Accelerator Option for Neutron Sources & the Front-end Injector of Proton Driver

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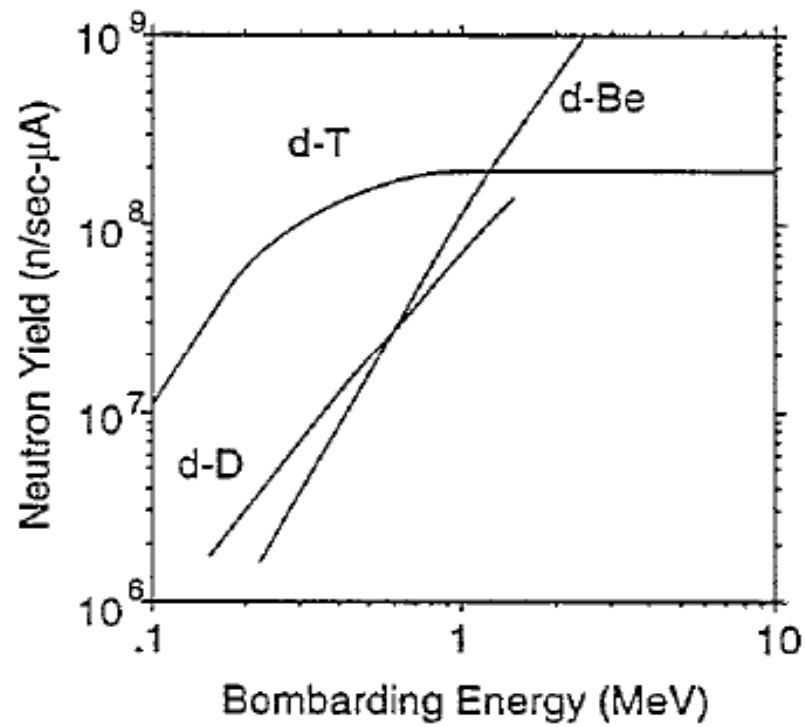
Application of prolific neutron sources

- Radioisotope production for industrial and medical uses.
- Using neutron beams for materials science research: as in spallation neutron source.
- Driving fission chains in sub-critical reactor for energy production.
- Nuclear transmutation applications:
  - Producing reactor fuels from abundant isotopes of ^{238}U and ^{232}Th.
  - Incineration of highly radiotoxic contents of spent nuclear fuel: minor actinides and long-lived fission products.

Nuclear reactions for neutrons

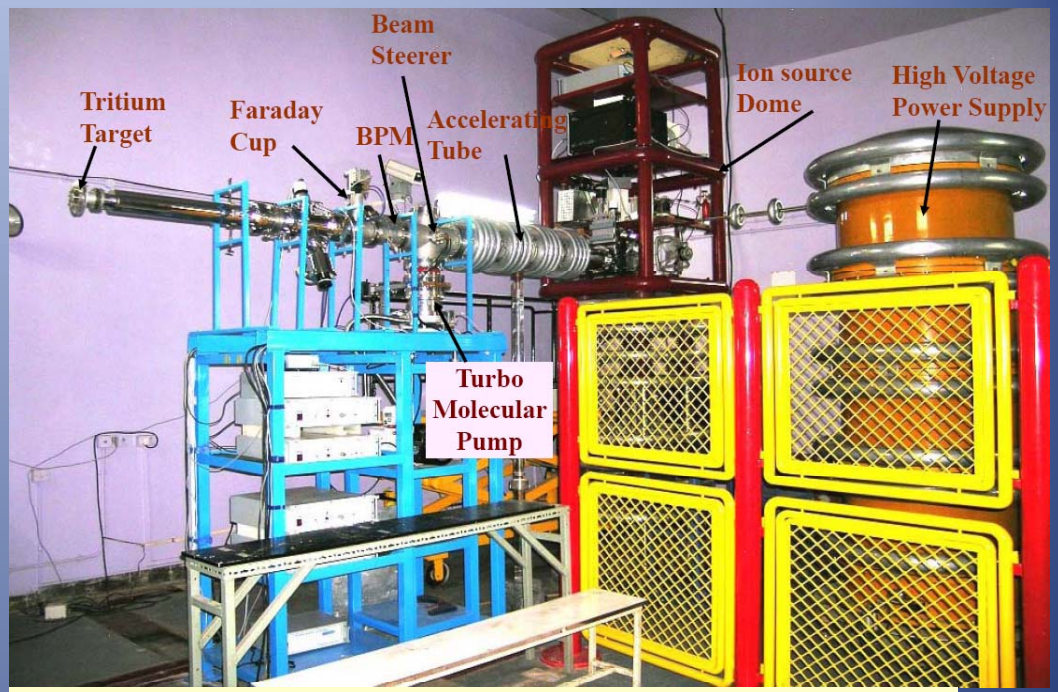
Some of nuclear reaction which have been utilized to generate neutrons are as following:

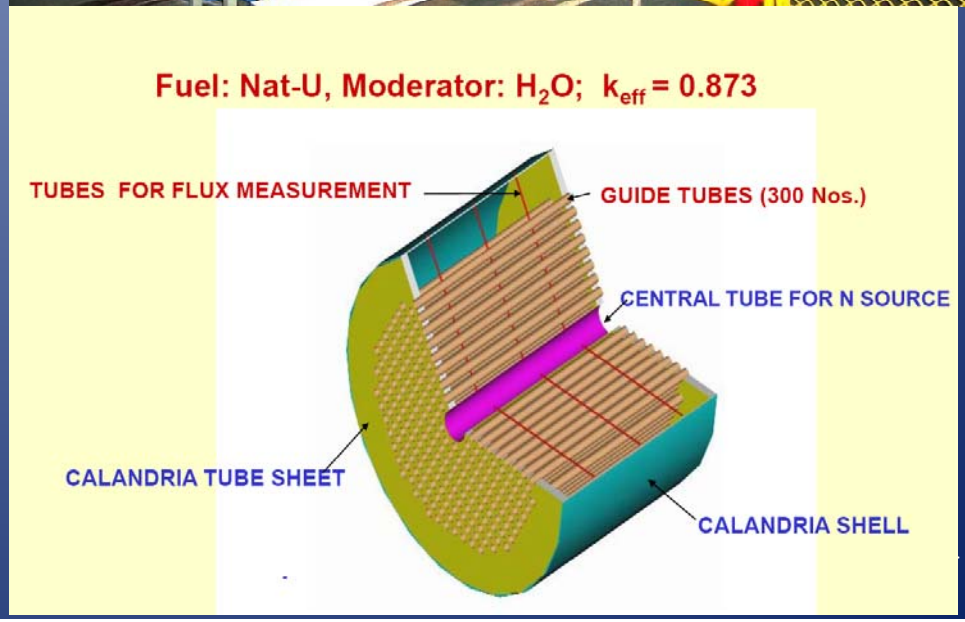
1. ${}^{3}_{1}H + {}^{2}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$;
   - the well-known deuterium-tritium reaction at ~0.3 MeV deuteron energy for 14-MeV neutron source of the order of 10^9 n/s with 50-100 W beam power.
2. ${}^{9}_{4}Be + {}^{2}_{1}H \rightarrow {}^{10}_{5}B + {}^{1}_{0}n$;
   - the beryllium target for deuteron beams
3. ${}^{9}_{4}Be + {}^{1}_{1}H \rightarrow {}^{9}_{5}B + {}^{1}_{0}n$;
   - with beryllium target for ~5 MeV proton beams
4. ${}^{9}_{4}Be + \gamma \rightarrow 2\ {}^{4}_{2}He + {}^{1}_{0}n$;
   - beryllium target with photons at energy 1.7 MeV and above from electron beam to photon converter target.
5. ${}^{7}_{3}Li + {}^{2}_{1}H \rightarrow {}^{7}_{4}Be + 2\ {}^{1}_{0}n$;
   - and other neutron stripping channels for lithium as target for deuterons.



