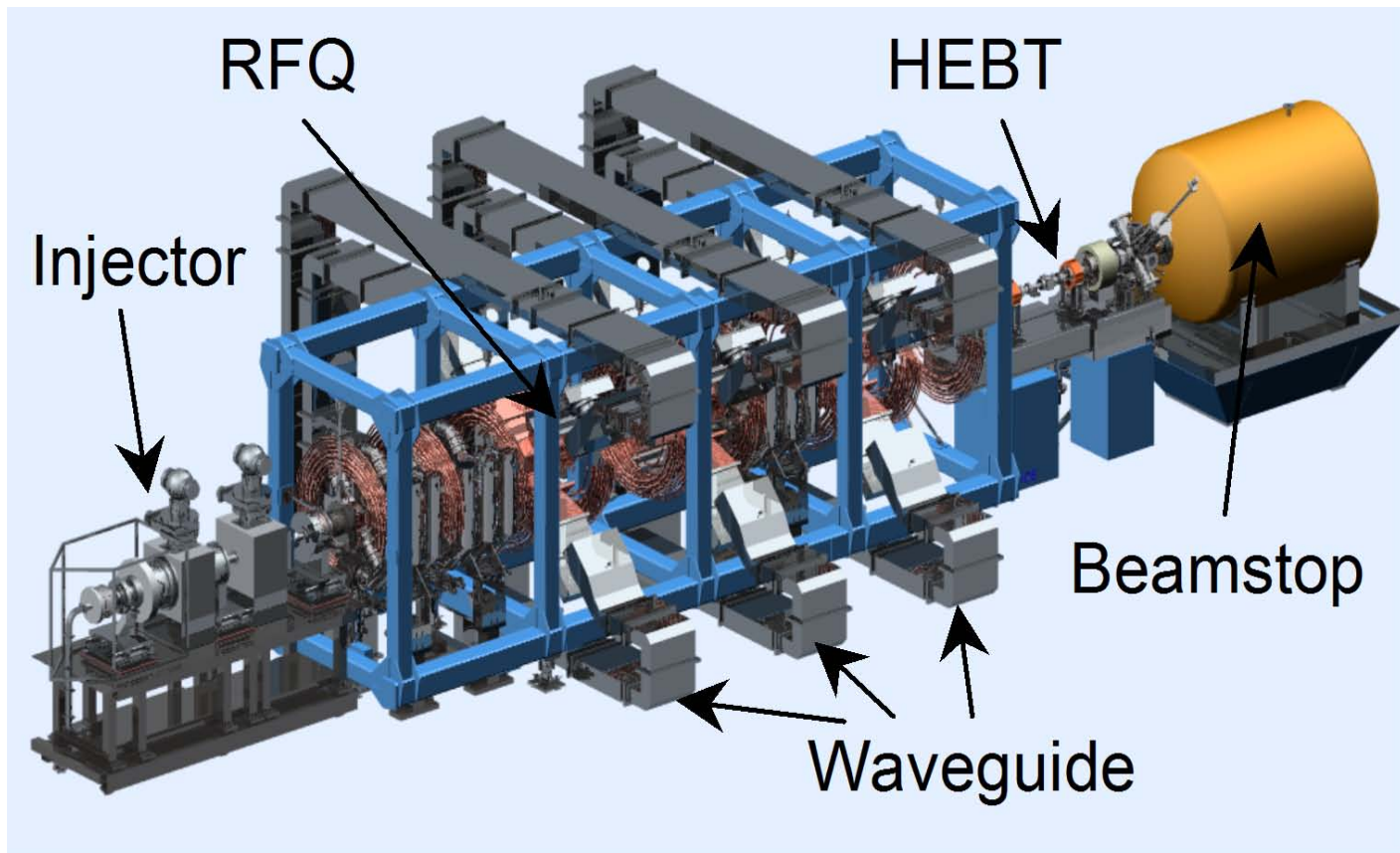
All new ion linacs now begin with with an RFQ at the front end.

