# ACCELERATORS IN NUCLEAR ENERGY PROGRAMME


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**Department of Atomic Energy**

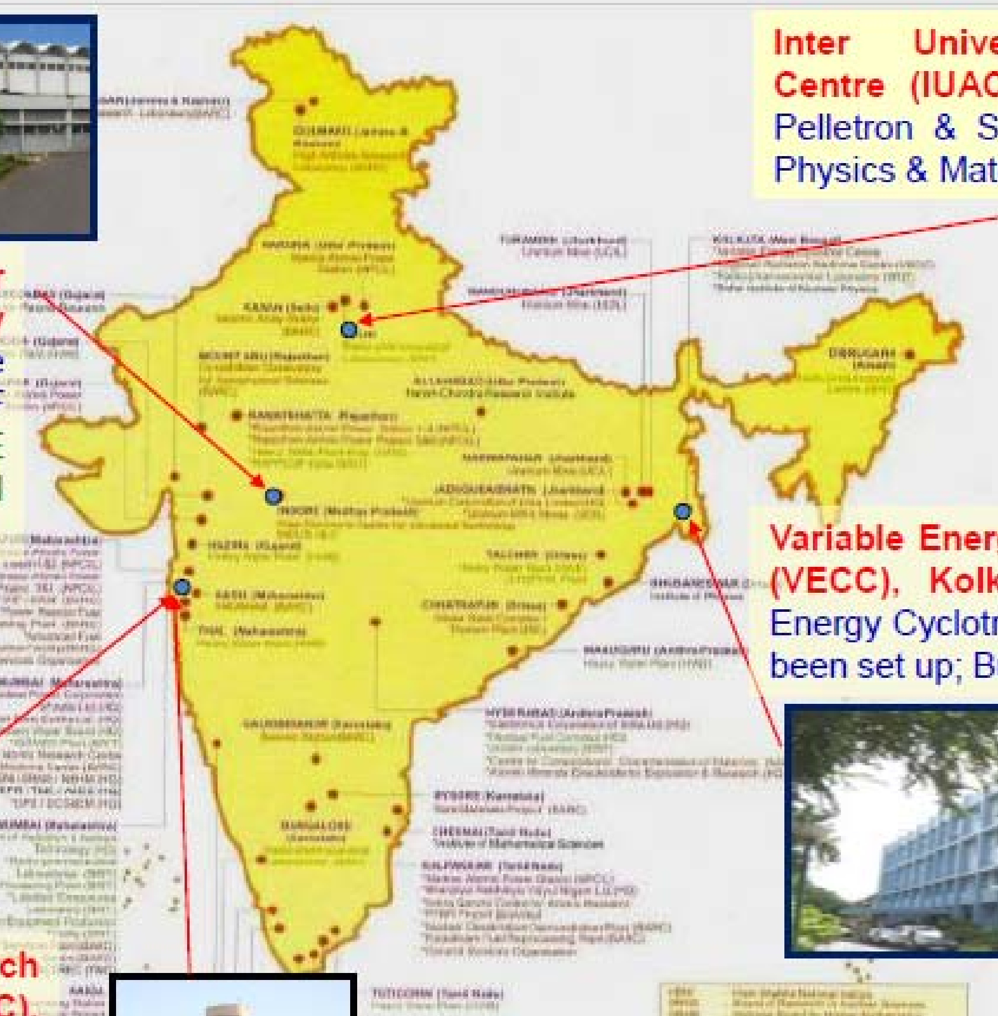
- ***For Long Term Energy Security , India has a robust Three Stage Power Programme in place.***

- ***Development of Thorium Based Reactor Systems for sustainable Nuclear Energy belongs to the Third stage***

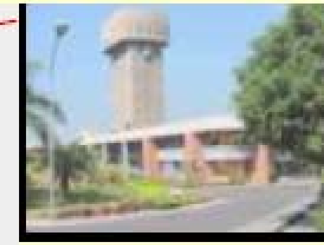
- ***Prospects of Accelerators in Nuclear Energy Programme in this context***

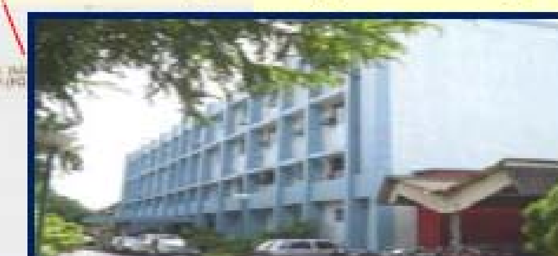
# Major Accelerator Laboratories in India

**Raja Rammana Centre for Advanced Technology (RRCAT), Indore** : Home for 2 SRS; Running SCRF Program Nodal DAE institute for CERN Collaboration



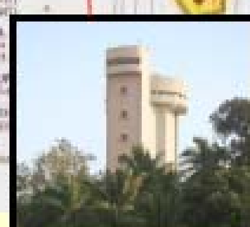
**Inter University Accelerator Centre (IUAC), Delhi** : 15 UD Pelletron & SC Booster - Nuclear Physics & Material Science.