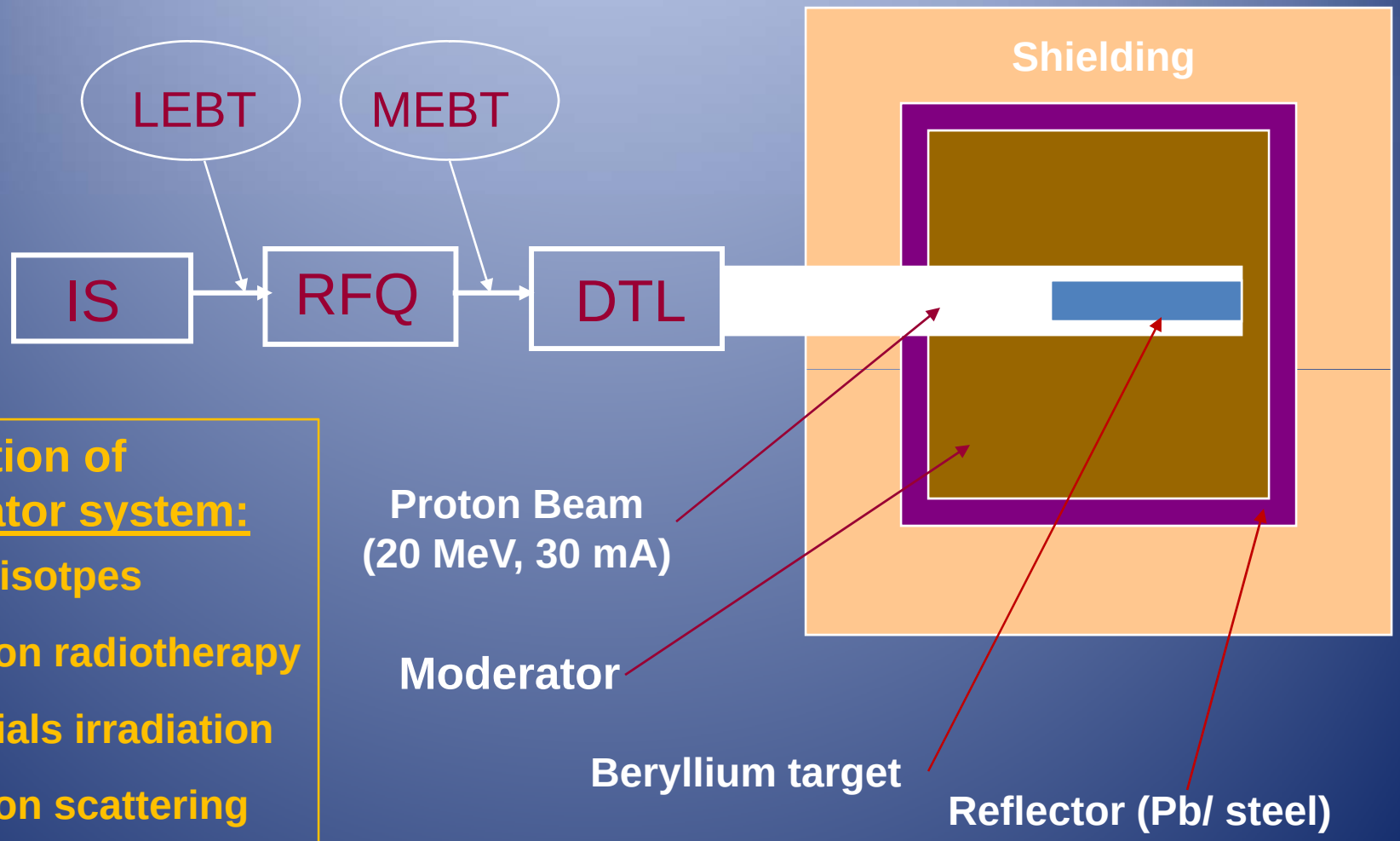
DD/DT neutron generator – BARC facility

- For experiments on physics of ADS and validation of simulations. Sub-critical assembly (k_{eff}=0.873) of natural uranium and light water is chosen
- To make use of fast neutrons (≈ 10^9 n/s) produced by 400 kV, 100-250 μA DC accelerator in D+D/T reaction.
- *Solid target of titanium deuteride/tritide on copper substrate for nuclear reactions.*
- Measurements of flux distribution, flux spectra, total fission power, source multiplication, and degree of sub-criticality will be carried out.





Linac-based facility for neutrons



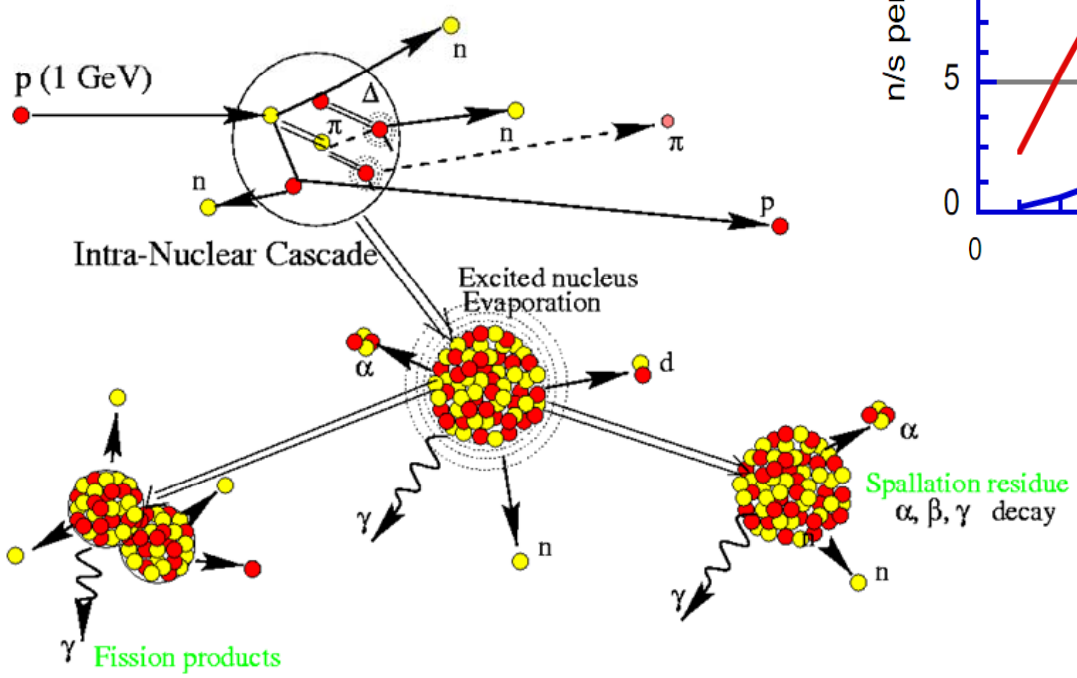
Application of accelerator system:

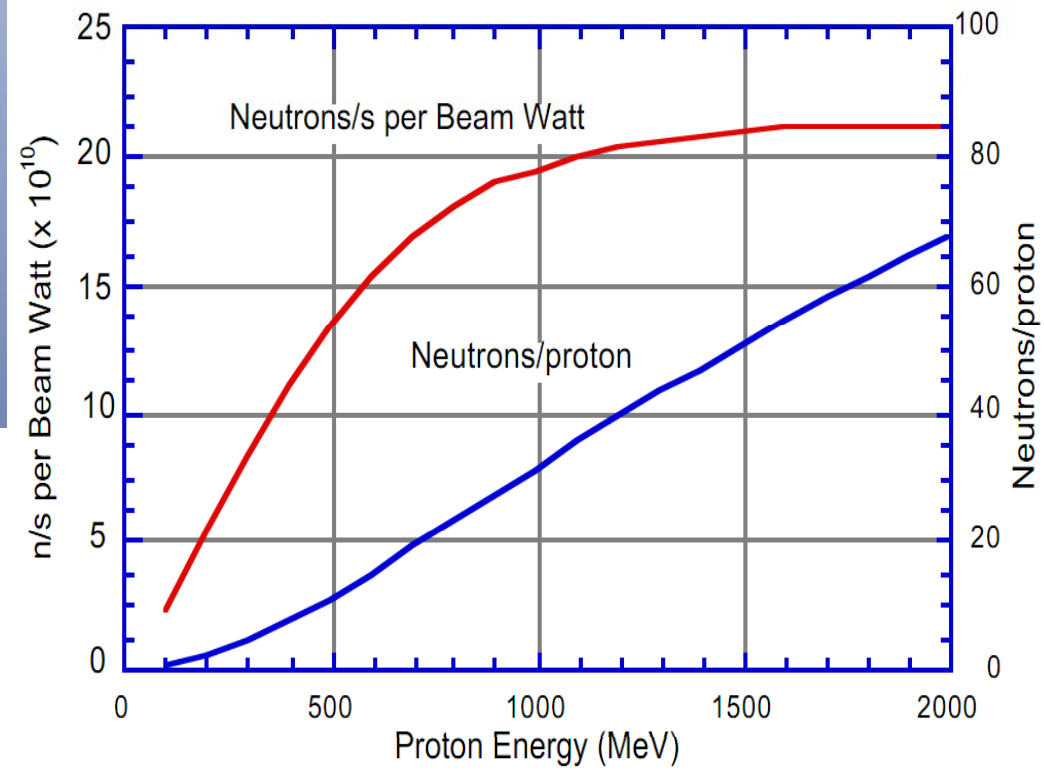
- Radioisotpes
- Neutron radiotherapy
- Materials irradiation
- Neutron scattering
- Transmutation