“BEAR” H⁻ RFQ operated in space for SDI missile defense program (1989). This RFQ is now in the Smithsonian.

30-keV to 1-MeV, 1-m long, 425-MHz, 30 mA H⁻



Most powerful RFQ was 350-MHz 8-m long CW RFQ that accelerated a 100-mA proton beam at Los Alamos (LEDA) from 75-keV to 6.7-MeV

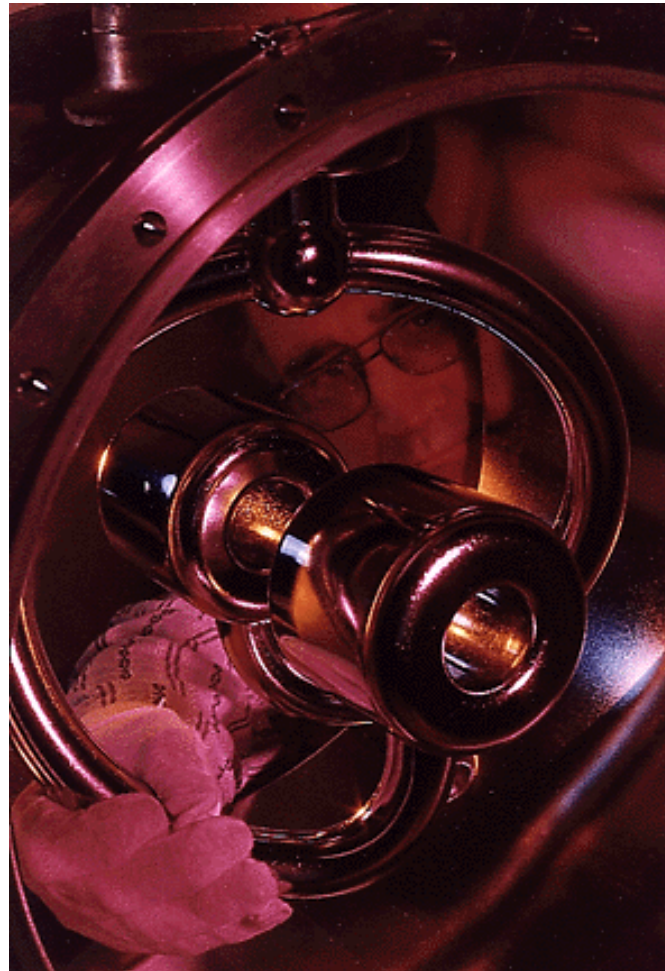


Growth of RF superconducting linacs

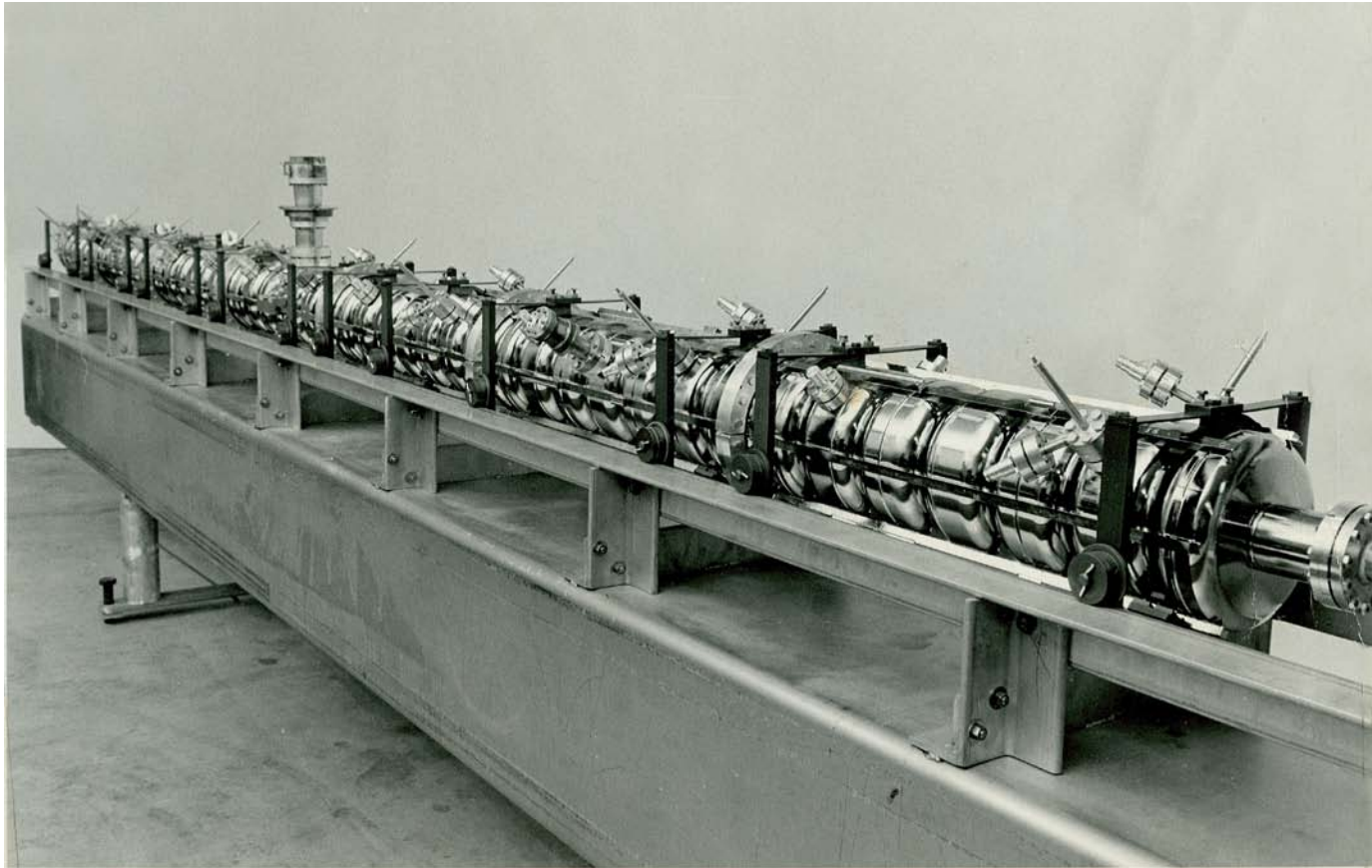
1990 to the present

RF superconductivity benefited from pioneering work in 1970 and 1980s