**Variable Energy Cyclotron Centre (VECC), Kolkata:** Hosts Variable Energy Cyclotron; SC Cyclotron has been set up; Building RIB Facility

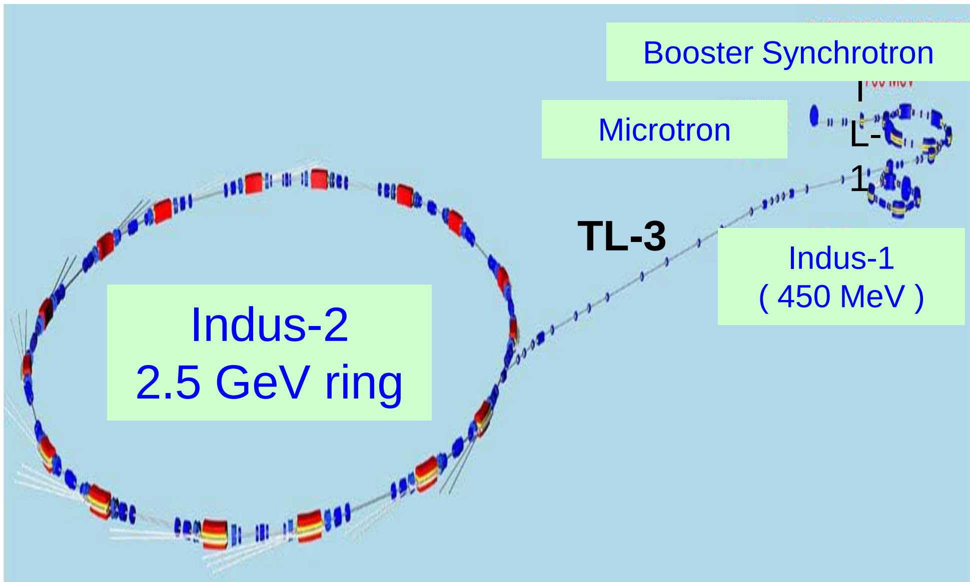
**Bhabha Atomic Research Centre (BARC), Mumbai:** Folded Tandem Ion Accelerator, Building an injector for HIPA



**Tata Institute of Fundamental Research (TIFR), Mumbai:** 14 UD Pelletron+SC Booster

# Indus-2 Synchrotron Radiation Source

## Raja Ramanna Centre for Advanced Technology, Indore




- Indus-2 operating in round the clock mode at 2 GeV, 100 mA since March 2010
- Beam life time at 2GeV, 100 mA ~ 22 hrs
- Six beamlines commissioned and made available to researchers

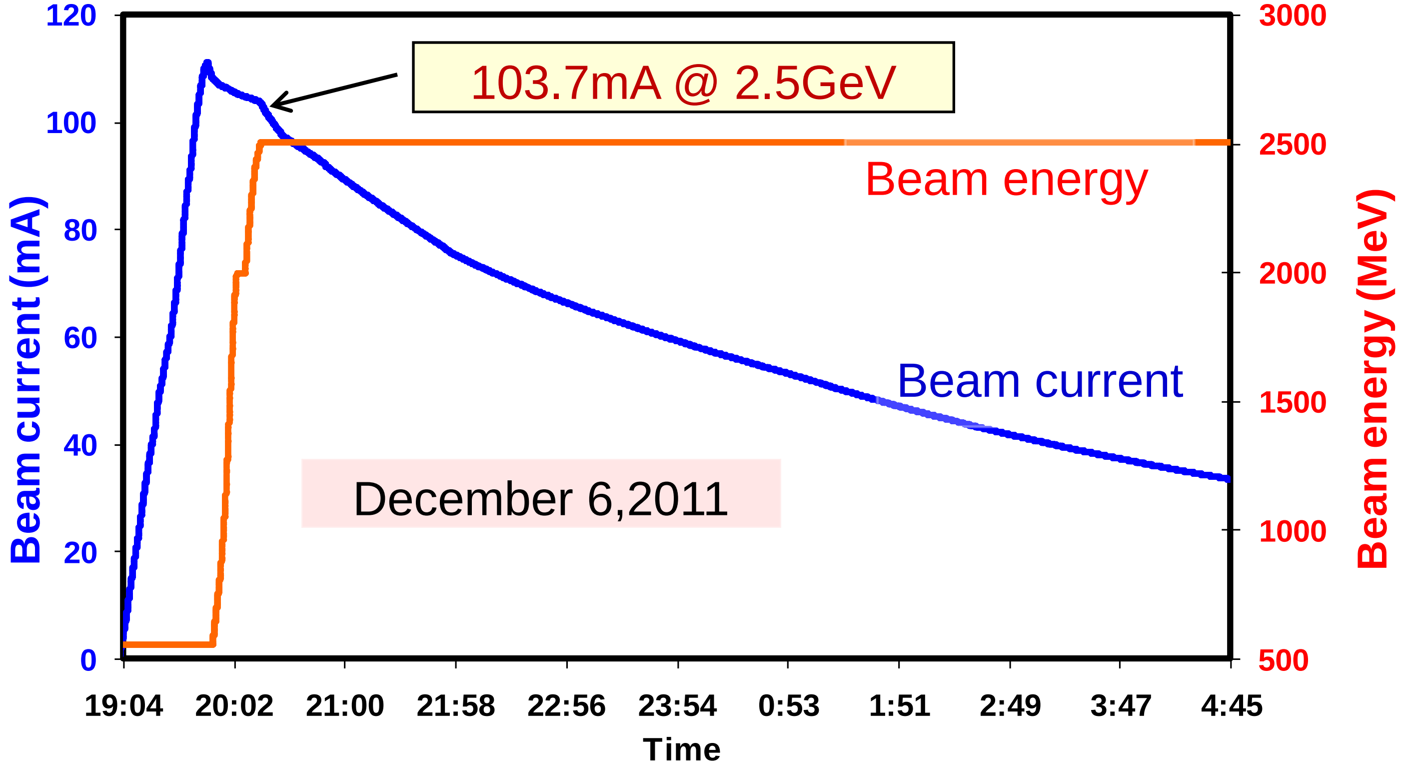
Indus-2 reached a major milestone on December 6, 2011

