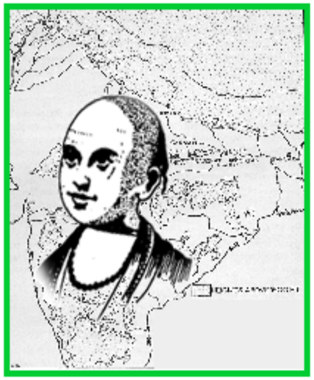
Quest for the Microworld
Story of Nuclei, Particles & Accelerators

Amit Roy

Atom - “that which cannot be cut up further”.

Democritus 560 – 470 B.C



Atoms are eternal, indestructible and cannot exist in the free state.

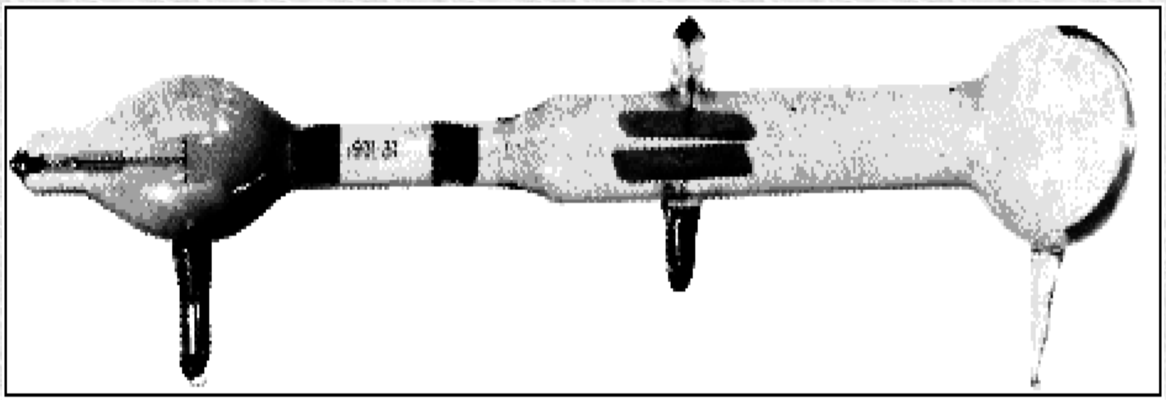
Kanada ~ 600-400 B.C

The smallest unit of each element is an Atom of that element.

John Dalton (1766-1844)

First elementary particle discovered by the first accelerator!

Discovery of **electron**, 1897.



(Photo: Science Museum, London.)

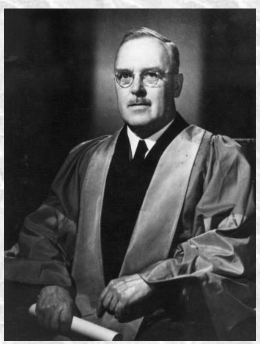
(Nobel 1906)

Cathode ray tube built by J.J. Thomson, Length ~ 30 cm

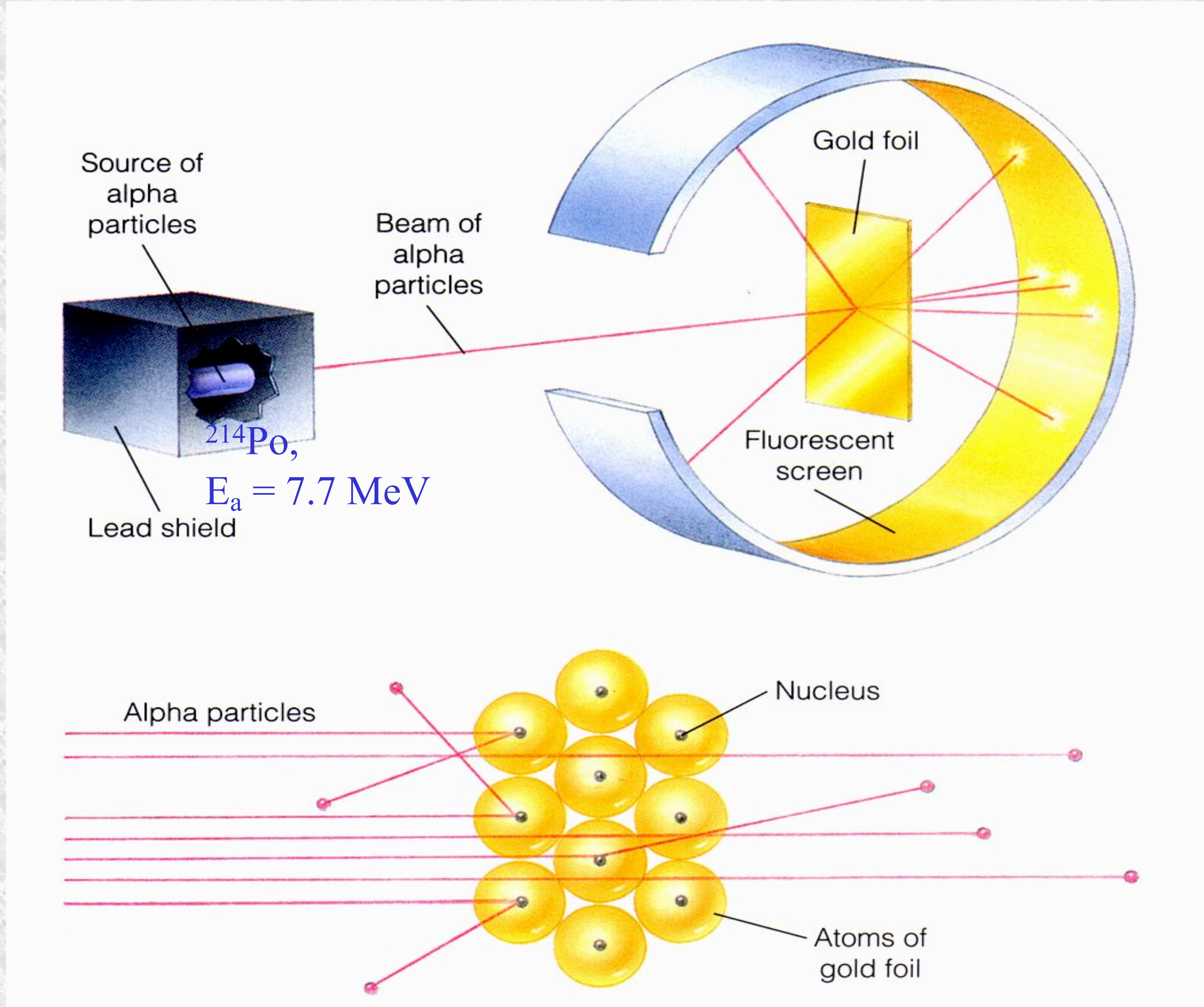
Discovery of the Nucleus using a natural particle source

Rutherford

Geiger



Marsden



^{214}Po,
$E_a = 7.7$ MeV

1927: Lord Rutherford

Call to build Accelerators

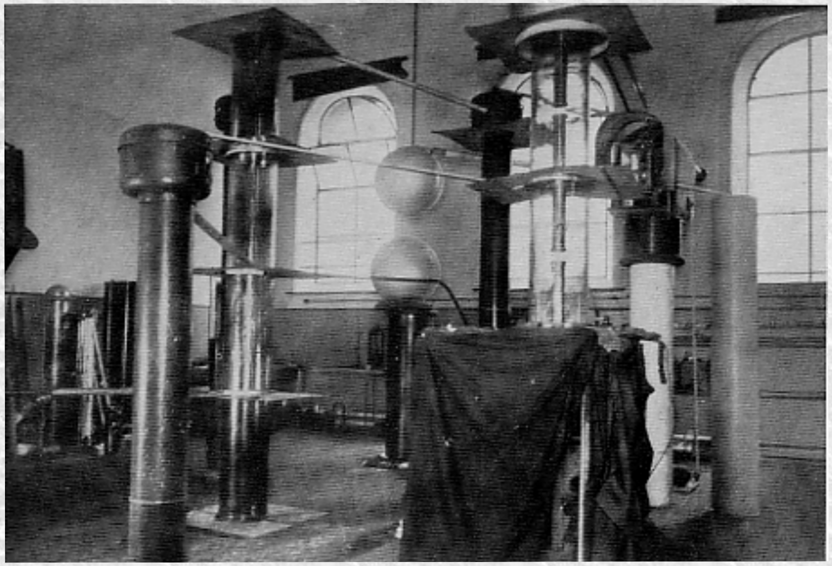
“What we require is an apparatus to give us a potential of the order of 10 million volts............… I see no reason why such a requirement cannot be made practical.”

Natural source of high energy particles – Cosmic rays

Particle flux is low, but many new particles were discovered in studying Cosmic rays.

Race to build Accelerators began.

DC machines

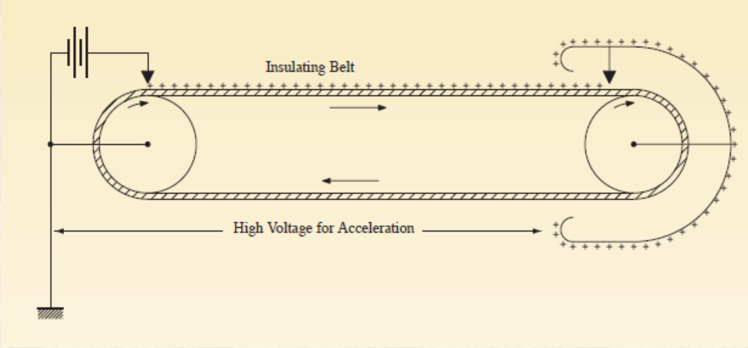


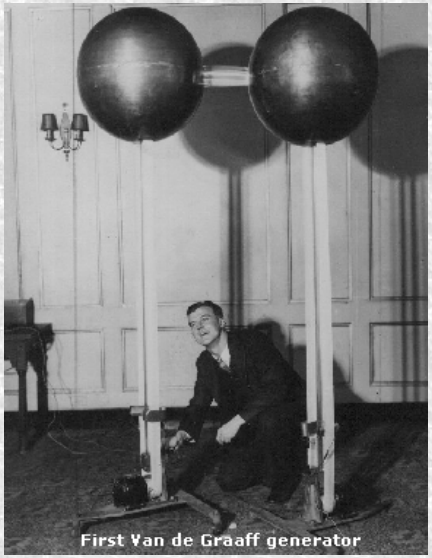
Cascade Generator, 1932

Nobel 1951

$^{7}Li + p = {}^{4}He + {}^{4}He$ at $E_p = 400keV$

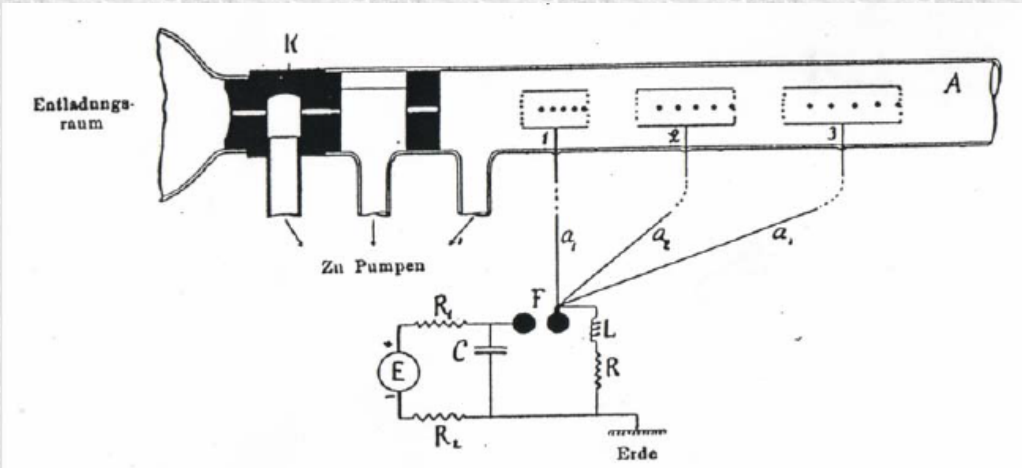
First reaction with artificially accelerated particles.