Superconducting splitting niobium resonator for ATLAS at Argonne National Laboratory, the world's first superconducting heavy ion accelerator. It produced first beam in late 1970s



The first superconducting niobium rf linac was built at Stanford for electrons (1977). Operated CW at 50 MeV energy gain in 27 m. U. of Illinois also built a superconducting microtron (1977).

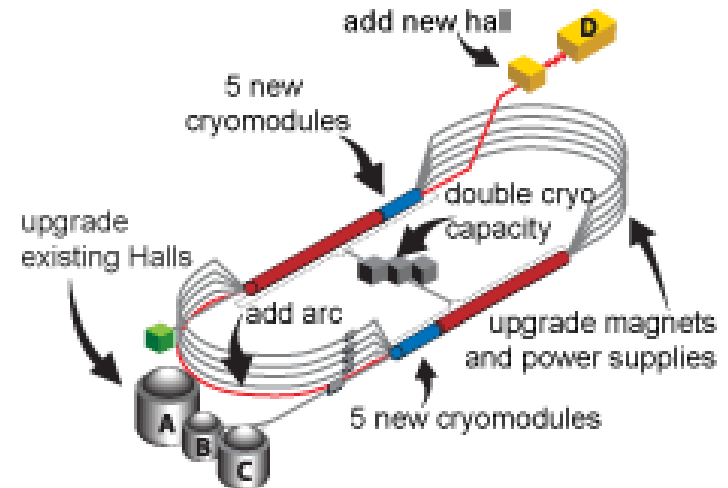


Decision to build a superconducting machine for CEBAF was a major step forward for acceptance of RF superconducting linacs.

