Indian Nuclear Power Programme & its linkage to ADS

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Elements of Indian nuclear programme

- **Indigenous development of a Reactor Technology (Pressurized Heavy Water Reactor- PHWR)**
  - Total technology development
  - Based on indigenous resources

- **Adopting Closed-Fuel Cycle**
  - Best use of fissile & fertile materials
  - Reduction of the waste burden

- **Three-Stage Programme**
  - Modest uranium reserve
  - Utilization of large thorium reserve

Salient Features of PHWR

- **Natural Uranium Fuel**
  - Low burn up
  - Efficient use of ^{235}U per ton of U mined
- **Heavy Water – moderator and coolant**
  - Development of heavy water technology
  - Tritium management
- **On-power fuelling**
  - Fuelling machine development
  - Daily entry into reactor core
- **Neutron economy**
  - Excellent physics design
  - Complex engineering
  - Careful choice of in-core materials
  - Neutrons: best utilized in fission & conversion
- **Large pressure vessel not required**
  - Distributed pressure boundaries

Challenges faced in PHWR programme – and successfully met

- **Indigenous capability in fabrication of fuel and structural materials:**
  - From low grade resources to finished fuel
  - Perfection in making in-core structural components
- **Mastering heavy water technology:**
  - Ammonia and H_2S exchange processes developed
  - Energy economy achieved
  - Production capacity consistent with power programme
- **Sophisticated equipment development:**
  - Fuelling machines, Steam Generators etc.
  - Technology transfer to Indian Industry
- **Computerized reactor control system.**
- **Repair/refurbishment/life estimation & extension:**
  - In-service inspection
- **Improved safety features.**
- **Operating experience:**
  - Record capacity utilization
- **Construction time:**
  - Reduced to 4½ years

Back end of fuel cycle

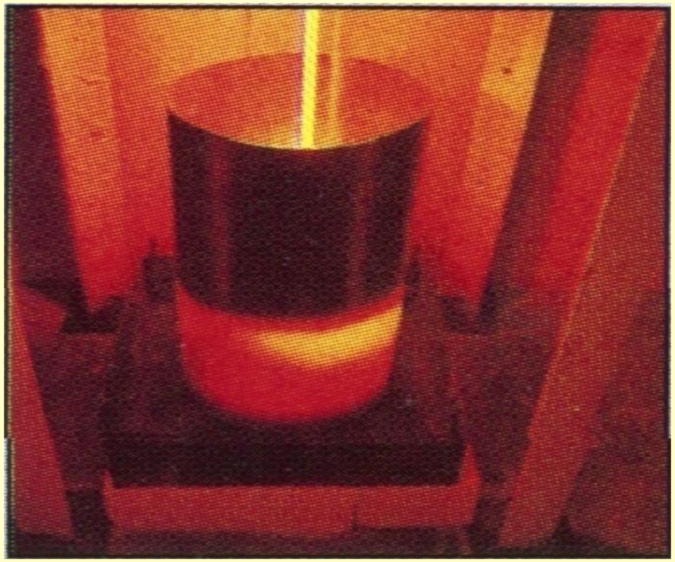
India's option: Closed Fuel Cycle

- Reprocessing, conditioning & recycling.
- Supply of fuel to fast breeder.
- Regular operation of vitrification plant.
- Minimization of waste burden.

Thrust Areas of Development:

- Multi-component reprocessing of Thoria-based fuels. (U, Pu &Th streams)

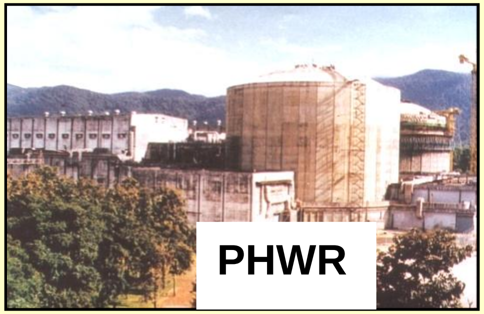
Reprocessing Plant-
Kalpakkam

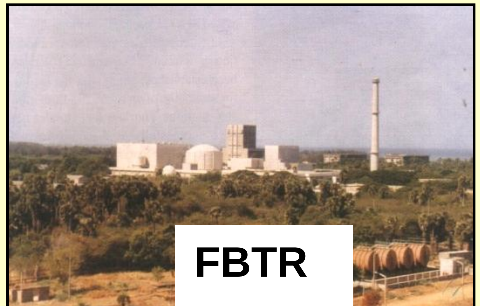


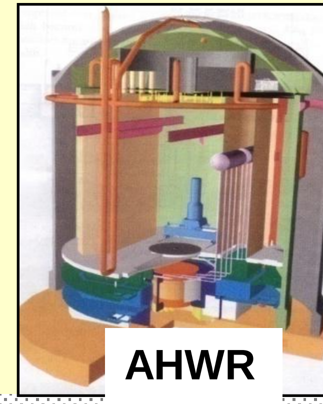
Waste immobilization-
vitrification plant at BARC

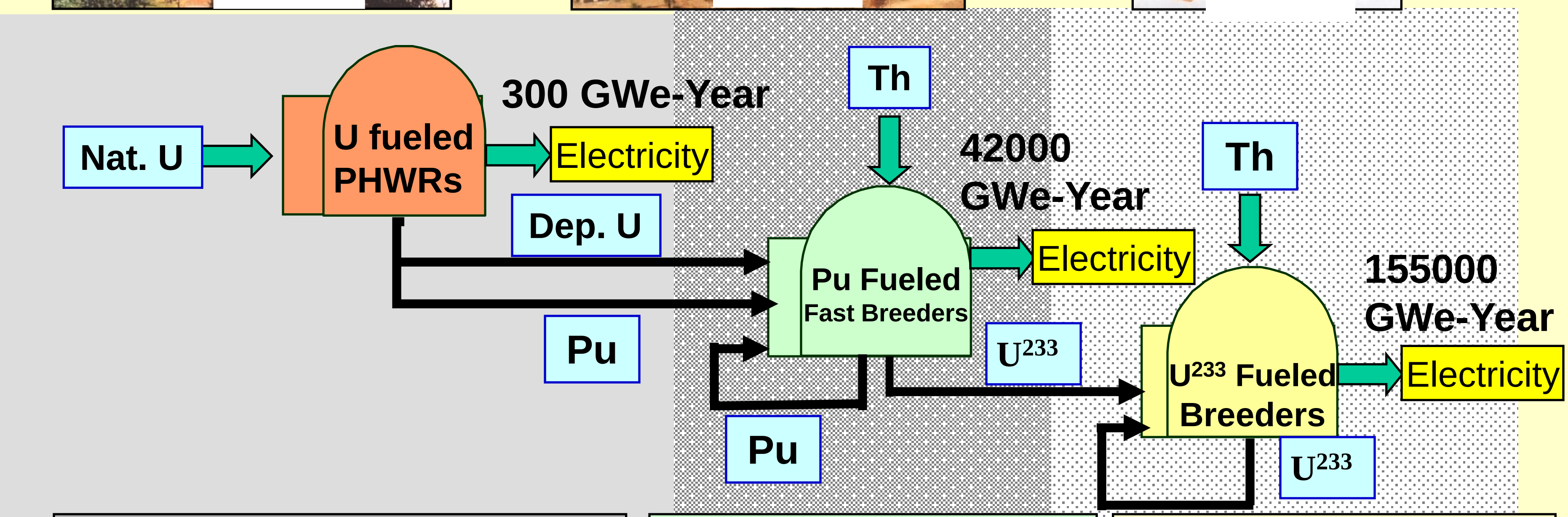
Three-Stage Indian Nuclear Programme

Thorium in the centre stage



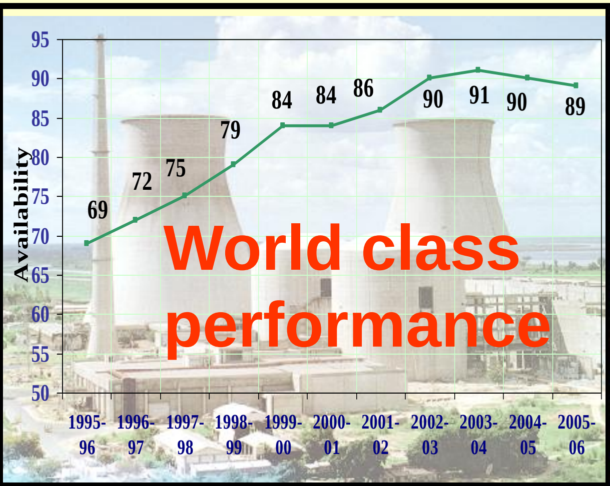






Stage 1	Stage 2	Stage 3
Power generation primarily by PHWR Building fissile inventory for stage 2	Expanding power programme Building U^{233} inventory	Thorium utilization for Sustainable power programme

Three Stage Nuclear Power Programme- Present Status



Stage – I PHWRs

- 15 - Operating
- 3 - Under construction
- Several others planned
- Scaling to 700 MWe
- Gestation period has been reduced
- POWER POTENTIAL ≅ 10,000 MWe

LWRs

- 2 BWRs Operating
- 2 VVERs under construction

Stage - II
Fast Breeder Reactors

- 40 MWth FBTR - Operating since 1985, Technology Objectives realized.
- 500 MWe PFBR- Under Construction
- POWER POTENTIAL ≅ 530,000 MWe

Stage - III
Thorium Based Reactors

- 30 kWth KAMINI- Operating
- 300 MWe AHWR- Under Development

POWER POTENTIAL IS VERY LARGE

Availability of ADS can enable early introduction of Thorium and enhance capacity growth rate.

Fast Breeder Reactors

- **20 years experience in operating Fast Breeder Test Reactor (FBTR):**

  Successful operation with indigenously developed unique mixed carbide (UC + PuC) fuel in FBTR - Burn-up exceeded 150,000 MWd/t without a single fuel pin failure .
- **Maturity in molten sodium technology.**
- **The FBTR fuel discharged at 100,000 MWd/t & successfully reprocessed: First time that the Plutonium-rich carbide fuel has been reprocessed anywhere in the world.**
- **Construction of prototype 500 MWe FBR started in October 2004.**

Indian Nuclear Power Programme - 2020

REACTOR TYPE AND CAPACITIES	CAPACITY (MWe)	CUMULATIVE CAPACITY (MWe)
> 17 reactors at 6 sites in operation Tarapur, Rawatbhata, Kalpakkam, Narora, Kakrapar and Kaiga	4,120	4,120
➢ 3 PHWRs under construction at Kaiga 4 (220 MWe), RAPP-5&6(2x220 MWe)	660	4,780
➢ 2 LWRs under construction at Kudankulam(2x1000 MWe)	2,000	6,780
➢ PFBR under construction at Kalpakkam (1 X 500 MWe)	500	7,280
> Projects planned till 2020 PHWRs(8x700 MWe), FBRs(4x500 MWe), AHWR(1x300 MWe)	7,900	15,180
➢ Additional LWRs through international cooperation	~ 20000	~ 35000

Growth of nuclear power through Fast Breeder Reactors (FBR)

- **Initially supported by Pu from PHWR spent fuel.**
- **Development of metallic fuel for improved breeding ratio (reduced fuel doubling time).**
- **Faster capacity growth in power generation from FBRs.**
- **Increased unit size up to 1000 MWe.**

World Thorium Resources

Country	Reserves (tons)
Australia	300,000
India	290,000
Norway	170,000
USA	160,000
Canada	100,000
S. Africa	35,000
Brazil	16,000
Malaysia	4,500
Other Countries	95,000
World total	1,200,000

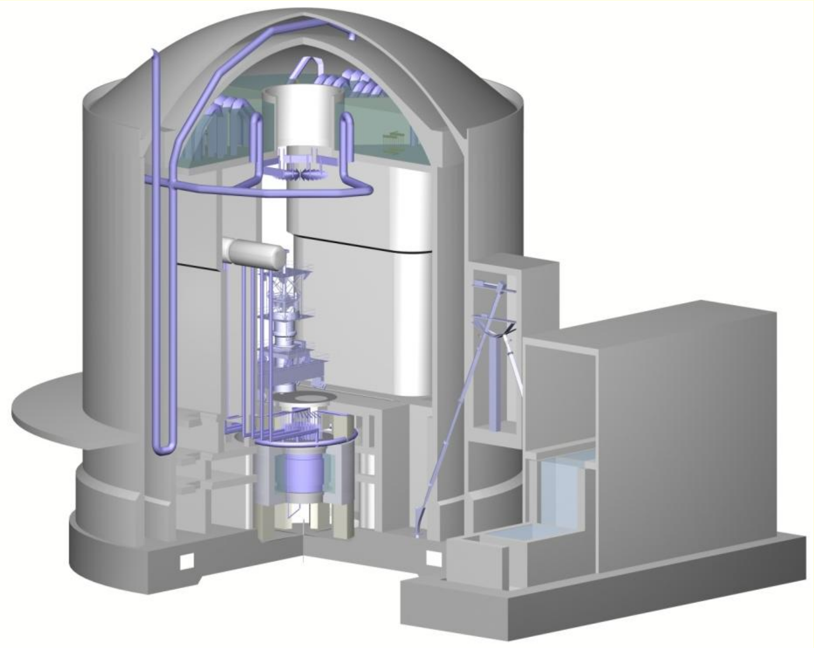
Advanced Heavy Water Reactor (AHWR)

- Vertical pressure tube.
- Boiling light water cooled.
- Heavy water moderated.
- Fuelled by ^{233}U-Th MOX and Pu-Th MOX.