R.J. Van de Graaff

AC machines



1928 Thesis
Reached 50 keV K+ with 25 kV drive

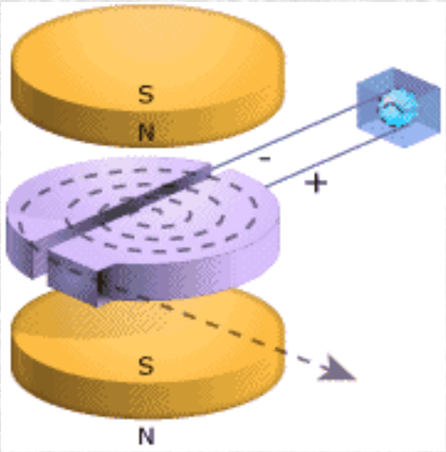
Linear Accelerator

$V = V_o \sin(\omega t + \psi_s)$

$L = \lambda/2.\ v/c$

$E = n.q.\ V_o \sin \psi_s$

R.Wideroe



Cyclotron, 1932

$\omega = qB/mc$

Diameter ~ 4.5", E_p ~ 80 keV

Lawrence

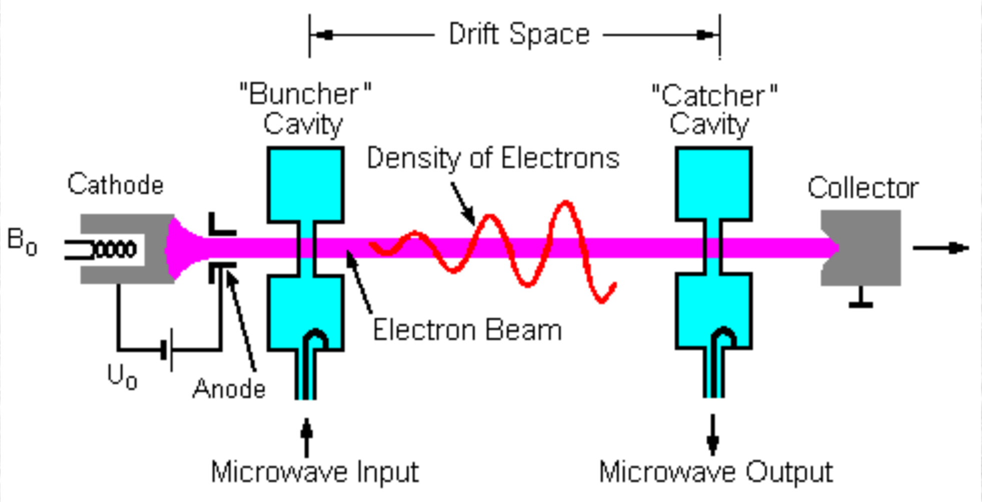
Nobel 1939

http://cso.lbl.gov/photo/gallery/

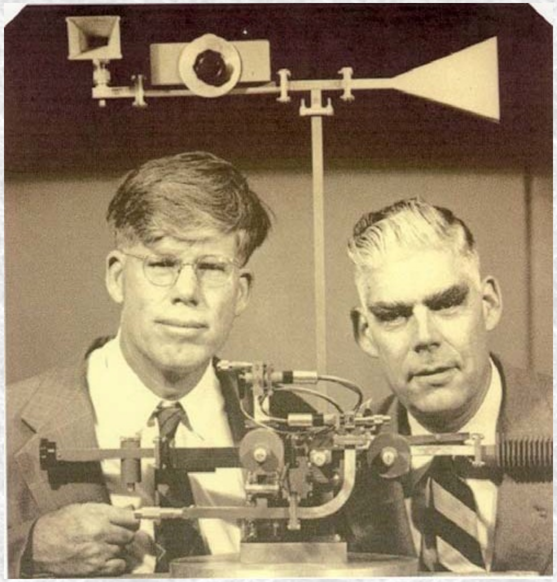
Progress towards higher energies!
A crucial step.

Stanley Kaisel, Clarence Carlson, William Kennedy, William W. Hansen

Stanford Mark I linac   6 MeV electron, 1947



Klystron



Russell and Varian, 1937

Large number of Accelerators were built (1940-1970)

Set I

Low Energy Accelerators,
Van de Graaff, Cyclotron

Providing wide variety of Ion beams

Objective:
Probing Nuclear Structure, Nuclear Reactions.

Set II

High Energy Accelerators,
Synchrocyclotrons, Synchrotrons
Linacs

Protons, Electrons

Objective:
Particle Properties, Sub-structure of Particles.

More sub-atomic particles…….

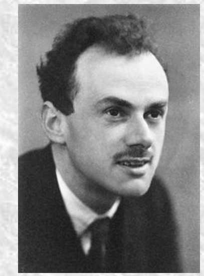
$\alpha + {}^{14}N = {}^{17}O + p$ - discovery of **proton**, Rutherford in 1917

$\alpha + {}^{9}Be = {}^{12}C + n$ – discovery of **neutron**, James Chadwick, 1932

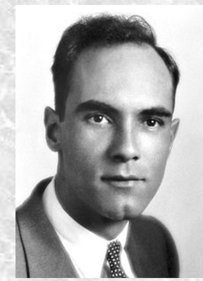
Nobel 1935

Prediction of **positron** – antiparticle of electron, **PAM Dirac**, 1928-31

Discovered in 1932 in Cosmic rays, **Carl D. Anderson.**



Nobel, 1933



Nobel, 1936

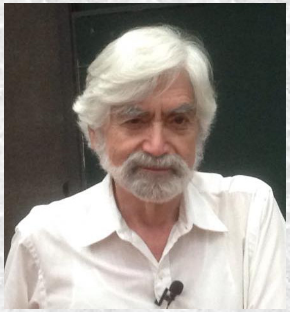
1936: μ-meson discovered using cosmic rays, Neddermeyer and Anderson

Cecil F. Powell discovered the π- meson using photographic emulsion in 1947.

Nobel 1950

Several other particles, viz., K- , Ω, ρ, Λ, Σ discovered in cosmic rays

M. Gell-Mann
Nobel 1969



George Zweig

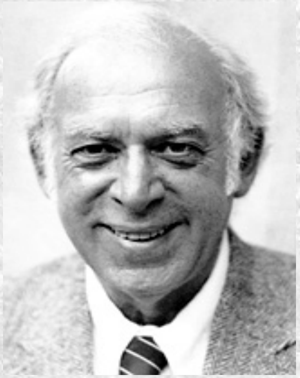
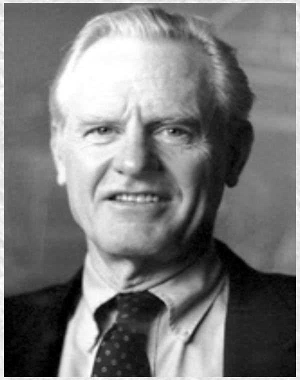
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

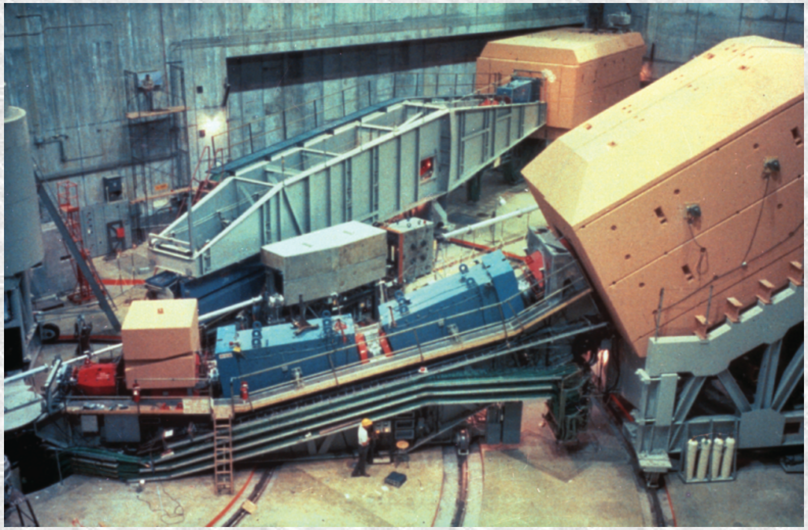
Received 4 January 1964

It is fun to speculate about the way quarks would behave if they were physical particles of finite mass instead of purely mathematical entities

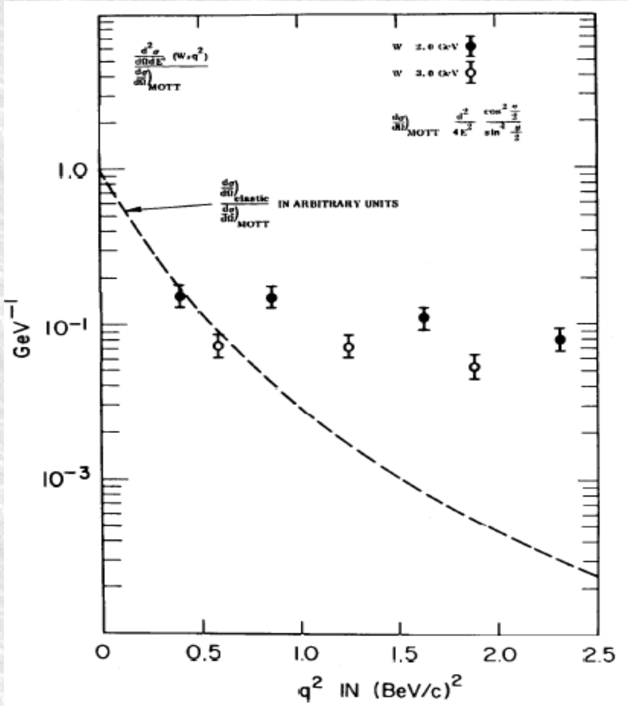
Zweig called them "aces"

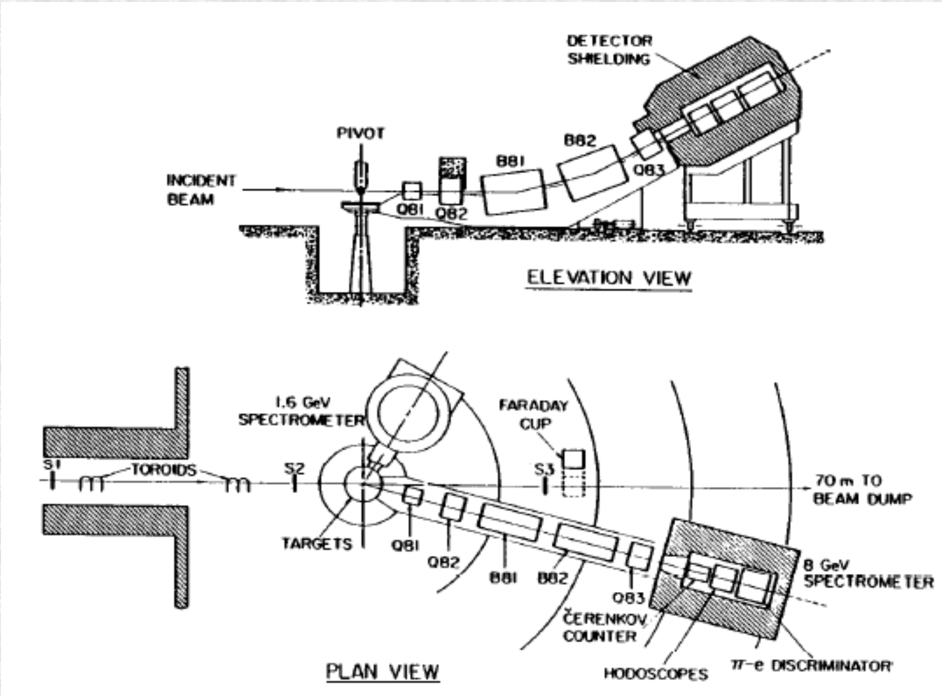




Jerome Friedman, Henry Kendall, Richard Taylor.
Nobel, 1990



Use electrons of still higher energy, **8 GeV**



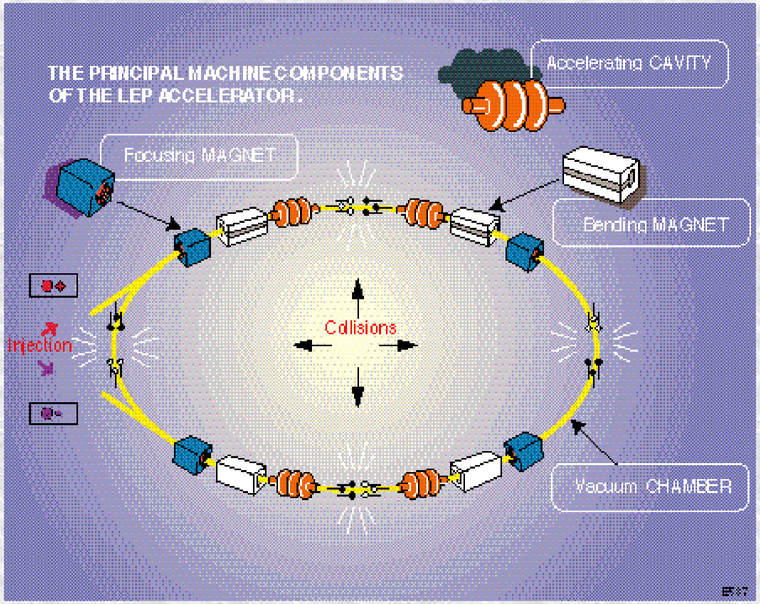


Protons have sub-structure!
Size ~ 10^{-15} m

Towards Higher Energies...