- CEBAF is a 5-pass recirculating CW electron-linac that uses two superconducting electron linacs joined by magnetic transport arcs. It is now being upgraded from 6 GeV to 12 GeV with 7-cell nb cavities.



CEBAF-7-cell niobium elliptical cavity

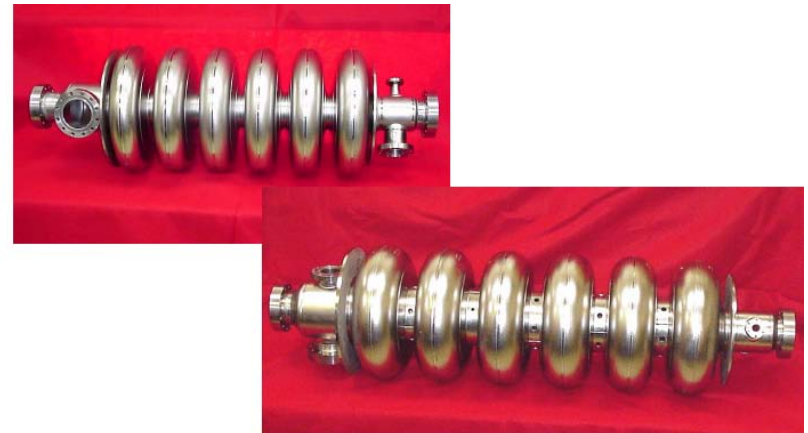


- CEBAF began operation in 1994.

SNS superconducting linac accelerates H⁻ beam from 0.186 to 1.1 GeV.



1.1-GeV H⁻ SNS linac incorporates the world's first H⁻ superconducting proton linac. Duty factor is 6%.



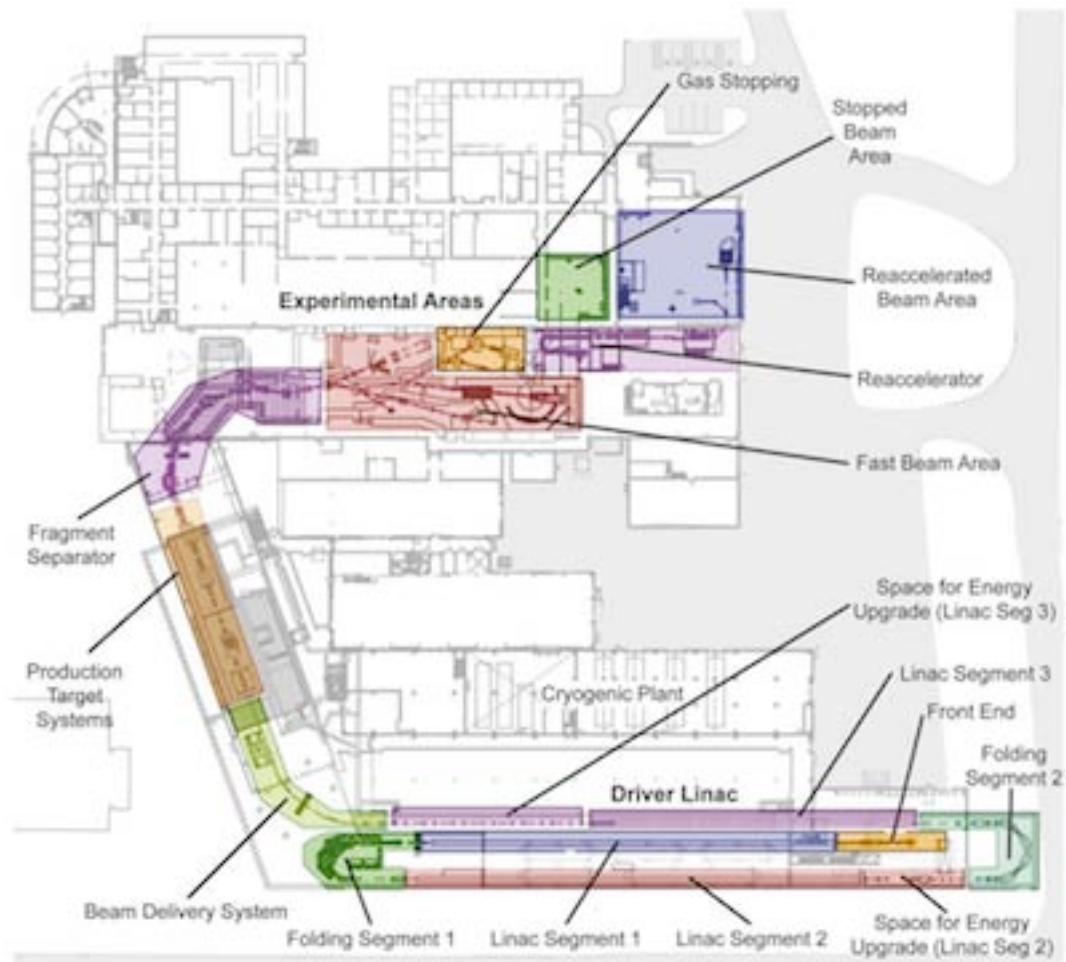
Six-cell 805-MHz medium-beta ($\beta=0.61$) and high-beta ($\beta=0.81$) superconducting niobium elliptical cavities. The SNS linac contains about 80 niobium cavities