Major Design Objectives

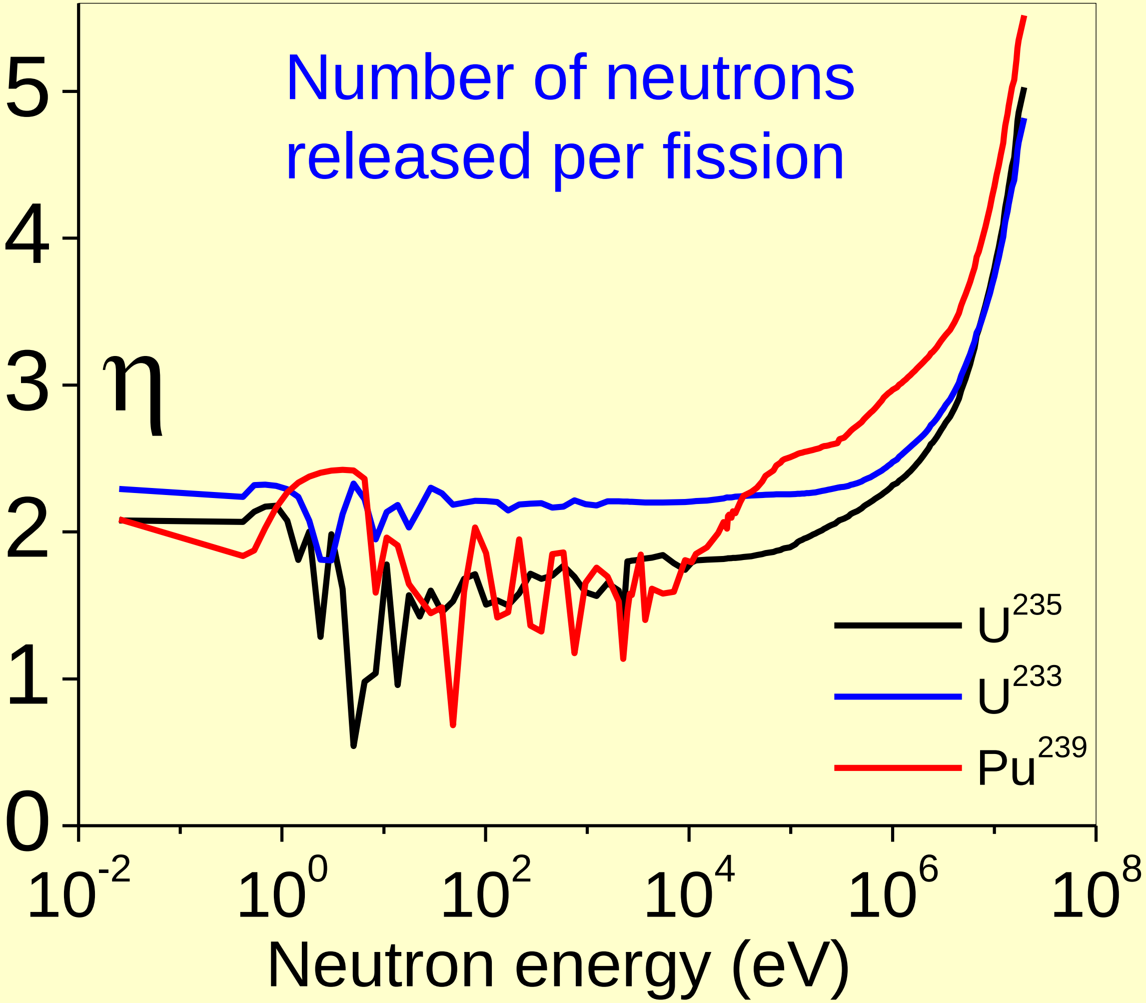
- Power output – 300 MWe with 500 m^3/d of desalinated water.
- Core heat removal by natural circulation.
- A large fraction (65%) of power from thorium.
- Extensive deployment of passive safety features – 3 days grace period, and no need for planning off-site emergency measures.
- Design life of 100 years.
- Easily replaceable coolant channels.

Technology demonstration for large-scale thorium utilization



- Currently under Pre-Licensing Safety Appraisal by AERB.
- International recognition as an innovative design.

Thorium fuel breeder reactor



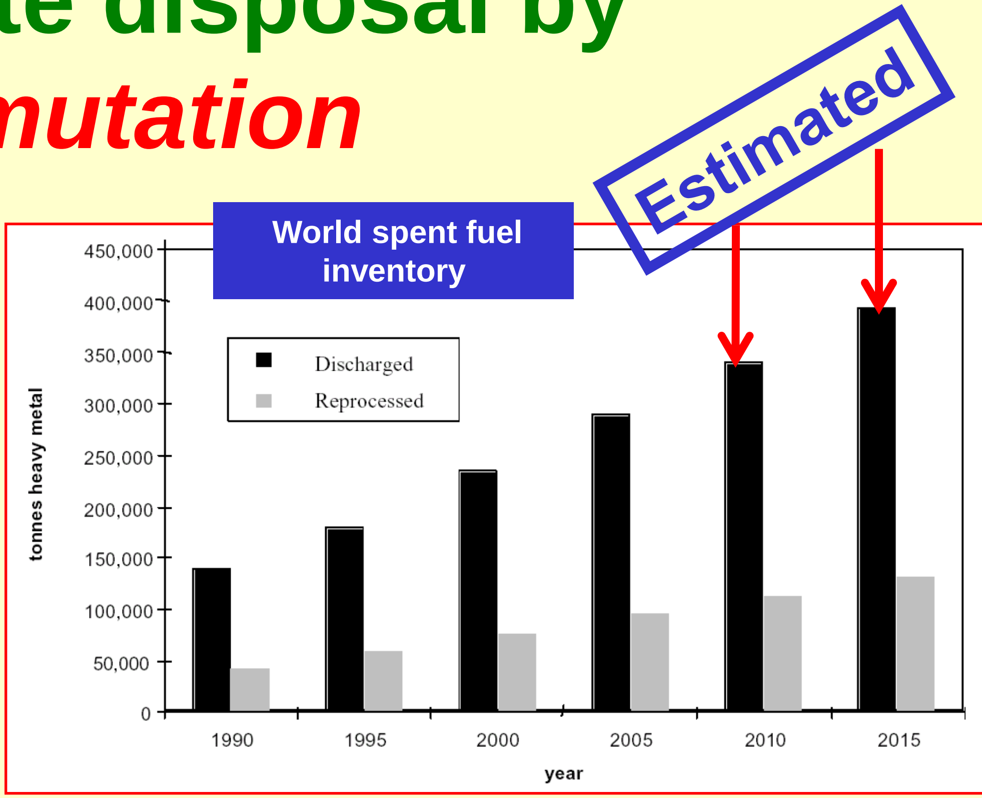
- **Fuel doubling time depends on: surplus neutrons per fission in the reactor system.**
- **Also ensure safe reactor operation.**
- **^{239}Pu-fuel : surplus neutrons only in fast spectrum.**
- **^{233}U-fuel : similar neutron surpluses in fast & thermal spectra.**

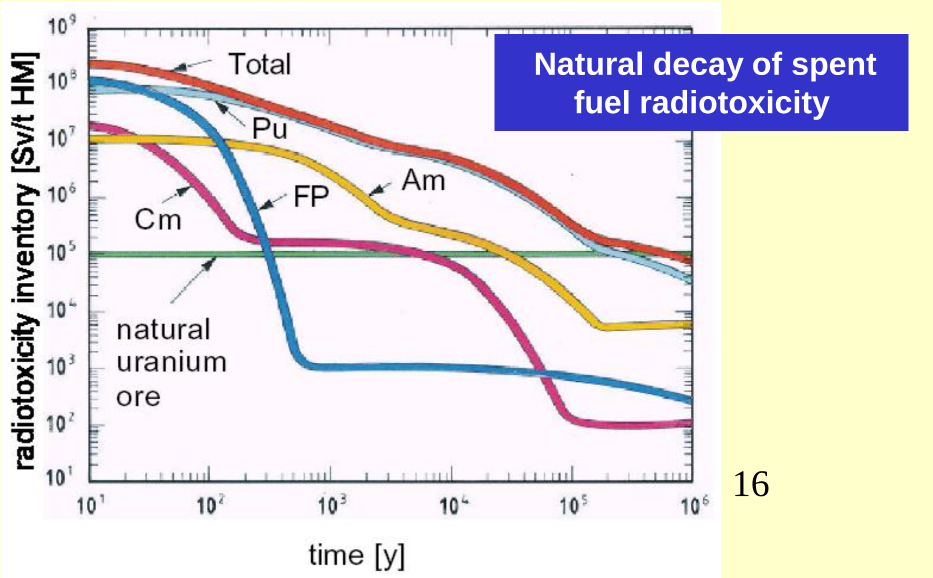
Fuel Breeding in Critical vs. sub-critical reactors (cases of ^{238}U-Pu & ^{232}Th-U)

Breeding condition, $\nu/k-2(1+\alpha)-\nu_c \geq 0$							
Fissile isotope	Neutron spectrum	Neutrons per fission (ν)	Alfa (α)= capture/ fission ratio	Surplus Neutrons for k = 1; ν_c= 0.25	Neutron balance for k = 0.95; ν_c= 0.25	Percentage improvement with k=0.95	Remark on breeding potential
Pu-239	Thermal	2.871	0.36	-0.10	0.05	150%	Poor breeding- with & without ADS.
…do..	Fast	2.98	0.14	0.45	0.61	35%	Can breed without ADS
U-233	Thermal	2.492	0.09	0.06	0.19	216%	Poor k=1 breeding; ADS helps
..do..	Fast	2.492	0.093	0.06	0.19	216%	Poor k=1 breeding; ADS helps

Nuclear waste disposal by *Transmutation*

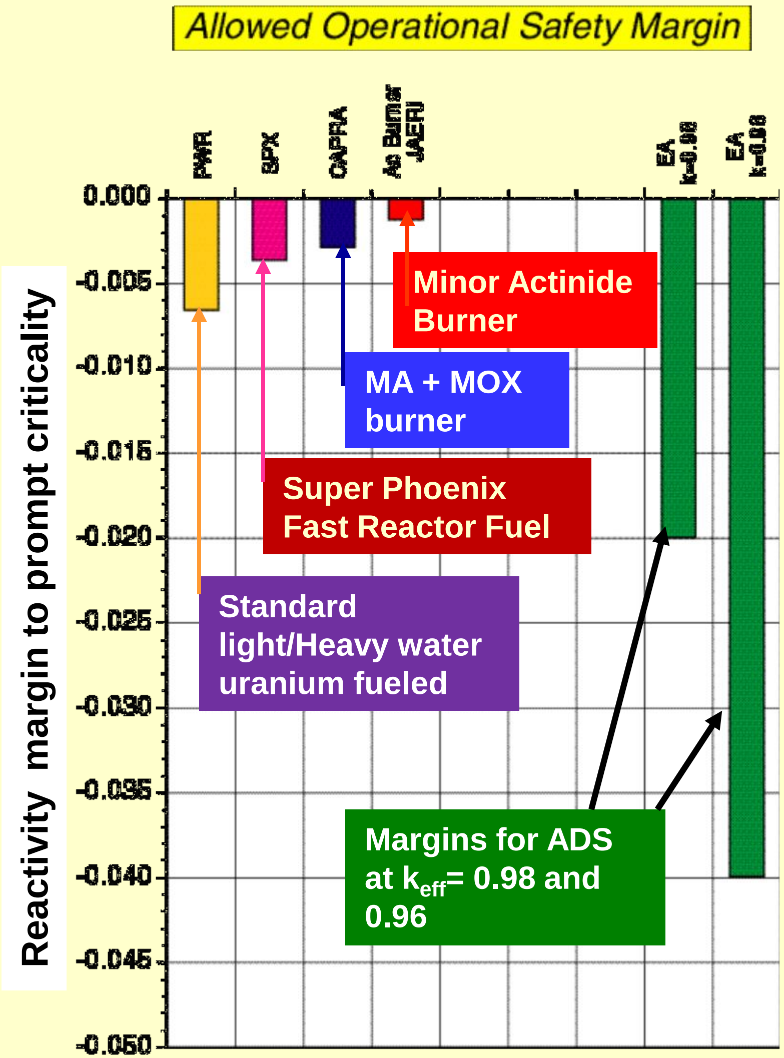
- **Accumulation of spent fuel: a global issue.**
- **Spent fuel requires > 100,000 years to decay.**
- **Transuranic elements (TRUs: Np, Pu, Am & Cm) + a few long-lived fission products (FPs): decay very slowly.**
- **Bulk of FPs decay to safe disposal levels in 3-5 centuries.**
- **If TRUs transmuted into FPs by fission: bulk of FPs decay very fast.**



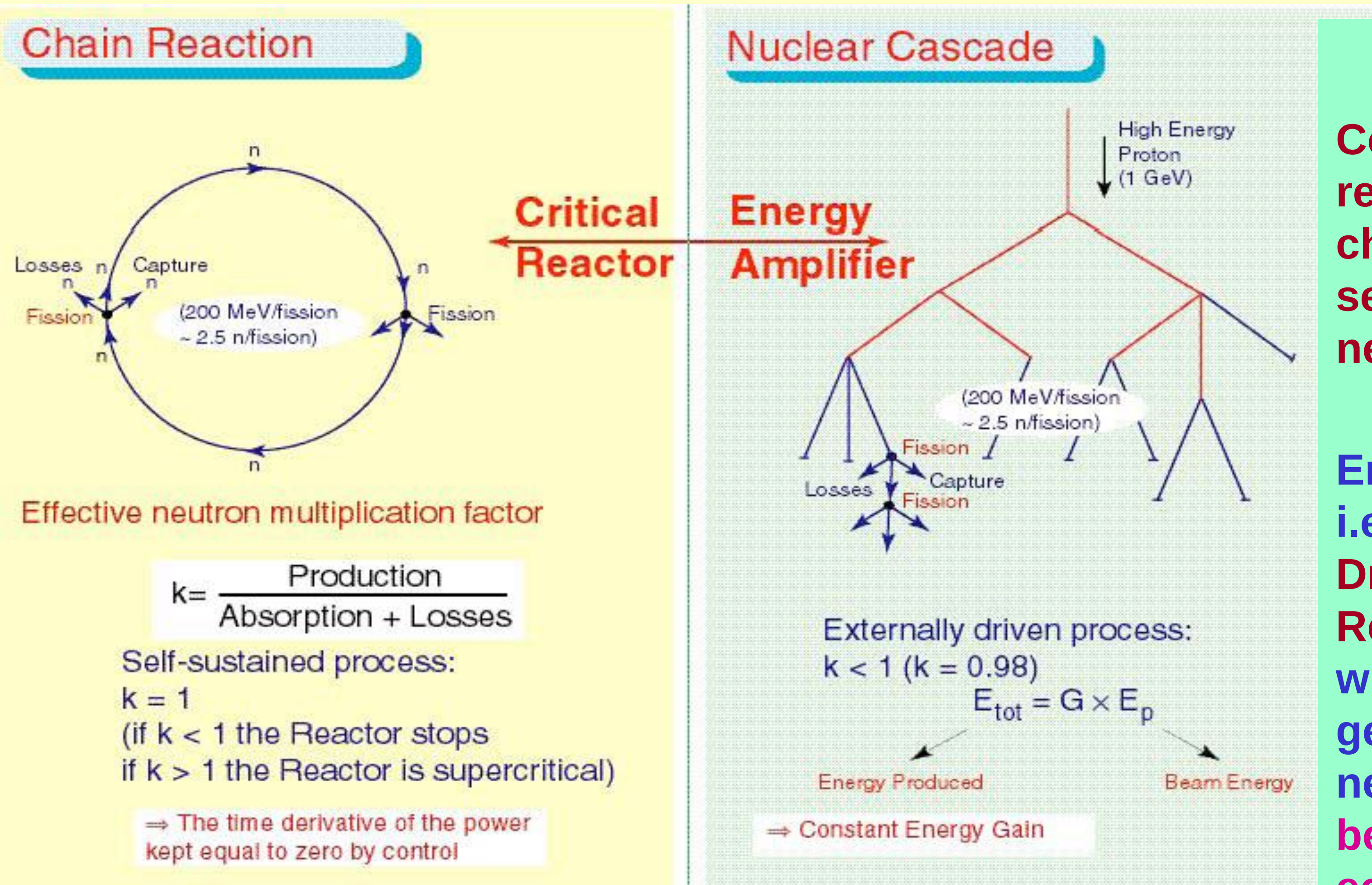


Transmutation of TRUs by fission

- Isotopes of transuranic element (TRU) : fissionable in fast neutron spectrum.
- TRU burner reactor needs fertile-free fuel feed.
- Difficult power control system of critical reactor due to:
  - Reduced delayed neutron fraction (factor called β_{eff}) giving lower safety margin to *prompt* criticality.
  - Safety parameters: (1) Doppler coefficient, (2) reactivity temperature coefficient, and (3) void fraction- all would not be benign in TRU incinerating *critical* fast reactor.
- There is strong case to operate such reactors in sub-critical mode- like <u>ADS</u>, for ensuring deterministic nuclear safety under all conditions.