$$S_0(E_p) = 4.476 \times 10^{11} \times E_p^{1.886} \times I_p \ \text{n/sec}$$

Spallation neutron source

2-step spallation reaction of high-energy proton on heavy nuclei





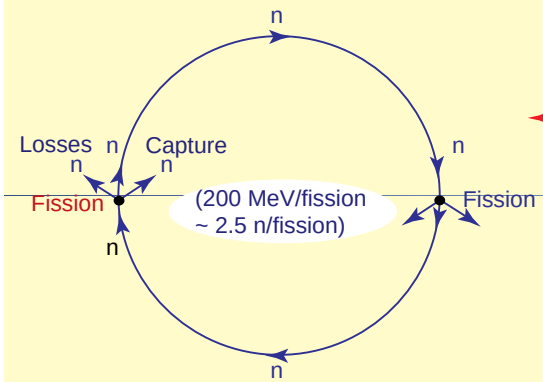
Typical neutron yield from thick target

Energy efficiency for neutron generation

Process	Example	Yield	Energy cost-on target only
(D,T) fusion	400 KeV on T	4×10^{-5} n/D	10,000 MeV/n
Li (D,n) break up	35 MeV D on Li	2.5×10^{-3} n/D	14,000 MeV/n
U-238(γ,n) photo-nuclear	20 MeV e^- on U-238	1×10^{-2} n/e^-	2000 MeV/n
^{9}Be (p,n; p,pn)	11 MeV proton on Be	5×10^{-3} n/p	2000 MeV/n
Spallation	800 MeV proton on U-238; 800 MeV proton on Pb	≈ 27 n/p ≈17 n/p	30 MeV/n 55 MeV/n

Critical & source neutron driven reactor

Chain Reaction



Effective neutron multiplication factor

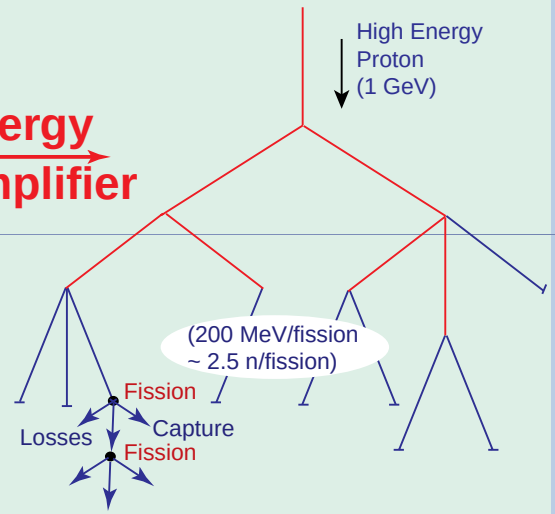
$$k = \frac{\text{Production}}{\text{Absorption + Losses}}$$

Self-sustained process:
k = 1
(if k < 1 the Reactor stops
if k > 1 the Reactor is supercritical)

⇒ The time derivative of the power kept equal to zero by control

Critical Reactor ⟷ **Energy Amplifier**

Nuclear Cascade



Externally driven process:
k < 1 (k = 0.98)

$$E_{tot} = G \times E_p$$

Energy Produced — Beam Energy

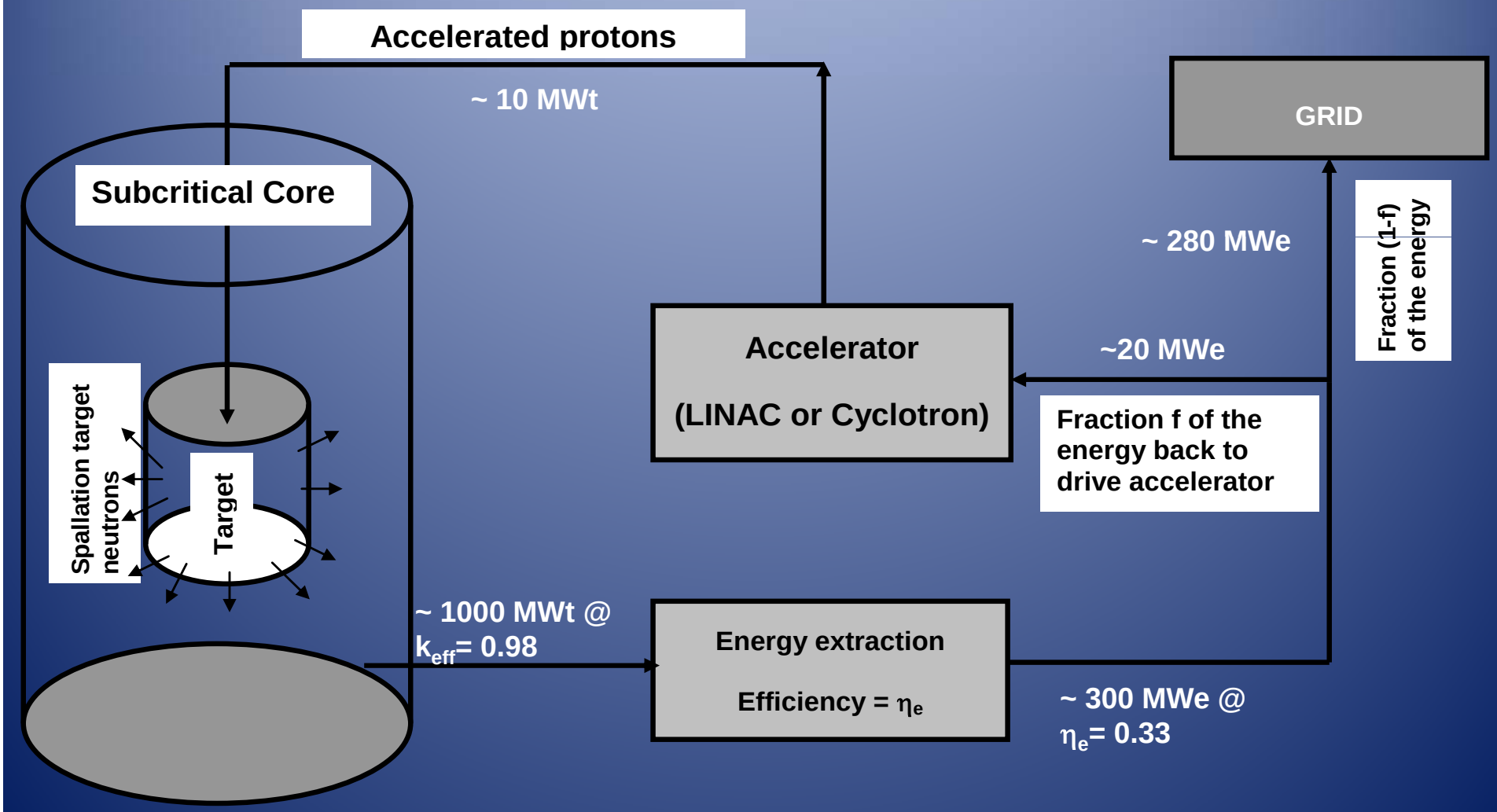
⇒ Constant Energy Gain

Conventional reactors work with chain reaction by self generated neutrons.