**Operation at 2.5 GeV energy, 100mA beam current**

# 2.5 GeV Energy, 100 mA Operation

Accomplished this milestone with successful in-house development of new technology of high power solid state RF amplifiers and its deployment in Indus-2 RF power system

Beam energy and current profile



# Indus-2 Operation with Support of Solid State RF Amplifiers

- Indus-2 has four RF cavities (505.8 MHz) powered by four klystron power stations of 60 kW each
- Its operation was limited to 2 GeV, 100 mA due to non-availability of klystrons to replace the two failed ones (for RF stations # 1 & 3)

**RF Station # 1 & 3 are now powered by solid state amplifiers**

Indus-2 RF station # 1 (20 kW)

Indus-2 RF station # 3 (30 kW)

## Our Plans for
## Accelerators in Nuclear Energy Programme

- Enabling Technologies for Development of
- high current, high energy accelerators

- Both Electron and Proton Accelerator options

- Design and Develop a Proton Spallation Neutron
- Source for Multidisciplinary Science Research

- Build Low Energy High Intensity Proton
- Accelerator – LEHIPA - Progressively scale up in
- energies using SC Technologies towards the ADS

# Proton Accelerator for Spallation Neutron Source on the way to ADS

- **The broad specification of the full energy continuous wave (CW) accelerator system needed for building a prototype ADS based nuclear power plant of thermal fission power in the range 500-1000 MW, corresponds to proton energy of 0.8-1.0 GeV and beam current of more than 5 mA with CW mode of operation.**

**On the path of achieving this challenging goal in India, a programme is envisaged for developing a pulsed high energy (0.8-1.0 GeV) and high power (1 MW) proton linear accelerator (LINAC), and a spallation target station that forms an interface between the high power proton accelerator and the sub-critical core of an ADS based nuclear power plant.**

# Spallation Neutron Source: A Mega Facility for Materials Research ( RRCAT)

- **A 1 GeV and 1 MW pulsed proton accelerator in conjunction with a ‘proton accumulator/storage ring’ and a suitable spallation target can form a ‘Spallation Neutron Source (SNS).**

**Neutron as a Probe**

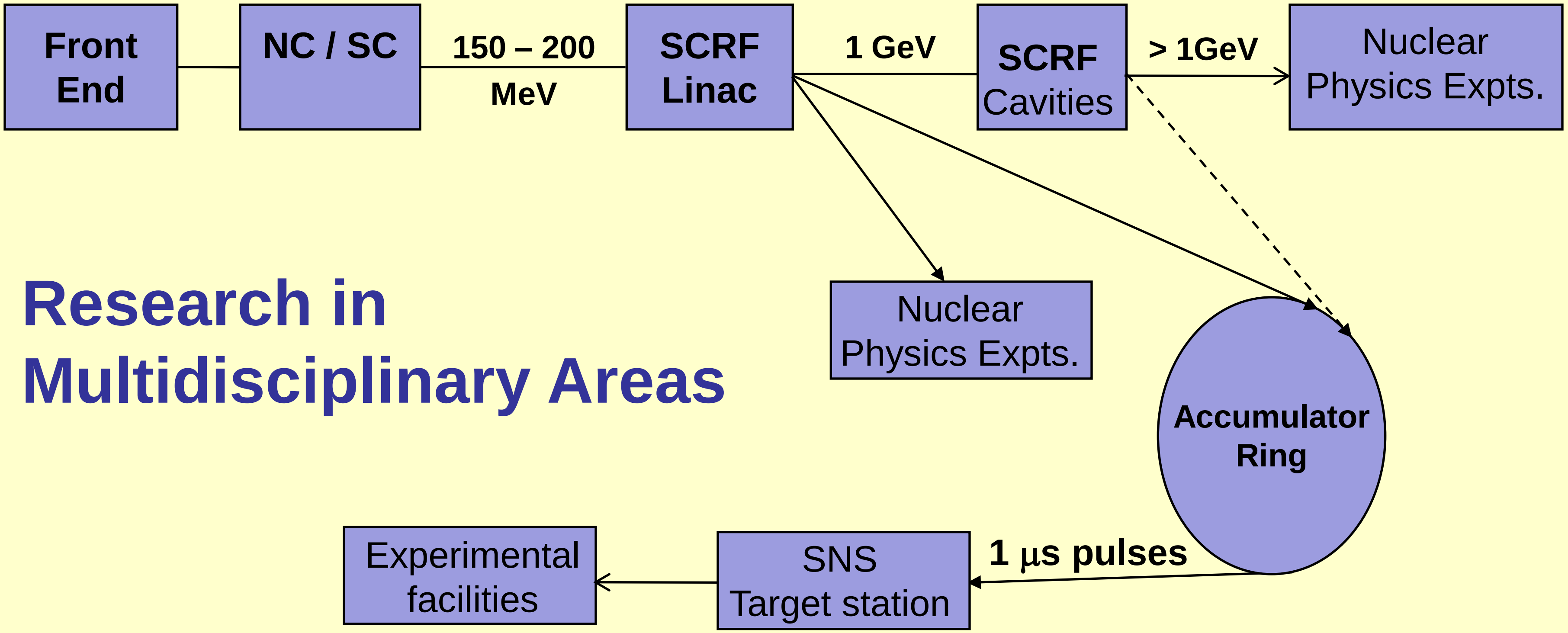
**•The atomic and molecular structure and of condensed matter and biological systems.**