Basic operating principles in conventional & sub-critical reactors {=Energy Amplifier}



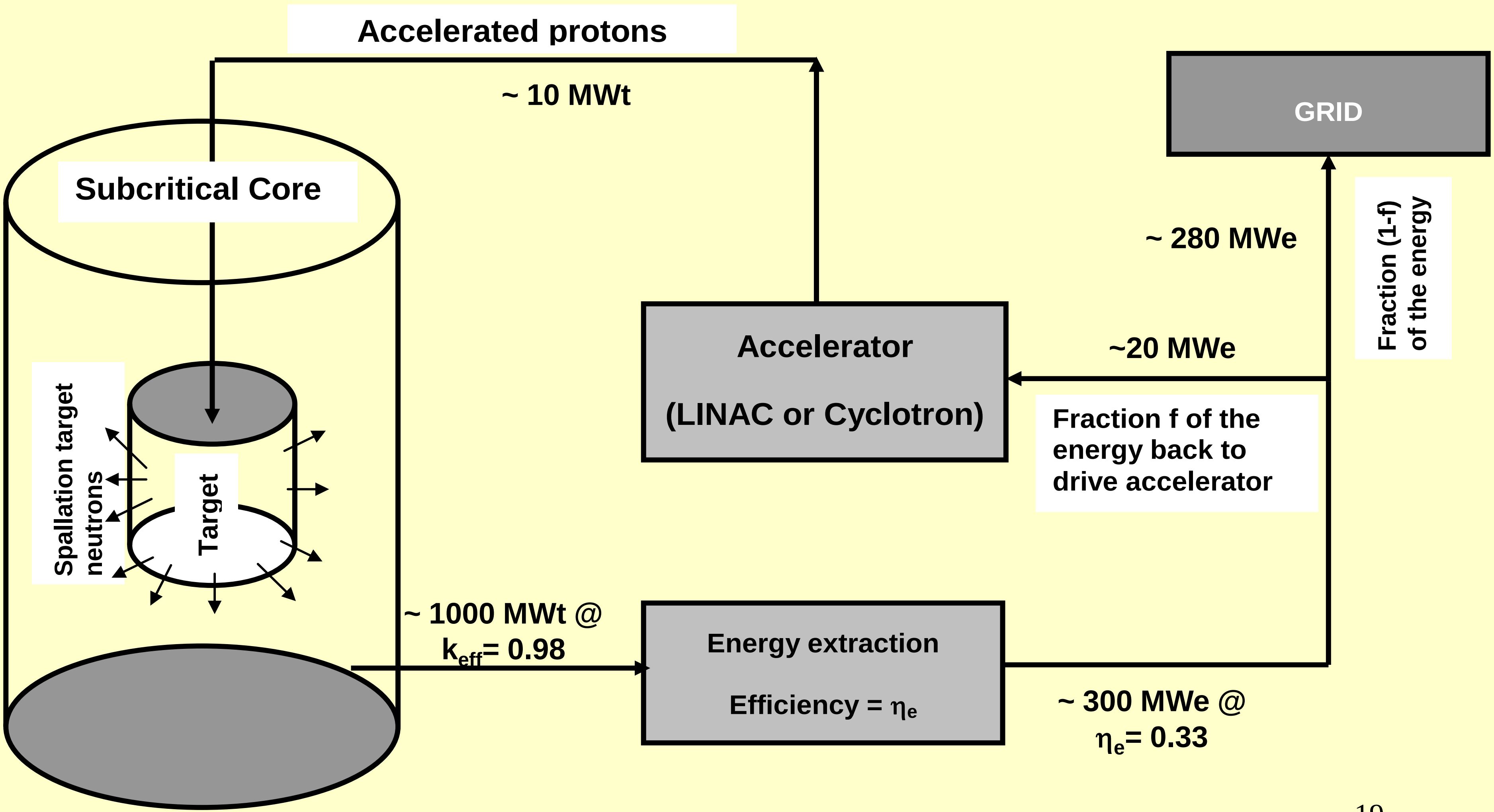
Self-sustaining chain reactions: conventional reactors

Self-terminating fission chains: sub-critical reactors

Conventional reactors work with chain reaction by self generated neutrons.

Energy Amplifier- i.e. Accelerator Driven Sub-critical Reactor, works with externally generated neutrons: giving better neutron economy and safety in operations.

Schematic of ADS- energy balance



ADS Reactor : start up & operation studies (for 200 MWe)

Heavy Water reactor (HWR)

- As ADS (10 MW beam): with thorium solid fuel: 20 years to reach full power.
- If reactor start with natural U fuel: self-sustainable power operation with 30 MW proton beam from day one. Then, gradually replace U with Th.
- Beam power can be 15 MW when spent fuel reprocessed and recovered ^{233}U is recycled.
- Otherwise, self-sustainable power operation @~ 200 Mwe; even for once-through thorium use & no reprocessing to recycle ^{233}U.

Molten-salt reactor (MSR)

- As ADS (10 MW beam)- with thorium only fuel salt & online removal of fission products: 5.5 year to reach full power using 10 MW proton beam.
- If reactor start with natural U salt fuel, full power from day one. Then, gradually replace U with Th-salts.
- Thereafter, self-sustainable power operation @~ 200 Mwe even for once-through thorium use & no reprocessing to recycle ^{233}U.

Technologies for ADS

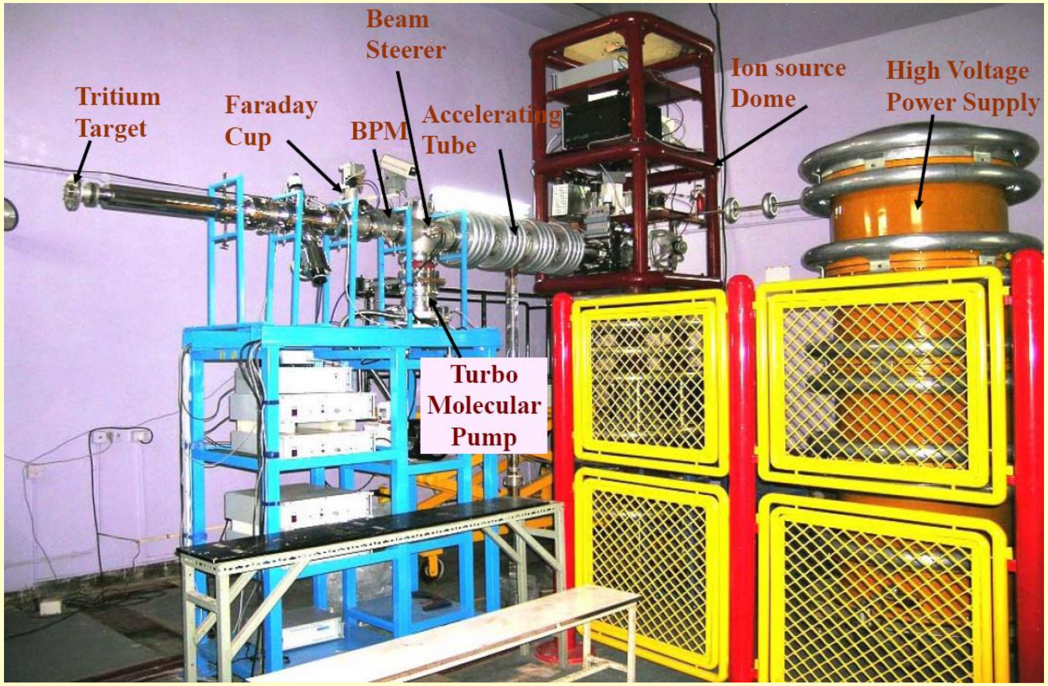
- **High power proton accelerator: 1 GeV, cw or high duty factor, high current**
    - **High beam current front-end**
    - **Superconducting RF cavities**
    - **RF power systems**
- **Molten heavy metal spallation target & associated process system.**
    - **High volumetric beam power density**
    - **Materials: irradiation and corrosion resistant**
- **Sub-critical reactor**
    - **Dedicated TRU transmuter fuel & fuel-cycle**
    - **Configuration: technology issues**
    - **Transients & safety studies**

Ongoing Indian activities in ADS programme

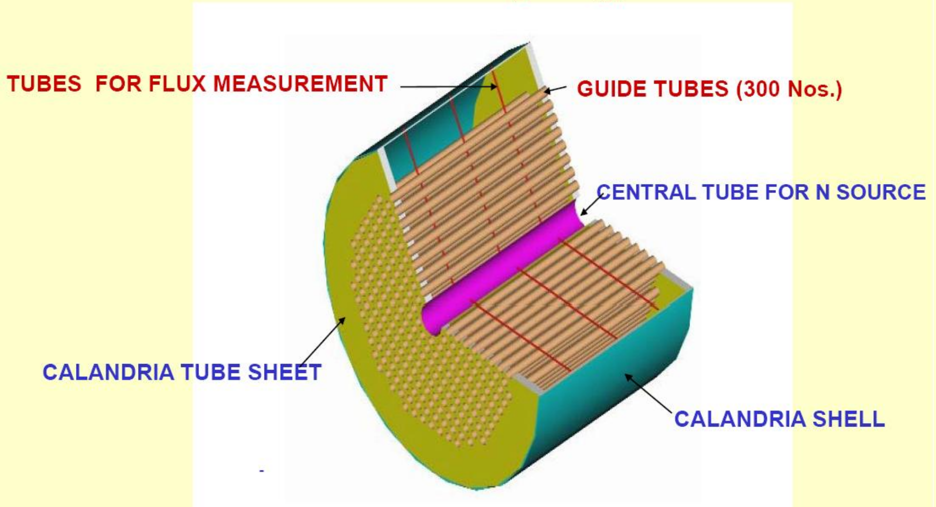
- Design studies of a 1 GeV, 30 mA proton linac.
- Development of 20 MeV high current proton linac for front-end accelerator of ADS.
- Construction of LBE experimental loop for design validation and materials tests for spallation target module.
- Development of computational tools and data for neutronics of spallation target and coupled sub-critical reactor.
- Experimental validation of reactor physics codes and data with 14-MeV neutrons in sub-critical core at PURNIMA labs.
- Design studies for ADS experimental reactor

14 MeV Neutron Generator - Experimental facility

- **Experiments on physics of ADS and validation of simulations.**
- **use of 14-MeV neutrons produced by DC accelerator & D+T reaction. Also, a 400-keV RFQ is being built *for higher beam curent.***
- **Simple sub-critical assembly (k_{eff}=0.87) of natural uranium and light water is chosen**
- **Plans for : measurements of flux distribution, flux spectra, total fission power, source multiplication, and degree of sub-criticality will be carried out.**



Fuel: Nat-U, Moderator: H_2O; k_{eff} = 0.873

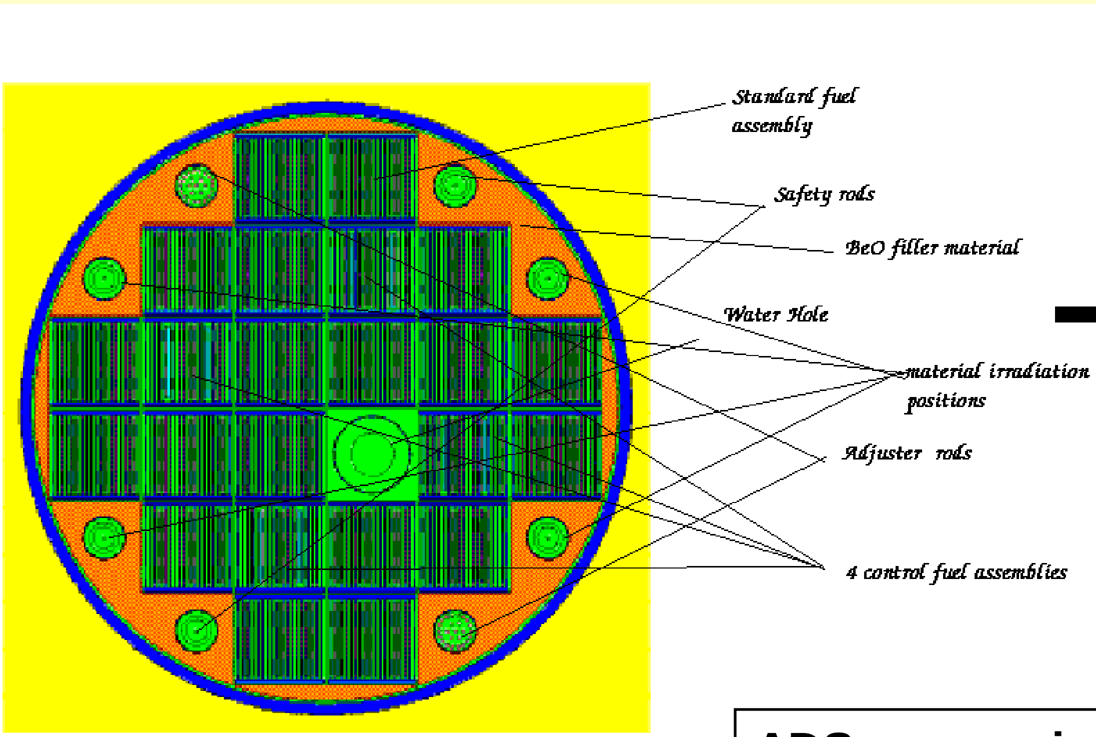


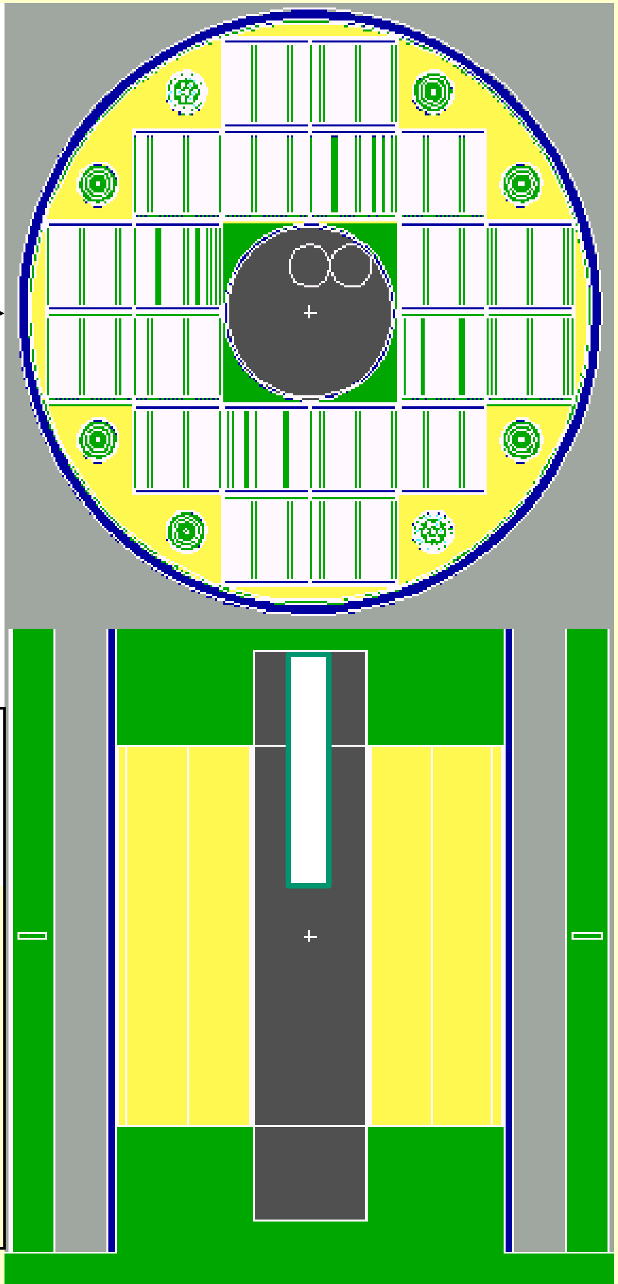
Code Development for High Energy Particle Transport & Nuclear Cross Sections

Programmes carried out so far………

- **Physics Simulation - spallation reactions- GeV protons**
- **Heat dissipation in spallation target /window; neutron production and spectra; different targets**
- **Comparison of FLUKA and CASCADE**
- **Compound Nucleus (CN) Reactions- EMPIRE**
- **Residual Nuclei production**
- **keV – MeV neutrons- measurements at the Pelletron**
- **Synergy between DAE and universities- BRNS**
- **Formation of Nuclear Data Coordination Committee – NDC@BARC**

Design studies: 30-MWt reactor → ADS

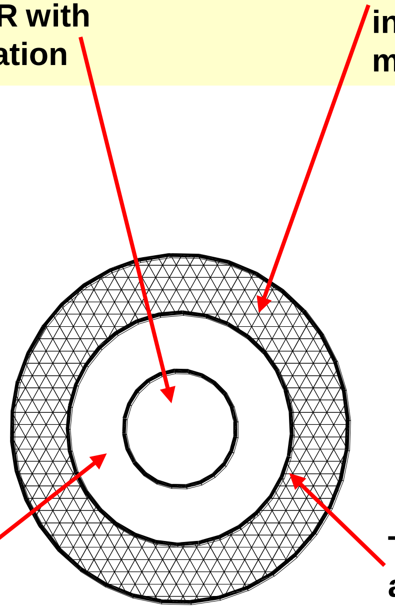




Critical Reactor with 24 lattice positions- 20 standard fuel & 4 control fuel assemblies.