Linacs have a great future

- **Facility for Rare Isotope Beams (FRIB)**, CW heavy ion superconducting linac at Michigan State University, 200MeV/u, 400kW, 344 superconducting cavities, 170m, start up in 2020.
- **European X-ray FEL**, Hamburg, superconducting electron linac, 17.5GeV, 2.1 km, $E_a=24\text{MV/m}$, 640 9-cell cavities, 1.3 GHz, construction began 2009 at DESY.
- **European Spallation Source (ESS)**, Lund, Sweden, 2.5GeV 50mA, proton superconducting linac, 5 MW power, RFQ-DTL-Spoke-Elliptical, 353 and 704 MHz, 2msec-20 Hz, operational in 2025.
- **J-PARC**, Takai-Mura, Japan, linac construction to 400 MeV in progress, normal conducting proton linac complete in 2012.
- **SPIRAL2**, Caen, France, Radioactive Ion Beam Facility, CW heavy ion superconducting linac, first operation 2013.
- **International linear collider (ILC)**, proposed, electron and positron linacs, each at 250 GeV and 12 km, 16,000 9-cell superconducting cavities.
- **Proton-linac-driven nuclear reactor (ADS)**, subcritical system for transmutation of nuclear waste. In a preliminary stage.
- **Project X**, Fermilab, a proposed multi-GeV superconducting proton linac

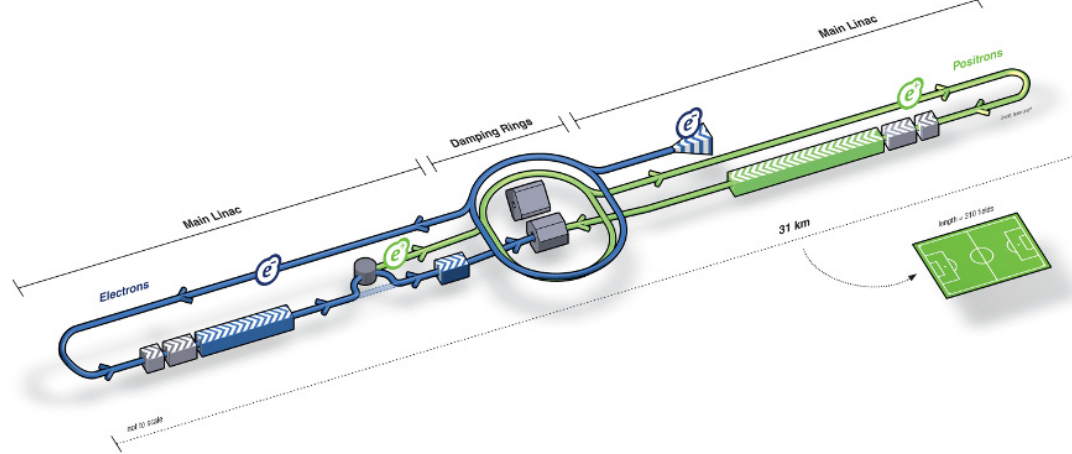
Facility for Rare Isotope Beams (FRIB)