**•Determination of magnetic structures of materials.**

**•Various dynamical aspects of condensed matter, e.g. molecular rotations, lattice vibrations, magnetic excitations and various other quasi particle excitations etc.**

**•Non-destructive inspection of materials.**

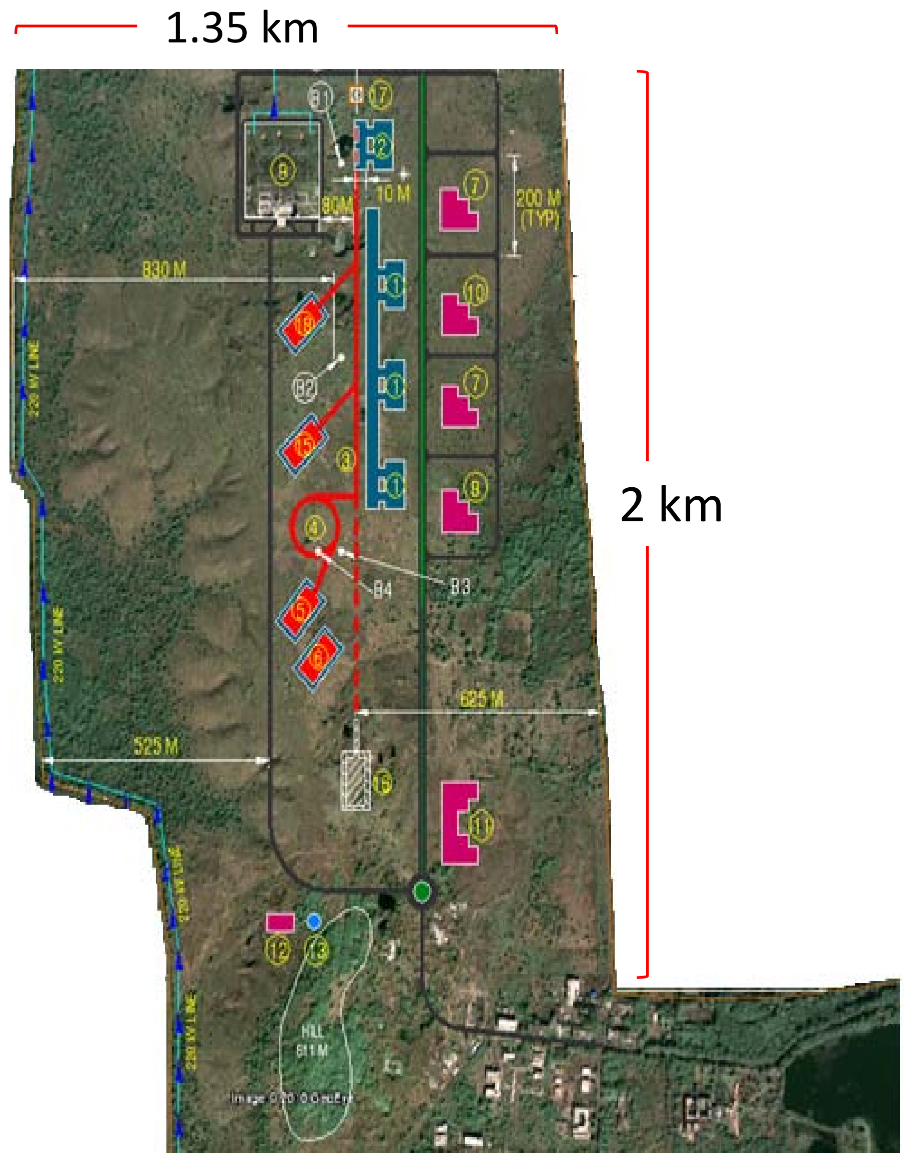
# Preliminary Schematic of ISNS Layout




## Research in Multidisciplinary Areas

# Preliminary Layout of Proposed Facility (RRCAT)

01 Klystron Gallary
02 Front End Building
03 Linac Tunnel 800M Long
04 Ring
05 Target Lab
06 Future Target Lab
07 Support Building
08 Cryogenic Plant
09 220/132/11 kV Sub Station
10 SCRF Facility
11 Lab & Office Building
12 Pump House
13 Over Head Water Tank
14 220 kV Over Head Line
15 Nuclear Exp. Facility
16 Future Nuclear Exp. Facility
17 Vertical Shaft for Tunnel Boring Machine
18 Proton Therapy Related Research Facility (~ 300 Mev)



# WHY ADS for India ?

- **Inherently safe**
- **Sub – critical ---self terminating fission chain**
- **No restriction on fuel type**
- **less dependence on delayed neutrons**
- **Ideally suited for long lived MA incineration**

- **(Note: Fast Reactor MA/Th > 3% not permitted)**

- **Better n per fission----Reduced Doubling time**
**Increased burnup – Less fissile material inventory**
**Fast / Thermal Reactor combination possible**

- **Large Scale utilisation of Th - complement AHWR**

# Accelerator Driven Sub-critical Reactor System (ADS)

With relevance to 3-Stage nuclear power program, an option being explored is a new type of fission reactor, where nuclear power (say, 500-1000 MWe) can be generated in a neutron multiplying core ($k_{eff} < 1.000$ ) without the need of criticality.

