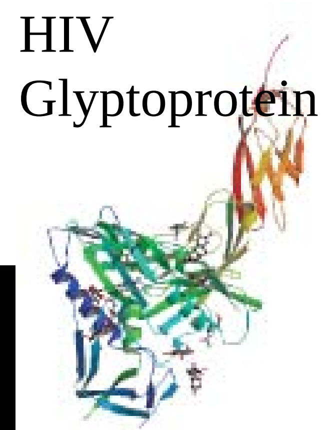
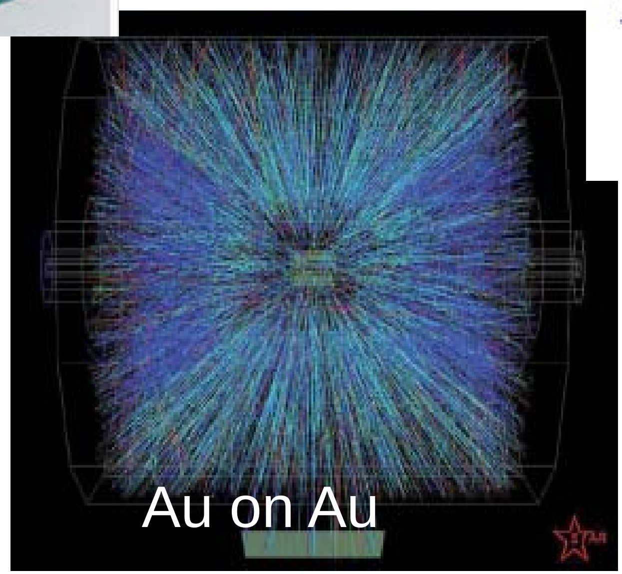
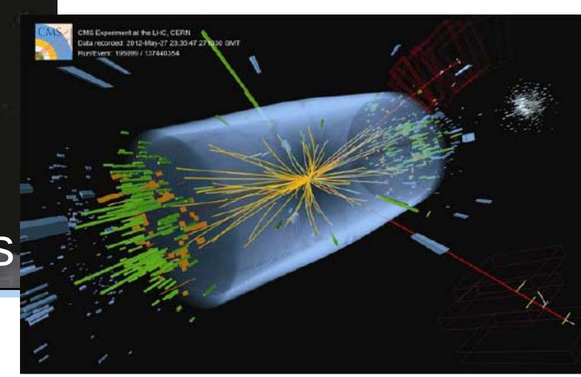
Accelerators:
The Technical challenges

Amit Roy
DAE Raja Ramanna Fellow
Variable Energy Cyclotron Centre, Kolkata

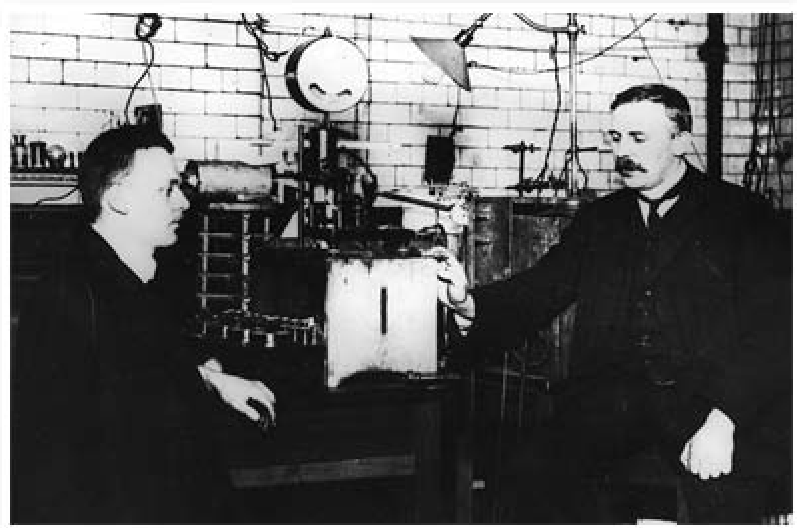




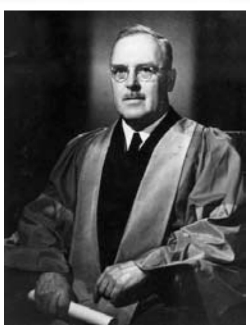


Of > 30000 accelerators in the world, only ~ 3% are used for basic research.

Ernest Rutherford discovers the nucleus. (1911)

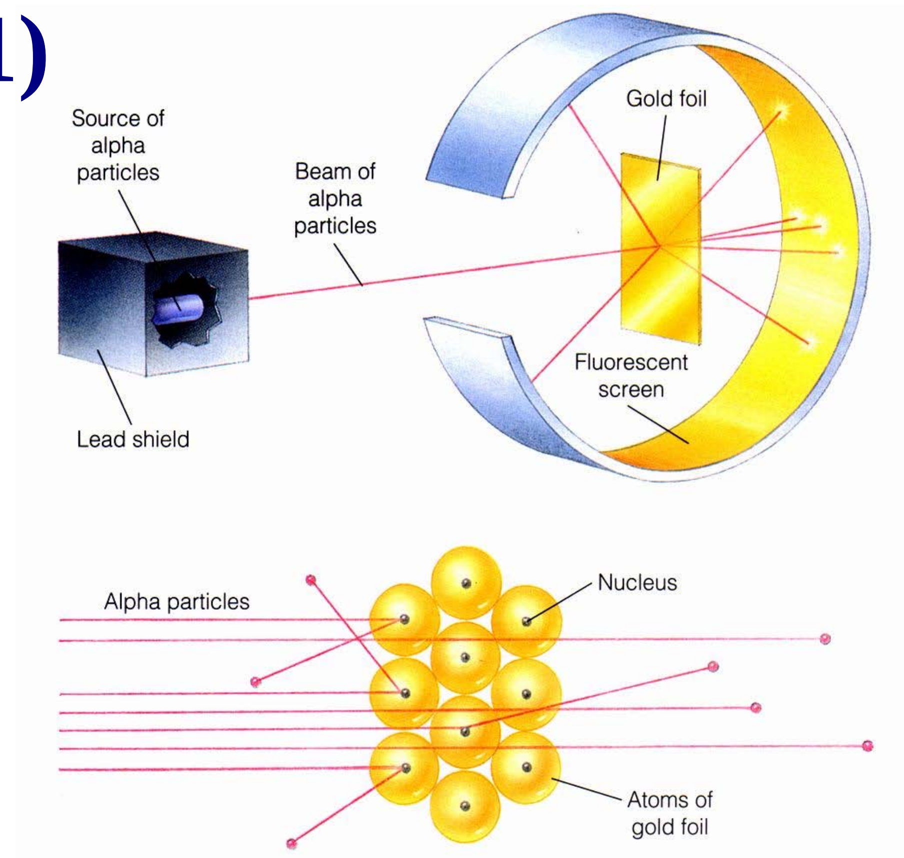


Geiger



Marsden

Rutherford



"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."

What constitutes an Accelerator?

1. **Source of electrons / ions.**
   1. Number
   2. Emittance (transverse, longitudinal)
2. **Accelerating Structure.**
   1. Electrostatic
   2. Electromagnetic (linear, circular)
3. **Beam guidance and transport.**
   1. Bending
   2. Focussing (transverse, longitudinal)
4. **High Vacuum enclosures.**
5. **Power supplies, either DC or AC(RF).**
6. **Control system.**

Early Accelerators

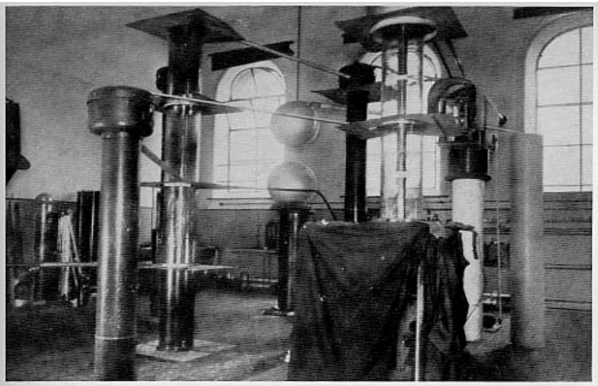
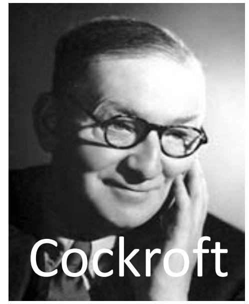
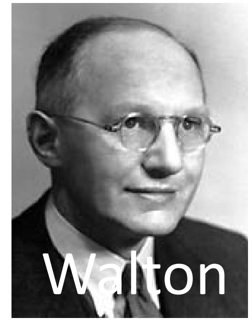


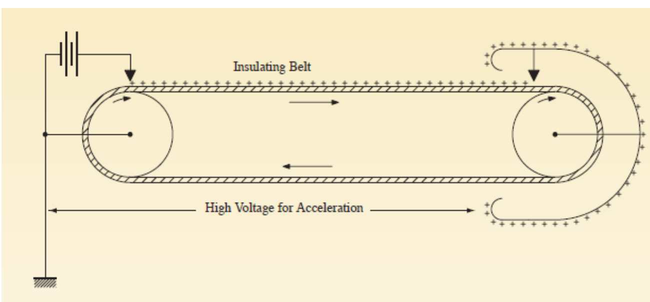
PLATE 3.7 Cockcroft and Walton's corner of the Cavendish. The tall transparent cylinder in the center is the discharge tube; the other cylinders are stacks of condensers and rectifiers. The curtained box is the observation center. Cockcroft and Walton, *PRS, A136* (1932), 625, plate 11.