Courant **Livingston** **Snyder**

Alternating Gradient, Strong focusing principle (Brookhaven, 1952).
Enables high energy machines to be built.
First design is 1.3 GeV electron ring at Cornell (1954)



Alternate Gradient Synchrotron,
BNL 33 GeV p, 1960

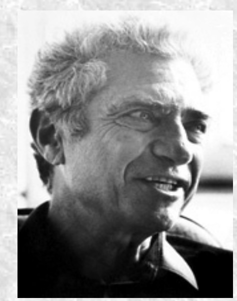
1956: F. Reines and C. Cowan detection of a neutrino via inverse beta decay reaction

$$\nu_e + p \rightarrow n + e^+$$

Clyde Cowan

Frederick Reines
Nobel, 1998

Discovery of the muon-neutrino, 1962



L.M. Lederman, M.Schwartz, J.Steinberger

Nobel, 1988

Reaching higher Energies.
Accelerator Innovation

Fixed-Target Machines:

Target particle m_t is at rest in the lab, $E_t = m_t c^2$, $p_t = 0$

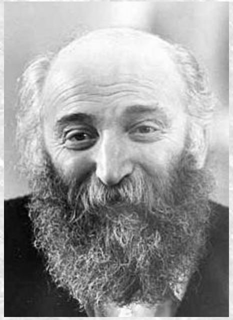
$$E^* = (2m_t c^2 E_p)^{1/2}$$

Colliding-beam Machine:

Incident and Target particles m_p and m_t travel in opposite directions

$$E^{*2} = 4 E_p E_t$$

Cooling of beams required



Electron Cooling, 1966
G. Budker

Stochastic Cooling,, 1971
S. van der Meer

Wolfgang Panofsky

http://www.slac.stanford.edu

2 mile long Stanford Linear Accelerator for electrons 20 GeV, 1966
Upgraded to 24, 42 GeV, Now converted to a Photon Source

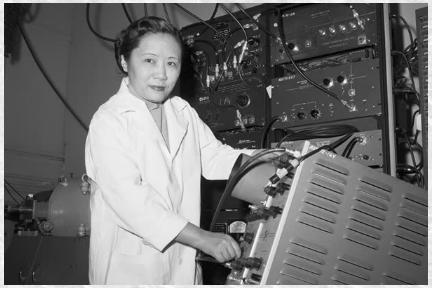
Nobel 1976
Burton Richter, Samuel C.C. Ting
Discovery of Charm quark
(1974, SLAC, BNL).

Anomaly observed in neutral K-meson decay. Yang and Lee postulate violation of Parity, 1956. Experimental verification of Parity Violation by C.S. Wu et al. 1957

C.N. Yang

T. D. Lee

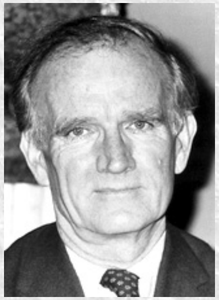
Nobel 1957



C.S. Wu   Beta Decay

Nobel 1980

"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons" Experiment was conducted in 1964 at BNL.



James W. Cronin, Val L. Fitch

The bottom and top quarks was theorized in 1973 by physicists **Makoto Kobayashi** and **Toshihide Maskawa** to explain CP violation.

$$\begin{pmatrix} u \\ d \end{pmatrix}, \quad \begin{pmatrix} c \\ s \end{pmatrix}, \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$+\tfrac{2}{3}\,(u,\, c,\, \text{or } t)$$

$$-\tfrac{1}{3}\,(d,\, s,\, \text{or } b)$$

Nobel

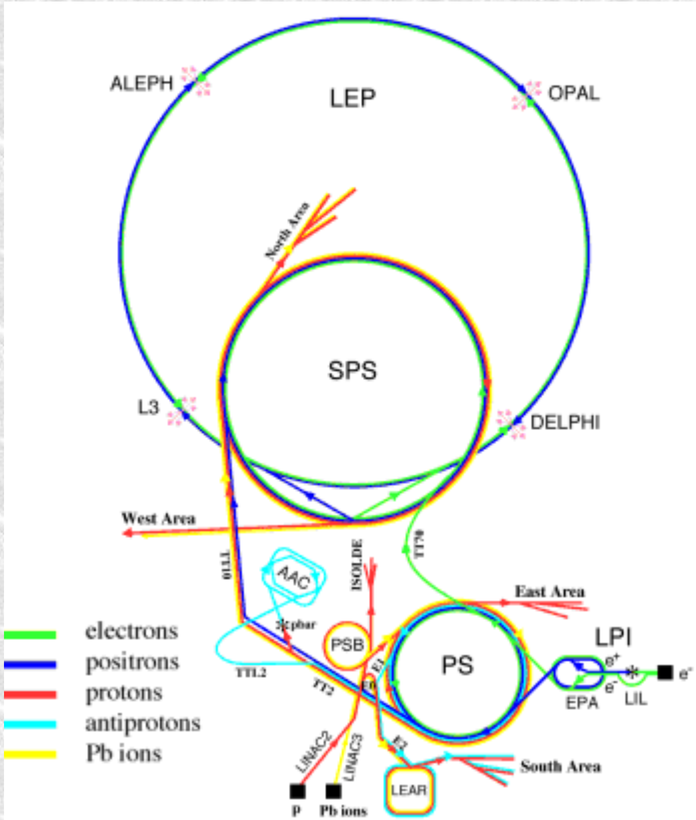
b-quark discovered in 1977 by the Fermilab E288 experiment team led by **Leon M. Lederman**

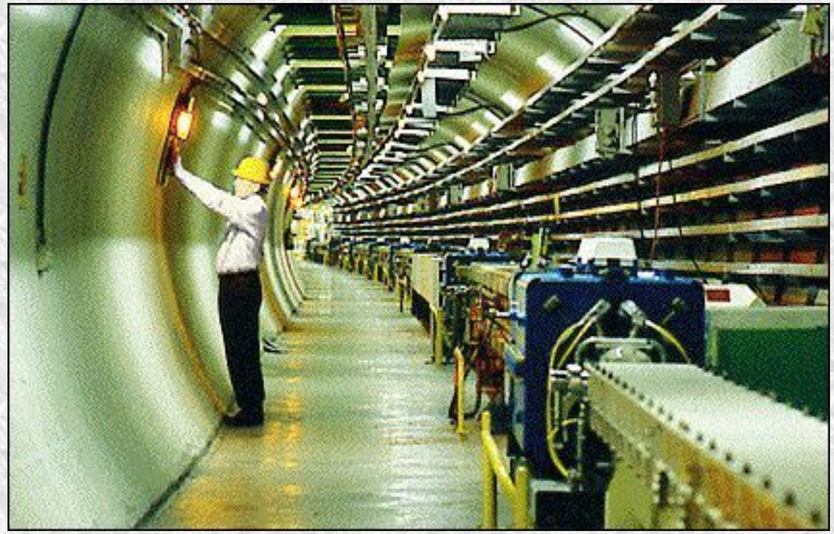
Discovery of tau lepton at SLAC, 1975

Completes the sequence e, μ, τ

M. Perl Nobel 1995

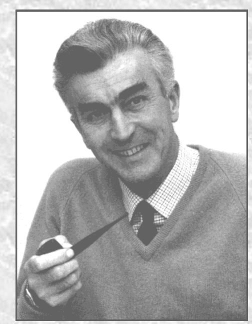
Large electron positron Collider
100 GeV $e^+ e^-$





Only 3 light weakly interacting neutrinos. => 3 generations of quarks and leptons.

Super Proton Synchrotron
270 GeV p ṗ



John Adams

Robert Wilson

FNAL: TeVatron

1 TeV p - ṗ Collider

http://www.fnal.gov/pub/presspass/vismedia/

Top Quark mass predicted by theory and precision measurements from high energy.

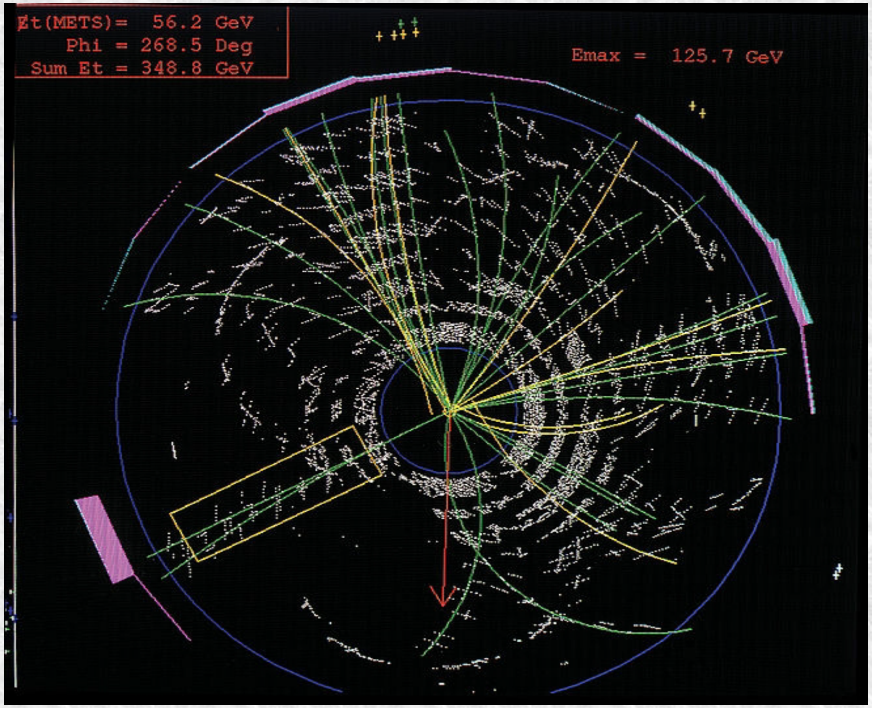
Discovered top quark at Dzero and Collider detectors at Fermilab. Tevatron, 1995

Indian Participation in experiments.

Quark: t:
mass predicted by theory and precision measurements from high energy.

Discovered top quark at Dzero and Collider detectors at Fermilab. Tevatron 1 TeV p

Top quark and anti top quark pair decaying into jets, visible as collimated collections of particle tracks, and other fermions in the CDF detector at Tevatron.