ADS conversion with removal of 4-central lattice positions: space created for spallation target module- driven with 600 MeV protons, 0.3 mA (av.).

One-way coupled ADS- concept



Inner Core: Fast Pb/LBE cooled and MOX (Pu-Th later ^{233}U-Th)

Outer Core: Thermal, PHWR type, MOX Fuel (^{233}U -Th)

1. S.B. Degweker et al. Ann. Nucl. Energy 26, 123 (1999).

2. O.V. Shvedov et al. IAEA-TECDOC 985, D4.1, pp 313-375 (1987).

By using two-energy amplifiers:

Requirement of primary proton beam current can be lowered substantially, such that gain:

$G_b = G_0 * k_1/(1-k_1)$ is gain in booster,

Net neutronic gain $G_n = G_b \dfrac{(1-k_1/k_{1\infty})}{(1-k_2)}$

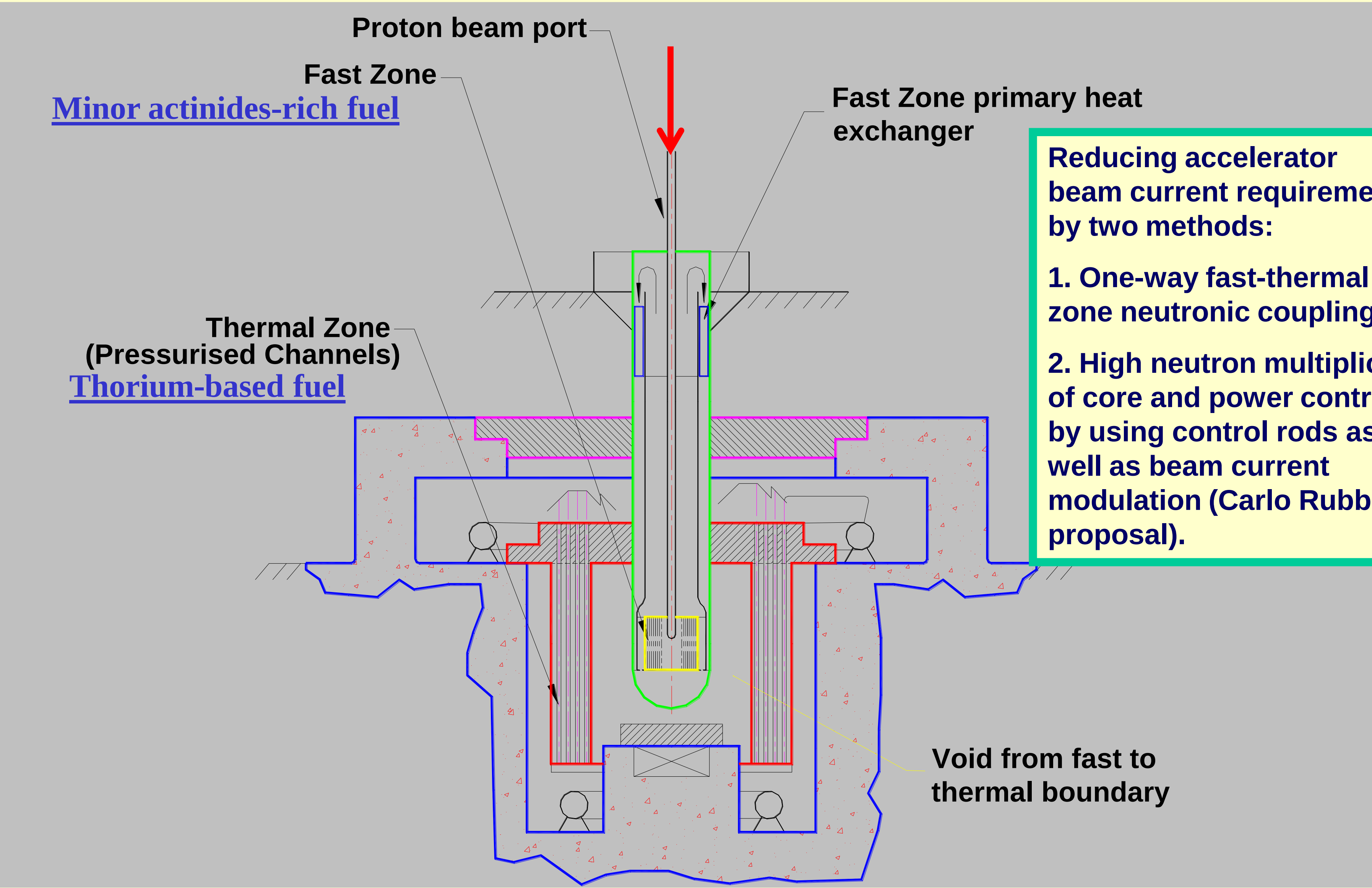
Driver beam current requirements reduced by factor $G_n\ (1-k_2)$.

In one-way coupled system, the overall Keff,

$k_{12} = k_1$ *or* k_2 *whichever is larger.*

Fast booster zone may consume $^{240,242}Pu$, Np etc….and thermal region has Th+ ^{233}U as fuel.

One-way coupled ADS scheme for Thorium Utilization & Actinides Transmutation

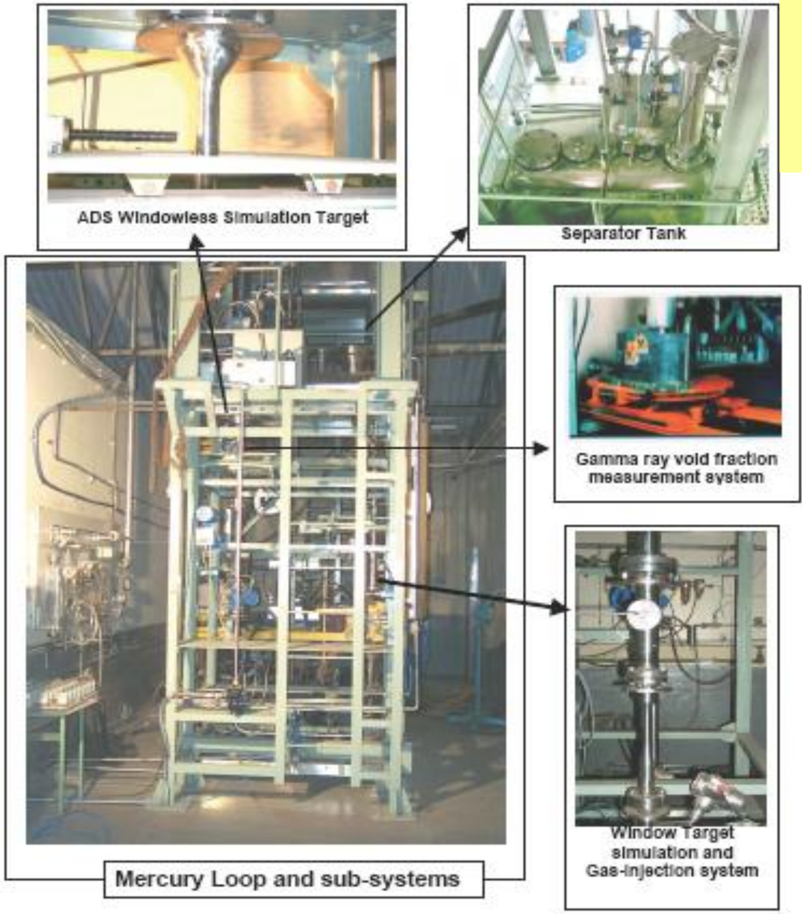


Reducing accelerator beam current requirement by two methods:

1. One-way fast-thermal zone neutronic coupling.

2. High neutron multiplicity of core and power control by using control rods as well as beam current modulation (Carlo Rubbia proposal).

Liquid heavy-metal flow diagnostics & corrosion studies



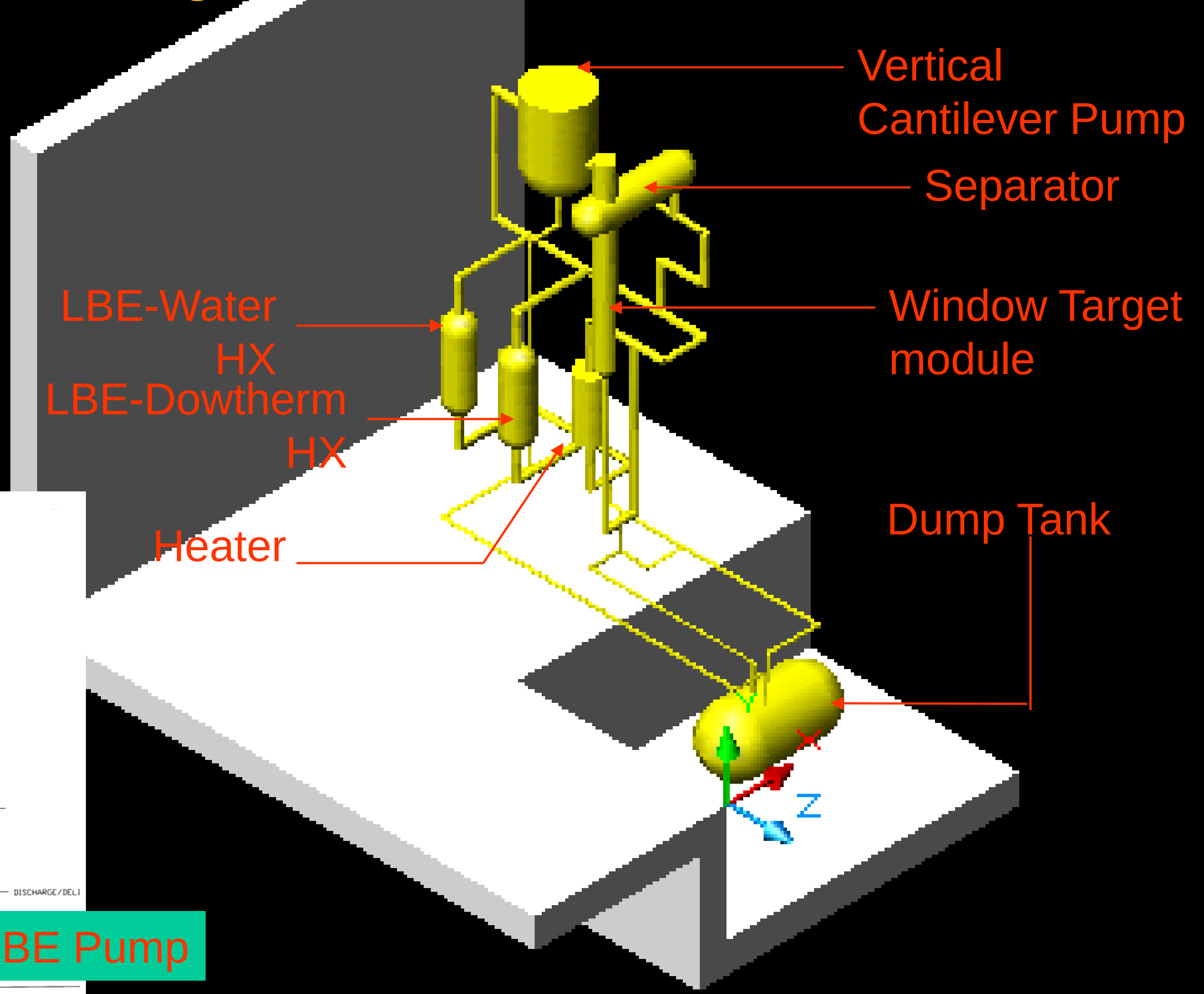
Mercury Loop

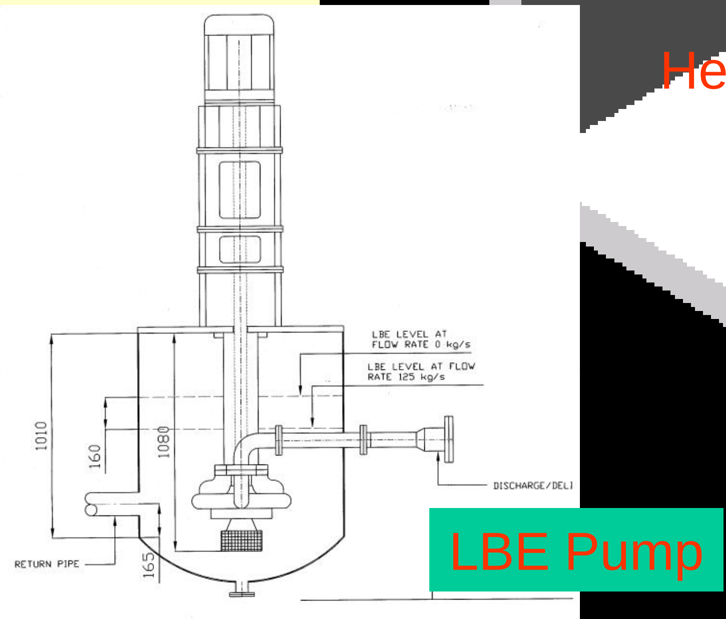
- Simulation of Window/Windowless Target
- Velocity field mapping by UVP monitor
- Carry-under studies
- Two-phase flow studies by Gamma Ray
- Laser-triangulation for free surface measurement
- CFD code validation
- Gas-driven flow studies