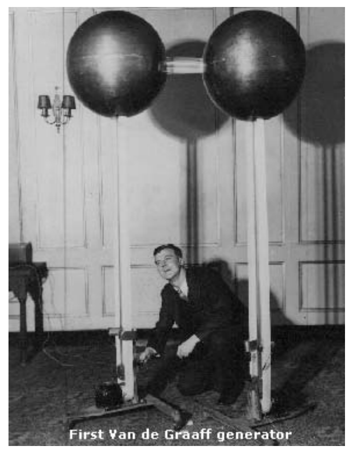


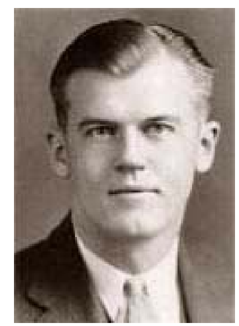


Nobel 1951

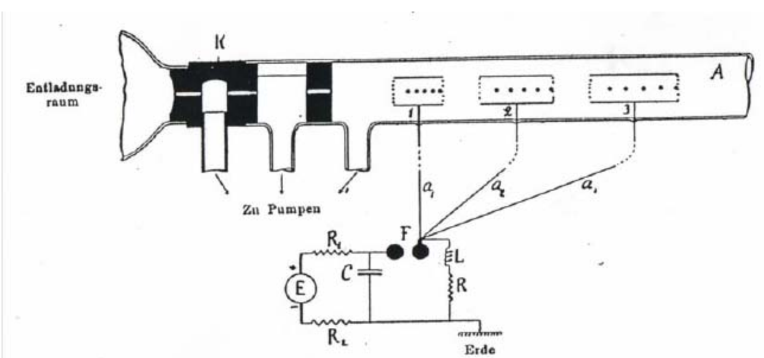
$^{7}Li + p = {}^{4}He + {}^{4}He$ at $E_p = 400keV$

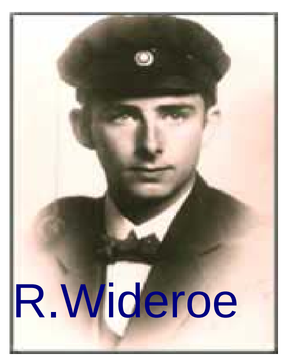






R.J. Van de Graaff





Linear Accelerator

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

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

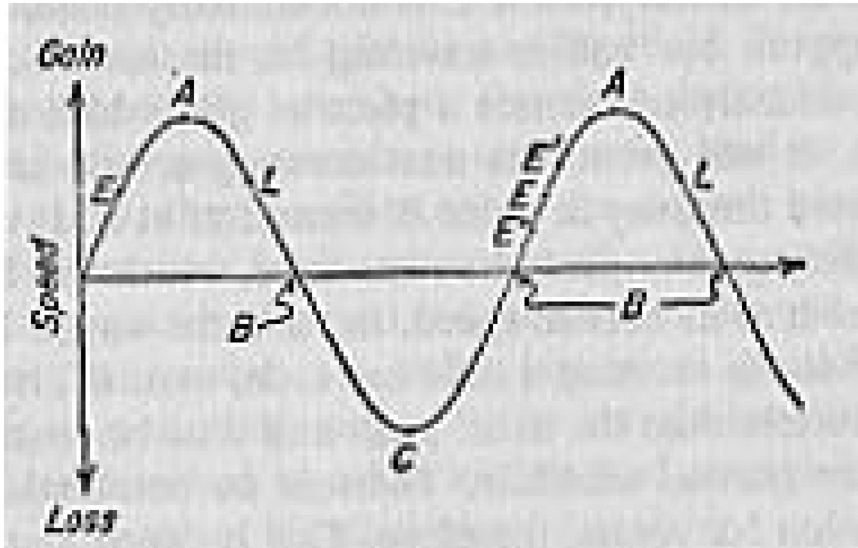
$E = n.q. Vo \sin \psi_s$

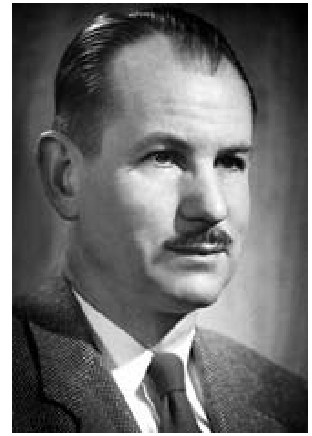
Nobel 1939

First Cyclotron built by E.O. Lawrence and his student M.S. Livingston, 1931. Diameter ~ 4.5" , Ep ~ 80 keV

$$f^{rel}_{cyclotron} = \frac{1}{\gamma} \cdot \frac{eB}{2\pi m}$$

Principle of Phase Stability: E.M. McMillan & V. I. Veksler, 1945



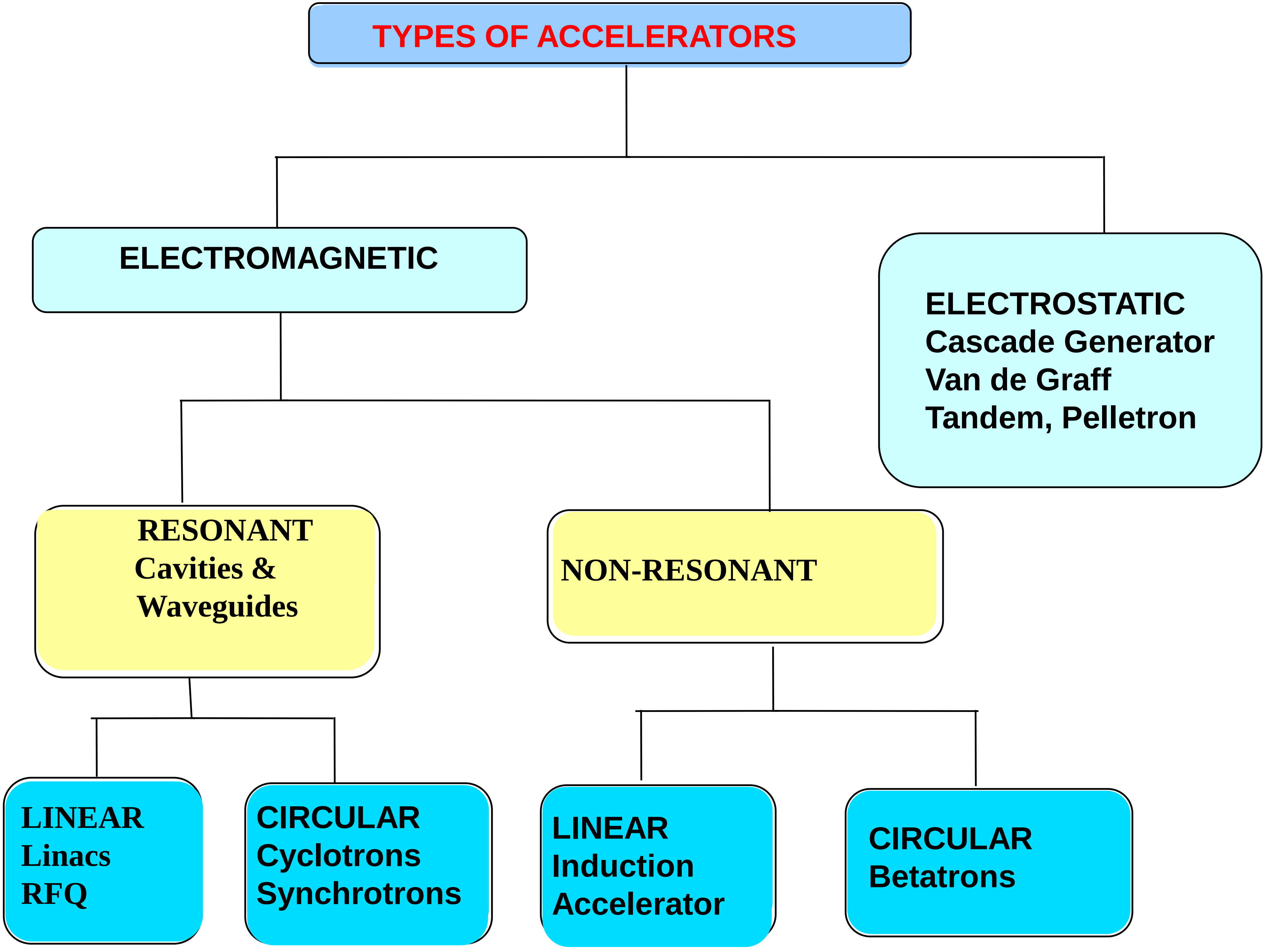


1) As particle energy increases, **decrease f_{RF}**

=> ***Synchrocyclotron***

2) As particle gains energy, **increase B**

=> ***Synchrotron***


TYPES OF ACCELERATORS
ELECTROMAGNETIC
ELECTROSTATIC
Cascade Generator
Van de Graff
Tandem, Pelletron
RESONANT
Cavities &
Waveguides
NON-RESONANT
LINEAR
Linacs
RFQ
CIRCULAR
Cyclotrons
Synchrotrons
LINEAR
Induction
Accelerator
CIRCULAR
Betatrons

Large number of Accelerators were built

Set I

Low Energy Accelerators:
Van de Graaff, Cyclotron
Providing wide variety of
Ion beams

Objective:
Probing Nuclear Structure,
Nuclear Reactions.
Materials Science, Atomic
Physics, Radiation Biology.

Set II

High Energy Accelerators:
Synchrocyclotrons,
Synchrotrons
Linacs

Protons, Electrons

Objective:
Particle Properties, Sub-
structure of Particles.

How to increase the useful Energy?

Sc Magnet - Higher magnetic fields

($B \propto n.I$)

Sc Cavity - Higher Accelerating field at low power

($E = q. \mathcal{E}$)

=> smaller size
lower cost

Fixed-Target Machines:

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

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

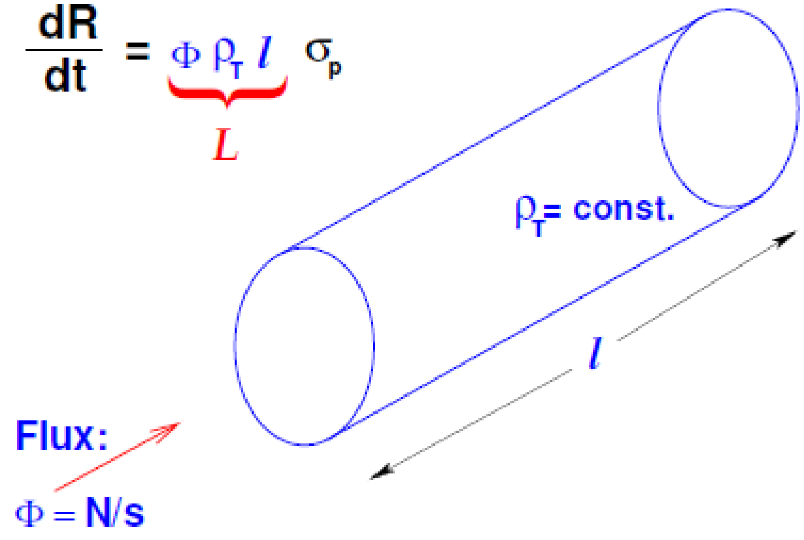
Colliding-beam Machine:

Incident and Target particles m_p and m_t travel in opposite directions

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

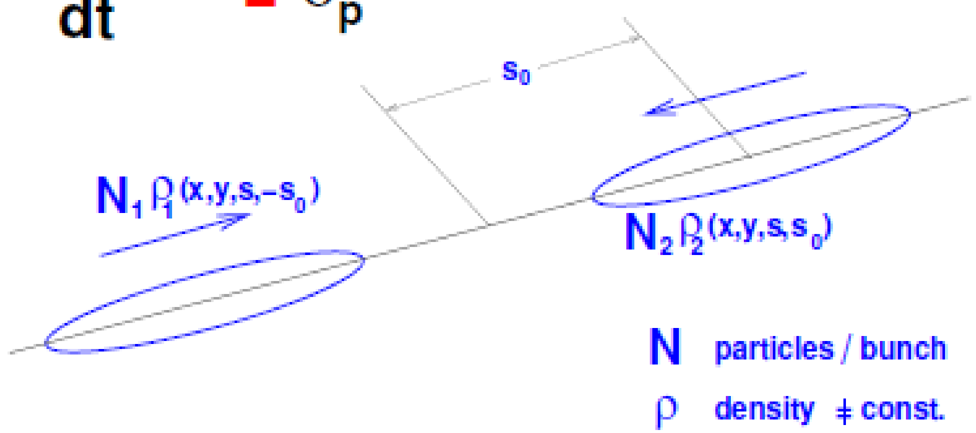
Fixed Target

$$\text{Event Rate} = \frac{dR}{dt} = \underbrace{\Phi\, \rho_T\, l}_{L}\; \sigma_p$$