This can be accomplished with the help of an external neutron source.

# Generating “External Neutrons”

These would be generated by non-fission events.

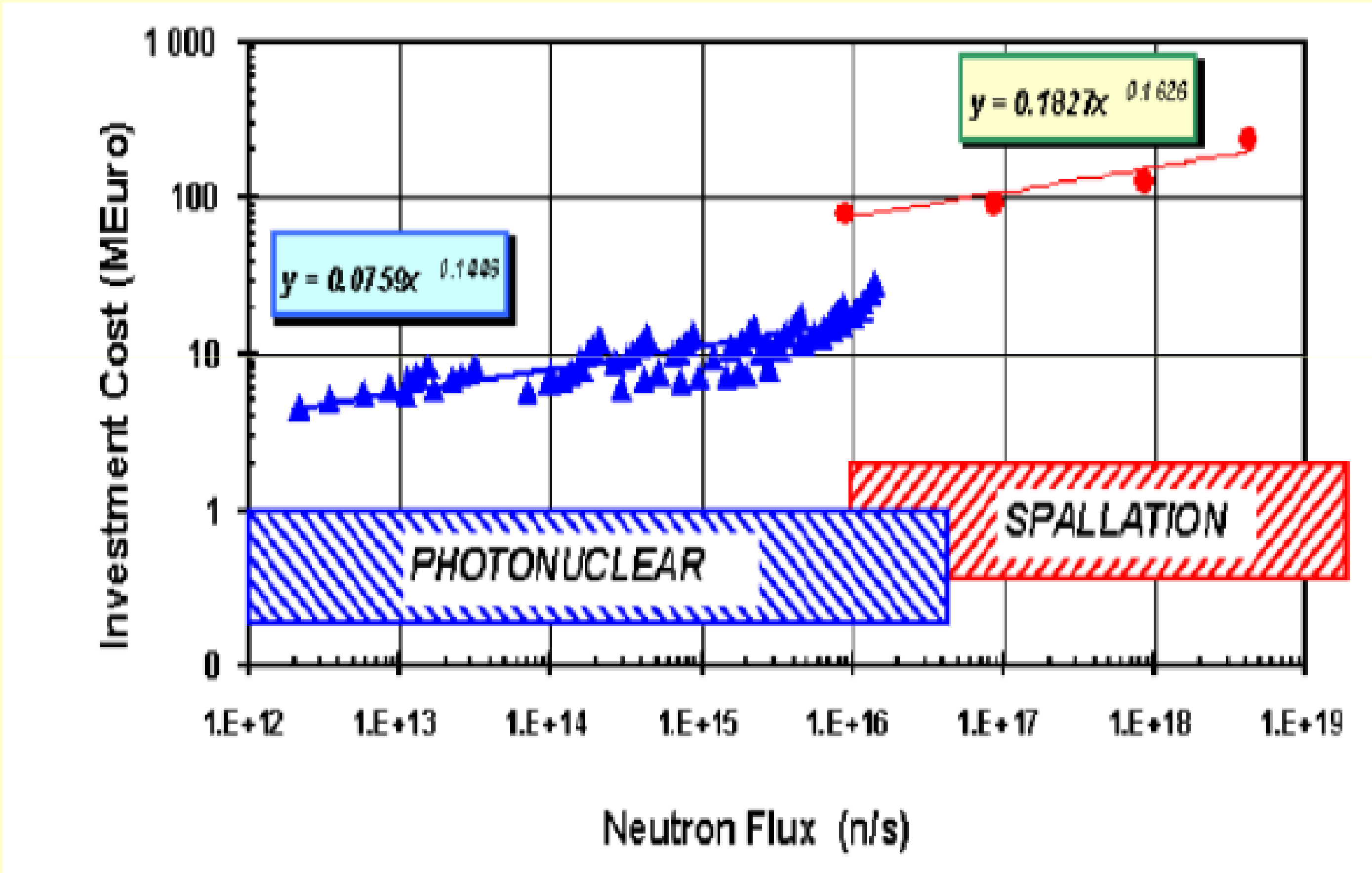
These could be knocked off from suitable nuclei by collision of energetic primary particles.

**Examples:**

| Process | Example | Yield | Energy cost-on target only* |
|---|---|---|---|
| (D,T) fusion | 400 KeV on T | $4\times10^{-5}$ n/D | 10,000 MeV/n |
| Li (D,n) break up | 35 MeV D on Li | $2.5\times10^{-3}$ n/D | 14,000 MeV/n |
| U-238($\gamma$,n) photo-nuclear | 20 MeV $e^-$ on U-238 | $1\times10^{-2}$ n/$e^-$ | 2000 MeV/n |
| Spallation | 800 MeV proton on U-238 | ~ 30 n/p | 27 MeV/n |

* Plug –point power/energy to particle kinetic energy conversion efficiency will affect overall (real) energy cost per neutron.