LBE Corrosion Loop

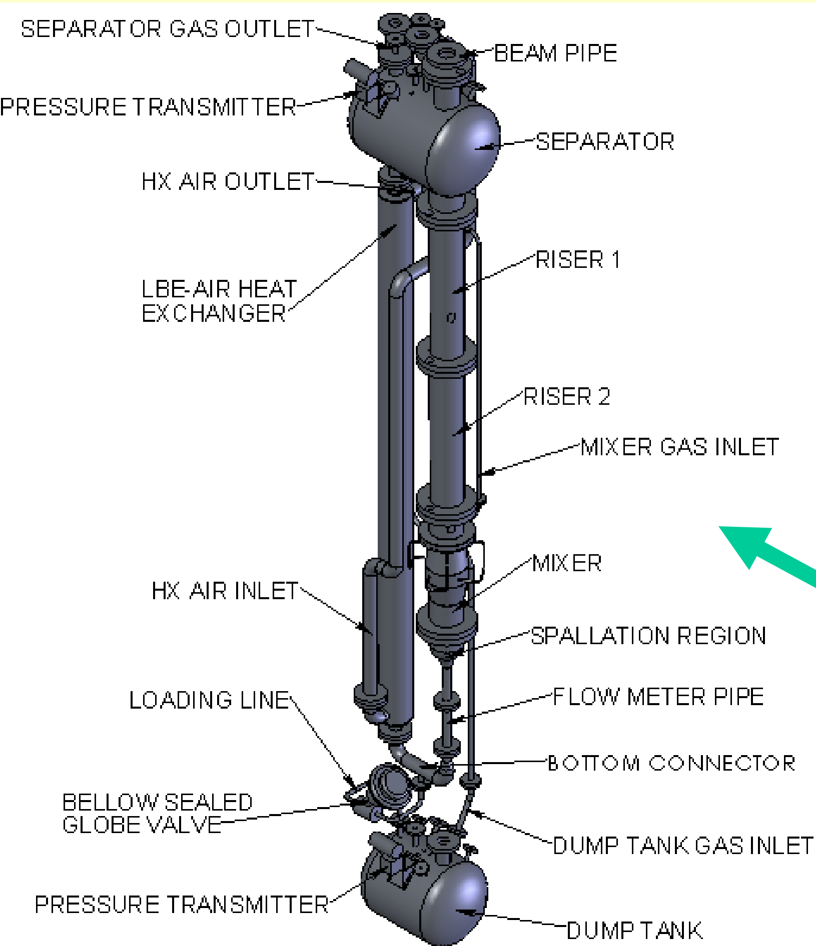
- Height ~ 7m
- Flow Rate ~1.7 kg/s
- Temp: 550^0C and 450^0C
- Velocity in the Samples~0.6 m/s
- Corrosion Tests: Charpy and Tensile after 3000 hrs in the flow

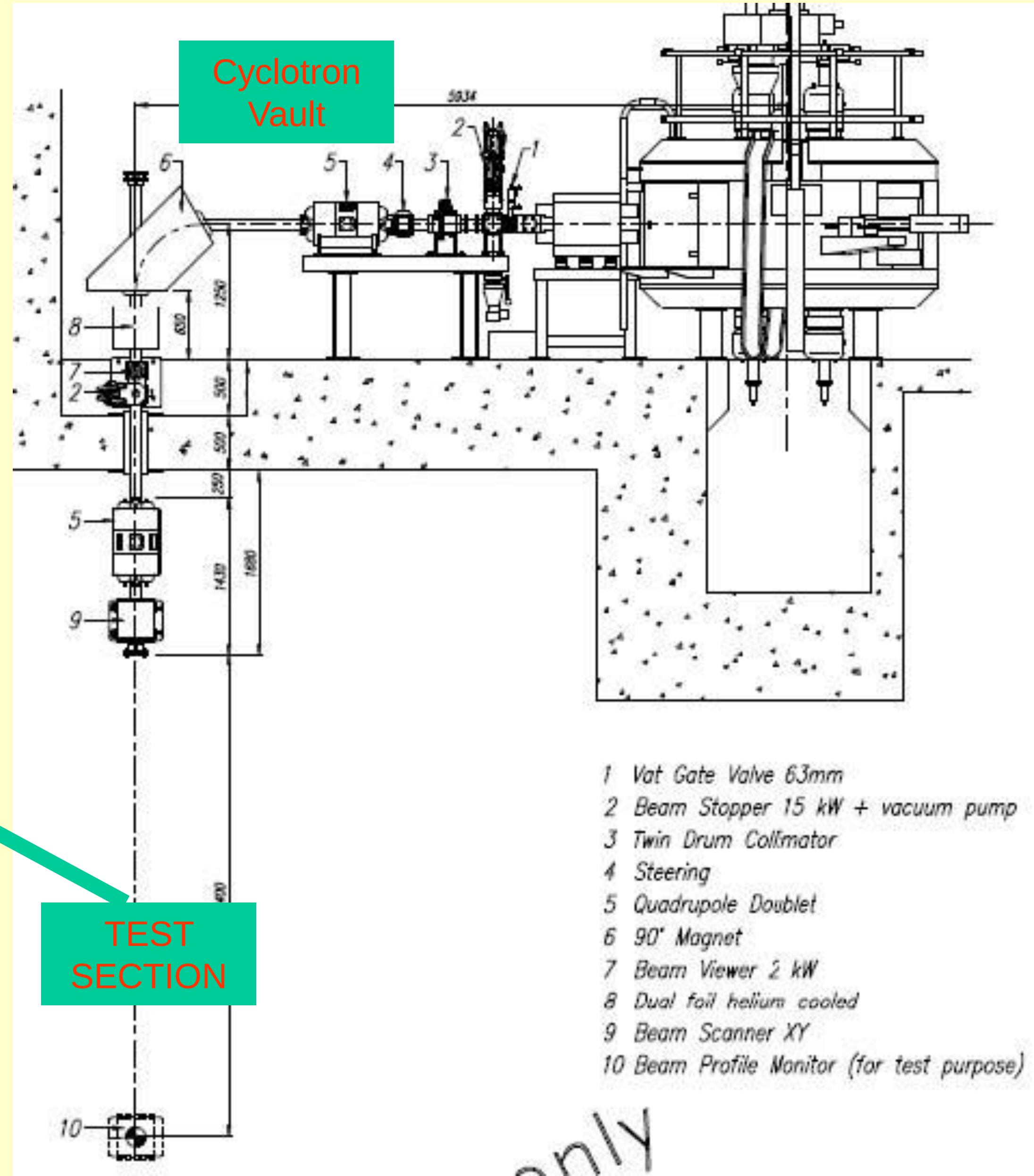
LBE-loop for Thermal-hydraulics studies





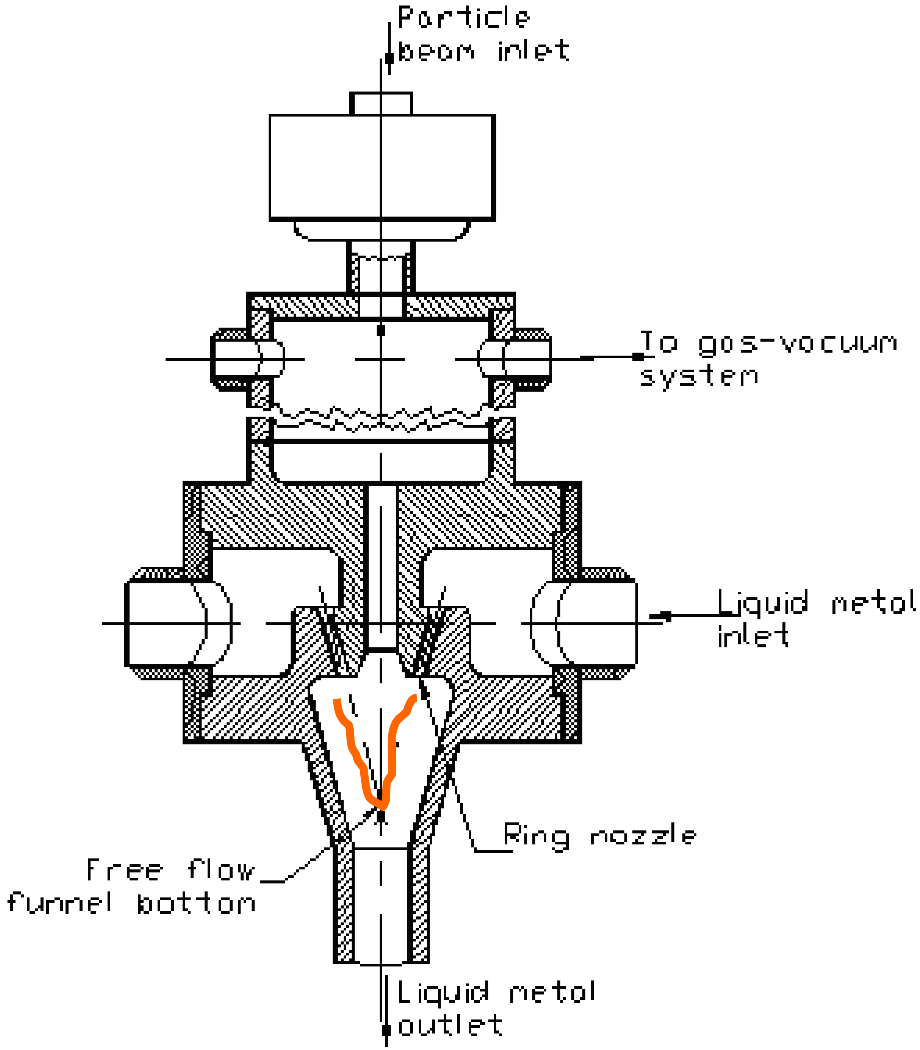
Proton cyclotron Beamline for target studies at VECC, Kolkata (30 MeV Cyclotron)





Windowless liquid-metal spallation target

(Presently under studies for feasibility)



Interface from target-coolant to accelerator vacuum is a free surface of the liquid metal. Liquid volume below serves as spallation target.

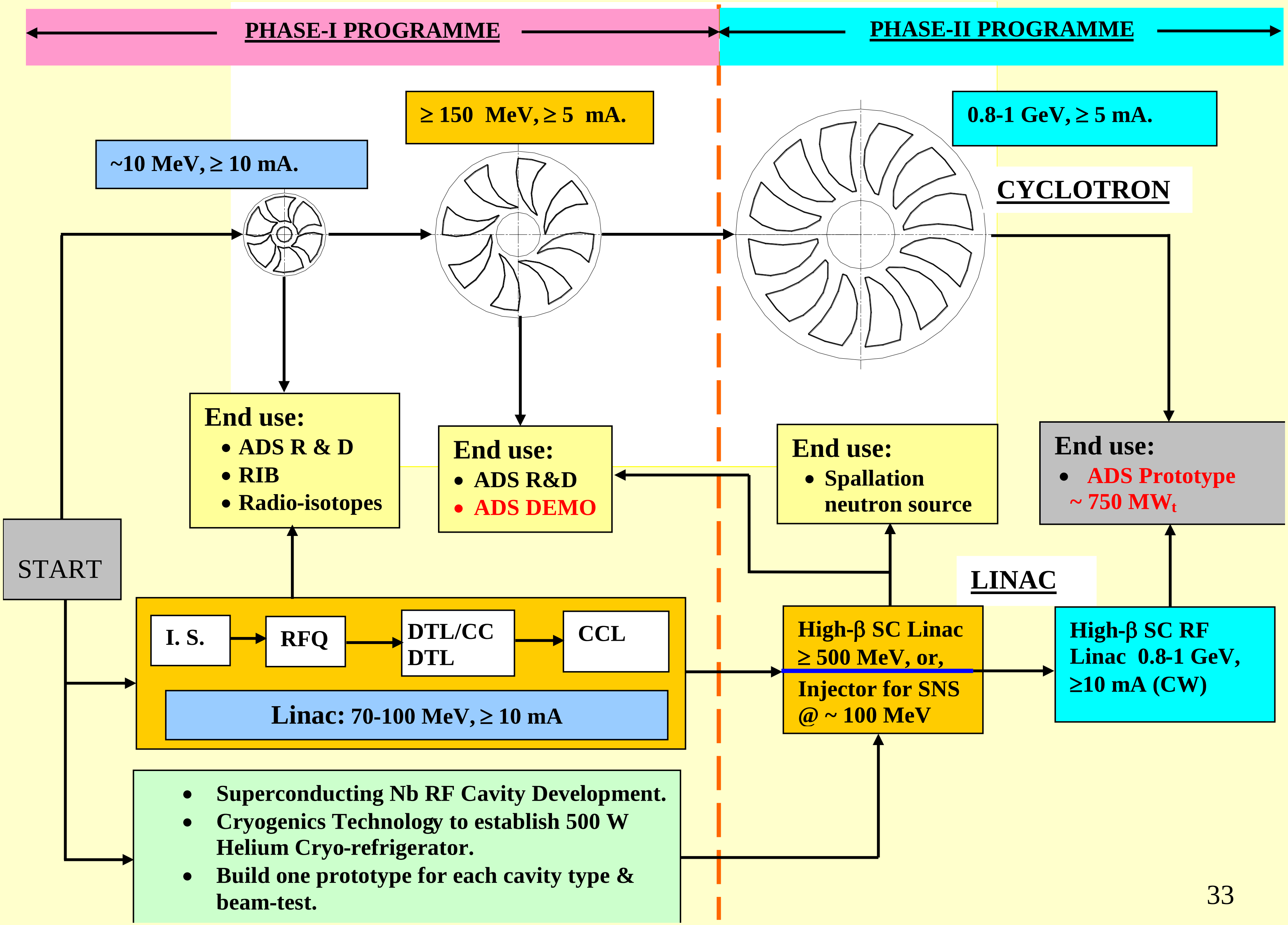
This is possible due to very low vapour pressure (~ 10^{-4} Torr) of lead and LBE at the operating temperatures of less than ~ 400 ^{0}C.

Need for a structural, safety-related item (window), exposed to peak intensity of particle flux in the spallation zone, is completely eliminated.

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.

Accelerator Driven System Roadmap with Proton Accelerator Development stages.