Colliding Beam

$$\text{Event Rate} = \frac{dR}{dt} = L\, \sigma_p$$



Gaussian beams

$$\mathbf{L} = \frac{N_{e+} N_{e-} f_c}{4\pi\, \sigma_x \sigma_y}$$

Circular colliders - high repetition rate

Linear colliders - lower repetition rate

Solution:

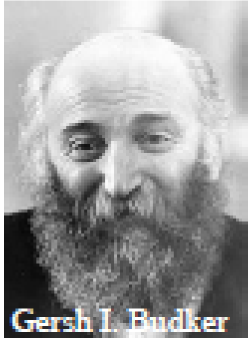
--Use more particles/ bunch

--Lower emittance through cooling

--Lower beam size through better focussing

Cooling of Beams:

Electron cooling, 1966



Stochastic Cooling, 1972

Nobel 1984

Limitations

Synchrotron Power Loss,

$$P_s \propto \gamma^4/R^2, \quad E = (\gamma + 1)\, m_0 c^2$$

– Forces future e^+-e^- colliders to be *linear*

LEP (180 GeV COM) is last of breed

– Large(!) circular machines for heavier particles

Limits of Acceleration

Breakdown electric field in air ~ 30 kV/cm

Max terminal voltage to ~ 3 MV in dry air.

Largest working electrostatic accelerator in the world, Oak Ridge Tandem (25 MV), 10 m diameter terminal filled with SF_6 at 80 psi.

Limit of RF field in vacuum

~ 20 -100 MV/m, ($E_{max} \propto$ freq $^{1/4}$).

Highest Accel. field achieved in a sc cavity

~ 60 MV/m.

Highest steady field magnet

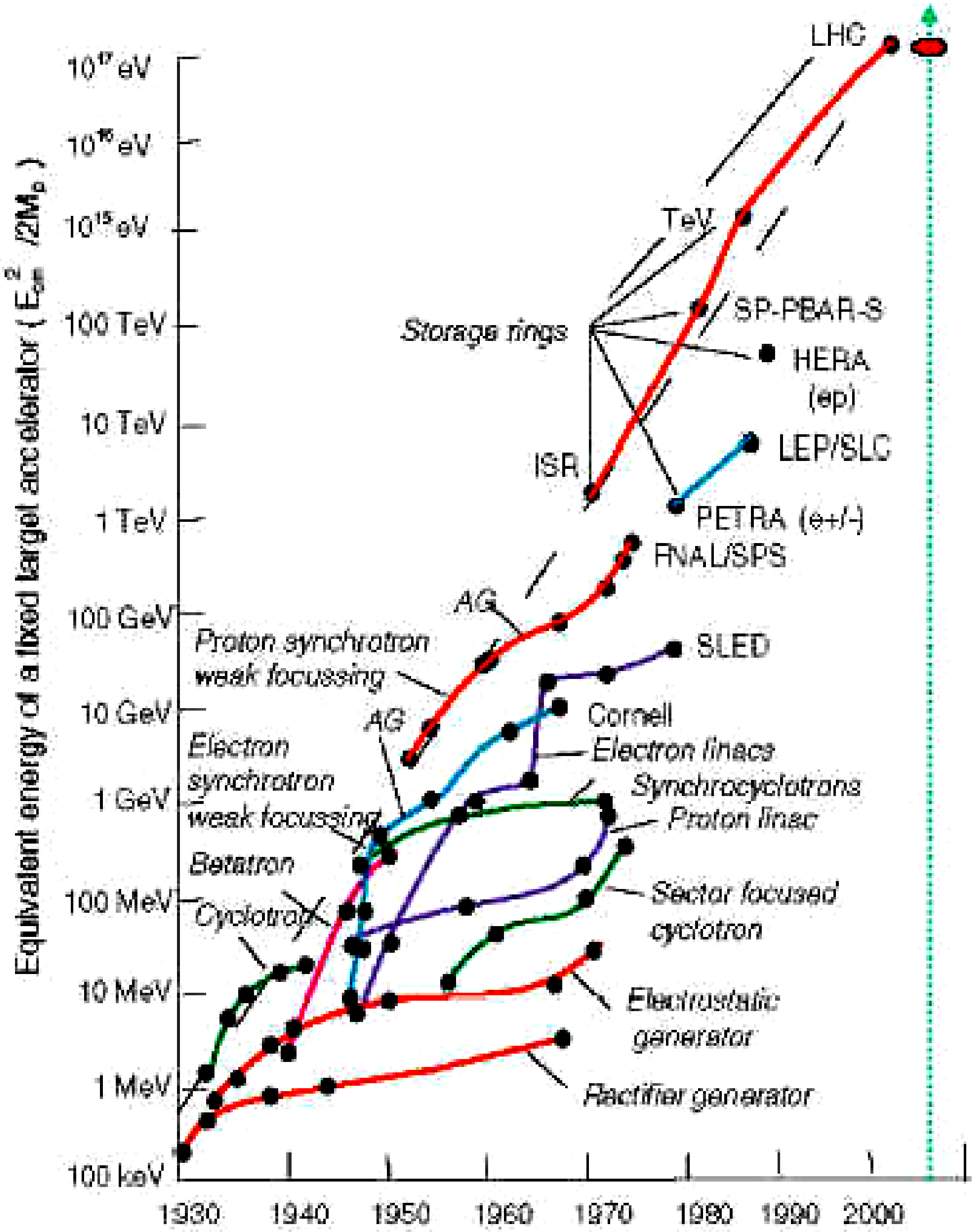
B = 45 tesla, Bore Dia: 32 mm, Power: 30 MW

Steady Magnetic Field over large area

~ 10-15 tesla

$B\rho \approx 3.3$ .p (GeV/c) T.m

$\therefore$ min $\rho \approx 0.3$ p (GeV/c) m



Equivalent energy of a fixed target accelerator (E_{cm}^2 /2M_p)
10^{17} eV
10^{16} eV
10^{15} eV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 keV
1930
1940
1950
1960
1970
1980
1990
2000
LHC
TeV
SP-PBAR-S
Storage rings
HERA
(ep)
LEP/SLC
ISR
PETRA (e+/-)
FNAL/SPS
AG
100 GeV
Proton synchrotron
weak focussing
SLED
AG
Cornell
Electron
synchrotron
weak focussing
Electron linacs
Synchrocyclotrons
Proton linac
Betatron
Cyclotron
Sector focused
cyclotron
Electrostatic
generator
Rectifier generator

How to reach even higher energies?

Use a broken-down medium:

i.e., plasma

Use New sources:

i.e., lasers

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

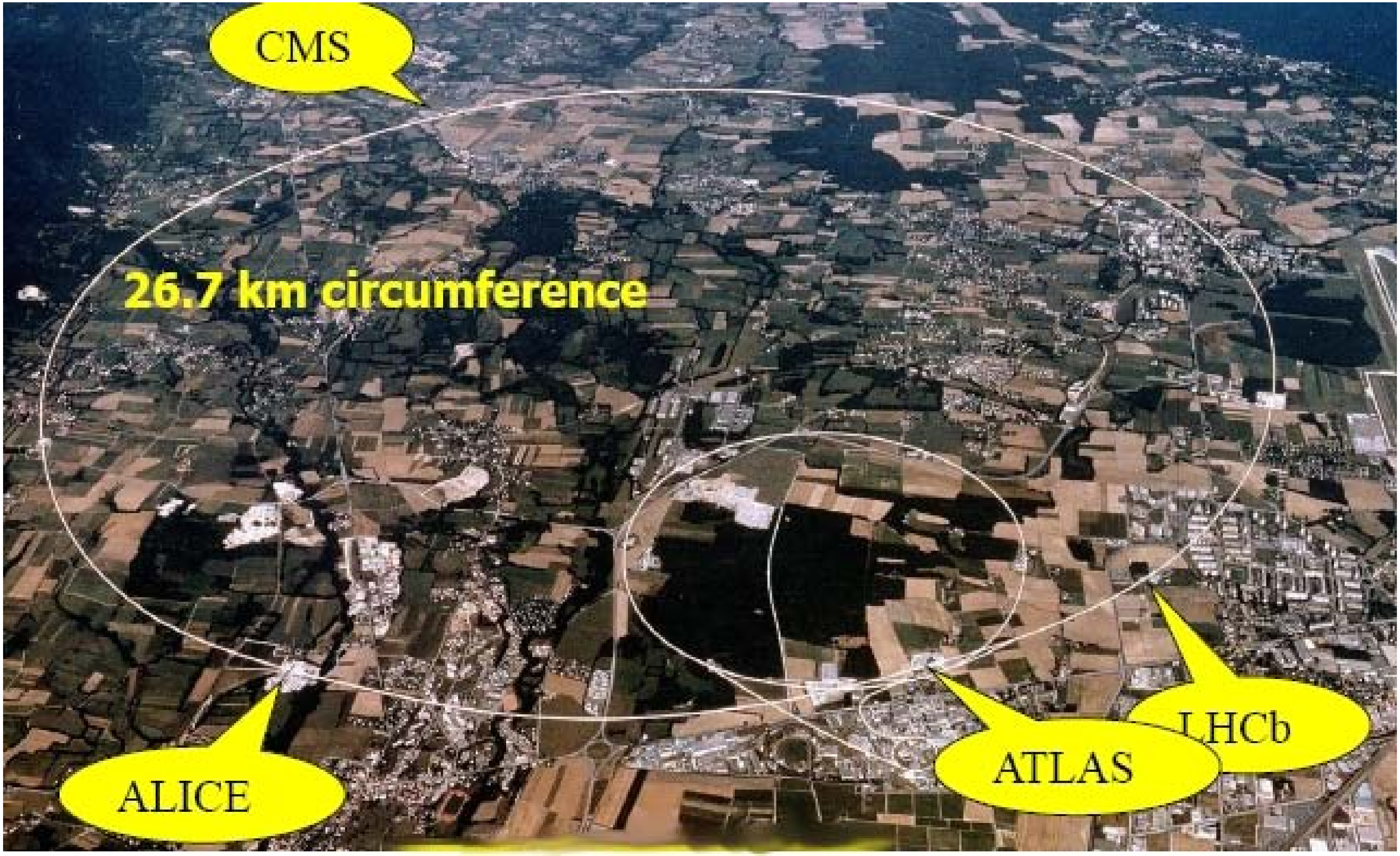
Plasma Wakefield Accelerator

Laser Wakefield Accelerator

Dielectric Laser Accelerator

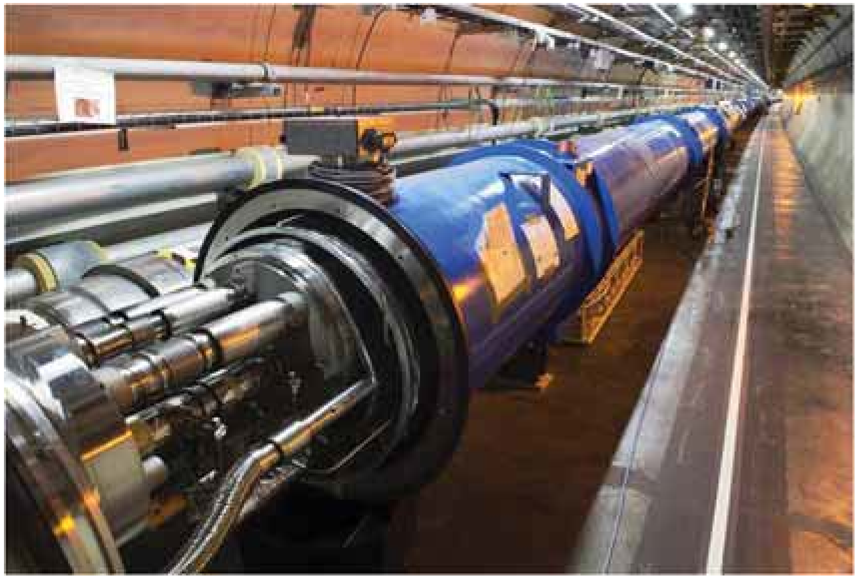
Largest Accelerator

Large Hadron Collider, CERN



Ref: http://www.cern.ch

Large Hadron Collider: 7 TeV p on p



Ref: http://www.cern.ch

LHC: 40MW for 1200 dipoles

Ultimate Field = 9 T, Nominal Field (for 7 TeV) = 8.33 T

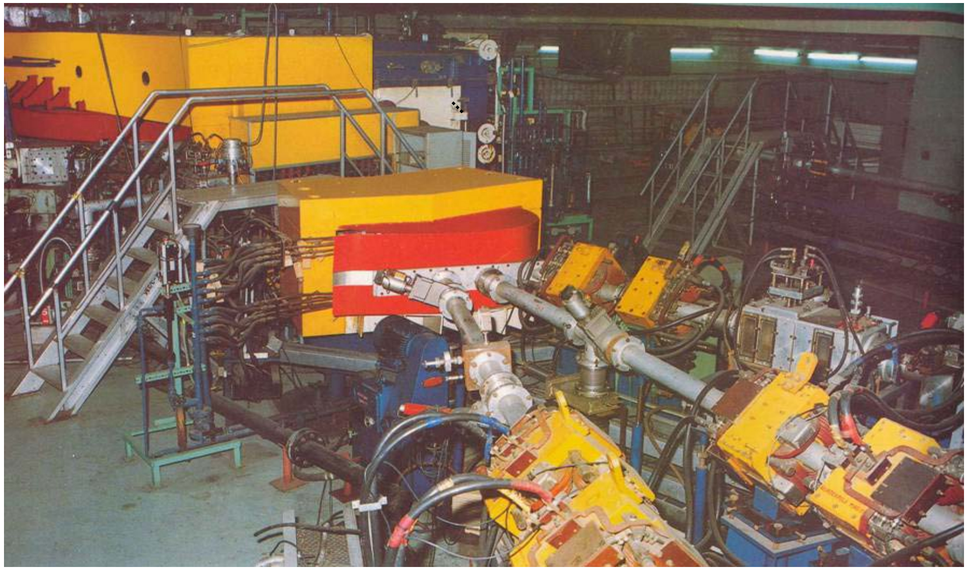
“with no Superconductors” => 4GW and 6000 dipoles (120 km)

=> Affordable higher CW/long pulse gradients => robust
Larger aperture cavity geometry for better beam quality

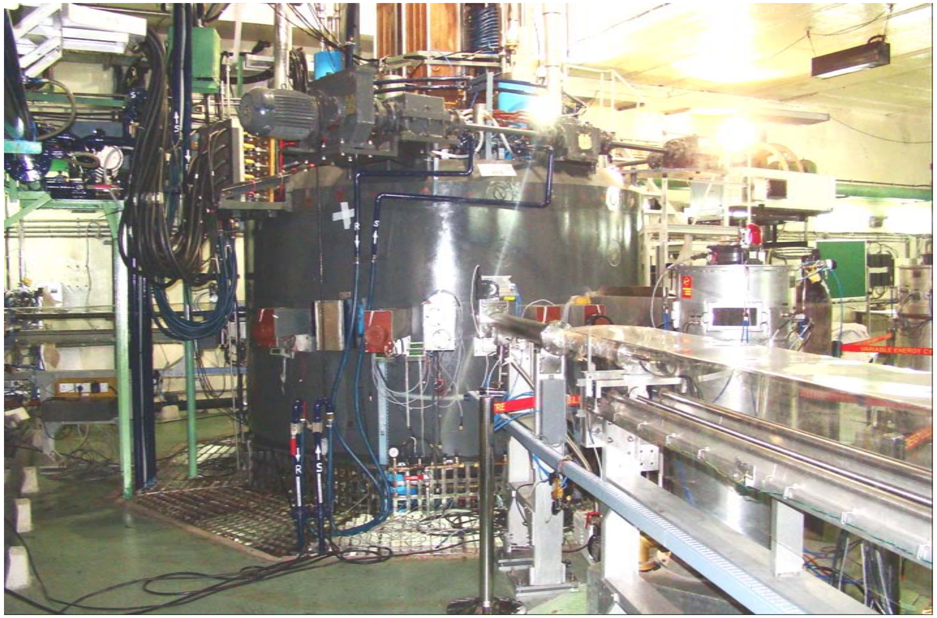
Indian contributions in Accelerator, Detectors & Experiments.

Indian Scenario

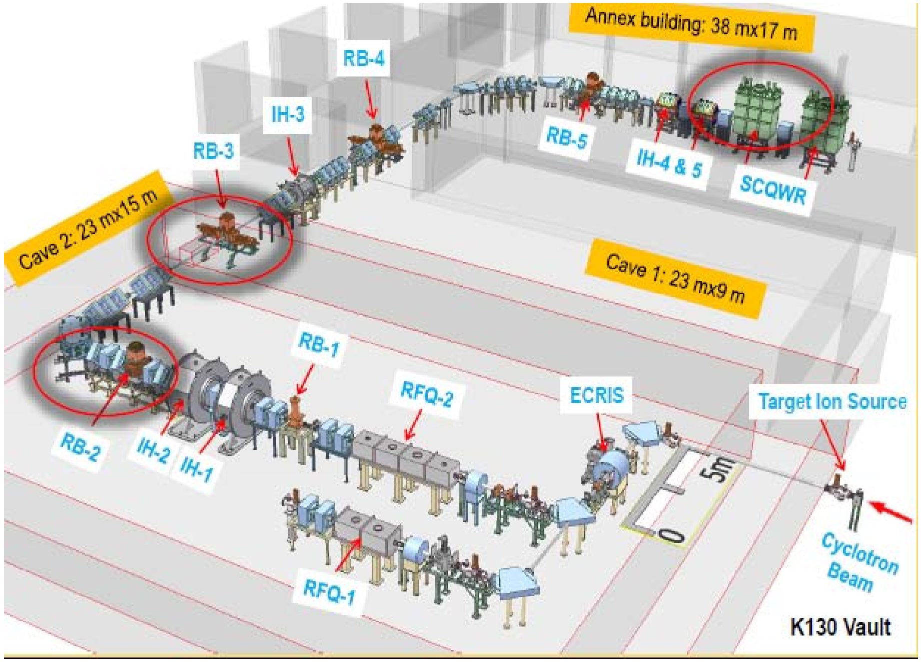
Variable Energy Cyclotron Centre, Kolkata