# Comparison Spallation / Photonuclear



# Specifications of the electron driver accelerator

- Electron driver is to induce more than 10**16 fissions/s in the uranium target (ignoring for the moment the issue of power density deposition in the target).
- This goal leads to beam specifications as follows:
- **Final beam energy: 50 to 70 MeV.**
- **Average beam current: 100 to 200 mA.**
- For 5- 10 MW electron beam, a high-power CW superconducting linac is Suitable

1. **100% of the RF power transmitted to the beam**
2. **Cryogenics**
3. **Compact Design**

# Neutron source requirement for ADS

- For k ~ 0.95 to 0.98, thermal fission power in range 500 - 1000 MW would require driving neutron source strength of ~ $10^{18}$ neutrons/sec.

- At 1 GeV kinetic energy, a proton interacting with heavy nuclei produces ~ 25-30 neutrons in spallation reaction. At 10 mA beam current or, 10 MW beam power, this reaction can yield ~ $10^{18}$ neutrons/sec.

High power proton accelerator (1 GeV, > 10 mA CW current) is required for ADS application

# Technologies for ADS

- **High power proton accelerator: 1 GeV, cw or high duty factor & (average) current**
- **High beam current front-end : low random beam losses for minimal radio-activation of hardware**
- **Superconducting RF cavities: high electrical efficiency & large aperture for beam**
- **RF power systems: high reliability against random beam trips- redundant & standby hardware.**
- **Spallation target & associated process system.**
- **Molten heavy metal for intense volumetric beam power density**
- **Materials: resistance to neutron irradiation & liquid metal corrosion at high-temperature.**
- **Sub-critical reactor**
- **Optimized asTRU transmuter or for thorium fuel-cycle.**
- **Configuration: technology issues- fast & thermal neutrons.**
- **Transients & safety studies- beam trips, reactivity swings.**

# Requirements for Building High Energy Accelerators

- Physics design studies, simulation, beam dynamics, halo formation..
- Critical Technologies for development of High Energy Accelerators
  - Design and fabrication of SC cavities for different energy ranges
  - High Power RF systems - Solid state amplifiers, klystrons, circulators..
  - Low Level RF power ( LLRF) electronics
  - Accelerator control systems
  - Cryogenics
  - Characterisation facilities

# Ongoing Indian activities in ADS program

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



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# SNS and other Accelerator Related Activities at RRCAT

# SCRF Activities at Indian Institutions

- **Superconducting Materials**
  - Materials R & D for SCRF application
  - Characterization of indigenously developed materials

- **SCRF Cavity Development**
  - Physics design
  - Cavity fabrication (spoke resonator cavities, elliptical cavities)
  - Cavity processing and testing
  - Tuner design and prototype development

Contd.

# SCRF Activities at Indian Institutions

- Cryogenic Engineering
  - Test Stands for SCRF Cavities
  - Cryomodule design and prototyping
  - Cryogenic systems with large scale refrigeration
- RF Technology Development
  - Measurement and characterization of SCRF Cavity
  - Capacity building for high power RF generation and transmission for proton accelerator needs.

# Development of 1.3 GHz, $\beta$ = 1 SRF Cavity
# Forming and Machining of Half Cells 2008-2011

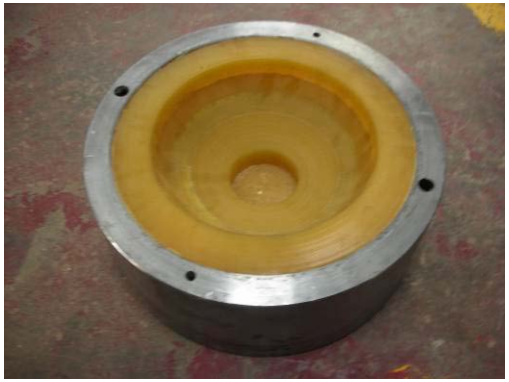
Half Cell Tooling (Aluminum alloy 7075-T6 from Fermilab)