Scheme of Proton Linac Development

Normal Conducting

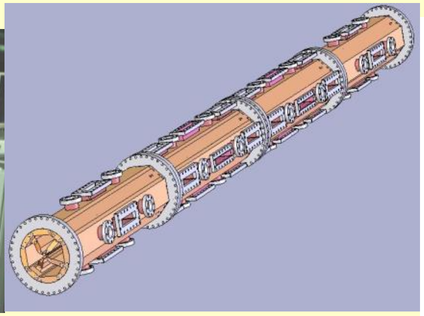
High current injector 20 MeV, 30 mA

Proton IS 50 keV → **RFQ 3 MeV** → **DTL 20 MeV** → **DTL/ CCDTL** (Normal Conducting) or **Super-conducting** → **100 MeV** → **SC Linac**

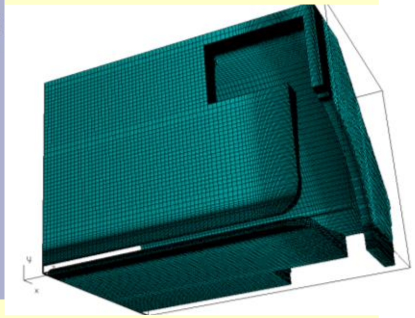
Design completed and fabrication is in progress

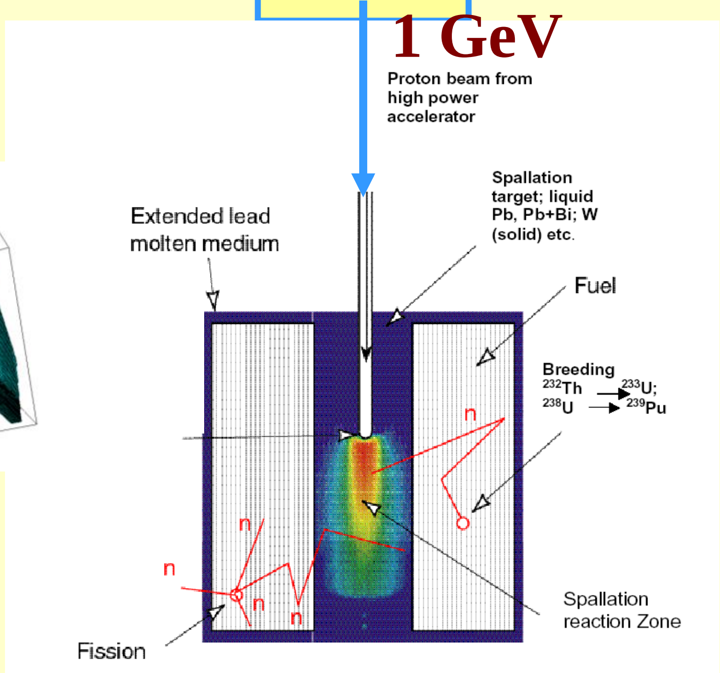
ECR Ion Source

RFQ

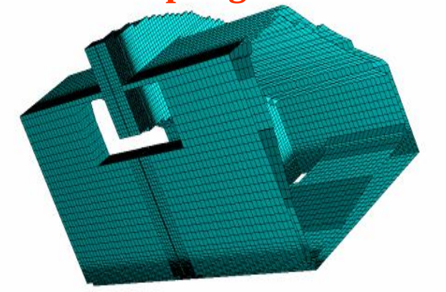


Beginning Cell

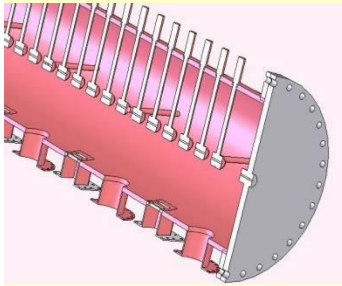




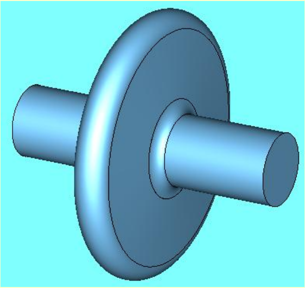
Coupling Cell



DTL

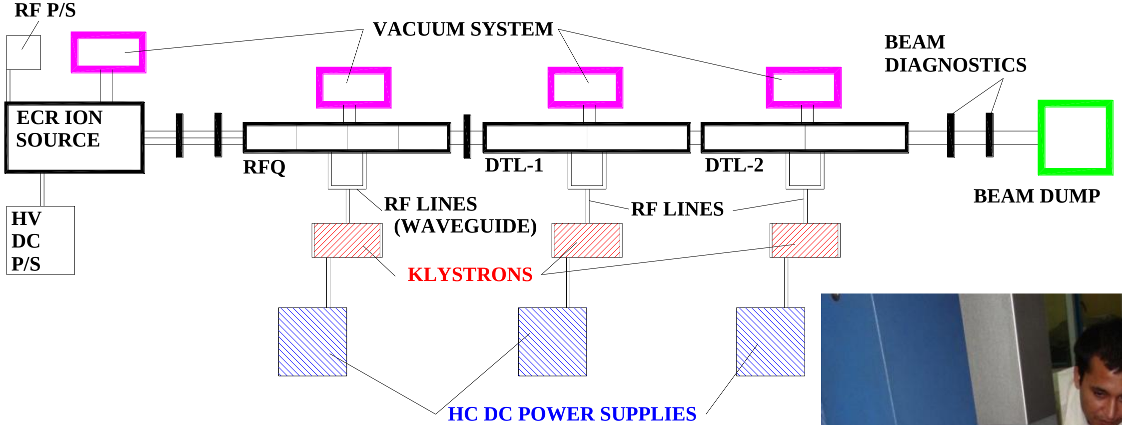


Elliptical SC Cavity



20-MeV proton linac-LEHIPA

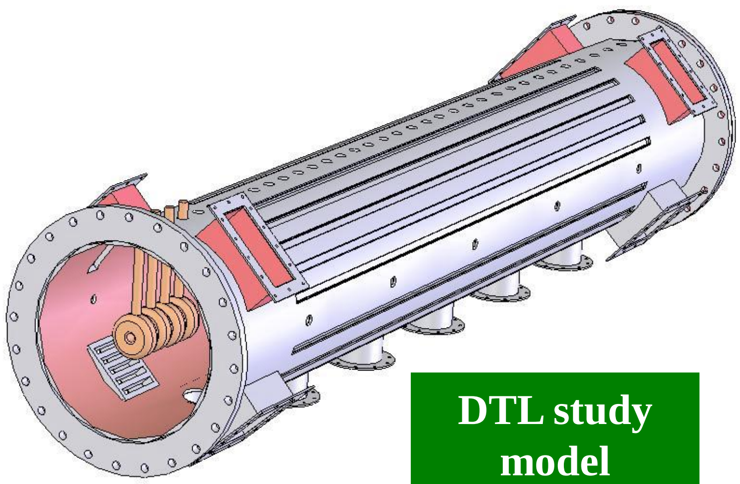
EQUIPMENT DIAGRAM OF LEHIPA




Aluminum short model


Pre-braze inspection


RFQ vane machined

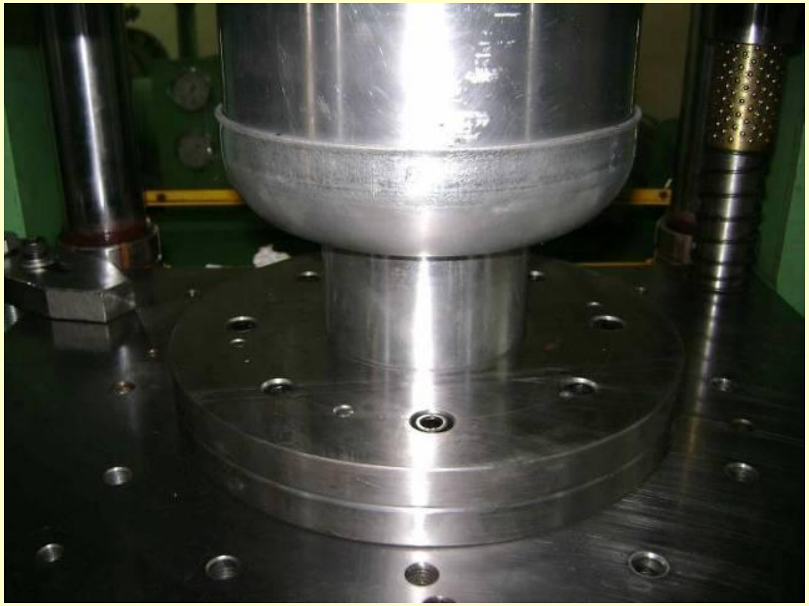

DTL study model

High-energy section for Linac

- **Use of multi-cell elliptical superconducting RF cavities: for > 100 MeV (β> 0.42) in high energy section of linac.**
- **Development of fabricating, processing and RF conditioning of bulk niobium SC cavities.**
- **Some experience exists in fabrication of QWR/HWR SC cavities for heavy-ion accelerators.**
- **Associated R&D progressing at BARC on:**
  - **Cryogenics technology**
  - **LHe plants and refrigerators**