CW linac at Michigan State University, 200MeV/u, 400 kW,
344 superconducting cavities, 170m, start up in 2020



International Linear collider (ILC) proposed electron-positron collider

Presently in planning/design stage

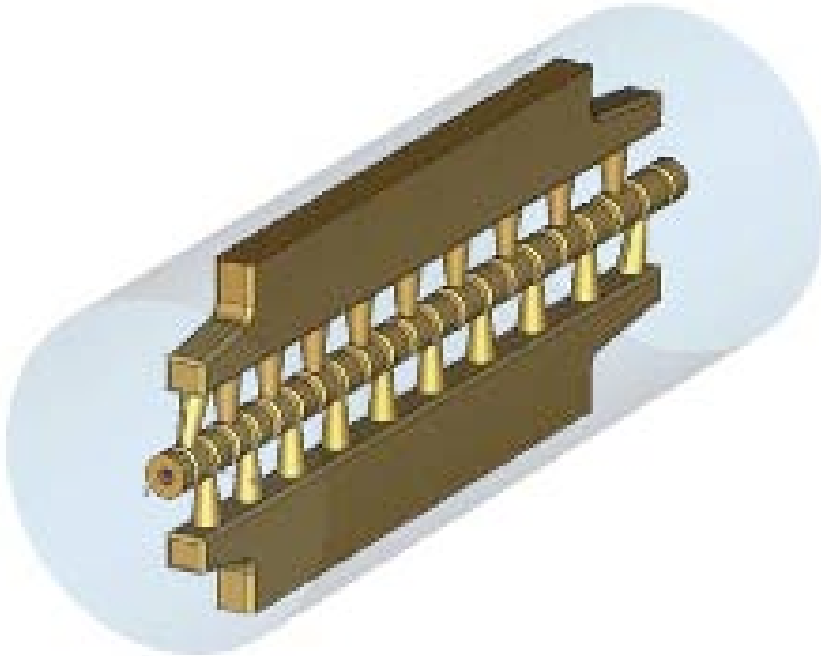


0.5 TeV center of mass, 16,000 niobium cavities, 31 km Long.



The ILC will use 9-cell superconducting niobium elliptical cavities similar to this one. Accelerating gradient is 31.5 MV/m at 1.3-GHz RF frequency.