Interactions

1933: **E. Fermi** used the neutrino to explain neutron β decay (model of weak interactions)

W,Z postulated in the theoretical framework developed to explain measurements over a wide energy range

Nobel 1979

S. Glashow, Abdus Salam and S. Weinberg

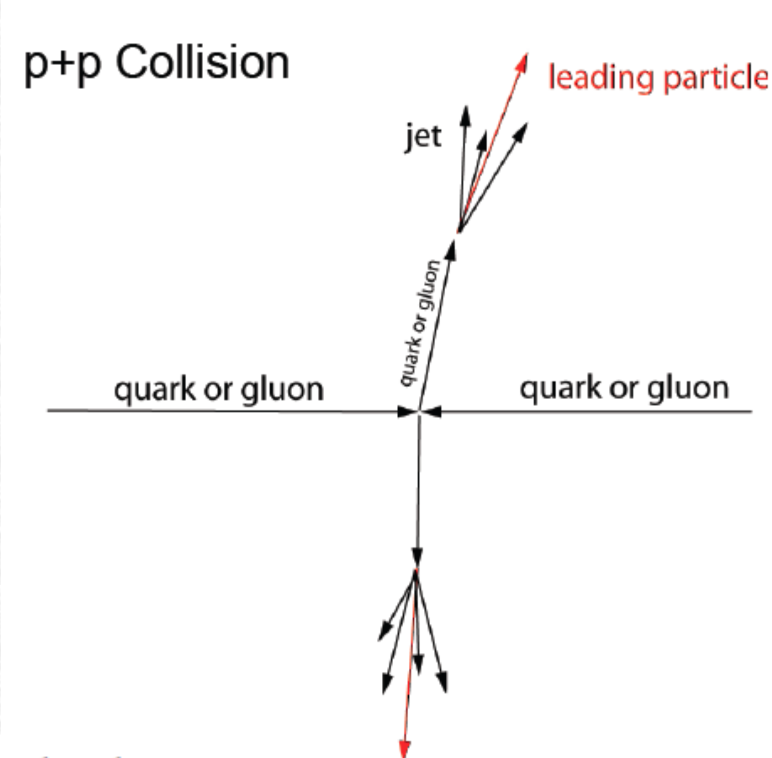
Nobel 1984

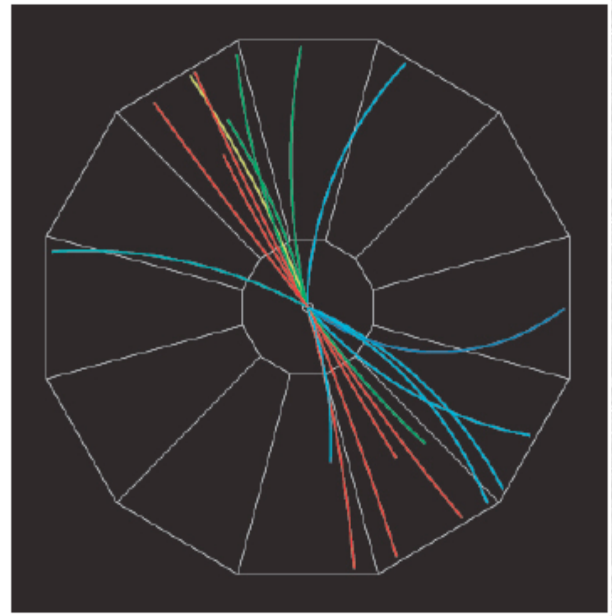
Carlo Rubbia, Simon Van Der Meer

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction".

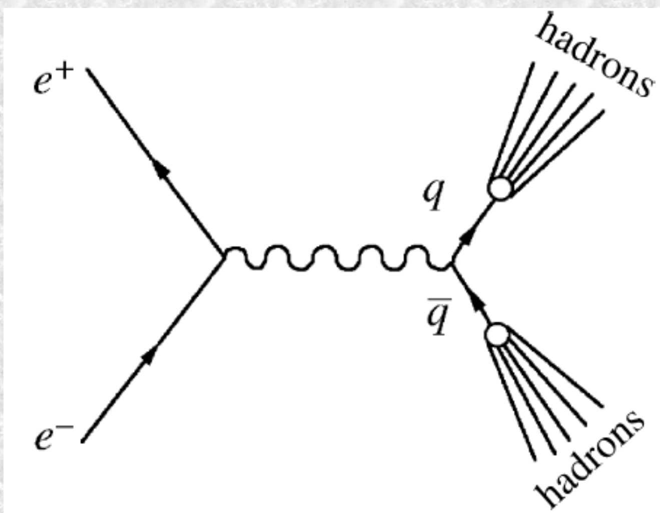
@CERN proton-antiproton collider.

Jets in pp collisions, fragmentation process or Hadronisation of quarks





$$e^+ + e^- \rightarrow \text{hadrons}$$



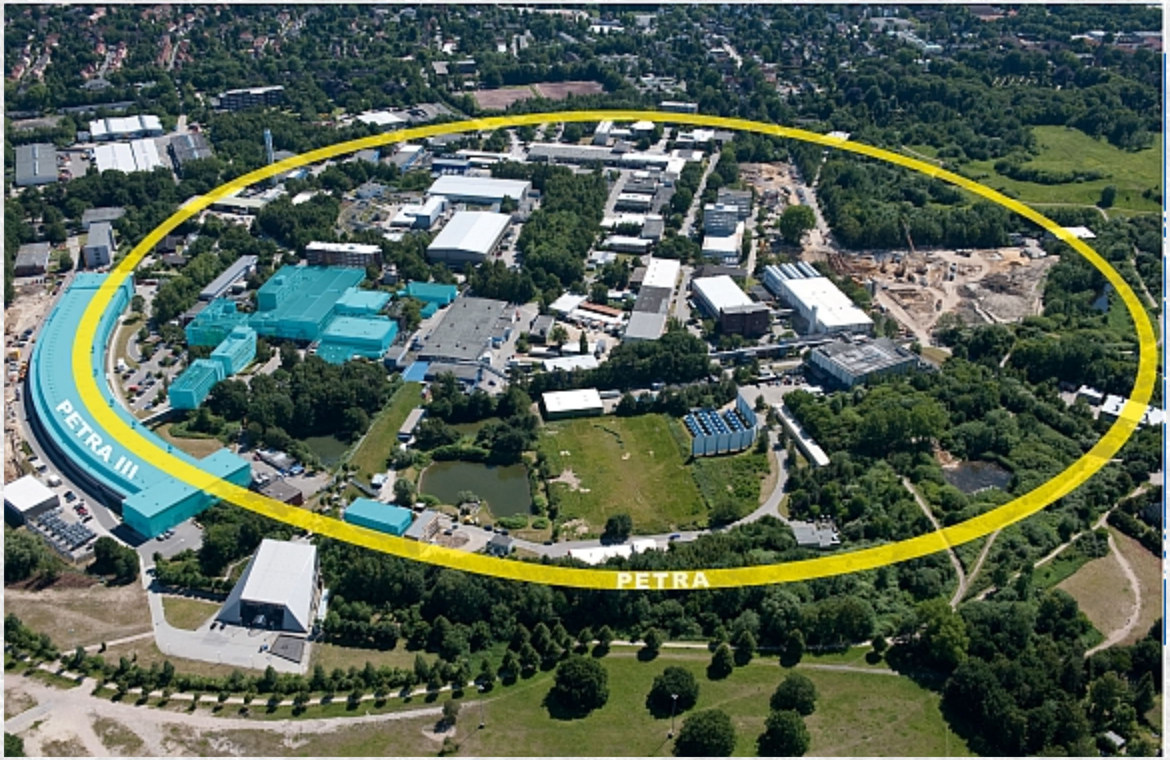
Jets observed at SPEAR, SLAC in 1975 by G. Hansen et al.

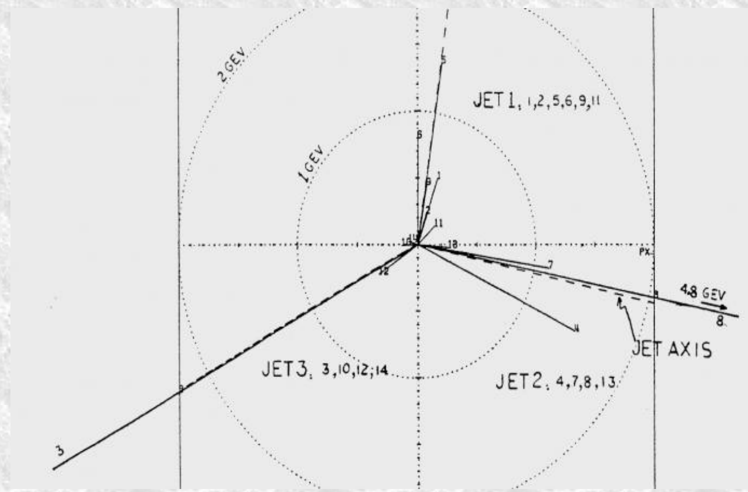
The total momentum vector, $\mathbf{P} = \sum_i \mathbf{p}_i$

closely reflect the parent quark/antiquark direction.

Evidence of quarks.

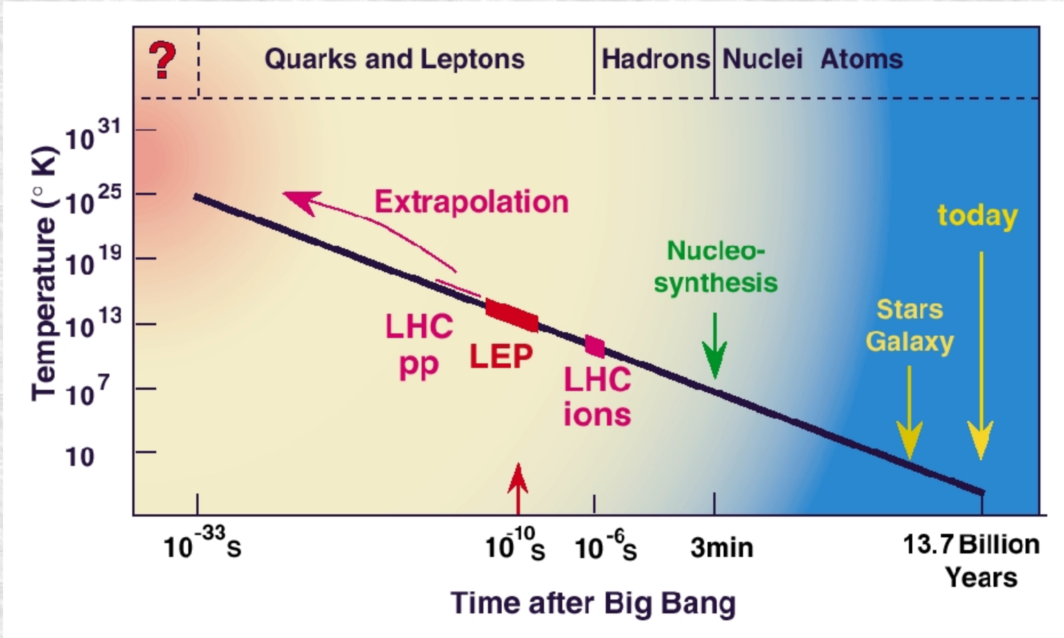
Gluon – carrier of strong interaction, predicted by Gell-Mann and colleagues, 1964-73



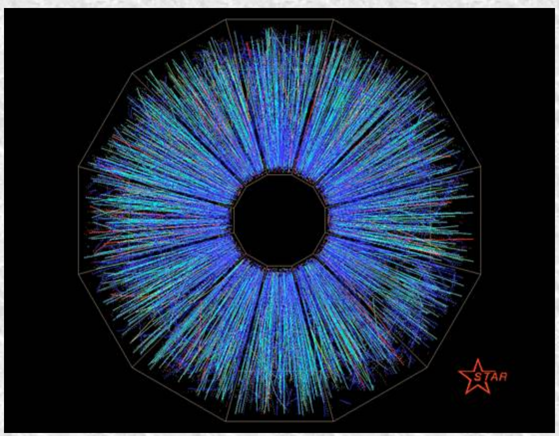


PETRA at DESY, Hamburg
e^+ e^- collider 19 GeV

1979 Discovery of gluon
Carrier of strong force



Heavy Ion Collisions: Recreating the early Universe!