Sub-critical reactor works with externally generated neutrons: giving better neutron economy and safety in operations.

This type of system is also considered essential for safely eliminating the TRUs by fission in fast neutron spectrum

Application of spallation neutrons: ADS with energy balance



Accelerator-Driven System for thorium fuel and waste transmutation

ADS has exclusive niche in:

- Thorium fueled reactor due to enhanced availability of non-fission neutrons of spallation target for faster breeding & high fuel burn up.

(This will enable early introduction and faster growth of thorium fuel-based economical power reactors in India.)

- Transmuting transuranic (TRU) elements in the spent fuel with enhanced safety with sub-critical operation, that is otherwise difficult in a conventional fast reactor.

(This will reduce/eliminate need for geologic repository to dispose spent fuel.)

Essential features of proton accelerator for ADS

Functional requirements	Design features
Proton accelerator: 1 GeV & ~30 MW beam power.	Requires elaborate radiation & *beam* safety measures.
High efficiency of conversion from electrical grid into beam power.	Requires superconducting RF cavities to save on dissipation in cavities
High Reliability to achieve less than ~10 beam trips per year.	• Redundancy of systems, • Standby modules • Relaxed design of system parameters
Beam spill: to be minimized <1 watt beam power loss per meter to reduce activation & allow hands-on maintenance by O&M personnel.	• Beam with low emittance, • As large aperture of accelerating structure as possible.

Scheme of linac for ADS/NS

High current injector 20 MeV, 30 mA

Proton IS 50 keV → RFQ 3 MeV → DTL 20 MeV

Normal Conducting: DTL/ CCDTL

Super-conducting

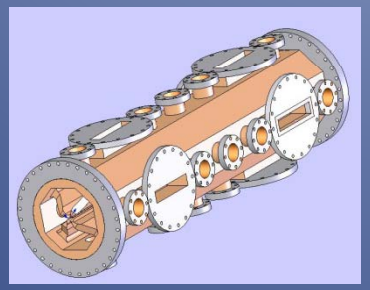
100 MeV → SC Linac

1 GeV

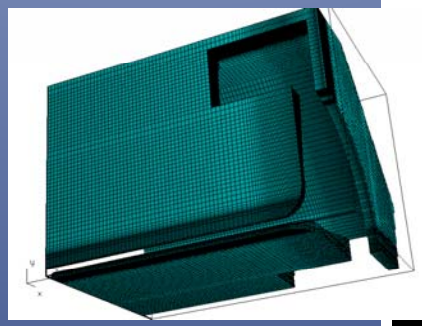
Design completed and fabrication is in progress

ECR Ion Source

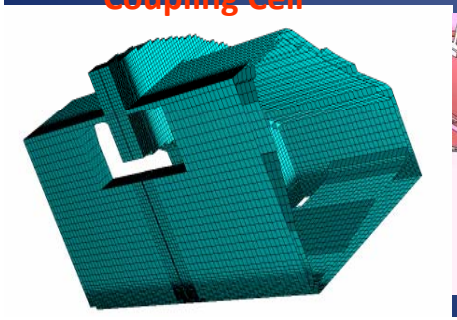
RFQ



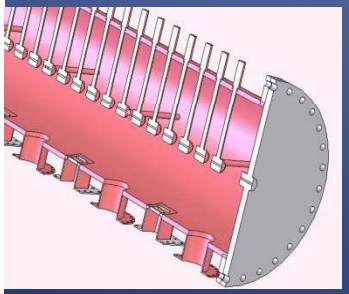
Beginning Cell



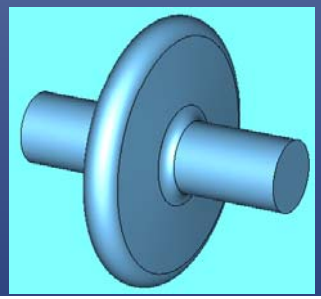
Coupling Cell

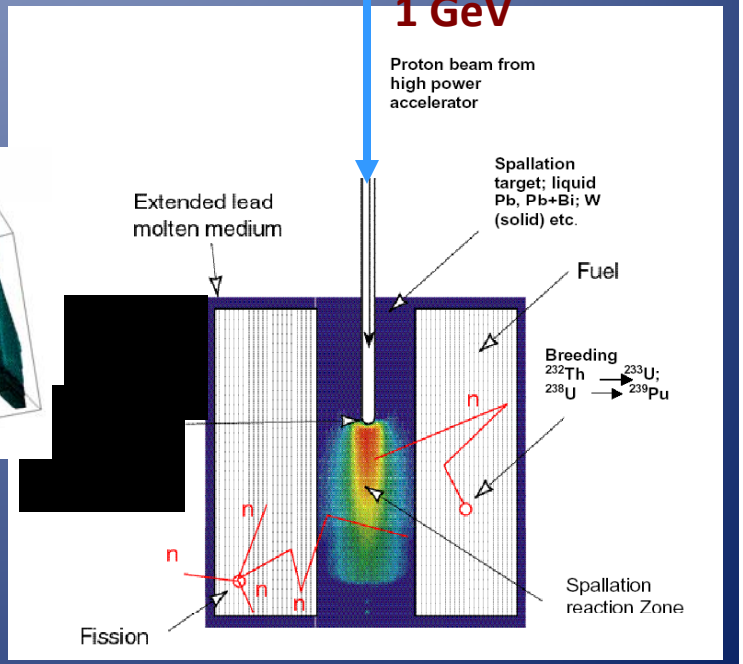


DTL



Elliptical SC Cavity



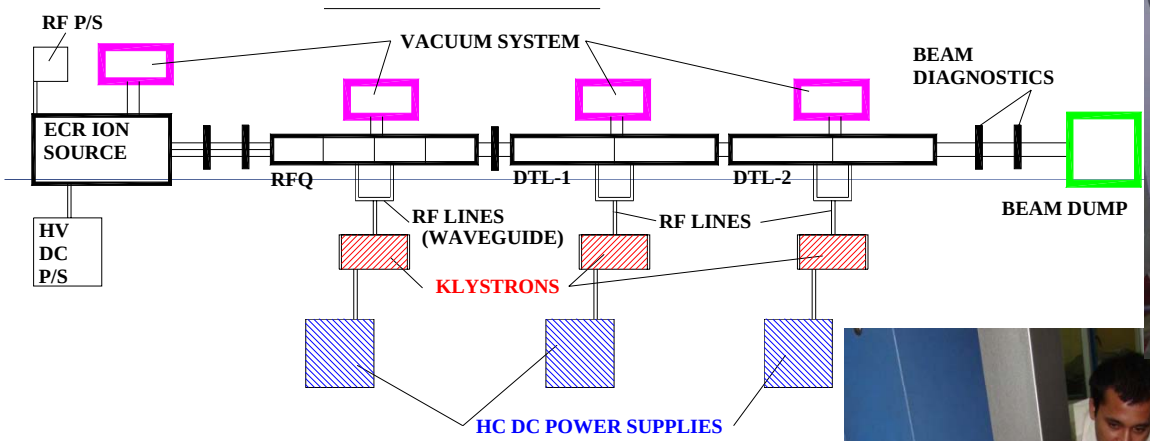


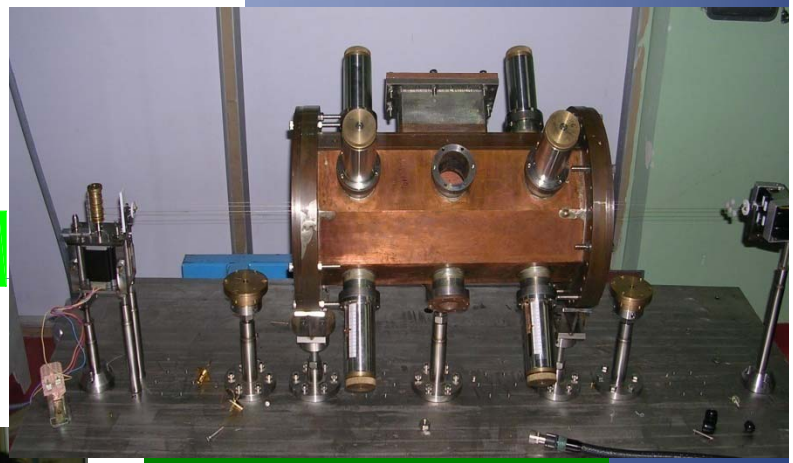
Status of
Front End Injector*
For Proton Driver
In BARC