Forming process

Machining

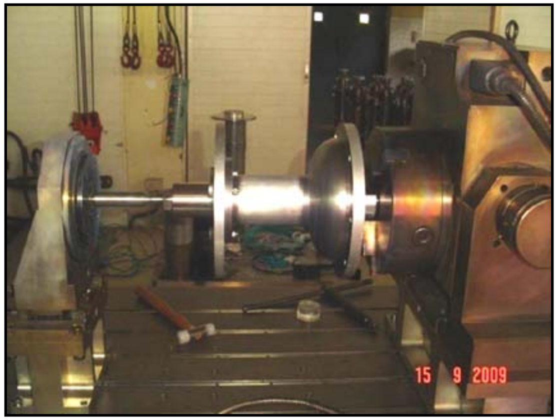
Inspection on CMM

Formed Niobium Half cell

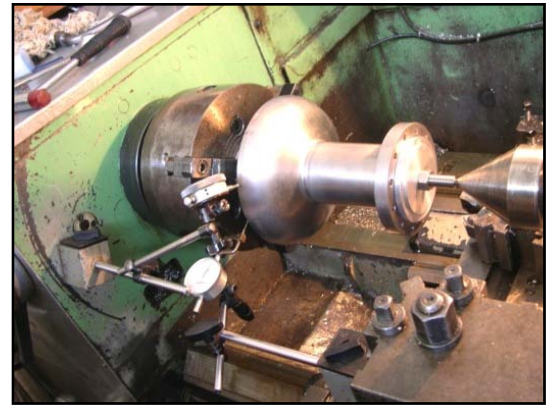


Improvement - rubber pad forming tooling completed

# Stages of Cavity Manufacturing & In-Process Qualifications



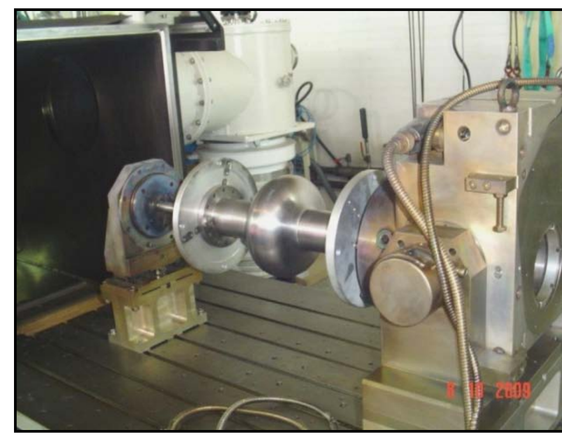

Outside iris welding



Equator trimming

Frequency measurement


Mechanical inspection

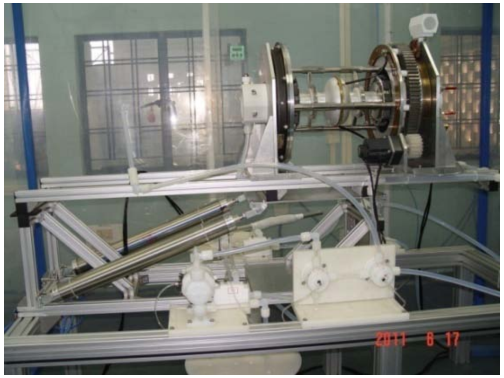


Final equator welding

# Infrastructure for SCRF Cavity Fabrication and Processing

- 120 T cavity forming facility
- Electro-polishing setup for 1.3 GHz
- Centrifugal barrel polishing machine for 1.3 GHz single cell cavities
- High pressure rinsing

Cavity forming facility installed



Electro-polishing setup developed

Centrifugal barrel polishing machine developed

High pressure rinsing Set up developed

- Electron beam welding machine (15 kW) and a vacuum annealing furnace are under procurement. These are expected to be installed by December 2012

# Building for SCRF Cavity Development

Cavity Fabrication, Assembly & Processing Building (1400 Sq. m)

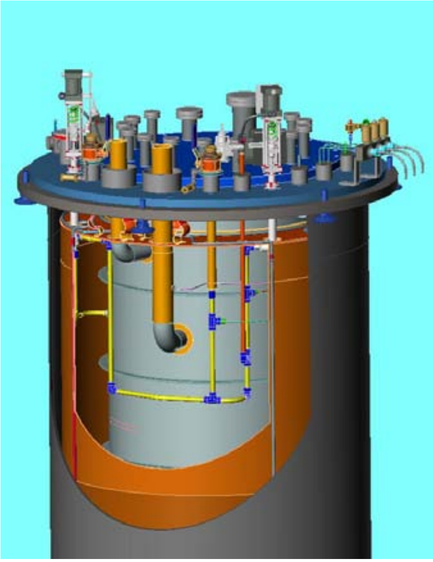
- The building will house clean rooms, Electron beam welding machine. High vacuum annealing furnace, Electro-polishing setup, Centrifugal barrel polishing machine, RF measurement set up etc.
- Building is ready.

Lab Building ( ~ 800 Sq. m)

- It will house CMM, SIMS, material testing facility, thin film deposition facility etc
- Building is ready, facilities under commissioning.


# Development of Vertical Test Stand

- RRCAT & Fermi Lab jointly carried out design of various components of 2K VTS Cryostat
- Three VTS cryostats are under fabrication at US vendor under joint supervision of engineers from Fermi Lab and RRCAT. One of these will be delivered to RRCAT.
- Expected delivery schedule : December 2011