Indian Institutes & FNAL Collaboration: recent activities

SRF Cavity Forming Tooling development at RRCAT

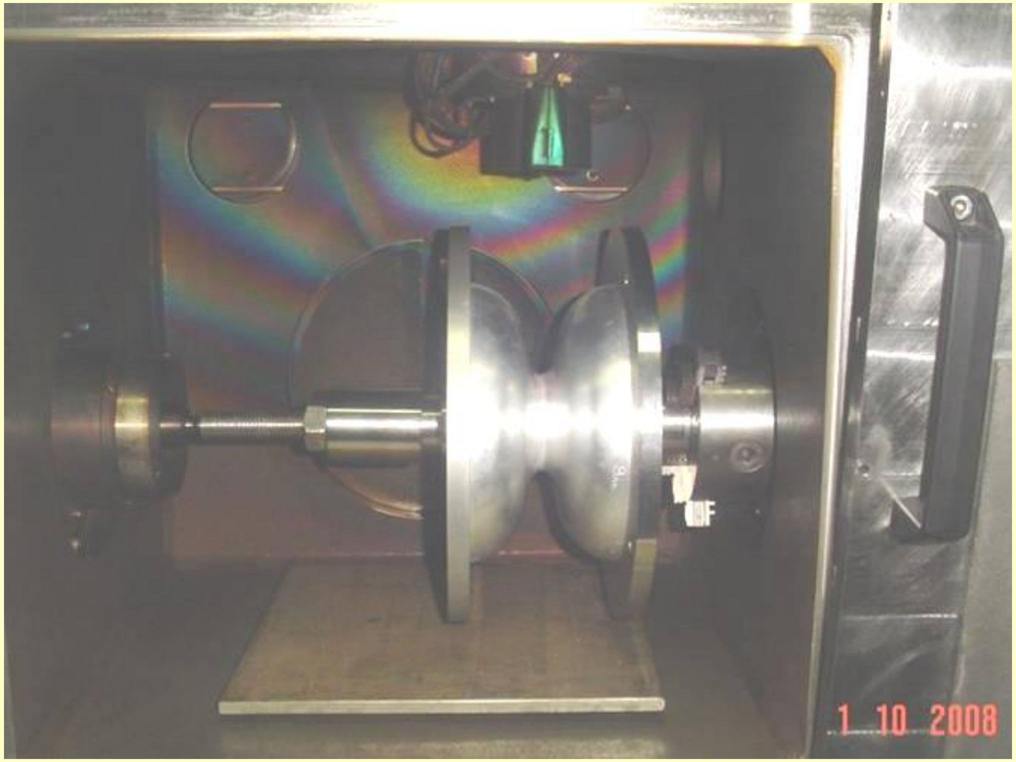


Forming Process

Formed Niobium
Half Cell

SRF cavity: EB welding activities

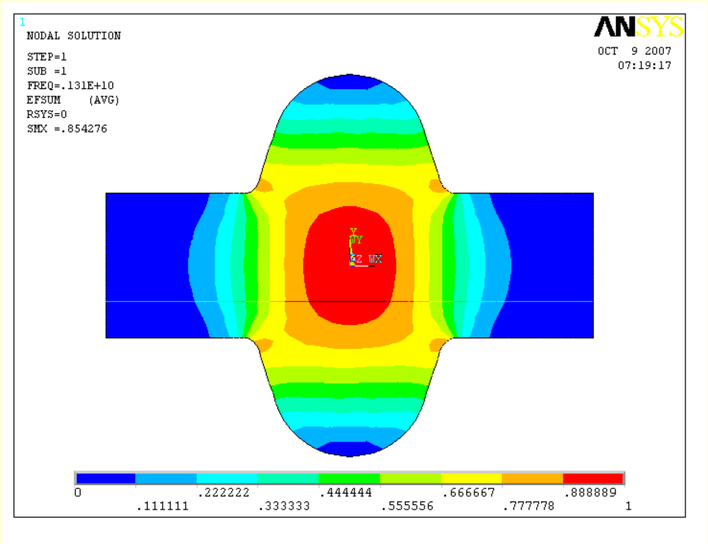
Welding half cells to make dumbell



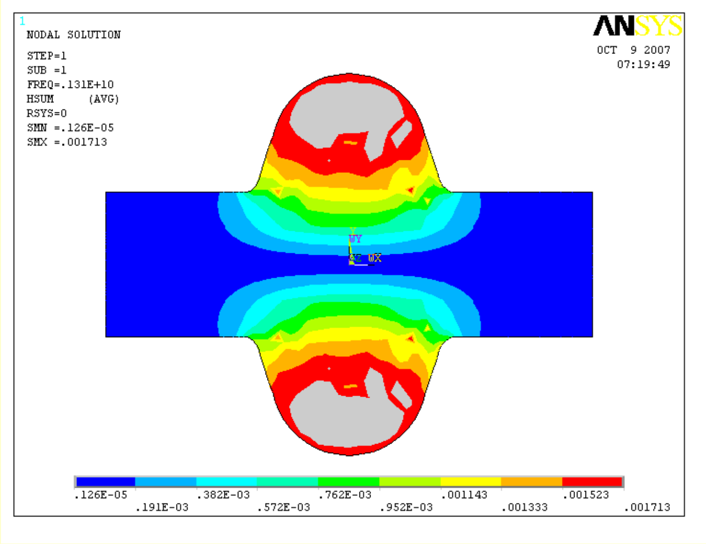
Setting inside the EBW chamber

Welded dumbell

Electromagnetic Simulation of Single Cell SCRF Cavity

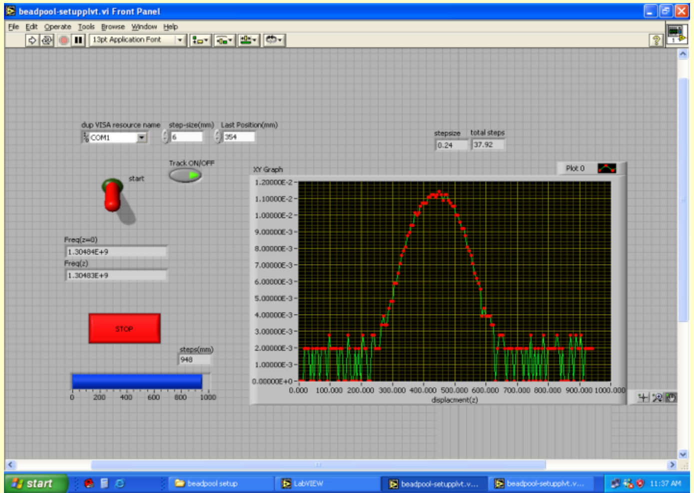


Electric field along the axis

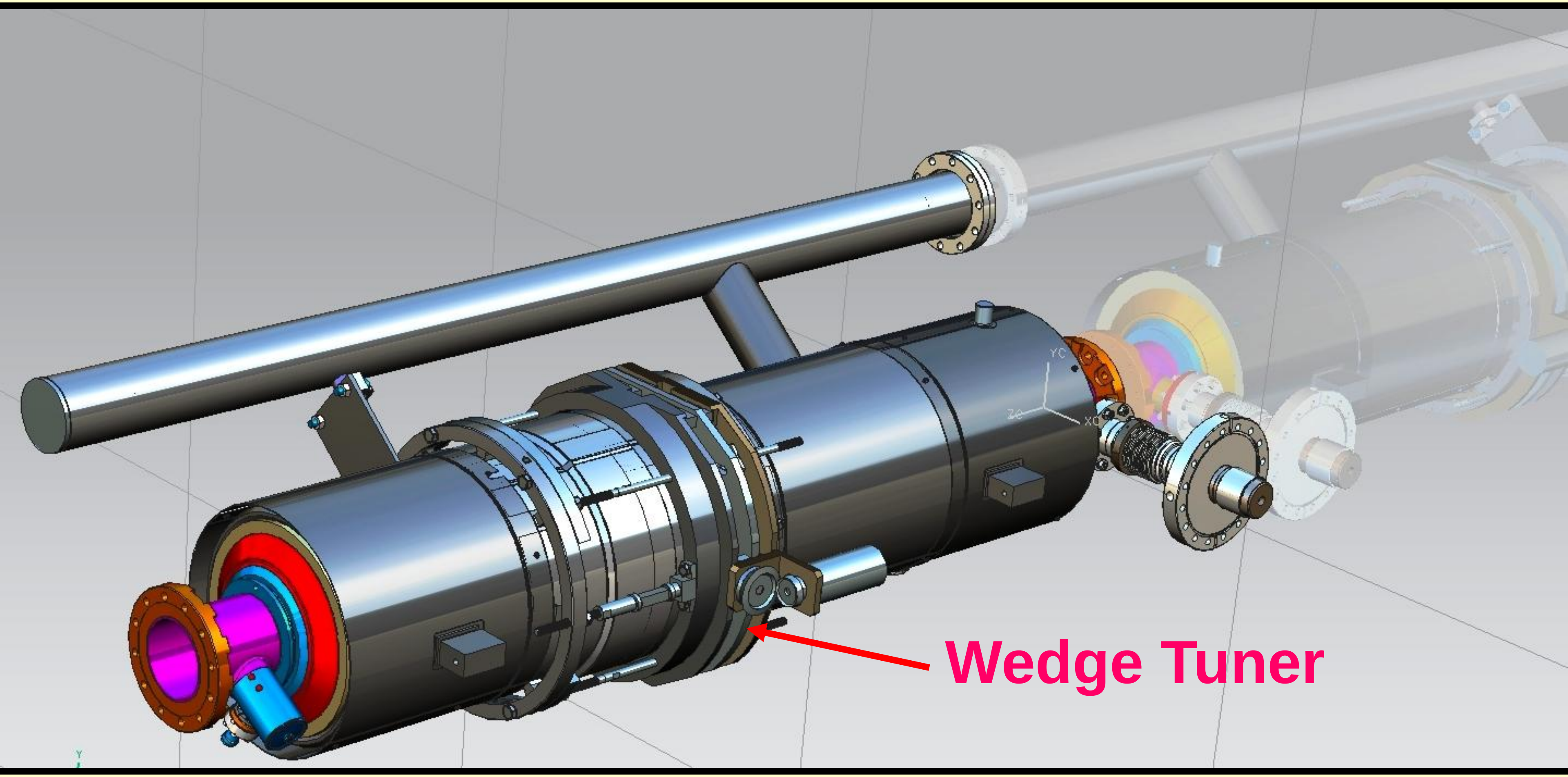


Magnetic field along the axis

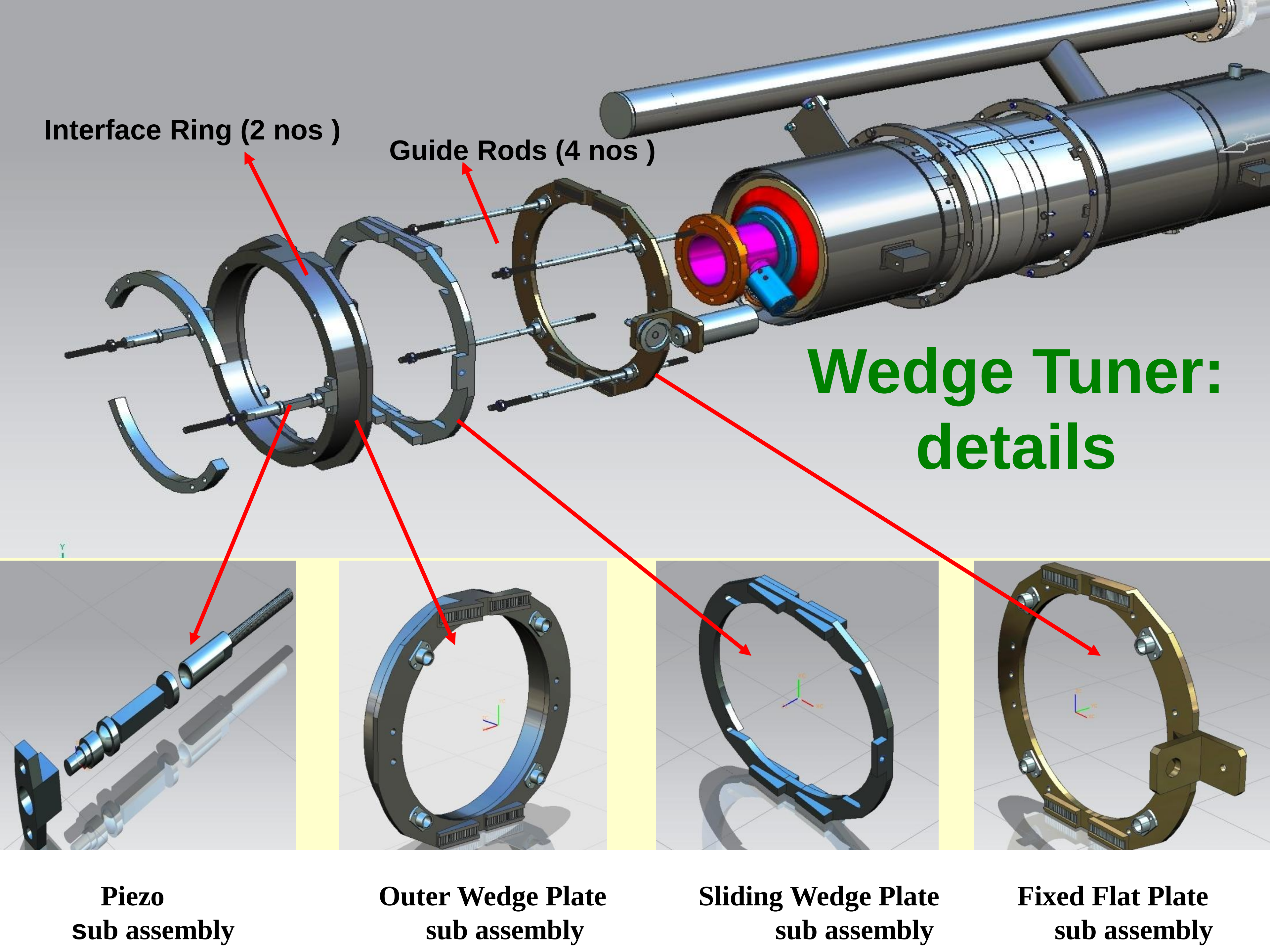
Bead Pull Measurement Setup for Single-Cell SRF cavity



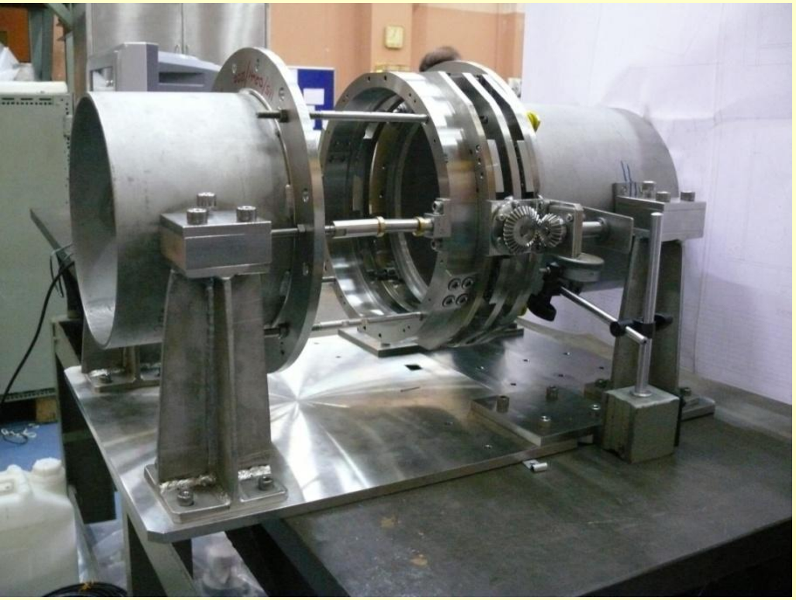
Wedge Tuner installed around the Helium Vessel

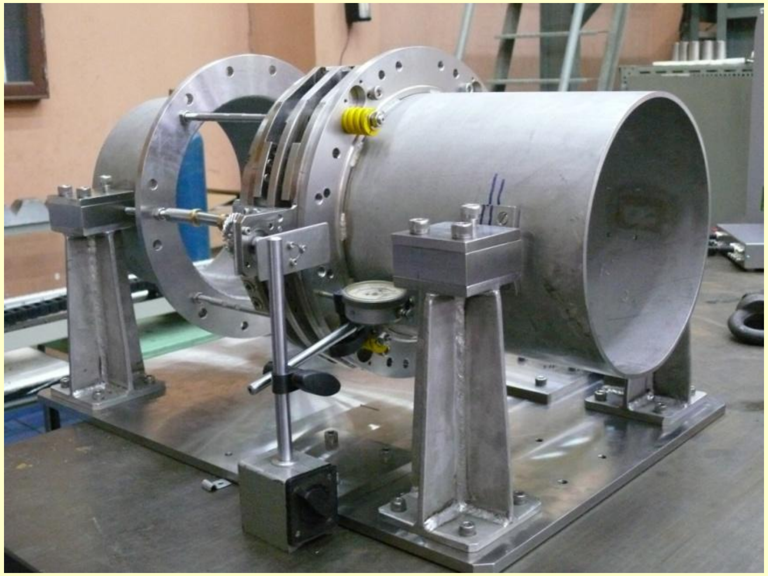


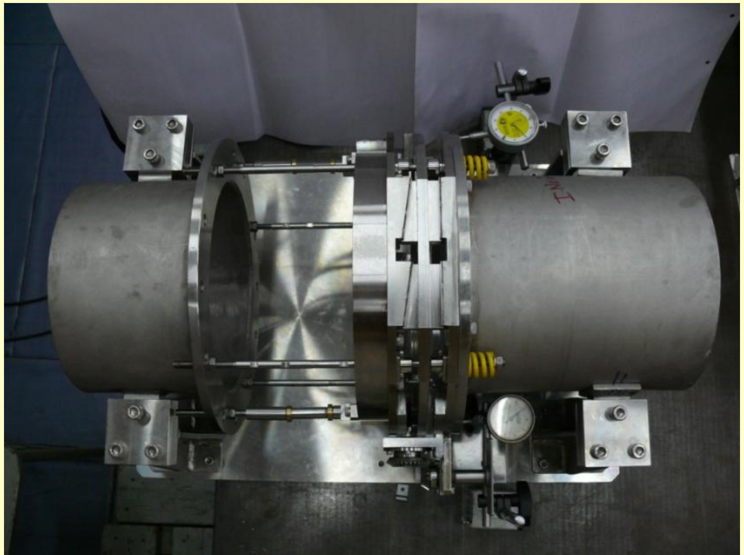
Wedge cavity tuner : required for slow and fast tuning of SRF cavity.


Interface Ring (2 nos)
Guide Rods (4 nos)
Wedge Tuner:
details
Piezo
sub assembly
Outer Wedge Plate
sub assembly
Sliding Wedge Plate
sub assembly
Fixed Flat Plate
sub assembly

Wedge Tuner Mock up Assembly at BARC





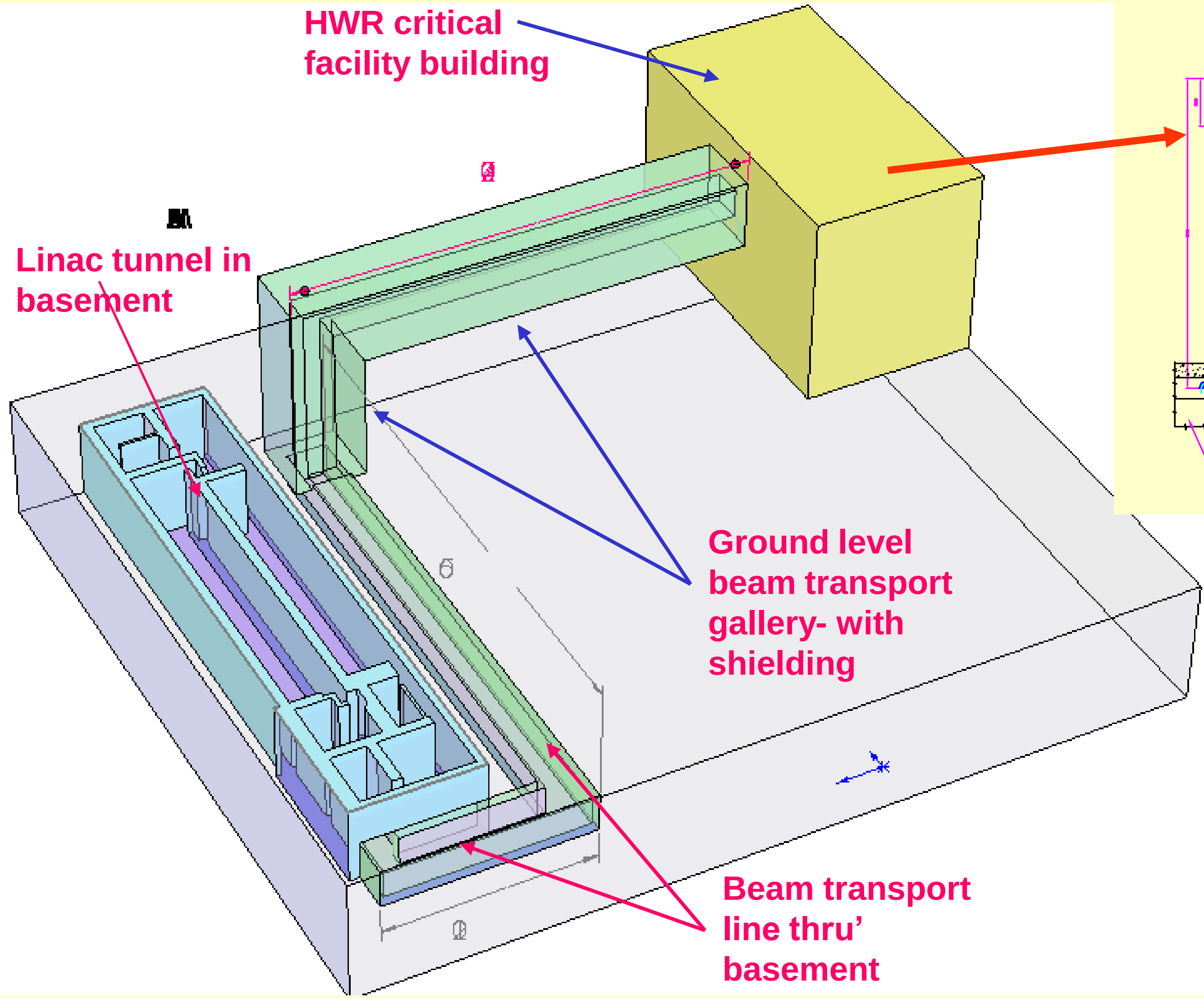


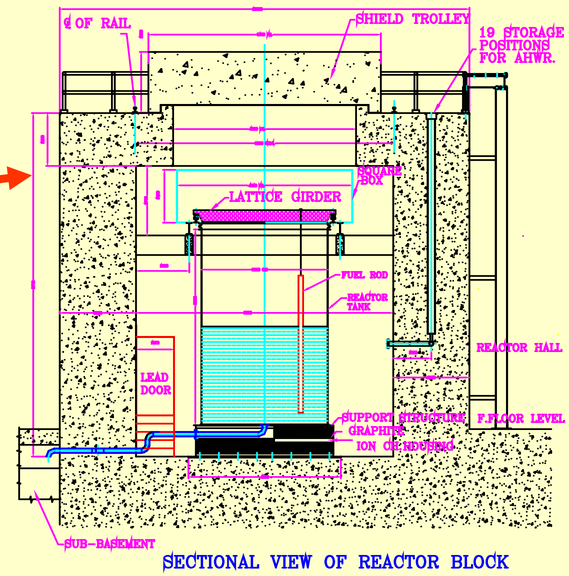
Summary

- **Indian objective on nuclear power- sustainable utilization of thorium fuel reserves via 3-stage plan.**
- **ADS helps in achieving sustainable Th-utilization & eliminate long-lived TRUs.**
- **Thrust areas in ADS R&D programme identified in a roadmap:**
    - **High power superconducting proton Linac.**
    - **Lead & lead-bismuth liquid metal system- thermal hydraulics**
    - **Molten LBE/Lead compatible structural materials.**
    - **Spallation target neutronics and sub-critical reactor kinetics.**
    - **Nuclear data for thorium fuel cycle.**
- **Ongoing ADS-related R&D activities:**
    - **14-MeV neutron based sub-critical reactor studies.**
    - **20-MeV high-current proton linac.**
    - **LBE experimental loop.**
    - **Fabrication of superconducting RF cavities.**

Thank You !