* **L**ow-**E**nergy **H**igh **I**ntensity **P**roton **A**ccelerator = LEHIPA

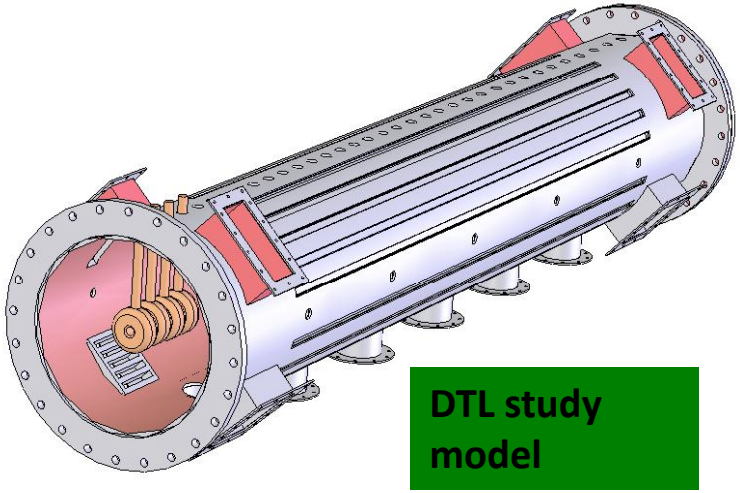
20-MeV proton linac- LEHIPA

EQUIPMENT DIAGRAM OF LEHIPA





RFQ model under bead pull tests



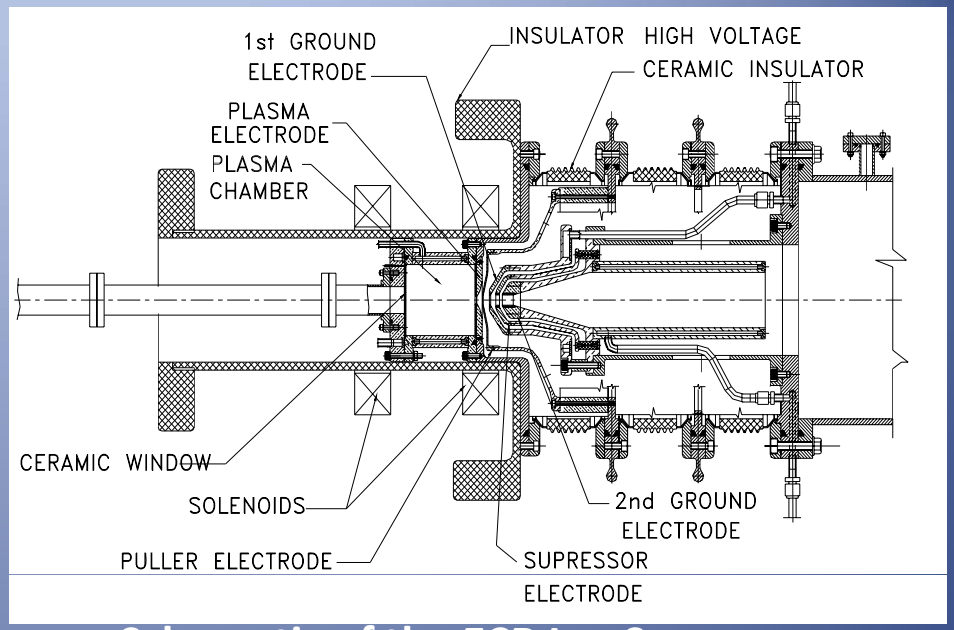
DTL study model

Pre-braze inspection

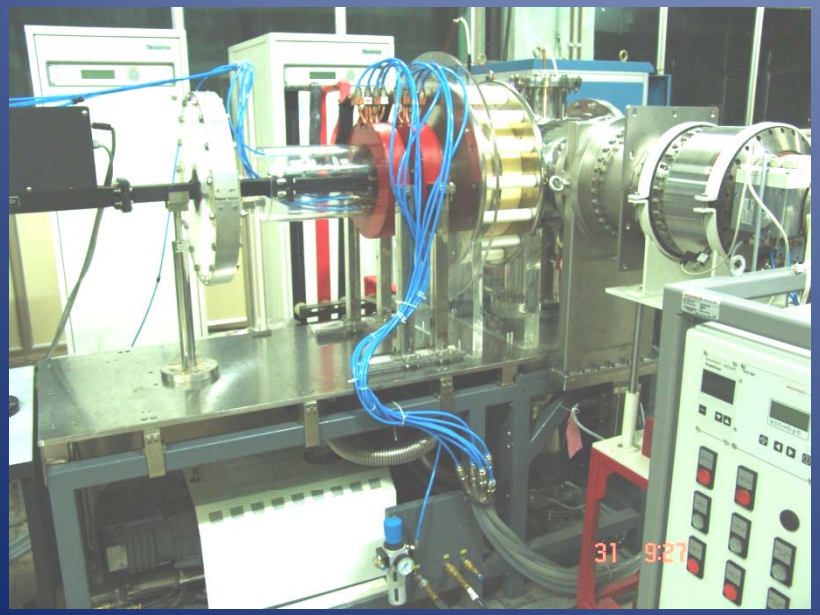
Aluminum short model

ECR Ion Source

- Five electrodes
- 2.45 GHz
- 50 keV
- 50 mA
- 0.02 π cm-mrad

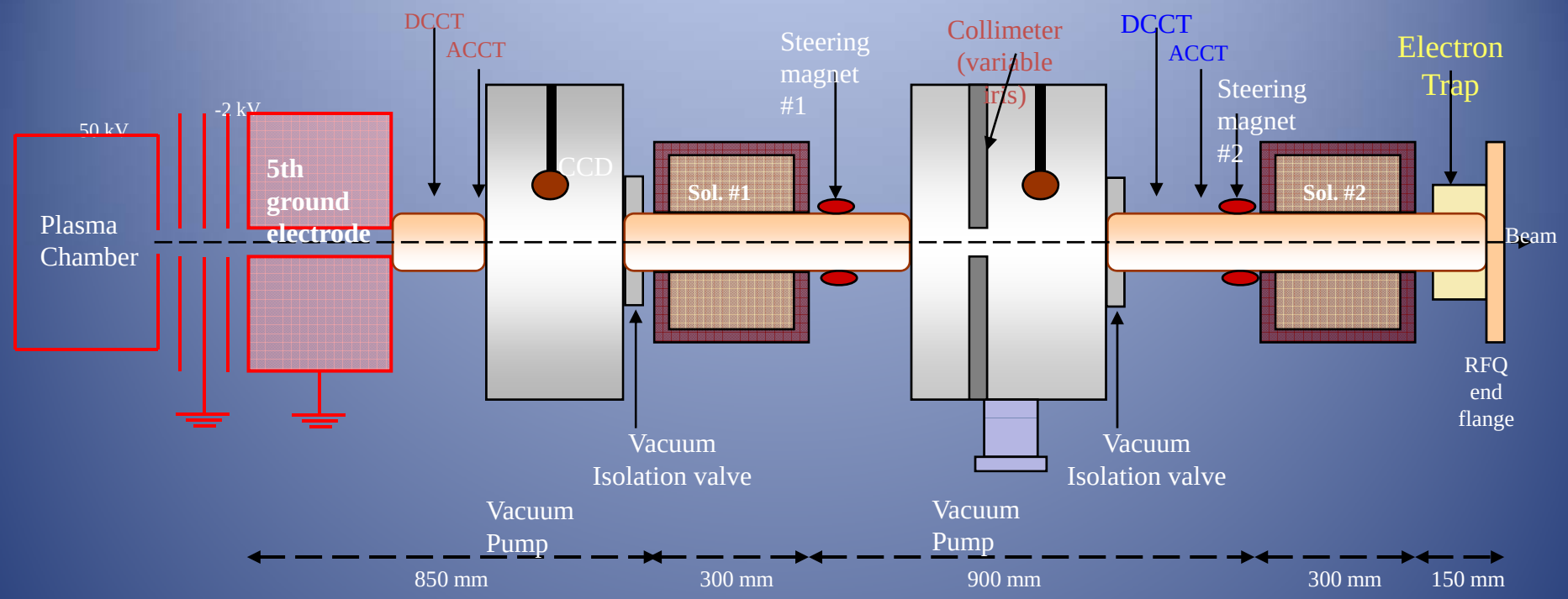


Schematic of the ECR Ion Source

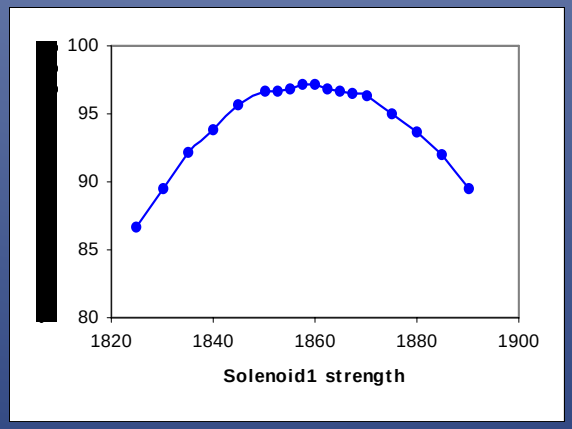


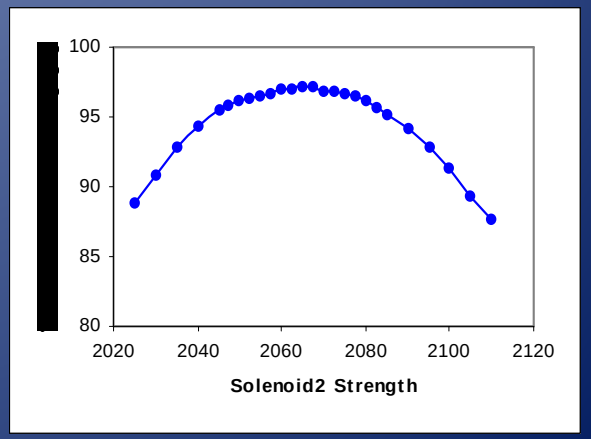
Ion source with 3 electrode extraction system made & Testing is in progress

Low Energy Beam Transport (LEBT) System



Error Analysis of Solenoids

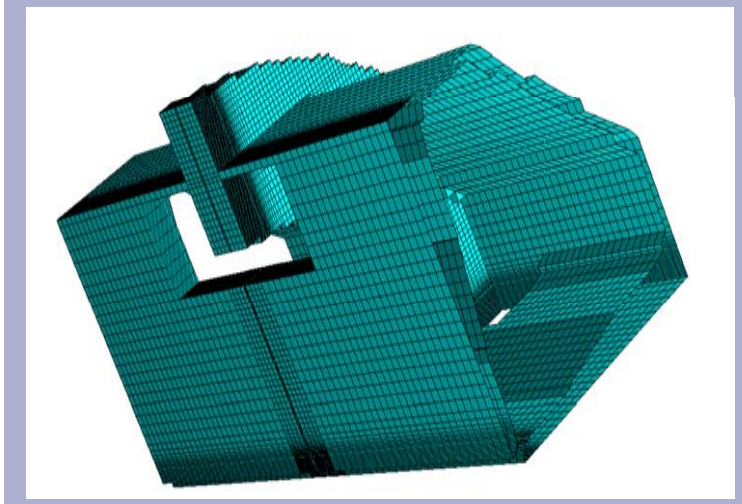