K = 140, Variable Energy Cyclotron



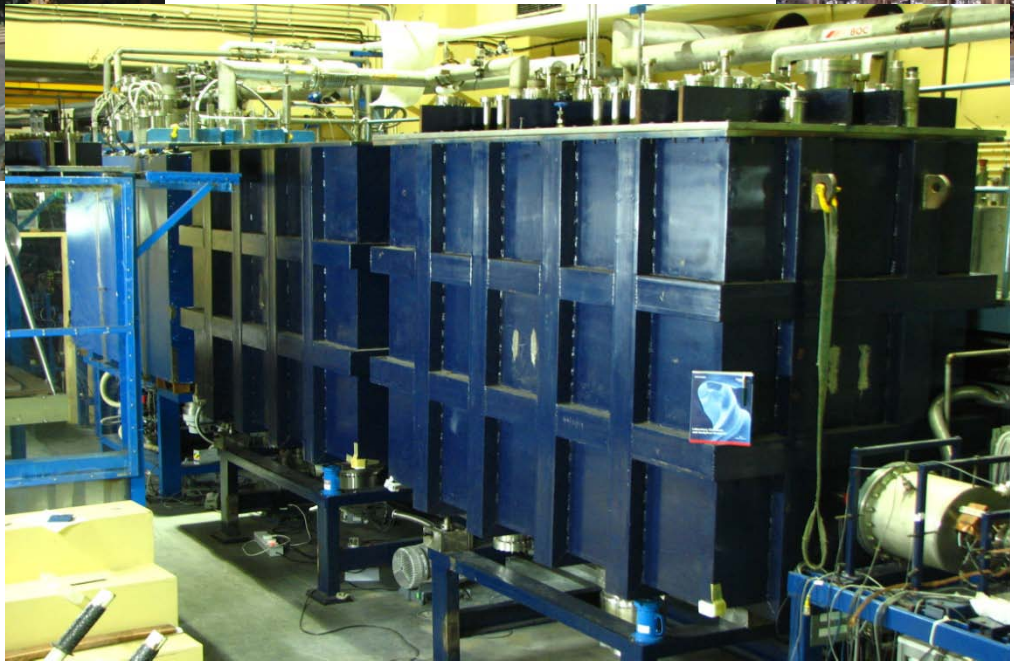
K = 500 Superconducting Cyclotron



Radioactive Ion Beam Facility

Inter-University Accelerator Centre, New Delhi

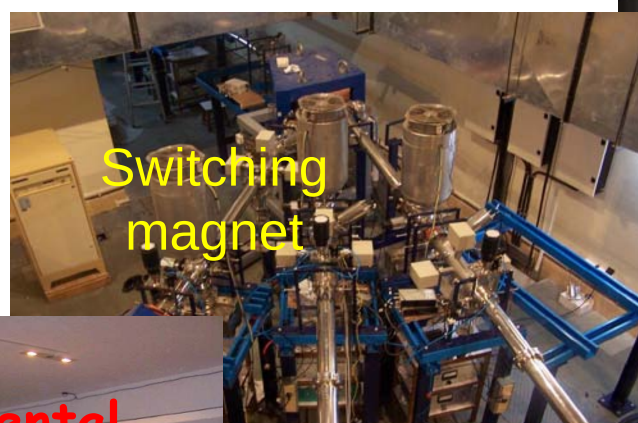
16 UD Pelletron



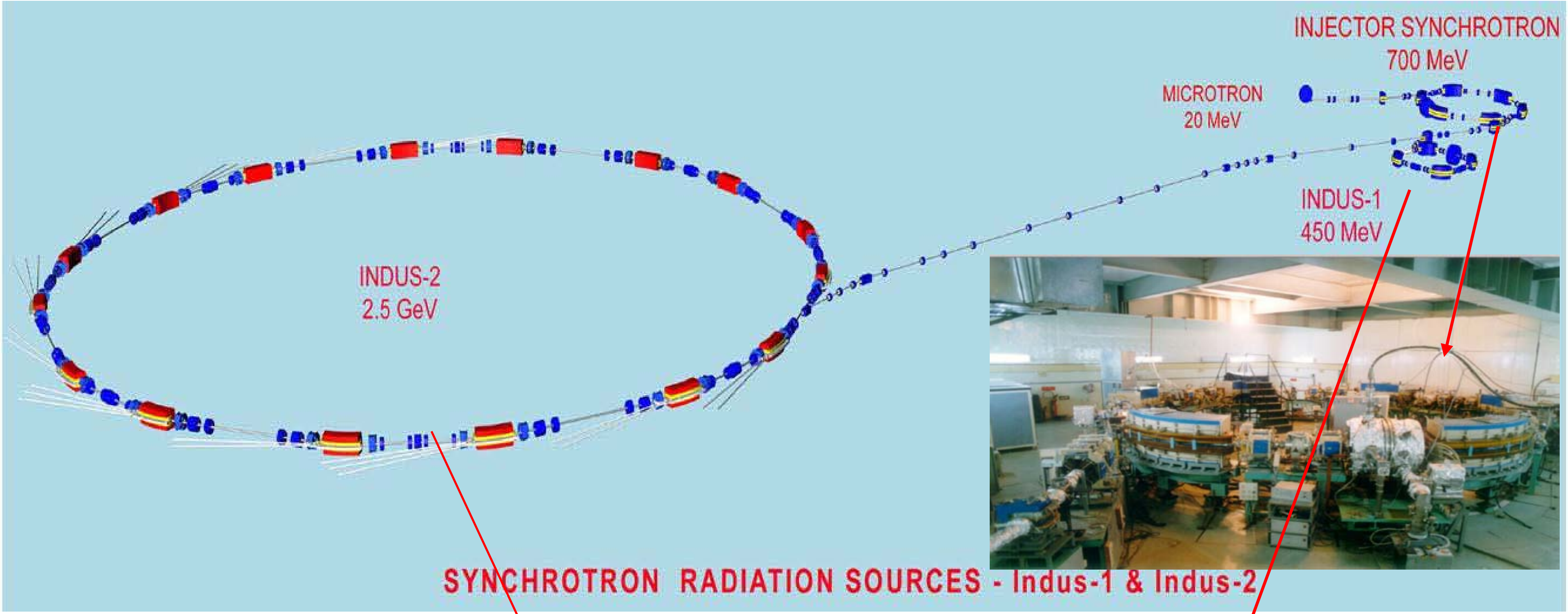
Superconducting Linac

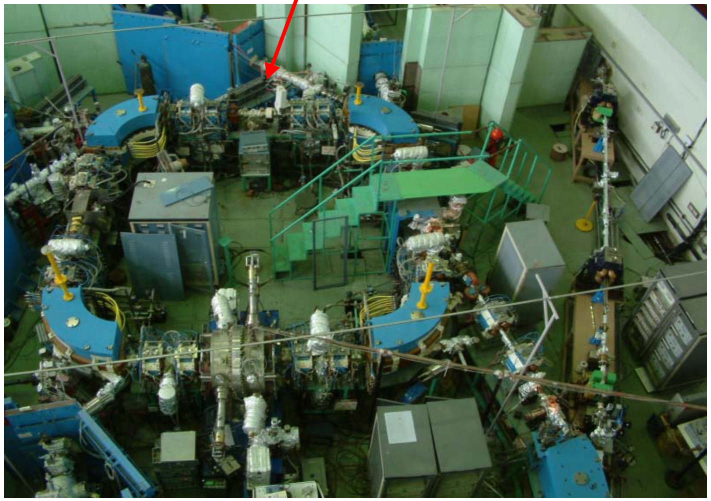
Tata Institute of Fundamental Research, Mumbai

14 UD Pelletron



Raja Ramanna Centre of Advanced Technology, Indore





New Accelerator Programmes in India

A National facility for Unstable and Rare Isotope Beams (ANURIB), VECC.

Accelerator Driven Subcritical System (ADSS), BARC.

Indian Spallation Neutron Source (ISNS), RRCAT.

Free Electron Laser, RRCAT, IUAC.

Fourth-generation light sources: FEL

Linac-based Free-Electron Laser

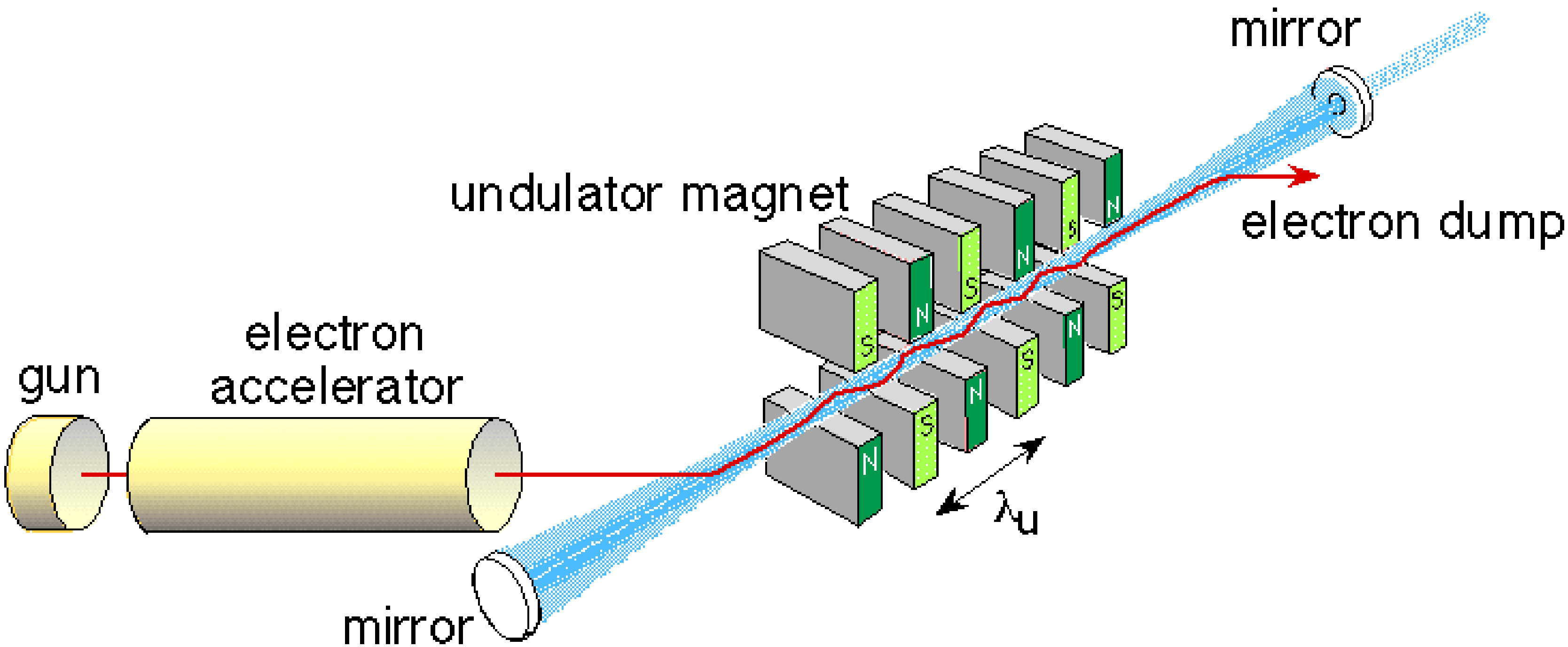
(Under development at RRCAT, IUAC)

Modular Approach

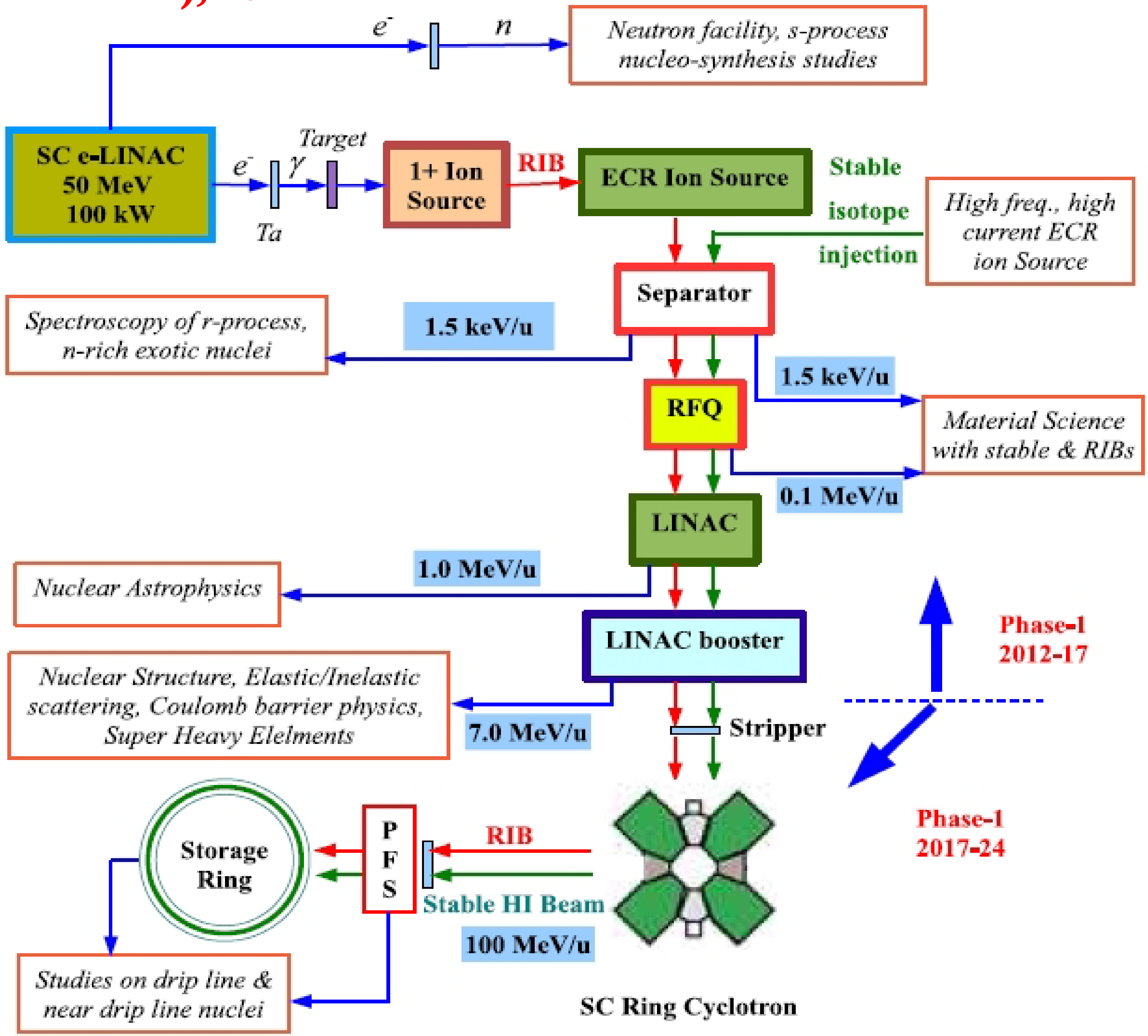
5 -10 MeV - THz;