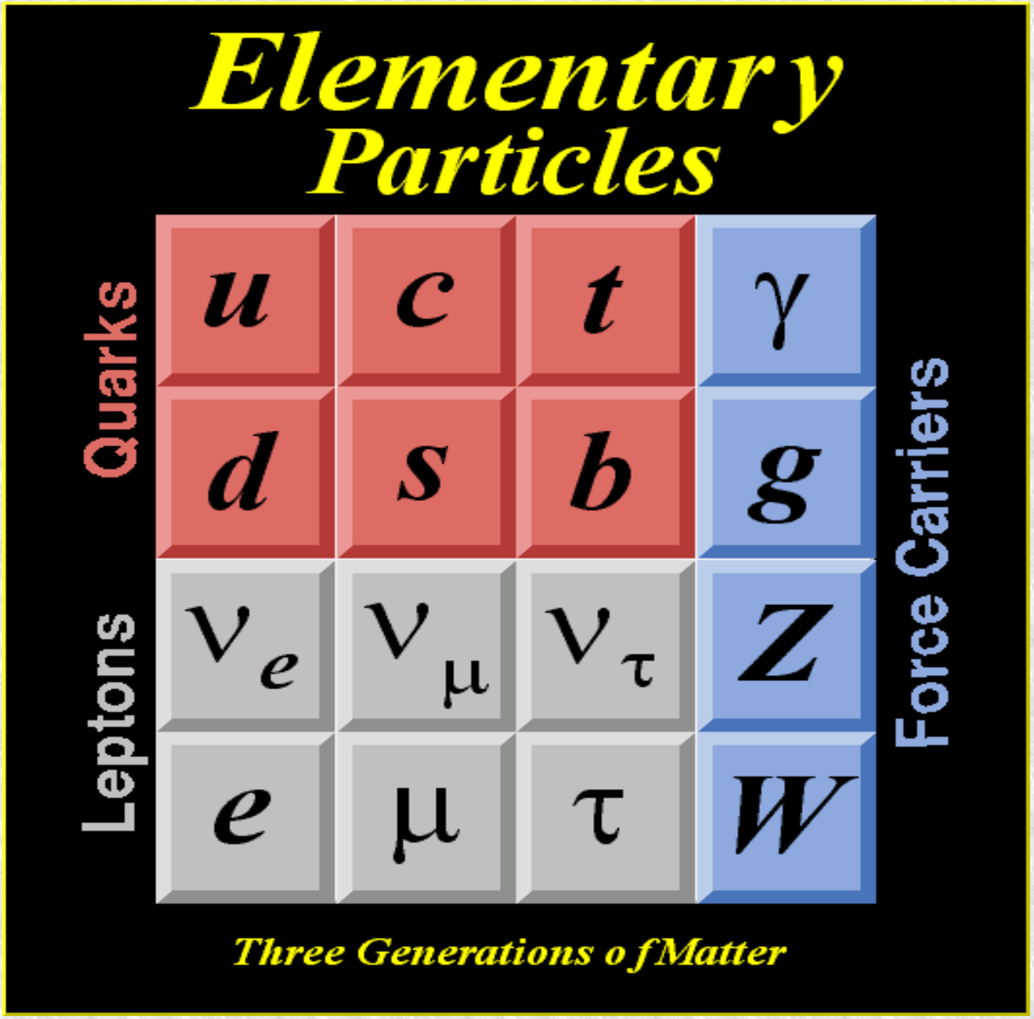
A collision of a nucleus of gold with a nucleus of gold.

Temp ~ 4×10^{12} K

BNL & LHC, Pb on Pb, p on Pb

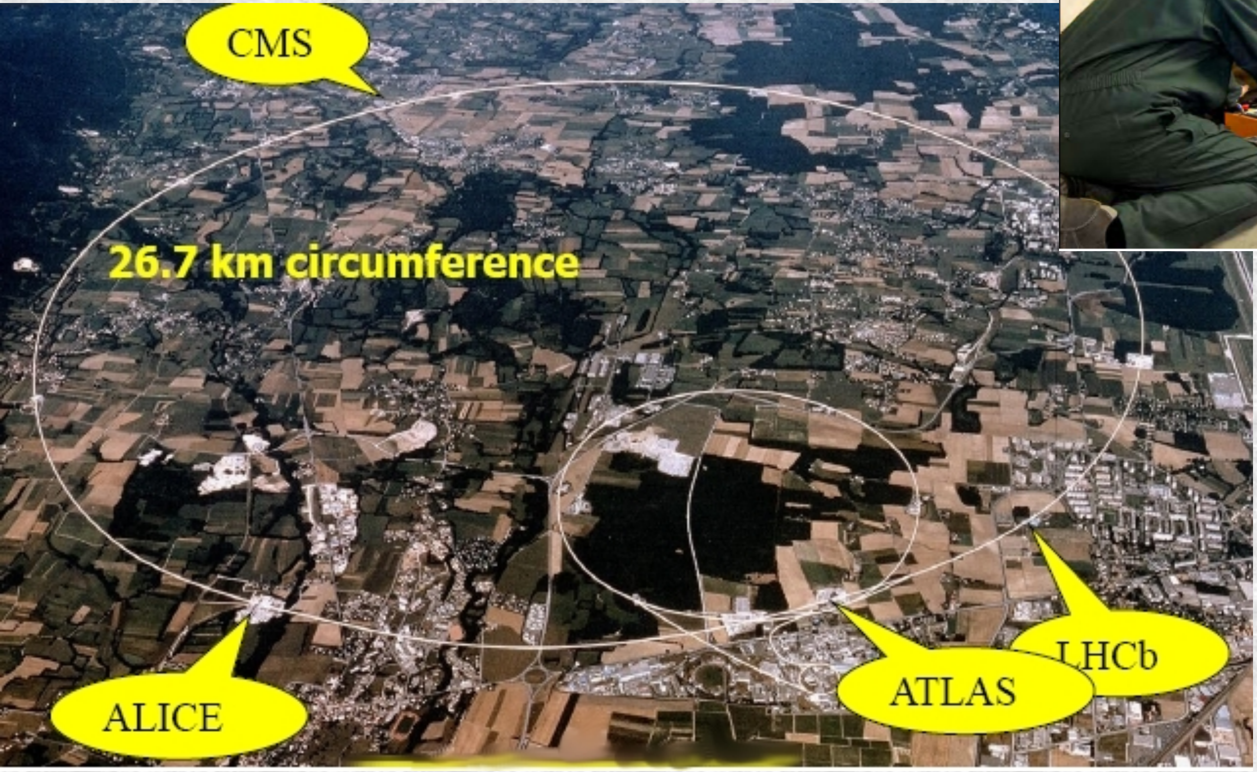
QGP a liquid?

Standard Model of Particle Physics

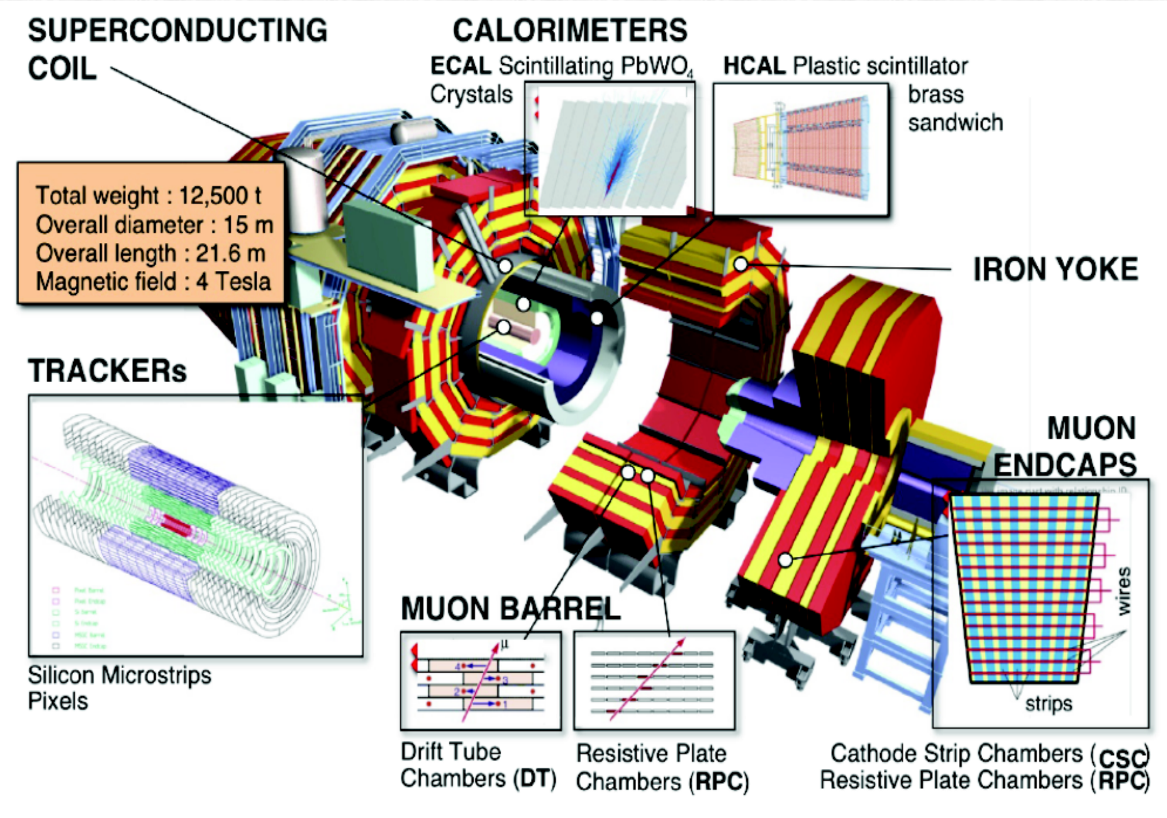


One particle remains - Higgs boson

Proton-proton collisions at LHC, CERN
Ultimate E 14 TeV



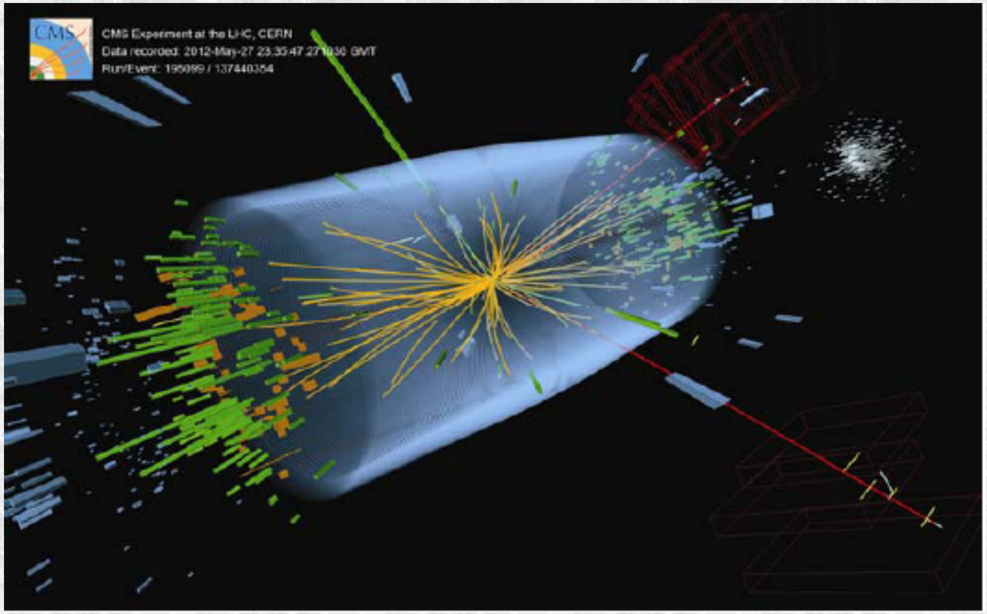
1746 Magnets, Ultimate Field = 9 T, Nominal Field (for 7 TeV) = 8.33 T
Ref: http://www.cern.ch



Indian participation in CMS

F. Englert **P. Higgs**

Nobel 2013



Event recorded with the Compact Muon Solenoid detector in 2012 showing characteristic expected from the decay of Higgs to a pair of Z bosons which then decay to a pair of electrons and muons.

Future directions

Tests of Validity of Standard Model

Nature of Neutrinos, their masses.
Is there a Right handed component?