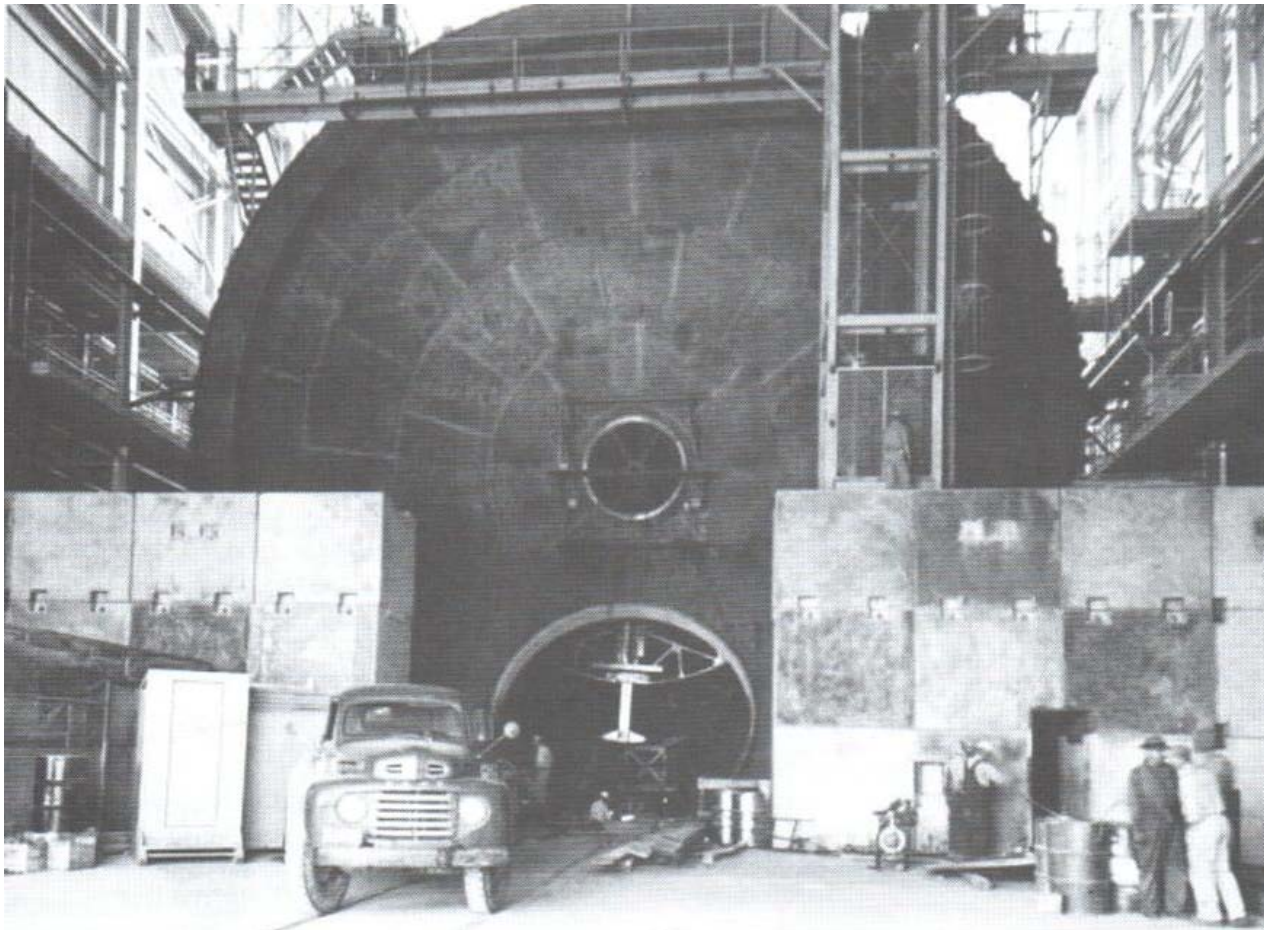
Within the past decade we have learned that a modern Wideroe proton linac can be an order of magnitude more efficient than the Alvarez DTL.



- Until the past decade the Wideroe linac was ignored for protons; it was believed that Alvarez drift-tube linac was inherently more efficient.
- But the Wideroe linac can be designed for much greater efficiency with better distribution of currents, and better concentration of electric fields in the gaps. *S.S Kurennoy, et al.*