50-100 MeV - Infra Red, Visible, Soft X-ray

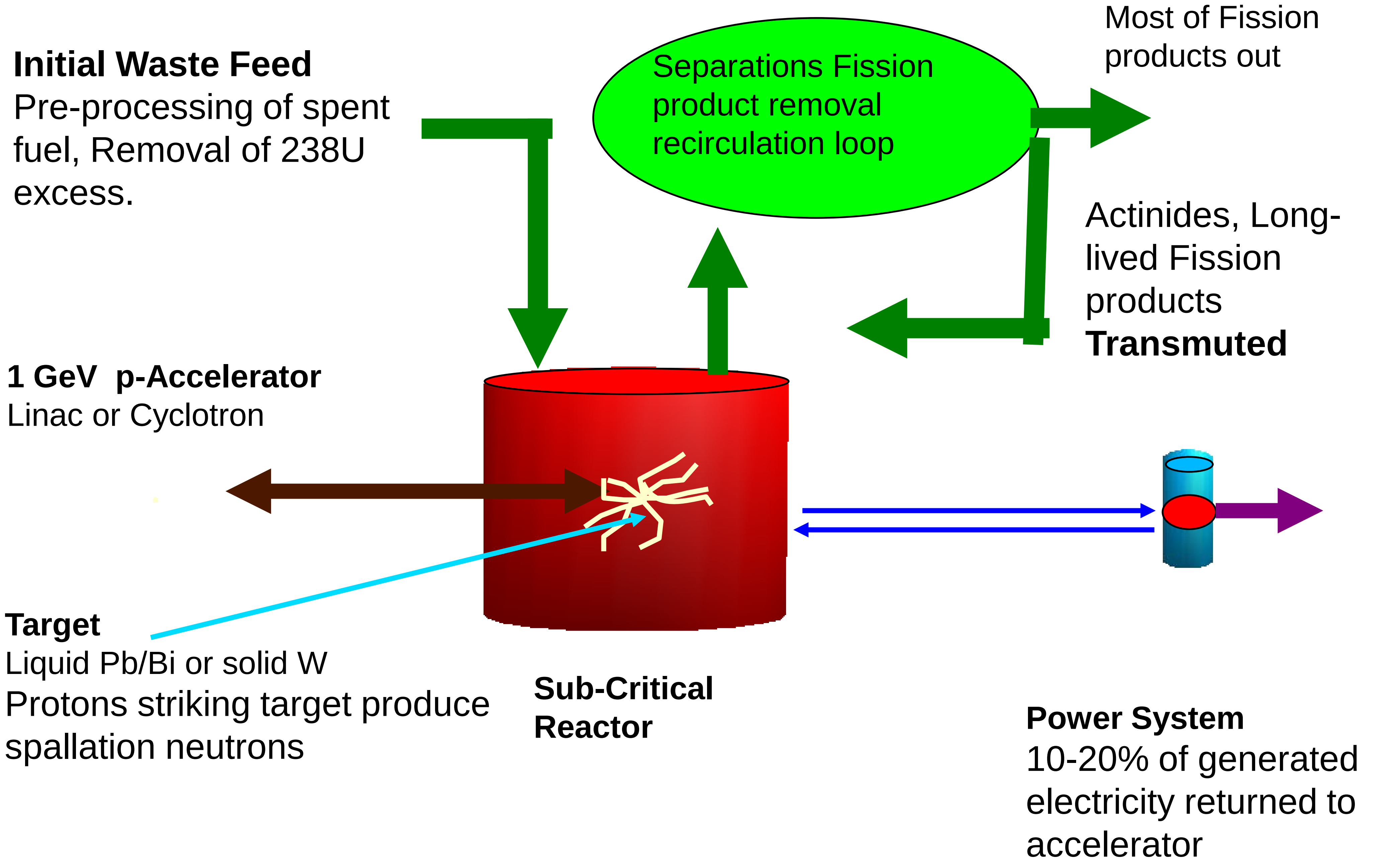
> 1 GeV - Hard X-ray

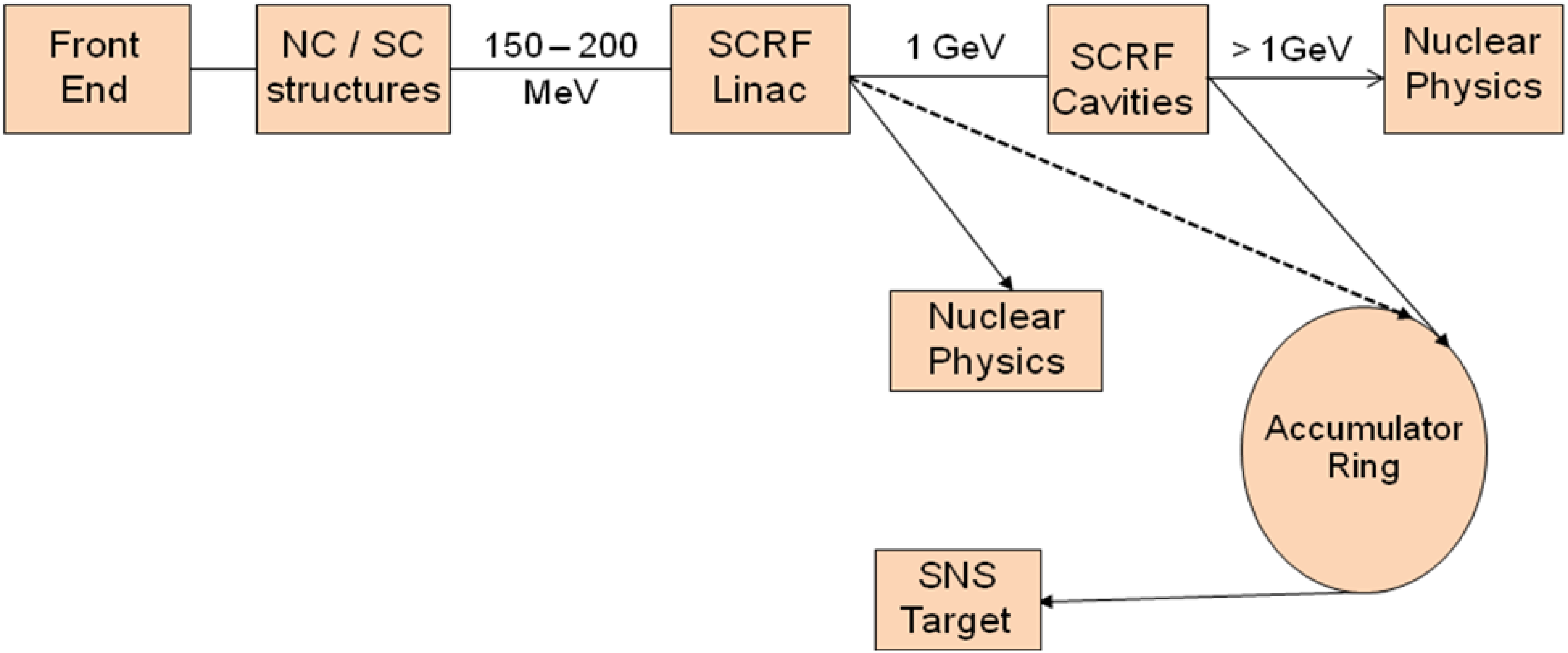


A National facility for Unstable and Rare Isotope Beams (ANURIB), VECC



Accelerator Driven Sub-Critical System





Indian Spallation Neutron Source (ISNS) at RRCAT, 1 GeV, 1 mA protons.

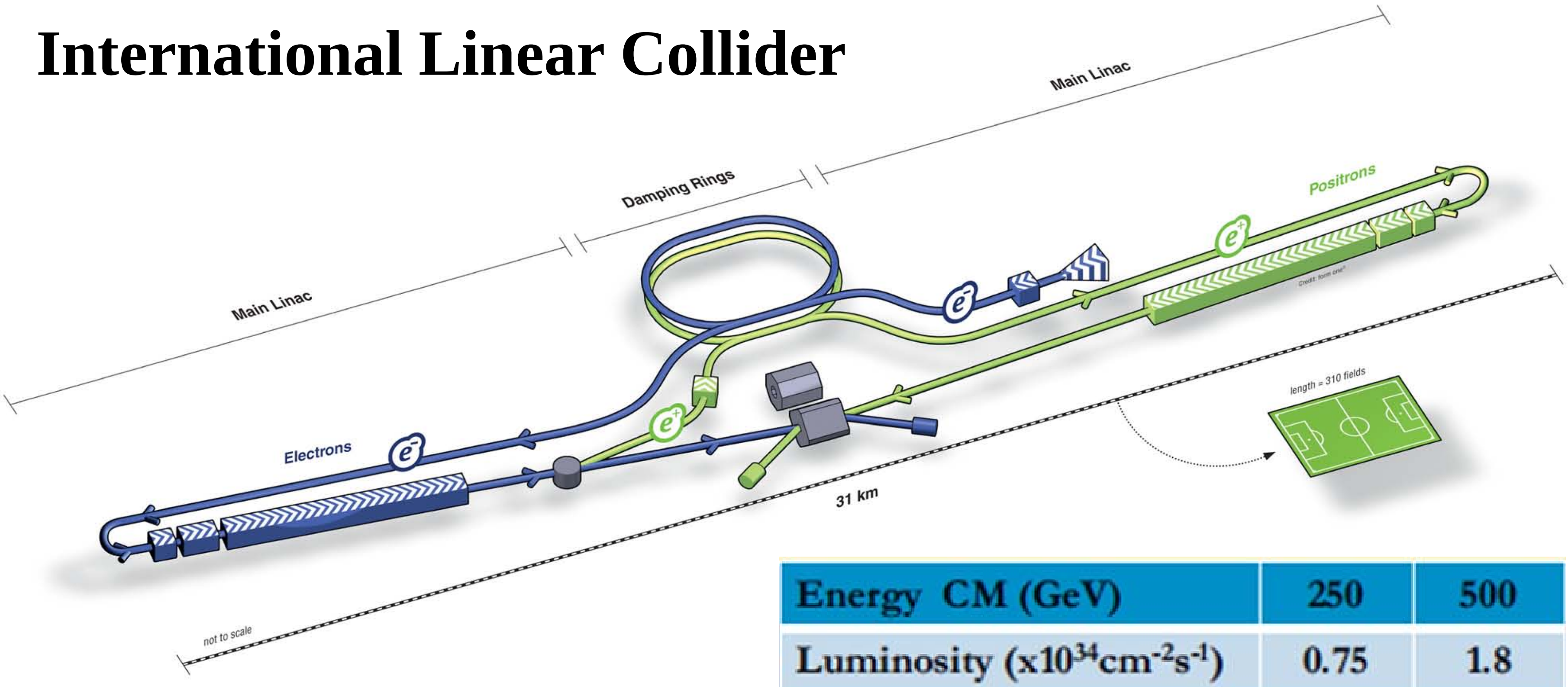
International Collaborations

TESLA/International Linear Collider.