Beam Energy = 50 keV
Beam current = 30 mA
RMS Normalized Beam Emittance = 0.02 π cm mrad

Tolerance on solenoid strength = ± 30 Gauss

3 MeV Radio Frequency Quadrupole



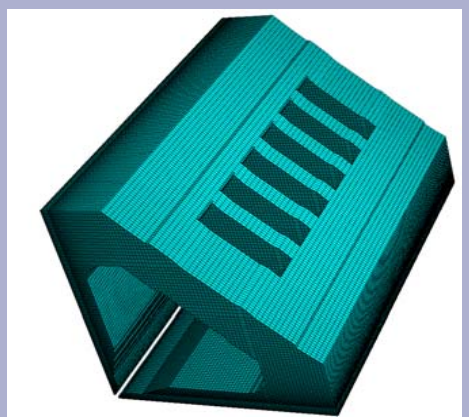
Coupling cell

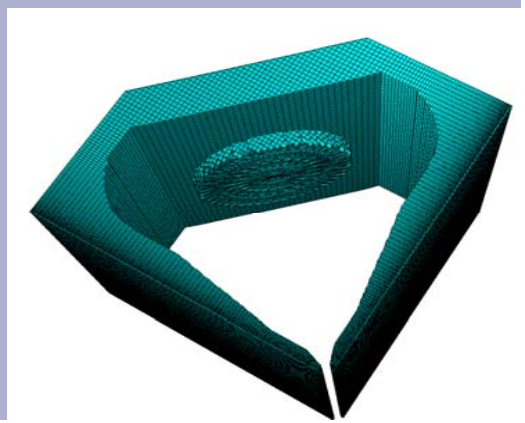
Tuners

- 64 tuners --- 16 per quadrant, symmetrically placed in each quadrant.
- Static tuners.
- Cooling required.
- Tuning Range : 468.5 kHz/mm (all)

Vacuum ports

- 24 vacuum ports
- Frequency detuning : 745.86 kHz (all)

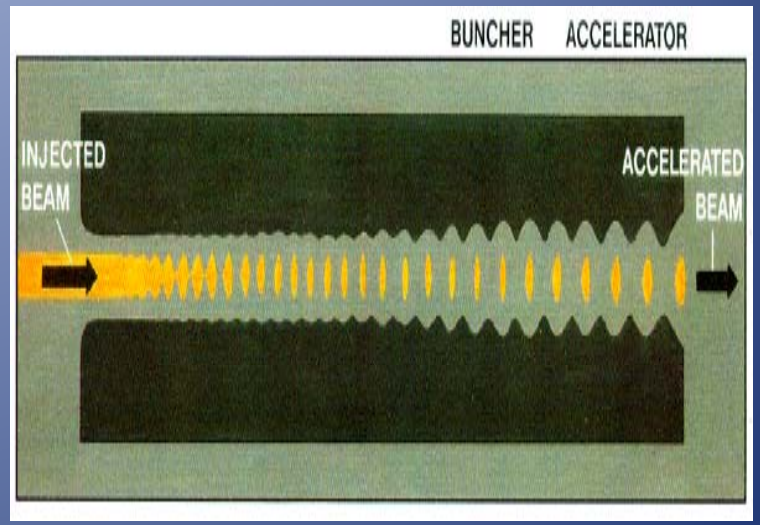




RFQ Design Parameters

1. Bunching 2. Focusing 3. Acceleration

Frequency	352.21 MHz
Energy	50 keV/ 3 MeV
Input current	30 mA
Vane voltage	80 kV
Avg. Aperture R_0	3.63-4.53 mm
Length	4 m
Total RF power	500 kW
Transmission	98%