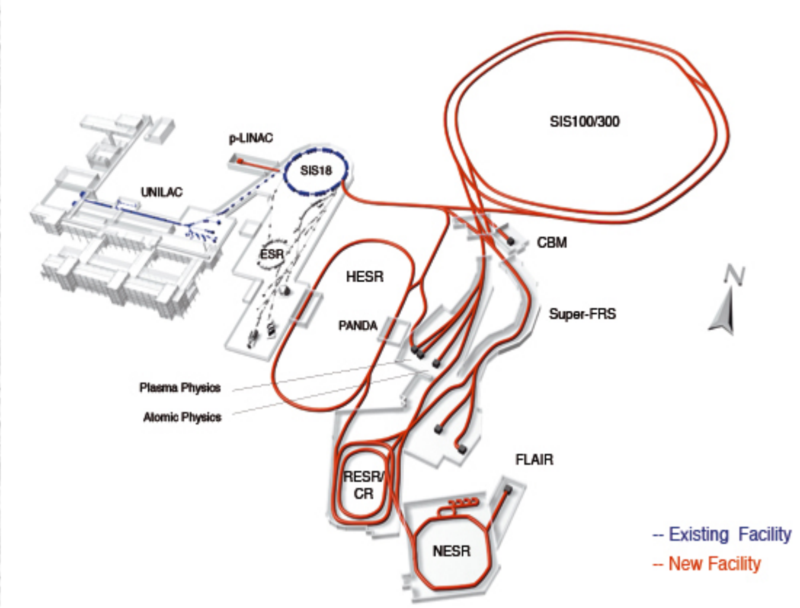
CP violation (and baryon asymmetry in the universe?)

True nature of ElectroWeak symmetry breaking.

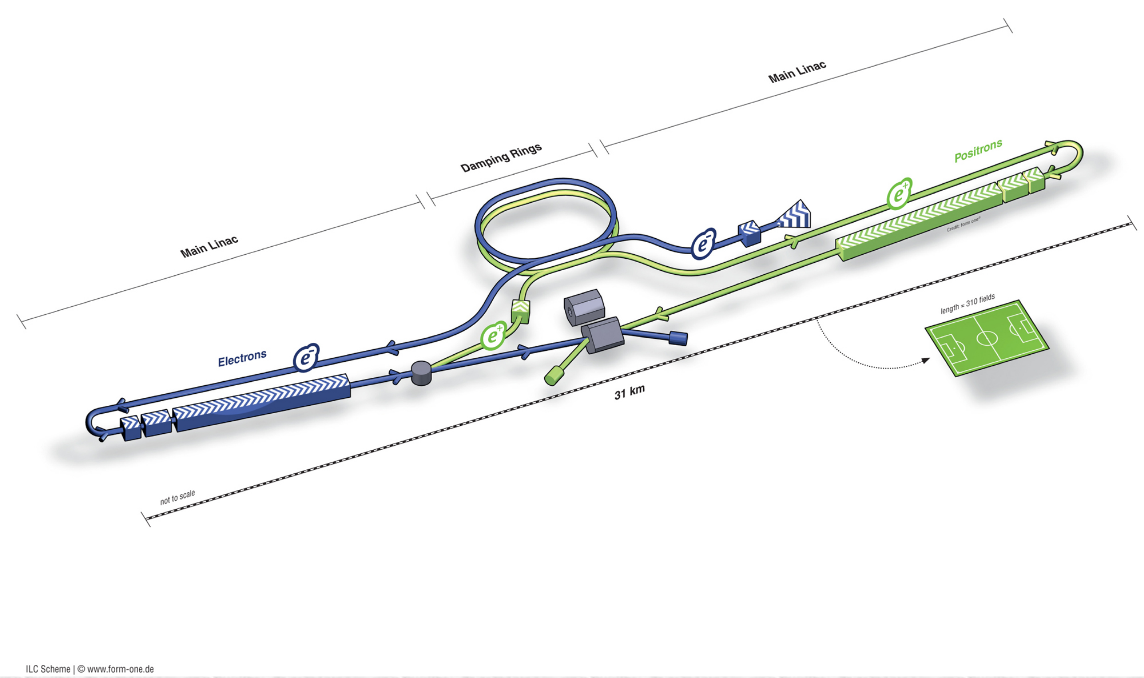
Exotic particle Searches.

Dark Matter Searches.

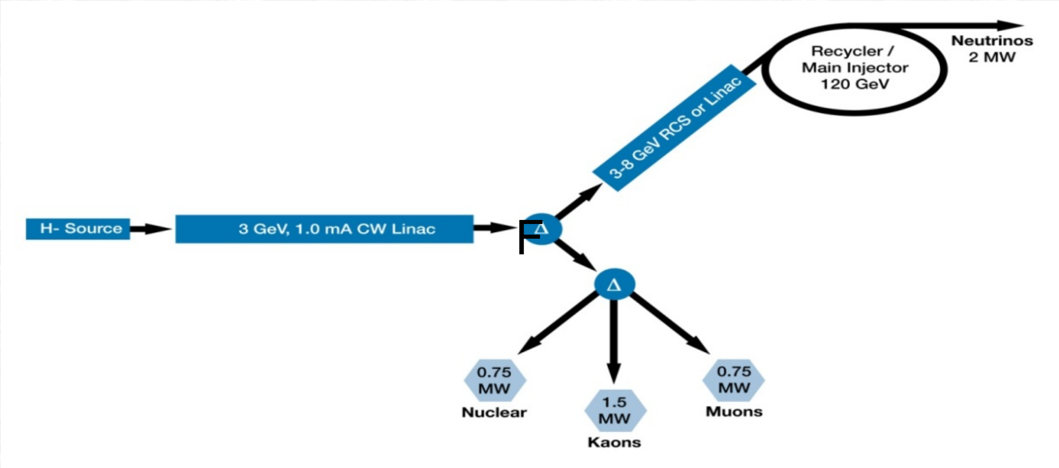
Planned & Future Accelerators:



FAIR at GSI, Darmstadt, Germany



International Linear Collider



PIP-II at Fermilab, USA

How to get to still higher energies?

Need

- stronger SC magnets

  material limitations ~ few tens of T

- high Gradient SC Cavities

  voltage breakdown due to field emission ~100-200 MV/m

Laser based Accelerators, $E_{acc} > 100$ GV/m

Plasma Wakefield Accelerator

Laser Wakefield Accelerator

Dielectric Laser Accelerator

Spin-offs

Out of a Total of > 30000 accelerators in the world, only about 3% are used in basic research, rest for applications.

APPLICATIONS

Radio-isotope production

Medical application: Radio-therapy, PET, SPECT

Environment & Art

Trace element Analysis, Accelerator Mass Spectrometry

Industry

Semiconductors,

Materials modification (Adhesion, Hardness, Corrosion resistance)

Ion-beam lithography,

Radiation Processing

Cross linking of Polymers,

Curing of Paints & Varnishes, Detoxification of Wastes,

Purification of industrial gases

Sterilisation of medical supplies

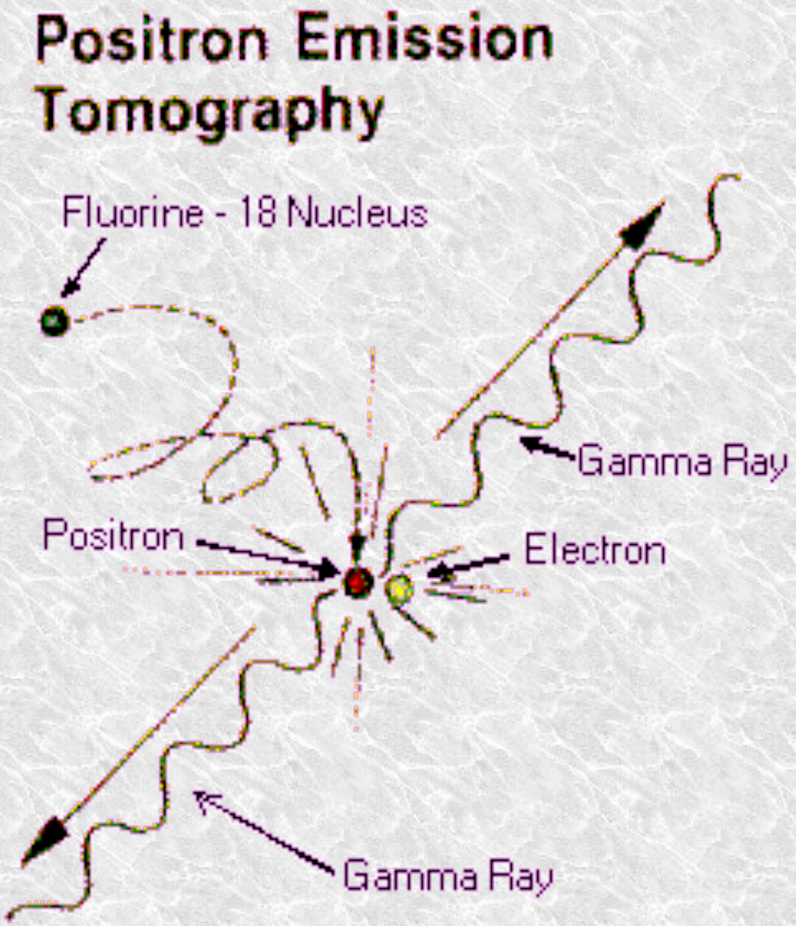
Security: **Explosives and contraband detection**

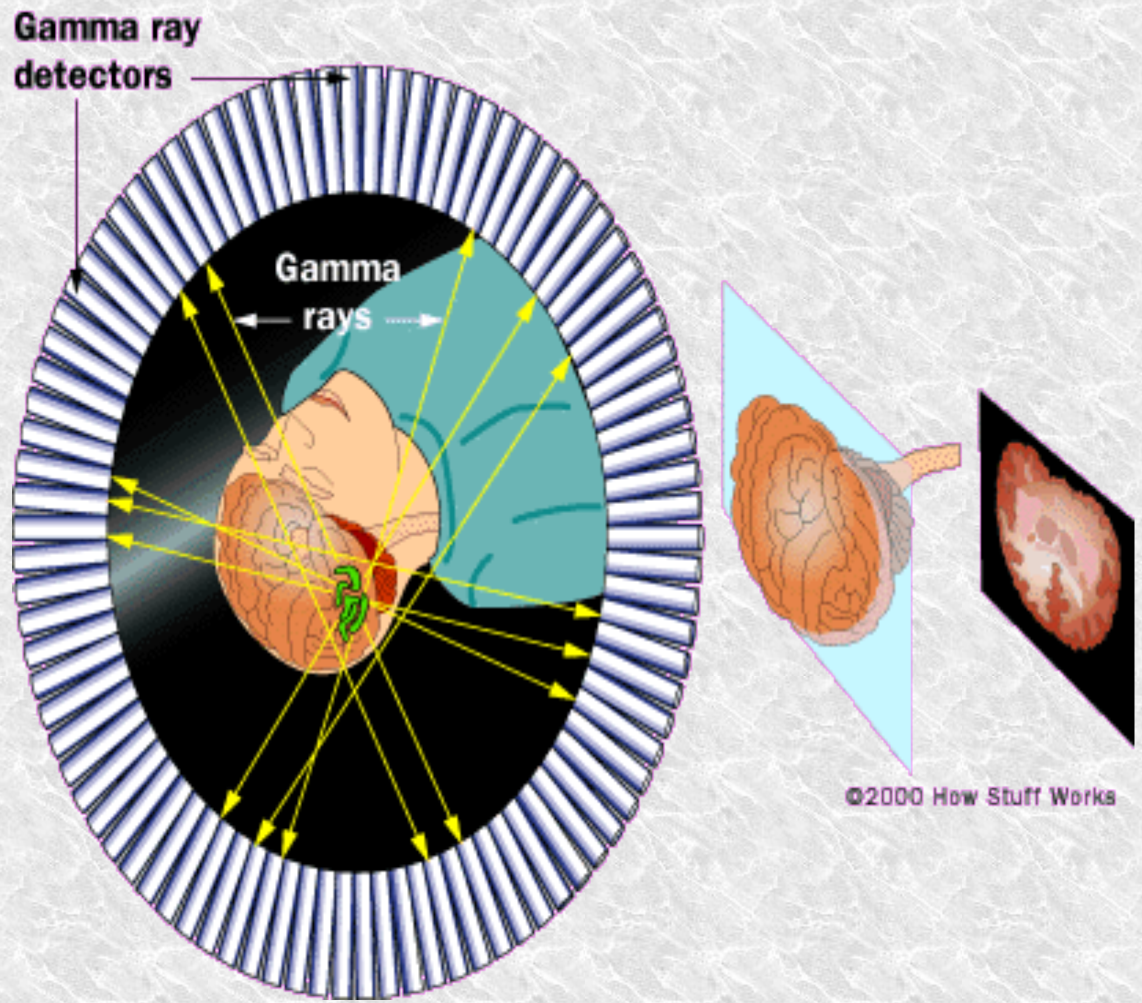
Agriculture **Sterilization of food**

Accelerators in Energy Generation

Imaging with Radioisotopes

Single Photon Emission Computed Tomography (SPECT)