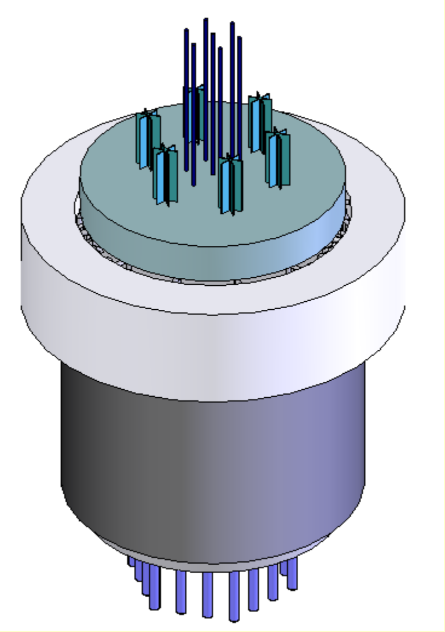
20 MeV Proton beam for ADS experiments in HWR critical facility

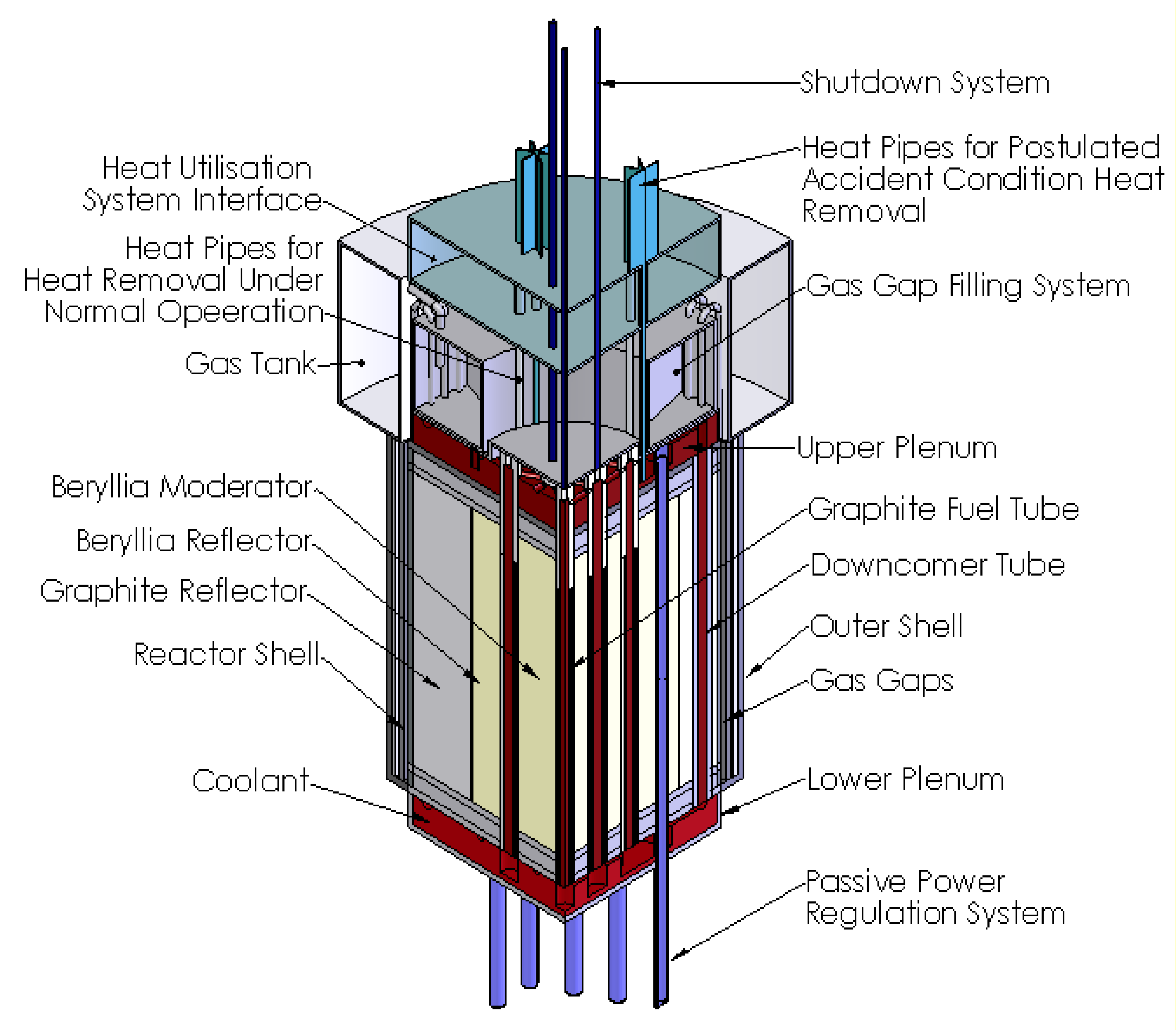




Studies have confirmed feasibility of extending 20-MeV proton beam to a target in the core of nearby HWR critical facility.

High Temperature Reactor





Nuclear energy in hydrogen economy

High Temperature Reactor for Hydrogen Production

Conventional Nuclear Power Plant – Off-Peak hour electricity

High Grade Heat

Electricity

Hydrogen Production Plant

Thermo-Chemical Process

Electrolysis including HTSE

Hydrogen

Reject and waste Heat

Electricity and Potable water

Hydrogen Storage

Solid Oxide Fuel Cell

Hydrogen Utilisation

Proton Exchange Membrane Fuel Cell

Indian HTR Design Features

- Power: 600 MWth
- High temperature (1000 °C) Process heat production
- TRISO coated particle fuel
- Molten heavy metal/ salt based coolant
- Extensive use of carbon based components
- Passive safety features
- Passive removal of reactor heat under normal and postulated accident condition

ADS-demonstration reactor

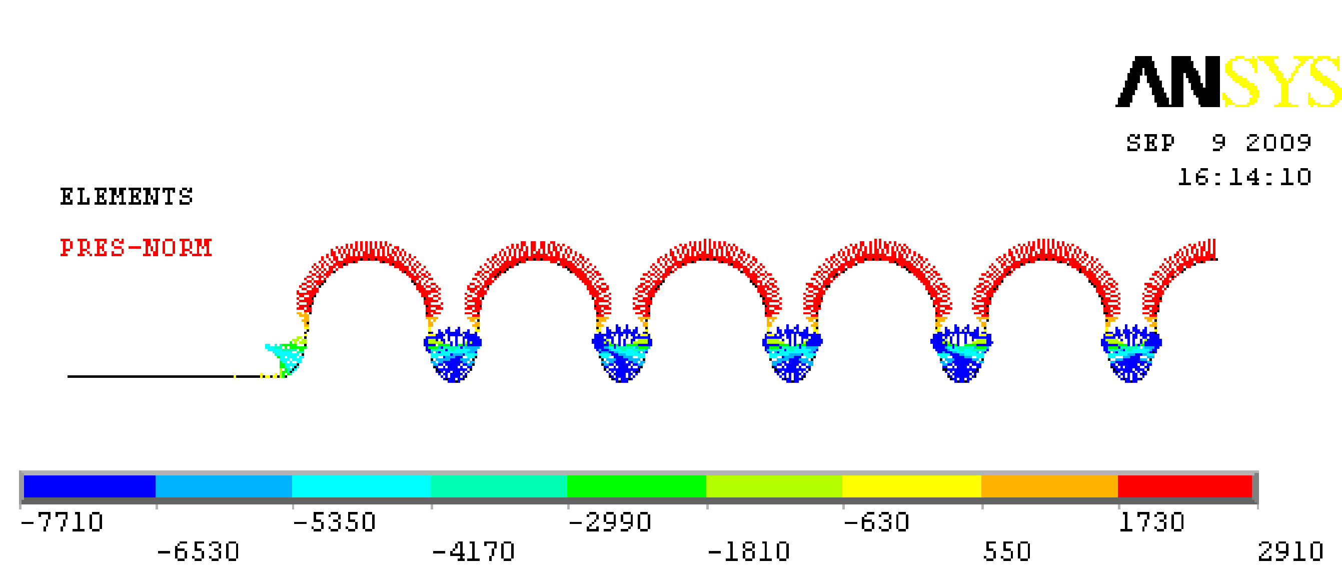
- Studies made on a design of 30-MWt thermal reactor compatible for ADS demonstration project.
- This ADS configuration is planned for feasibility demonstration at a few MWt fission power level.
- Physics studies are in progress at BARC-reactor has pool type core in open tank, light water is moderator & heavy-water makes reflector shield. LEU used as plate type fuel assemblies of uranium silicide (U_3Si_2) dispersed in aluminum matrix.

Work on SRF cavity electromagnetic design

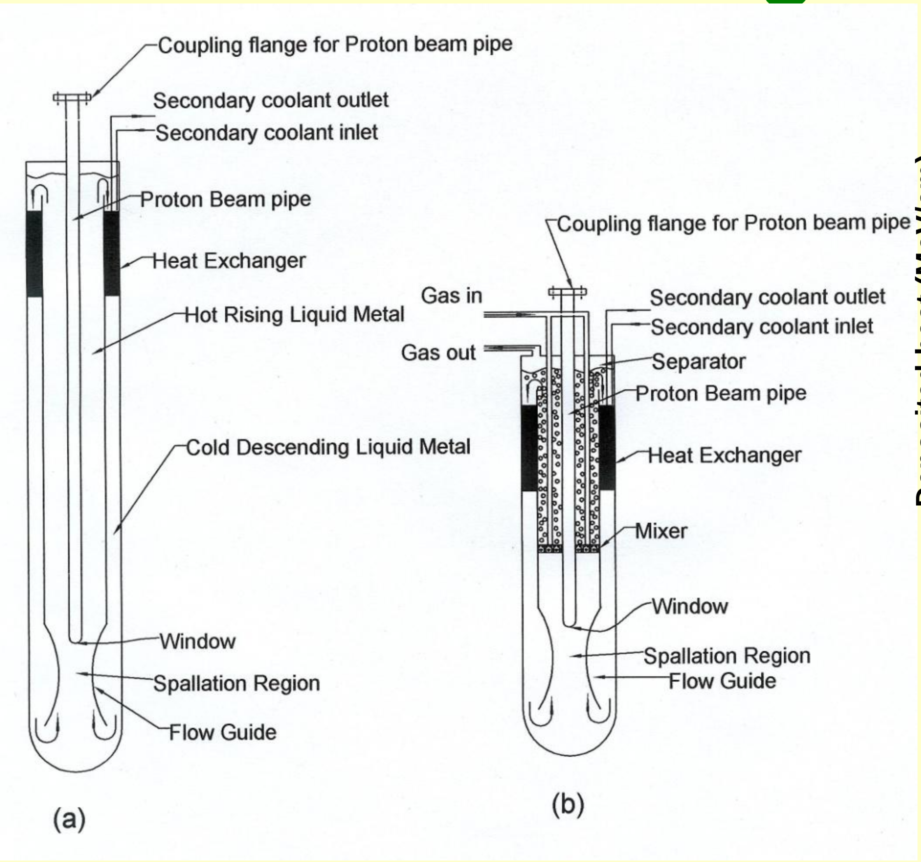
Cavity design work with MSU/FNAL for:

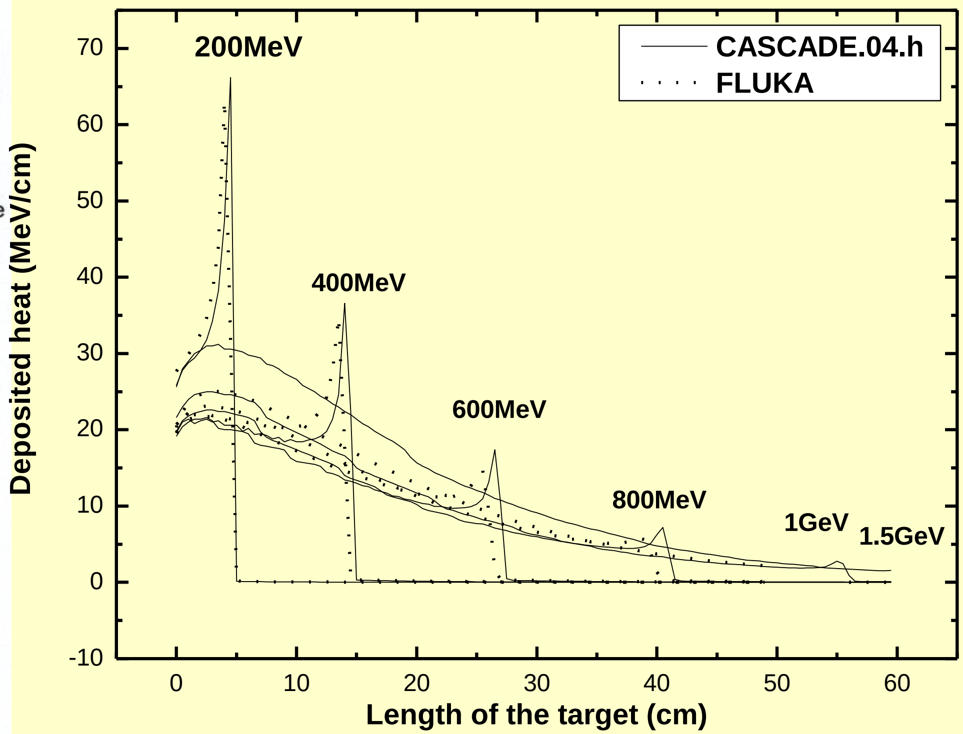
- Benchmarking cavity simulation codes/techniques
- Study of β= 0.8 new cavity geometries with FNAL and comparison of results.

ANSYS simulations to study LFD



Design simulations of spallation target for ADS





Thermal hydraulics models for flow of spallation target-coolant LBE-

(a) <u>by buoyancy</u>,

(b) <u>by gas-injection </u>enhanced flow

Simulation results of proton beam heat deposition rate in lead (Pb) spallation target at different beam energies using FLUKA (CERN) & CASCADE (JINR, Russia) codes.

Nuclear Data Measurements

$^{232}Th(^{6}Li,^{4}He)$ surrogate reaction for $^{233}Pa(n,f)$

(Experiment at BARC-TIFR Pelletron facility, Mumbai)