RF Power system : Prototypes

High Power RF System for 400 keV RFQ

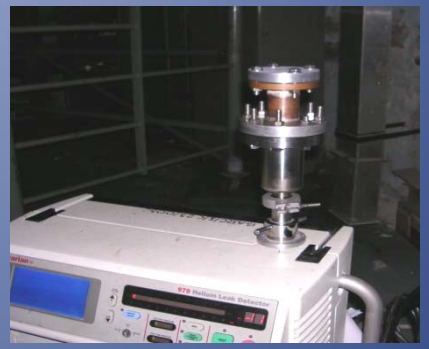
New Driver: 350 MHz, 2.5 kW

Development of Coaxial Coupler for RFQ cavitiy of 400 keV deutron accelerator

Coaxial coupler connected to RFQ Cavity

Alumina tubes metallized in BARC

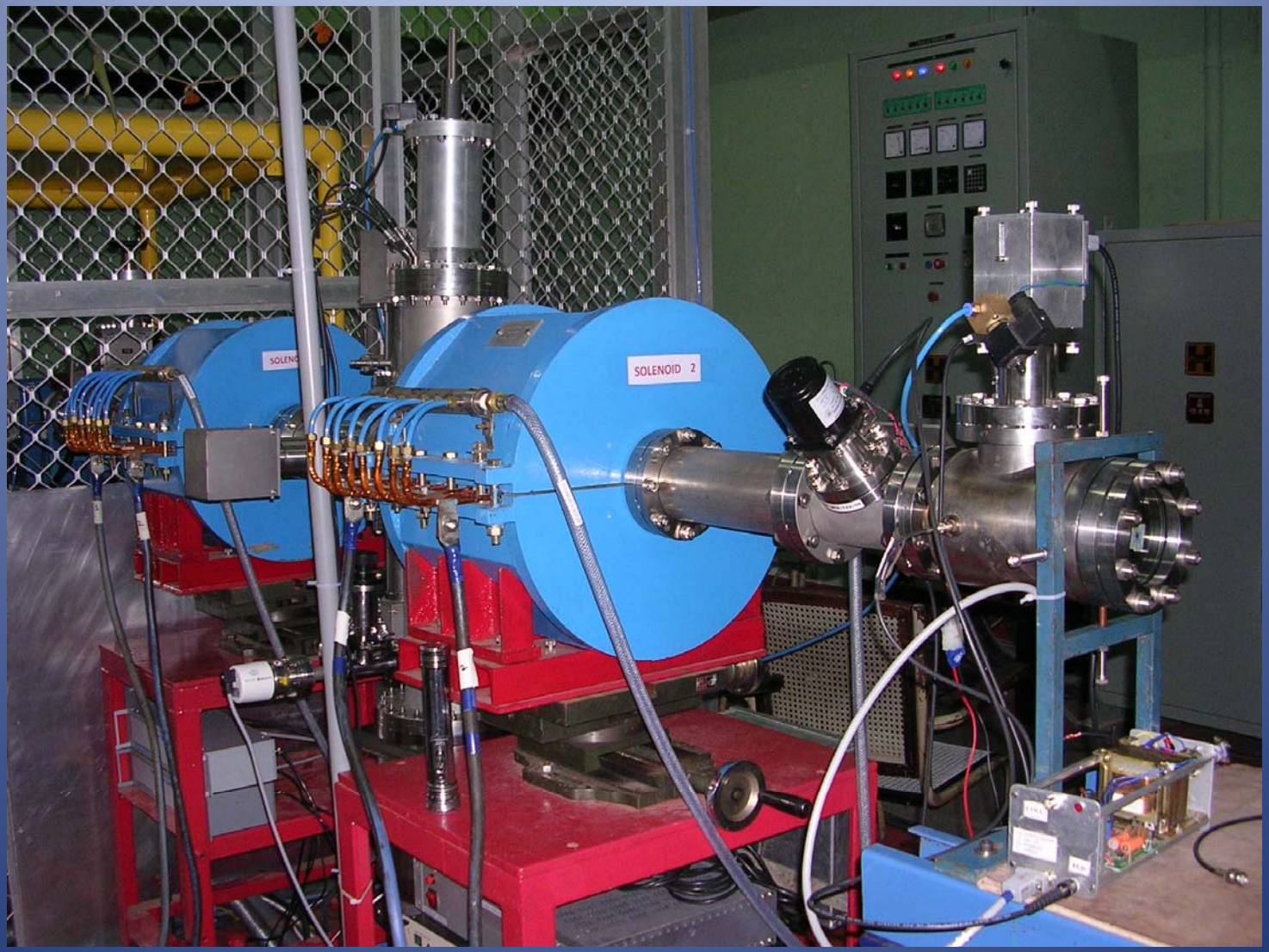
First RF window prototype after vacuum brazing



RFCouper prototype being tested for vacuum

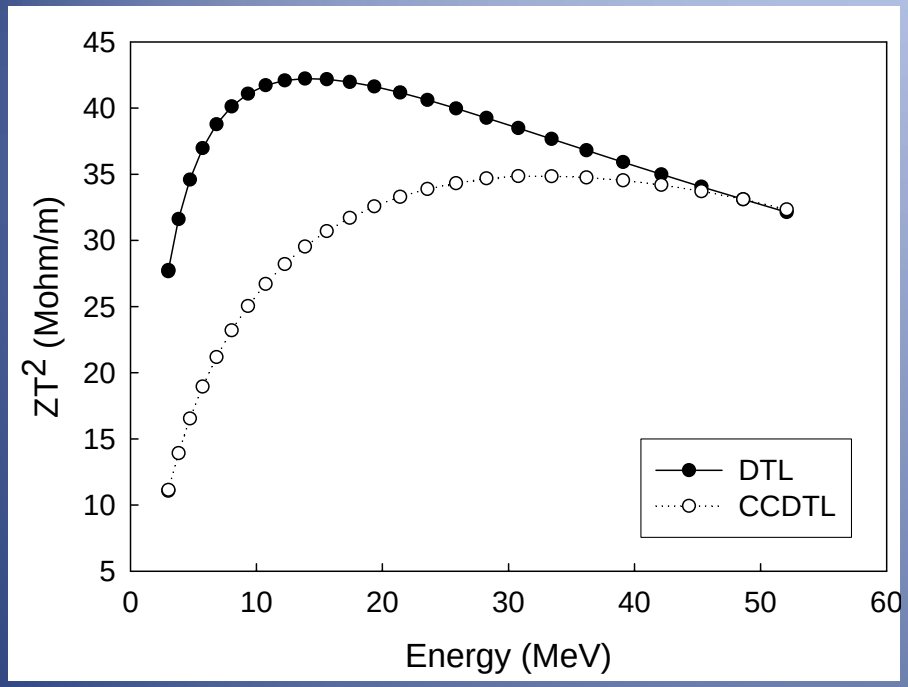
Coaxial adapters under RF Chracterization

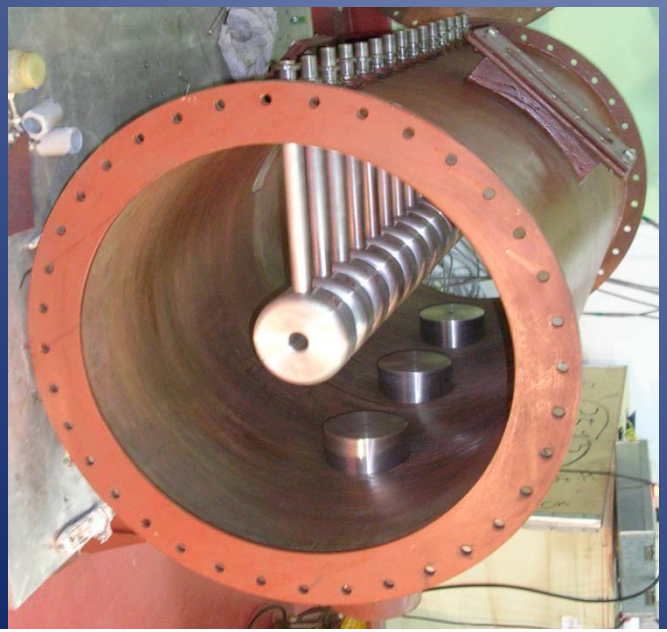
350 MHz RF cavity developed for Coupler conditioning