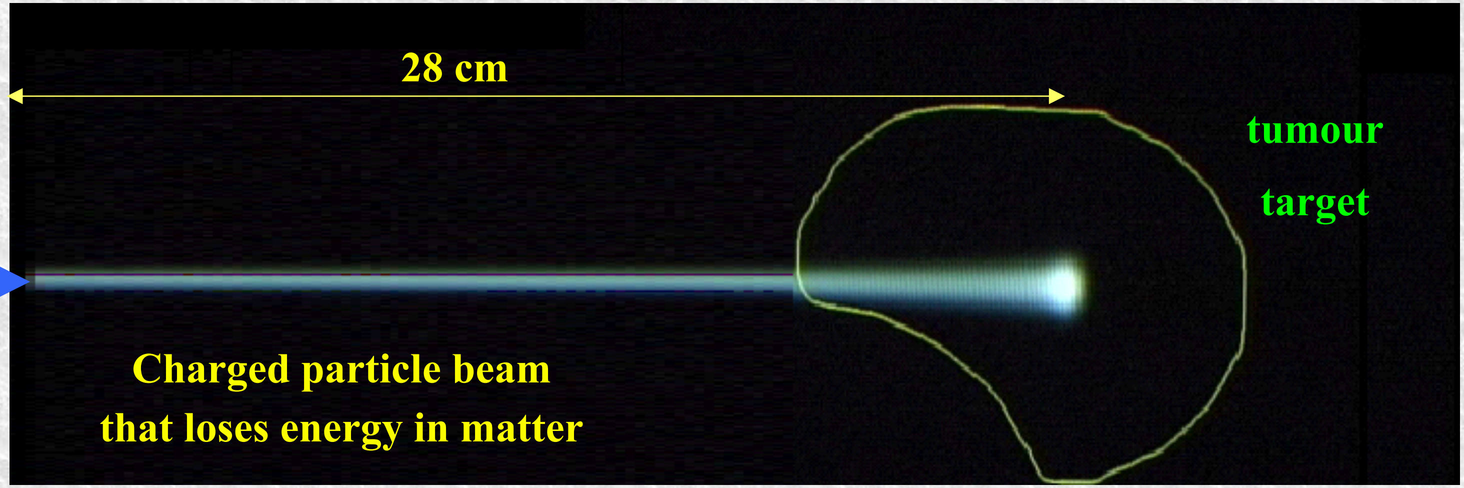
Medical Therapy

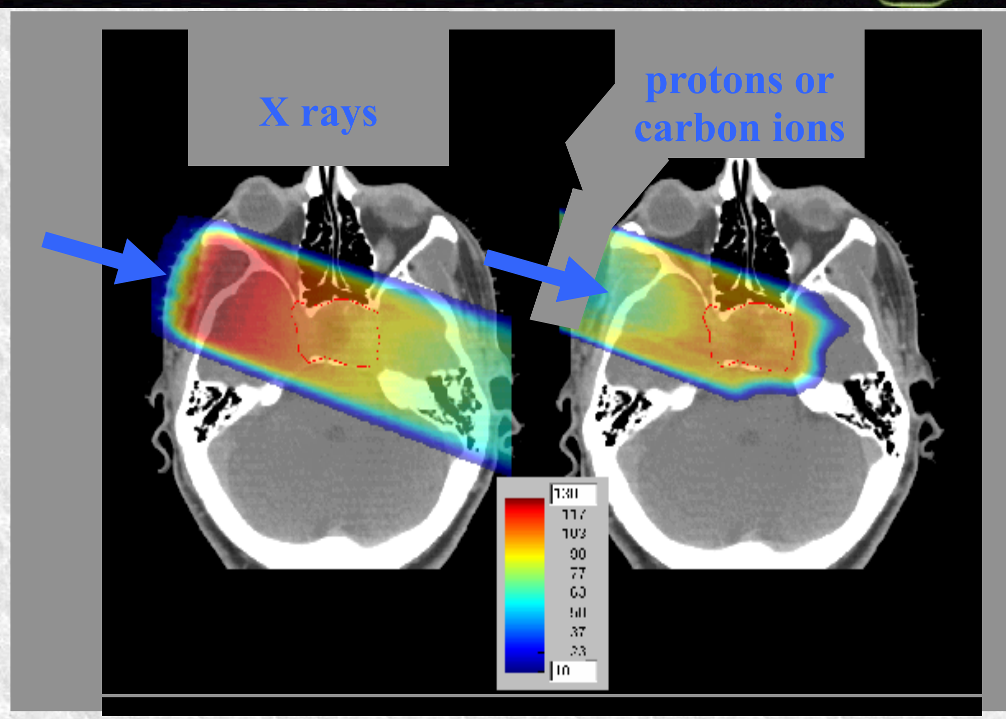
Electron Linac at RRMC, Kolkata

Ion Beam Therapy

200 MeV protons

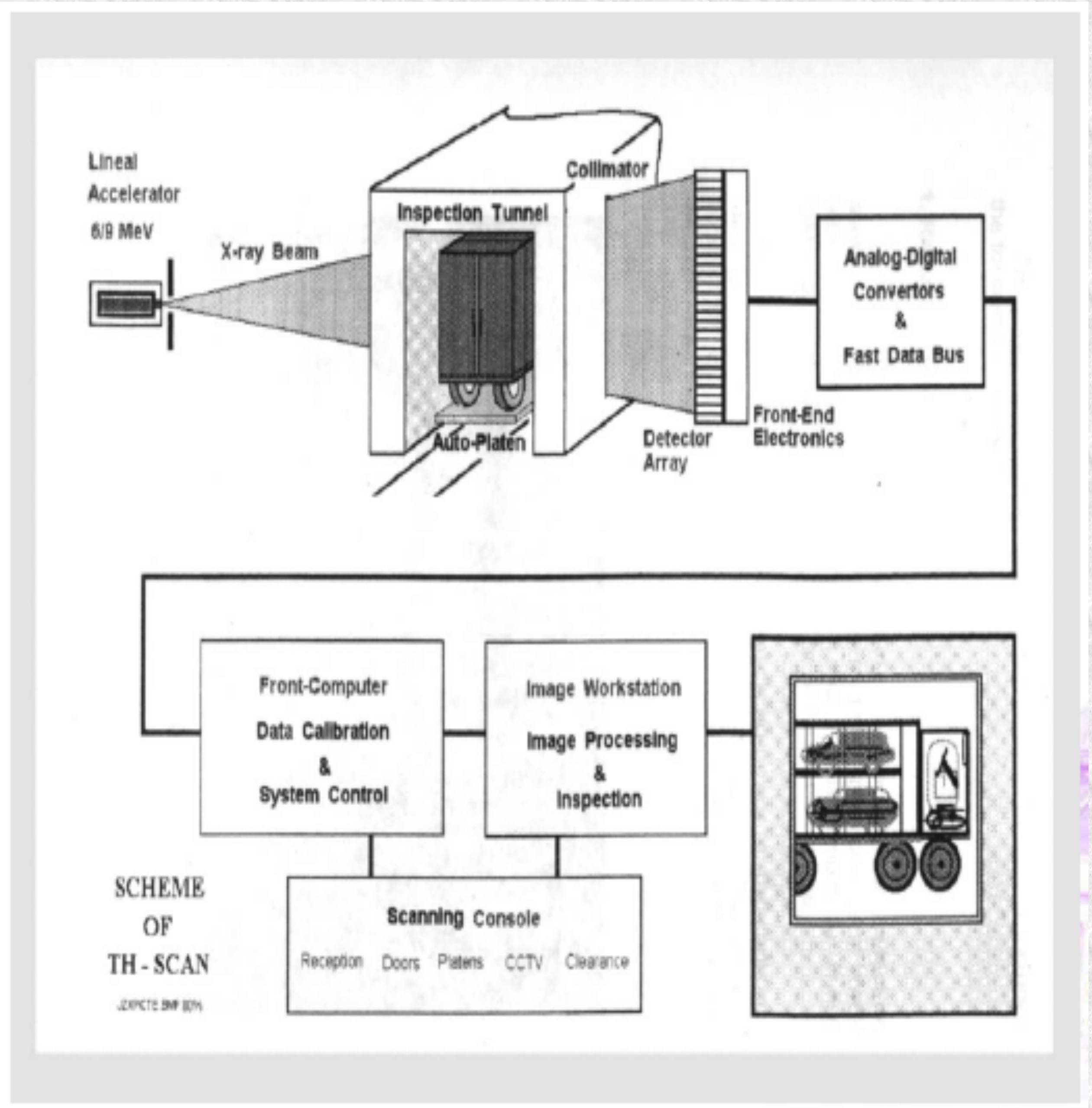
480 MeV carbon ions
which control radioresistant tumours
(G. Kraft)





GSI

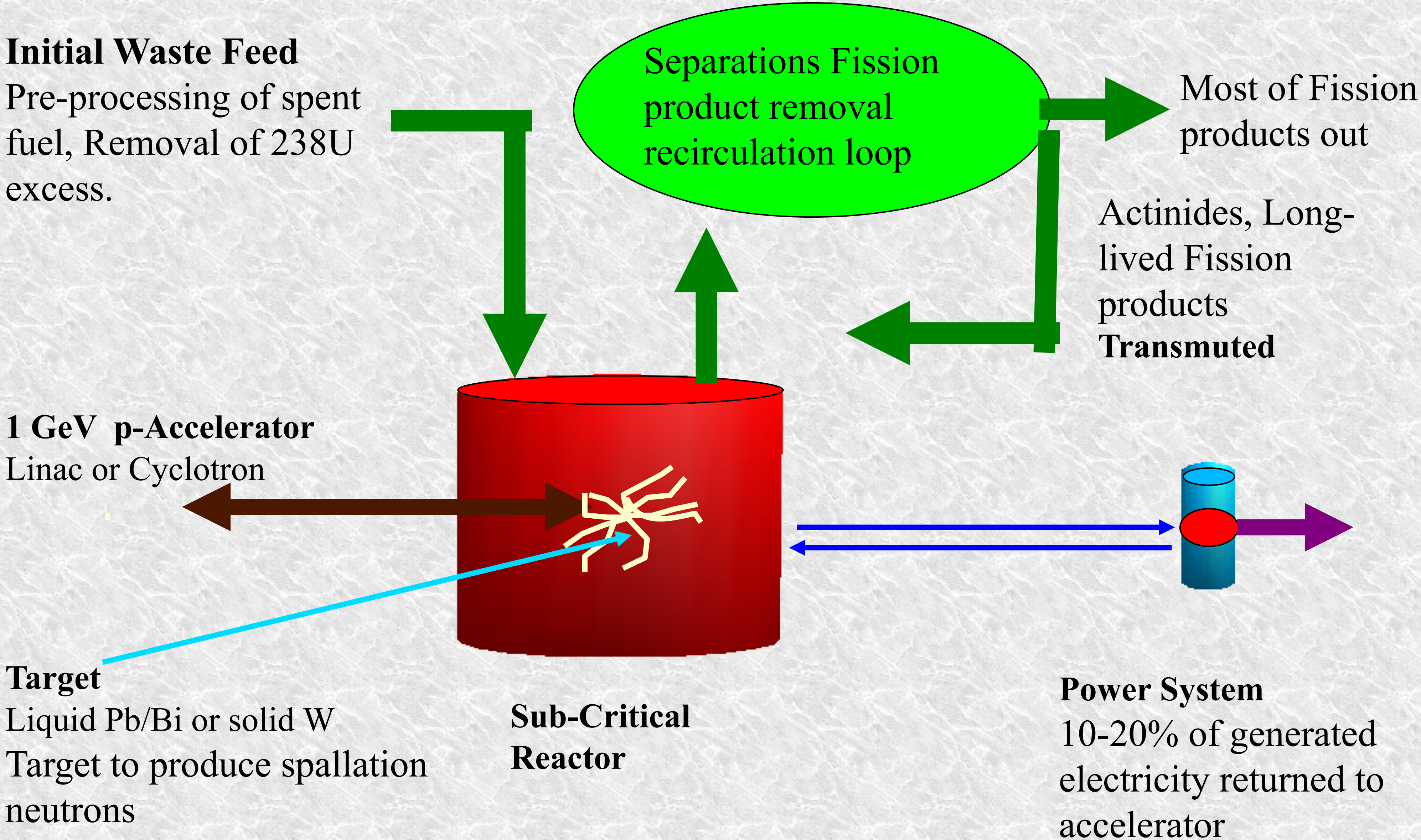
Security



Cargo Inspection system

Energy

Accelerator Driven Sub-Critical System



SUMMARY

Major Advances in the quest for structure of matter have been made using Accelerators of higher and higher energies.