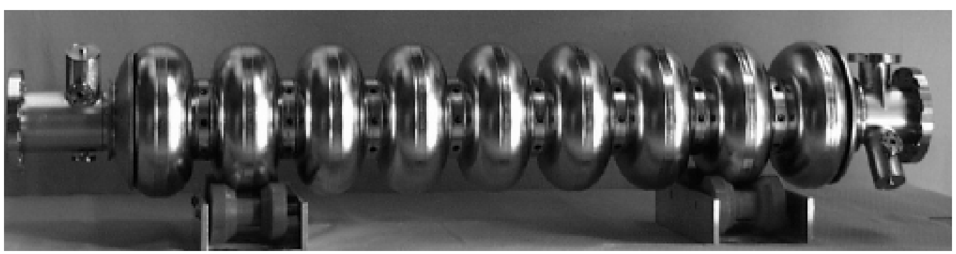
Fermilab, USA for High Intensity protons.

Contributions to FAIR, Germany.

International Linear Collider

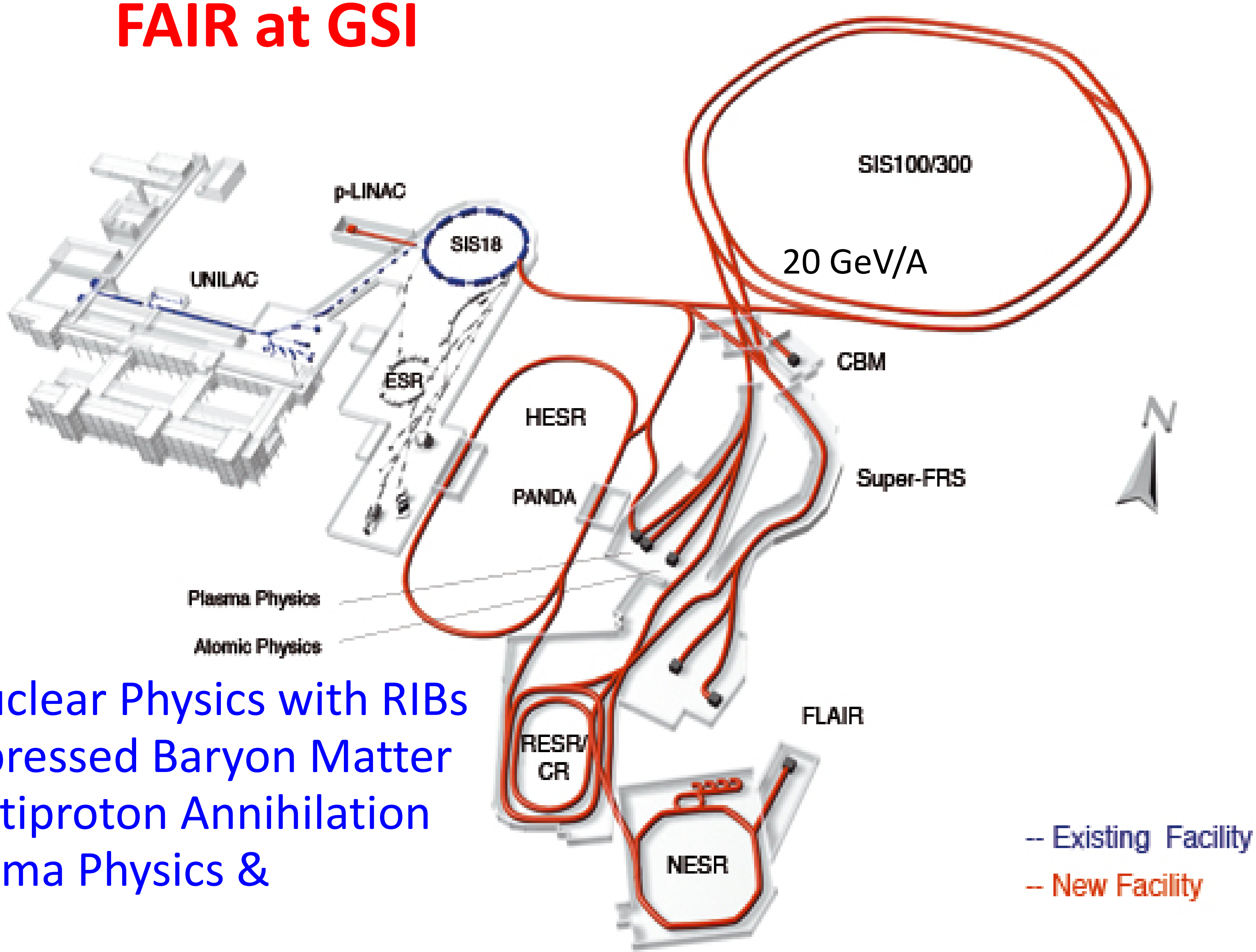


Energy CM (GeV)	250	500
Luminosity ($x10^{34} cm^{-2} s^{-1}$)	0.75	1.8
Beam size (σ_x / σ_y nm)	730/8	470/6
Pulse duration (ms)	0.75	0.75
Beam power (MW)	5.2	10,5
Total AC power (MW)	128	162



Cavity Gradient (MV/m)	31.5
#9-Cell cavities	~16000
#Cryomodules (2K)	~1800
#RF units (10MW Kly)	~560

FAIR at GSI

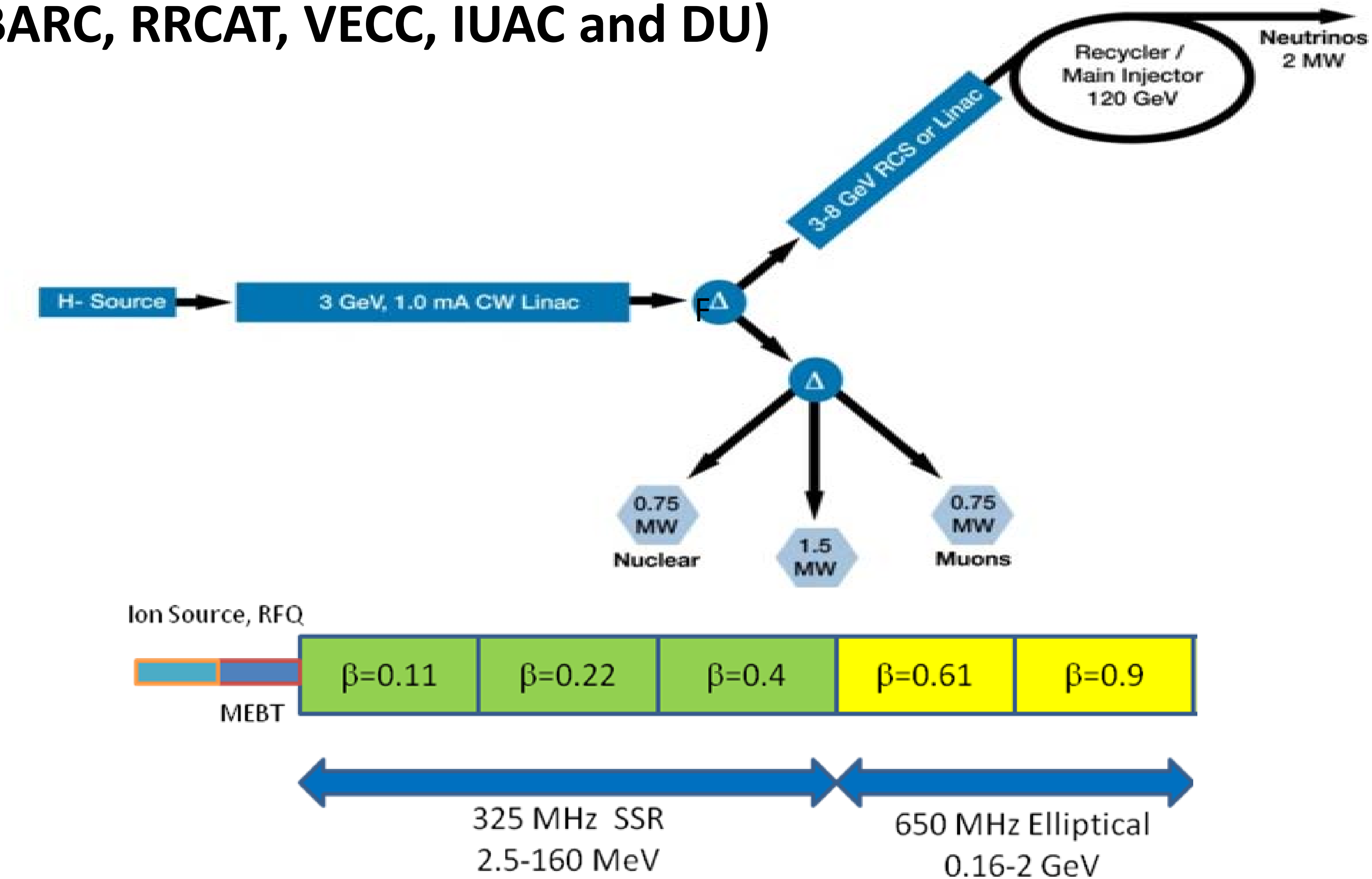


NuSTAR – Nuclear Physics with RIBs
CBM – Compressed Baryon Matter
PANDA - Antiproton Annihilation
Atomic , Plasma Physics &
Astrophysics