Test Bench for LEBT using Alphatros Ion source

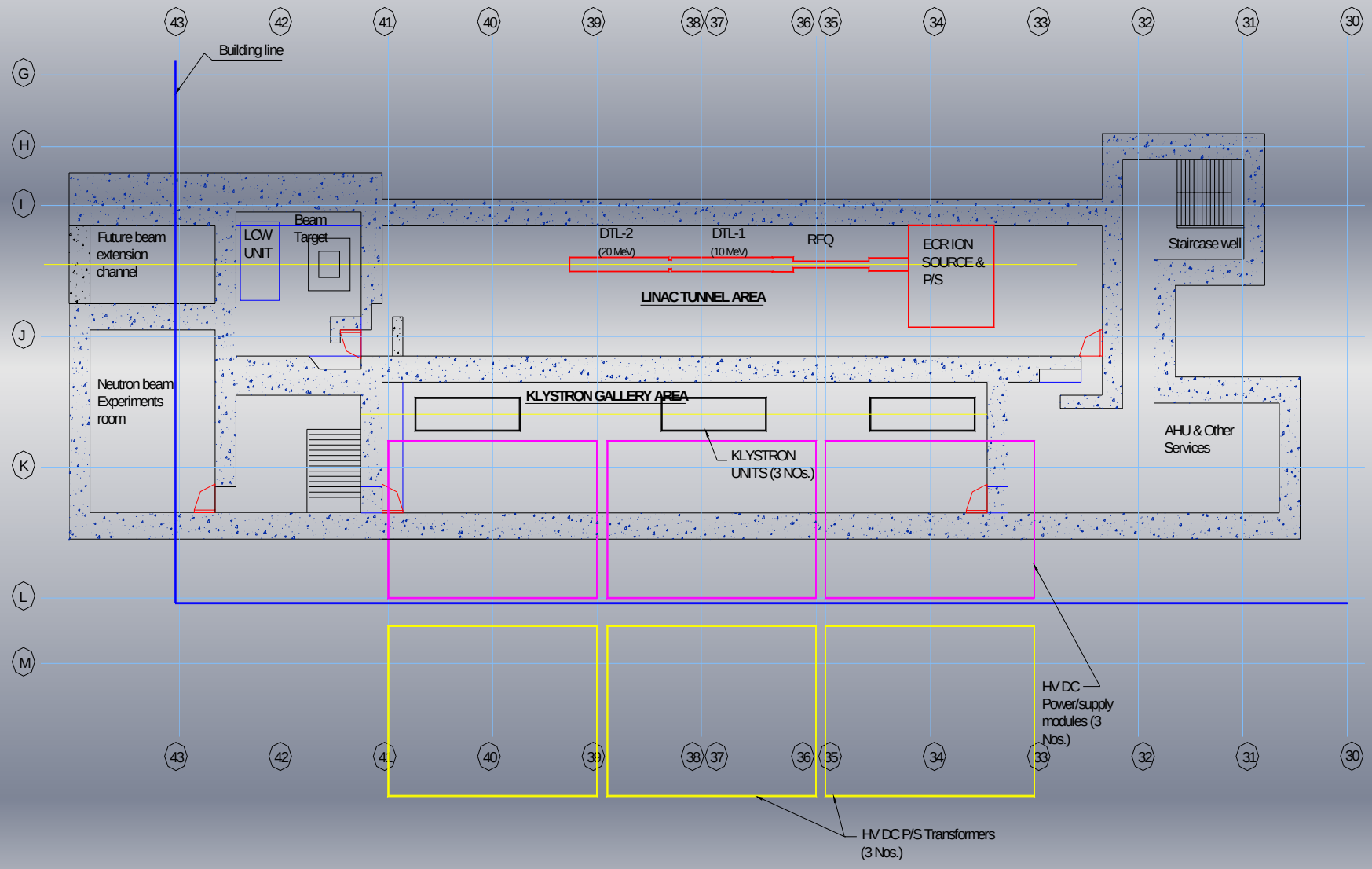
20 MeV DTL Parameters





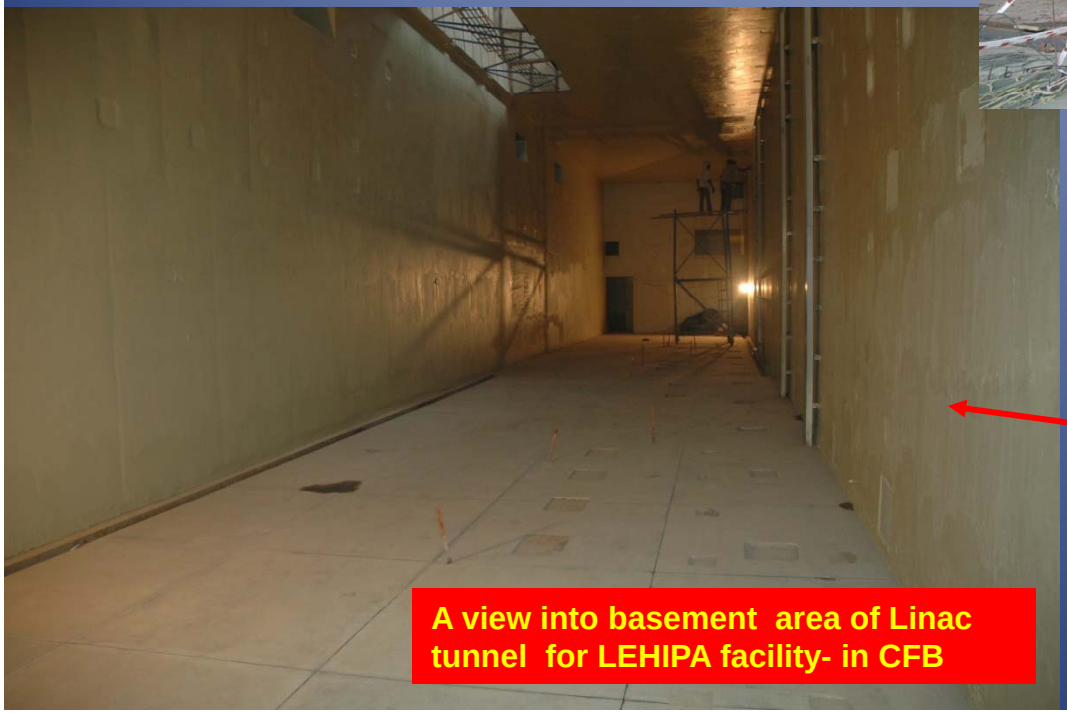
Parameter	DTL
Energy Range (MeV)	3-20
Frequency (MHz)	352.21
Current (mA)	29.3
Quadrupole Gradient (T/m)	43
Eff. Length of Quad. (cm)	4.72
No. of Quadrupoles	85
Avg. Acc. Gradient (MV/m)	2.5
Aperture Radius (cm)	1.0
Total Length (m)	10.2

Layout of LEHIPA Building



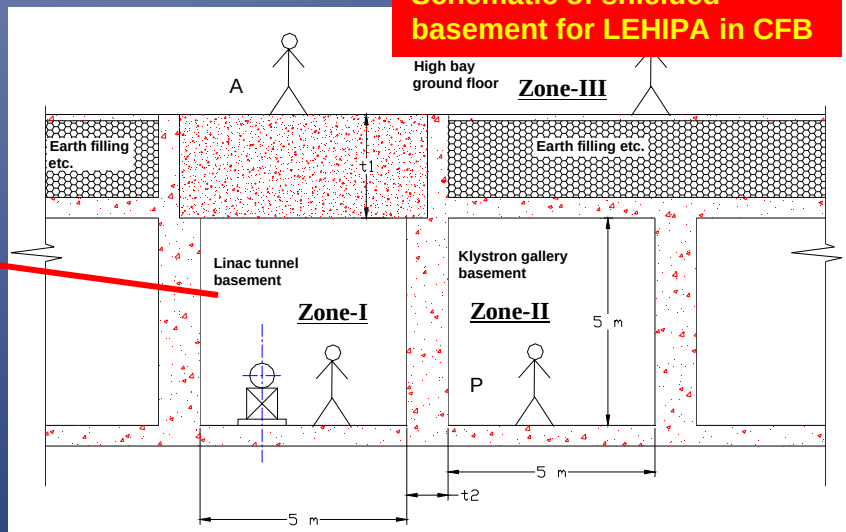
LEHIPA Building (CFB) in construction

High-bay roof under construction for LEHIPA facility- North Site, BARC



A view into basement area of Linac tunnel for LEHIPA facility- in CFB

Schematic of shielded basement for LEHIPA in CFB



Thank You !