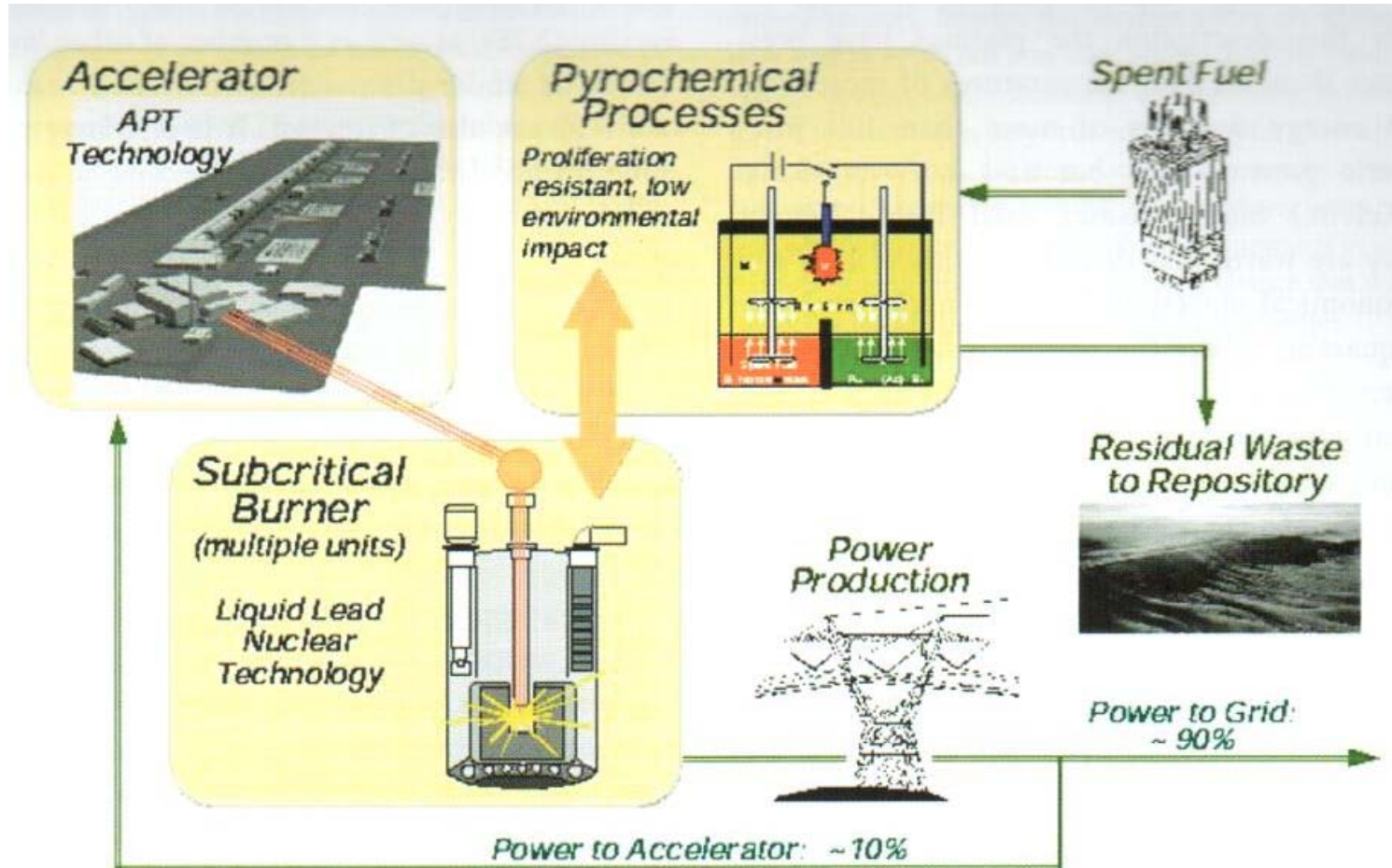
MTA (built at Livermore 1950), largest drift-tube linac ever built, 60 ft diameter tank-designed to accelerate 0.33 A of deuterons to produce plutonium and tritium

It was never used after the discovery of uranium in Utah (1950).



Proton-linac driven nuclear reactor

In a preliminary stage. No major programs yet.



Summary

- Linacs are used for at least 5 projects now under construction or approved, as well as potential projects ILC, Project X, and ADS for waste transmutation.
- Almost all of these are superconducting linacs.
- Linac performance has continued to improve from clever inventions like the **side-coupled linac**, the **RFQ**, and advances in **RF superconducting technology**.
- **Thousands of electron linacs are now used in hospitals around the world for radiation therapy, an application that represents one of the most significant spins-offs of basic research.**