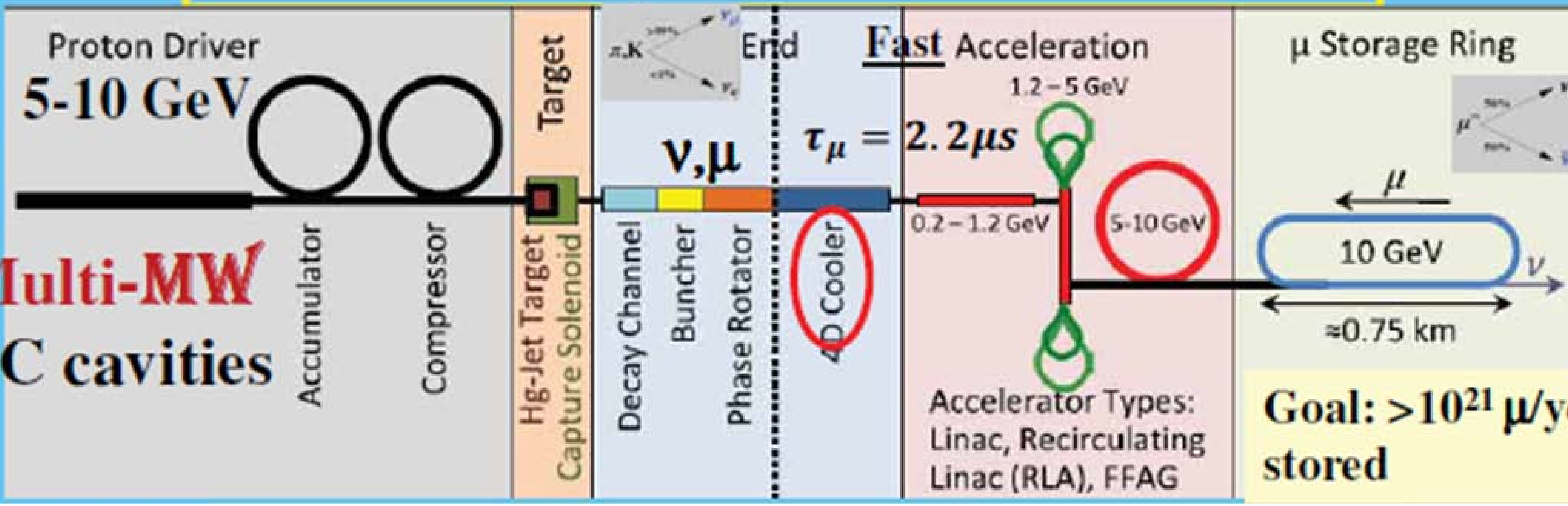
India to supply Beam diagnostic chambers, Sc solenoid magnets for Super-FRS, Power supplies, high power cables, High power beam catcher.

Indian Institutions-Fermilab Collaboration on Project X (Proton Improvement Project)

(BARC, RRCAT, VECC, IUAC and DU)



From neutrino superBeams toward ν-factories



Goal: >10^{21} μ/year stored

Either using existing LEP/LHC tunnel to reach 26-32 TeV collisions

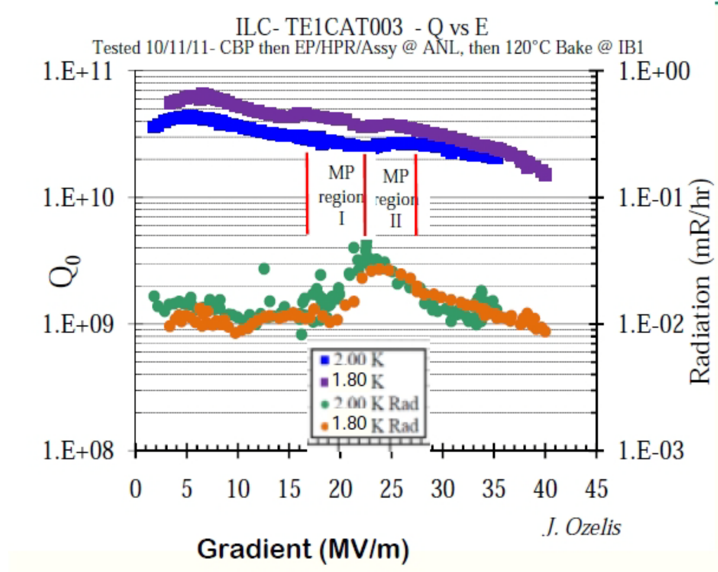
Or build (or reuse) a 80km tunnel to reach 80-100 TeV collisions

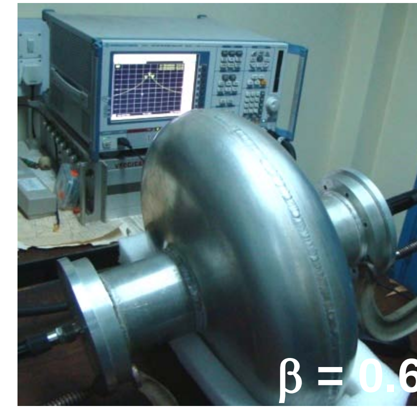
In both cases, SC challenge to develop 16-20 Tesla magnets!

How prepared are we?

Development of SCRF Cavities at RRCAT – IUAC - VECC Under Indian Institutions & Fermilab Collaboration

Single Cell, 1.3 GHz

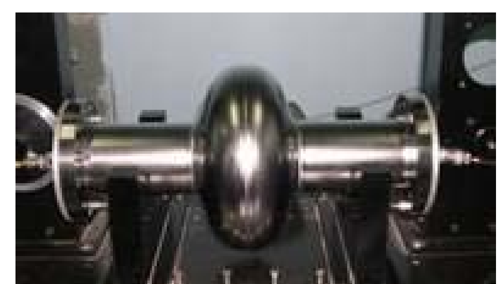




Spoke Cavity, β = .22

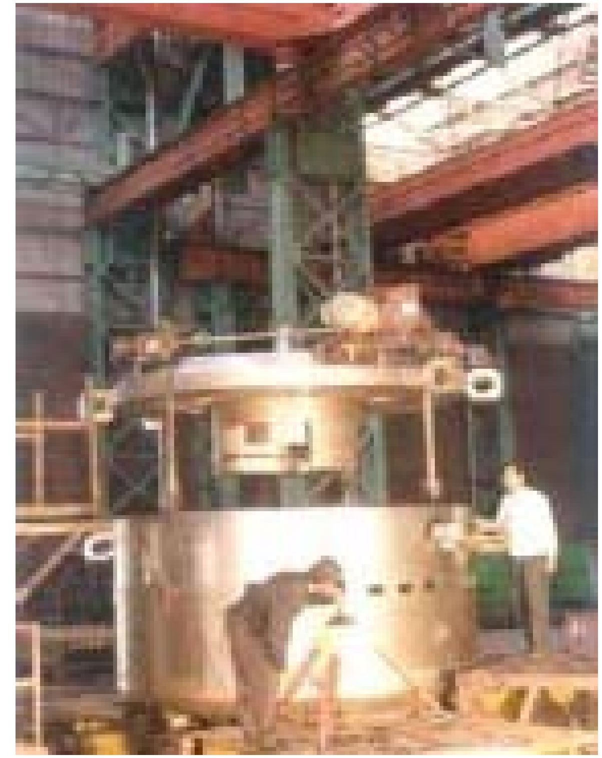
5-Cell 1.3 GHz cavity

9-Cell Cavity

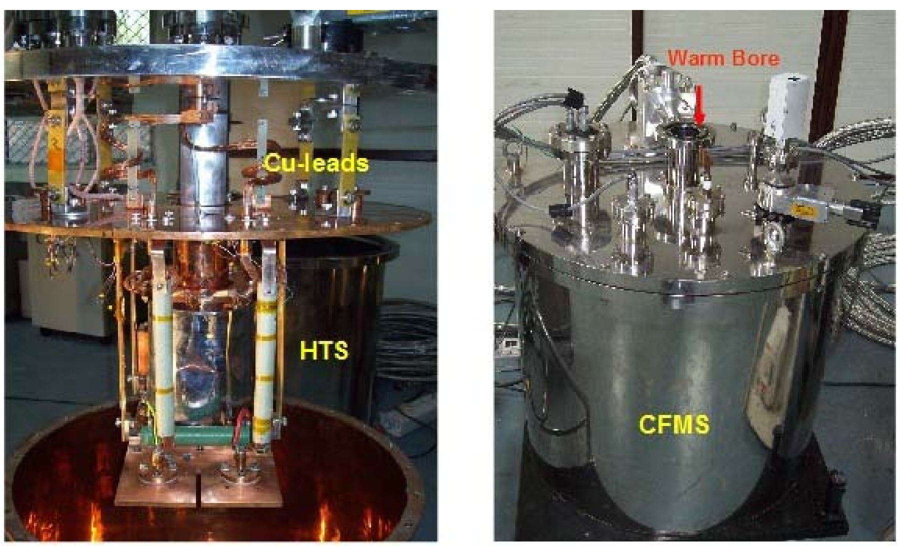


World's 1st Laser Welded Cavity

Superconducting Magnet coil winding facility, VECC



Magnet Assembly



Cryofree High T_c Superconducting Magnet, 6.2 T, IUAC

Indigenous Development of Nb-Materials

NFC, Hyderabad

Development of materials and testing of mechanical properties

RRCAT,Indore

Electrical and superconducting properties, elemental analysis

On-line CICC Fabrication Facility Developed at AFD, BARC

Cross section of 20x20mm CICC

0.8mm dia SC wire having 492 Nb-Ti Filaments, Tested for11 kA.

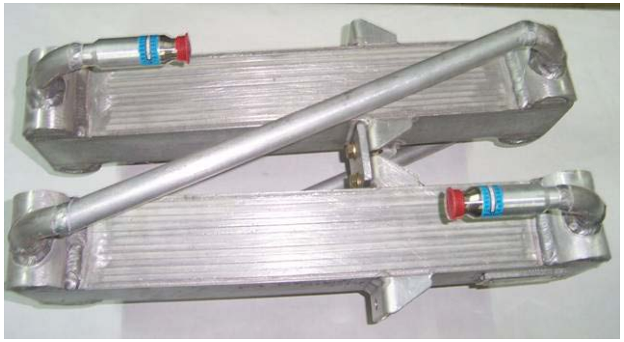
First indigenous helium liquefier,
RRCAT 20-50 l/hr

20K Helium Refrigerator Developed at BARC

16 mm turbine
264,000 RPM

Assembled turboexpanders

He Impurity Monitor,
IUAC



Compact Brazed Plate & Fin Heat Exchangers

Conclusion

Higher and higher energies of Accelerators were built as demand went up from Physicists.

New methods and technologies invented for accelerators have found wide use. Numerous societal applications have been found.

State-of-Art Accelerator projects have been taken up in India.

New Technologies are needed for higher energy accelerators.

Exciting challenges for the young researchers.