As a given acceleration mechanism reached its limit of energy, new techniques have been invented to meet new demands.

Applications in other areas of science as well as in industry as spinoffs.

But we have a long road to travel

……. Cosmic Rays observed ~ 10^{20} eV

The Quest continues! Many challenges ahead!

"Thousands of years hence, archaeologists and anthropologists may judge our culture by our accelerators."

- Leon Lederman (in The God Particle)

Detection Methods

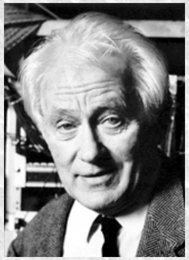
Nobel 1927 CTR Wilson "for his method of making the paths of electrically charged particles visible by condensation of vapour"

Nobel 1948 PMS Blackett "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation"

Nobel 1960 Donald A. Glaser " for the invention of the bubble chamber"

Nobel 1968 Luis W. Alvarez "for his decisive contributions to elementary particle physics....... through his development of the technique of using hydrogen bubble chamber and data analysis".

1992 Georges Charpak "for his invention and development of particle detectors, in particular the multiwire proportional chamber".



What have we learned about the nucleus ?

Nucleus : unlike ordinary matter

- made up of protons and neutrons
- size ~ $A^{1/3}$ Fermi
- high density (10^{14} gms /cm^3)
- very high binding energy (~ 8 MeV/A)

Nuclear Force

Moderate distances attractive (~ 1.4 fm), shorter range repulsive (< 0.7 fm).

Quantum many-body system. Central force behaviour and collective motion co-exist.

Nuclear Masses: (with precision of ~ 5 keV)

(Some cases with much higher precision of ~ 100 eV, i.e., 1 in 10^9)

Spin *(10^{21} Hz) - fastest rotation in the Universe*

Nuclear Reactions: Fusion, Fission

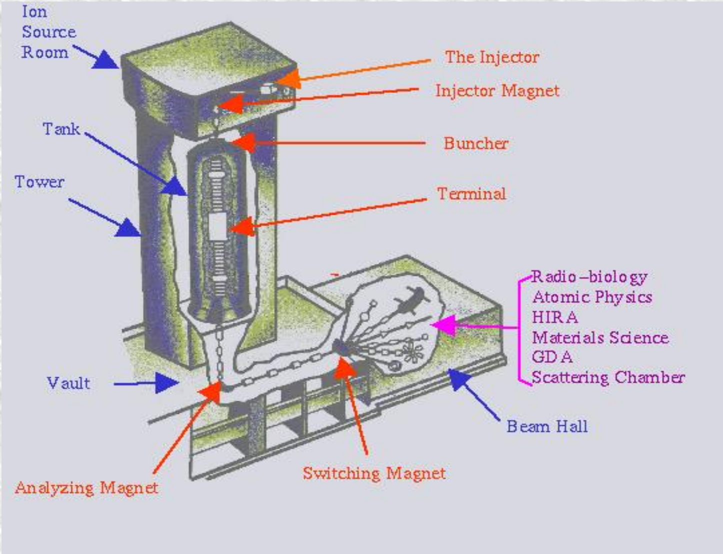
Some Questions that remain in Nuclear Physics

What is the form of n-n interaction?

What are the Limits of stability of nuclei?

How are the elements synthesized?

What are the heaviest nuclei that can exist?

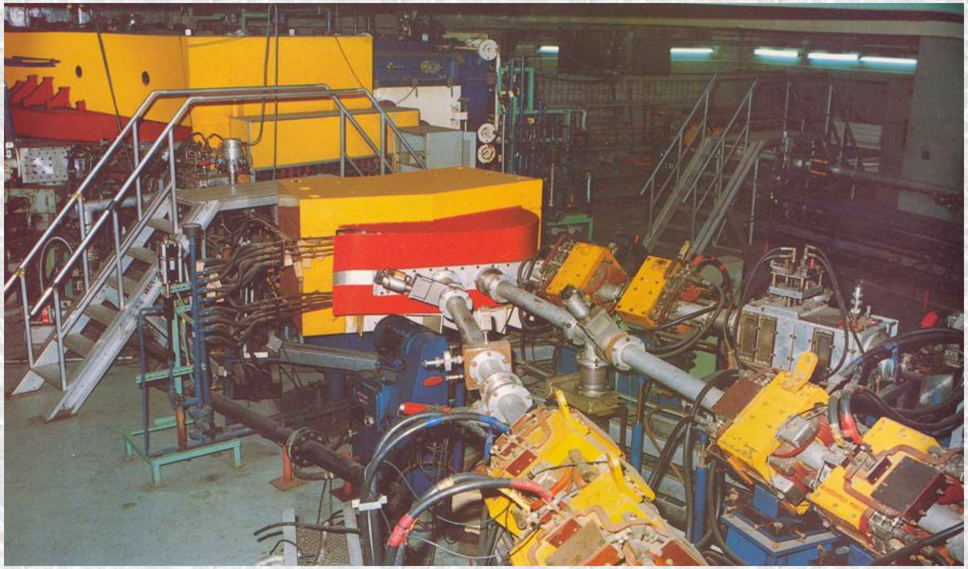


15 UD Pelletron and Superconducting Linac Module, IUAC

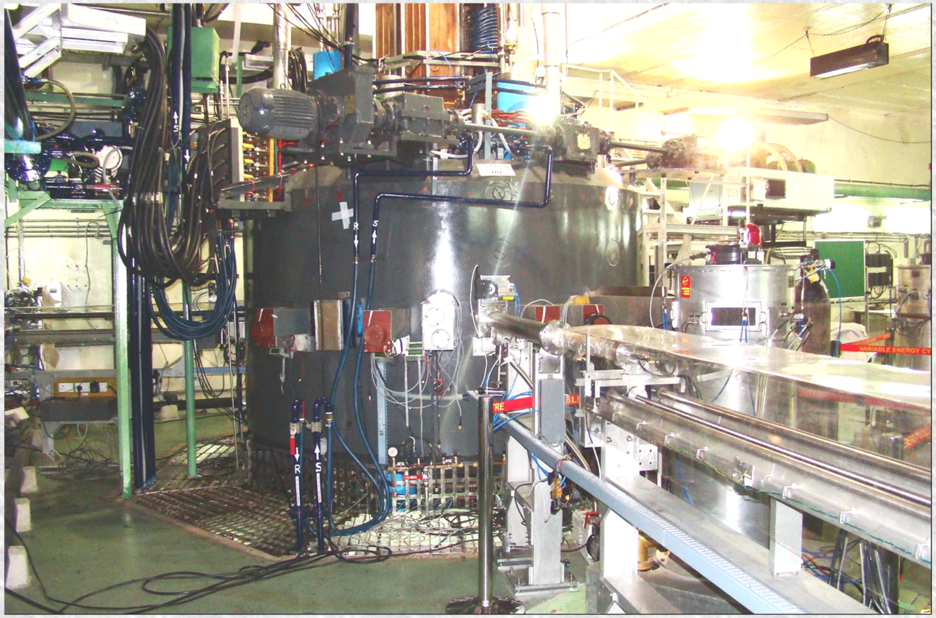
Tata Institute of Fundamental Research, Mumbai

14 UD Pelletron

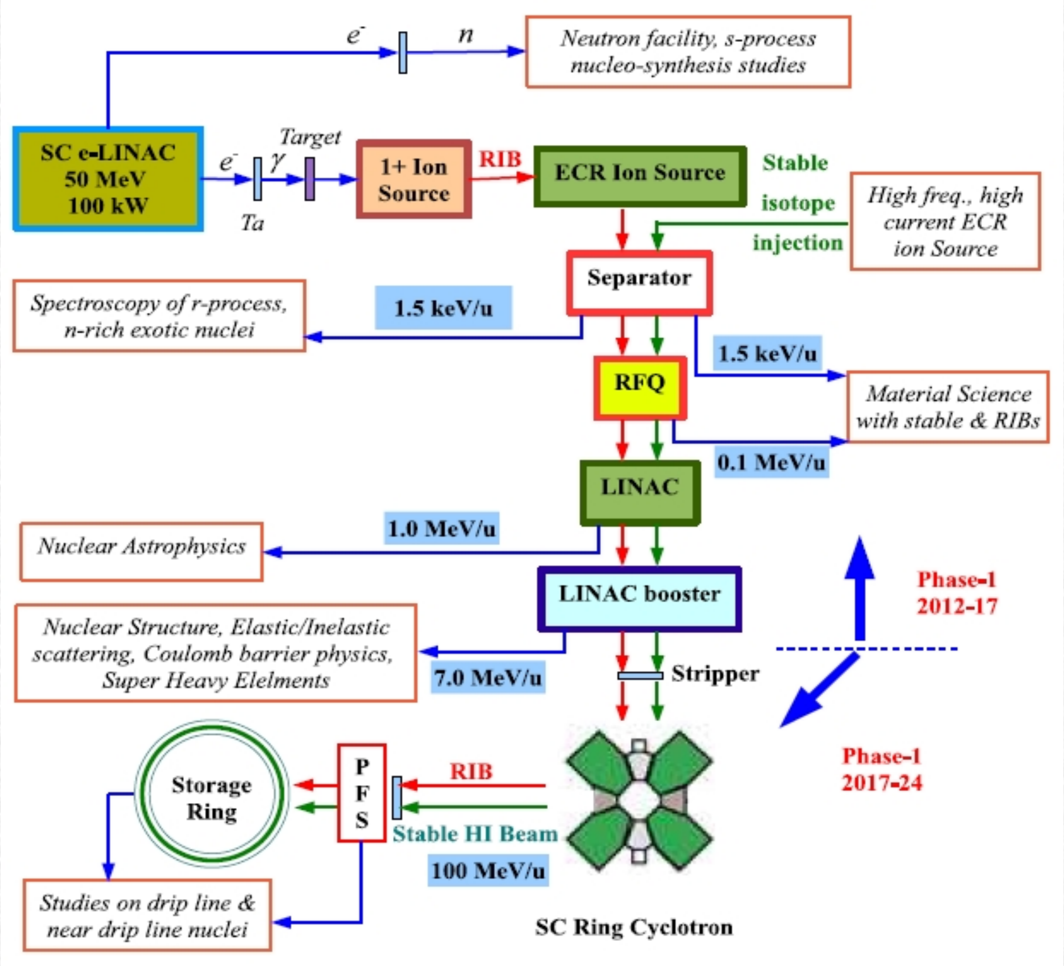
Variable Energy Cyclotron Centre, Kolkata



K = 140, Variable Energy Cyclotron



K = 500 Superconducting Cyclotron



A National facility for Unstable and Rare Isotope Beams

RRCAT electron synchrotron, 2.5 GeV