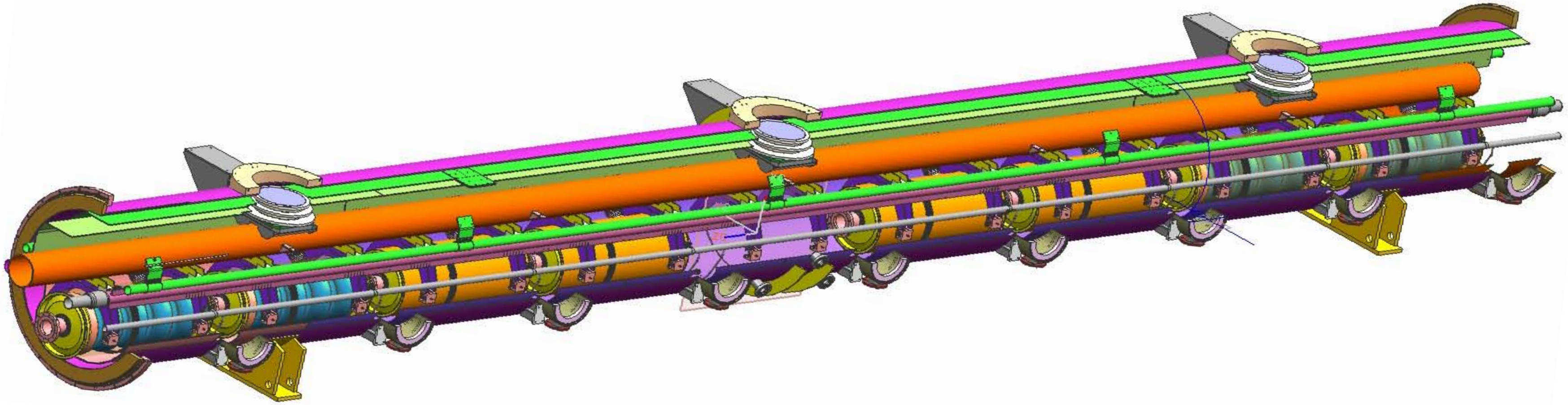


3D model of VTS

- Building to house VTS at RRCAT is under construction and expected to be ready by December 2011
- Cryogenics system under process
- Components of RF and DAQ system fro RRCAT VTS is under process and expected to be ready by Dec 2011.

# Design of Beta= 0.9 Cryomodule for 650MHz Cavities

- Design effort progressing smoothly
- Major specifications of the cryomodule have been ascertained
- Engineering design has made considerable progress for vacuum vessel, thermal shield ,cavity support system etc.

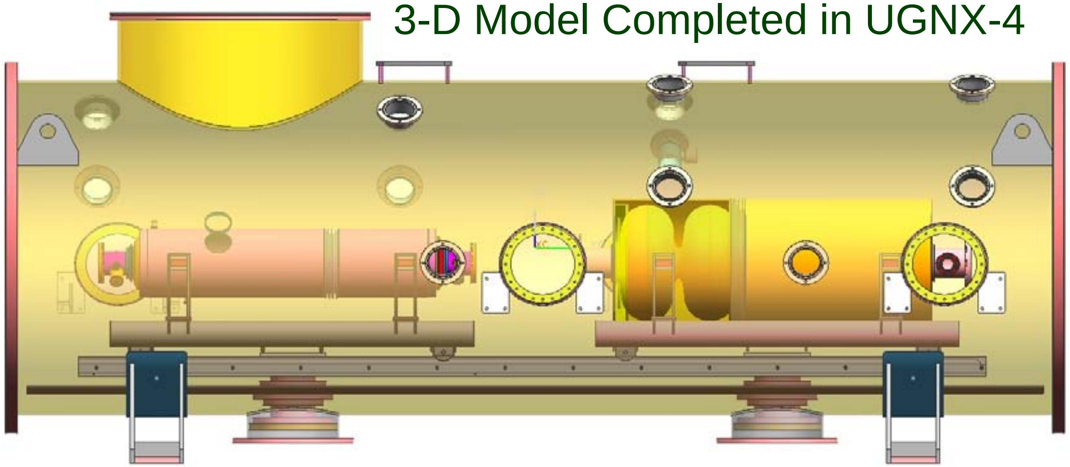


Cut Section of Cryomodule & subsystems

# Horizontal Test Stand (HTS-2)

Design and development work of a horizontal test stand has been taken up in collaboration with Fermilab

3-D Model Completed in UGNX-4



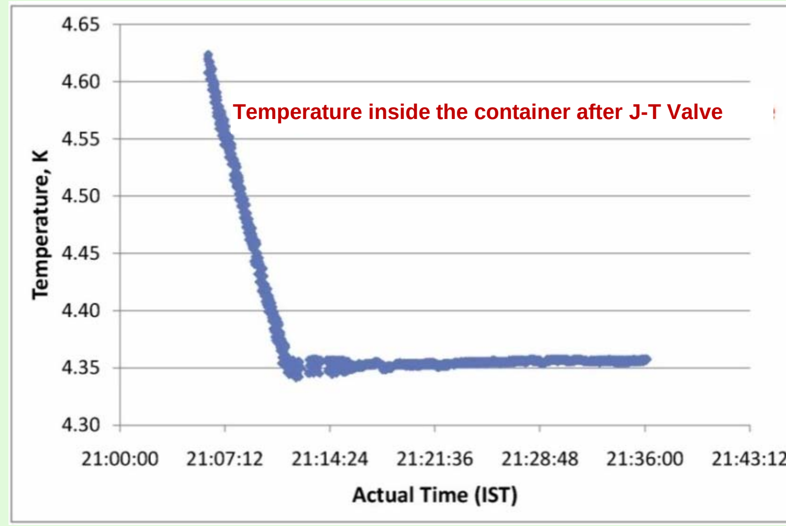
## Functional requirements

- Capability to test two dressed cavities at a time but separately.
- Testing of both 650 MHz and 1.3 GHz cavities.
- Throughput of 4 cavities in 6 weeks.

An important aspect of this design effort is the improvements made to accommodate operational experience of HTS at Fermilab

# Indigenous Development of Helium Liquefier

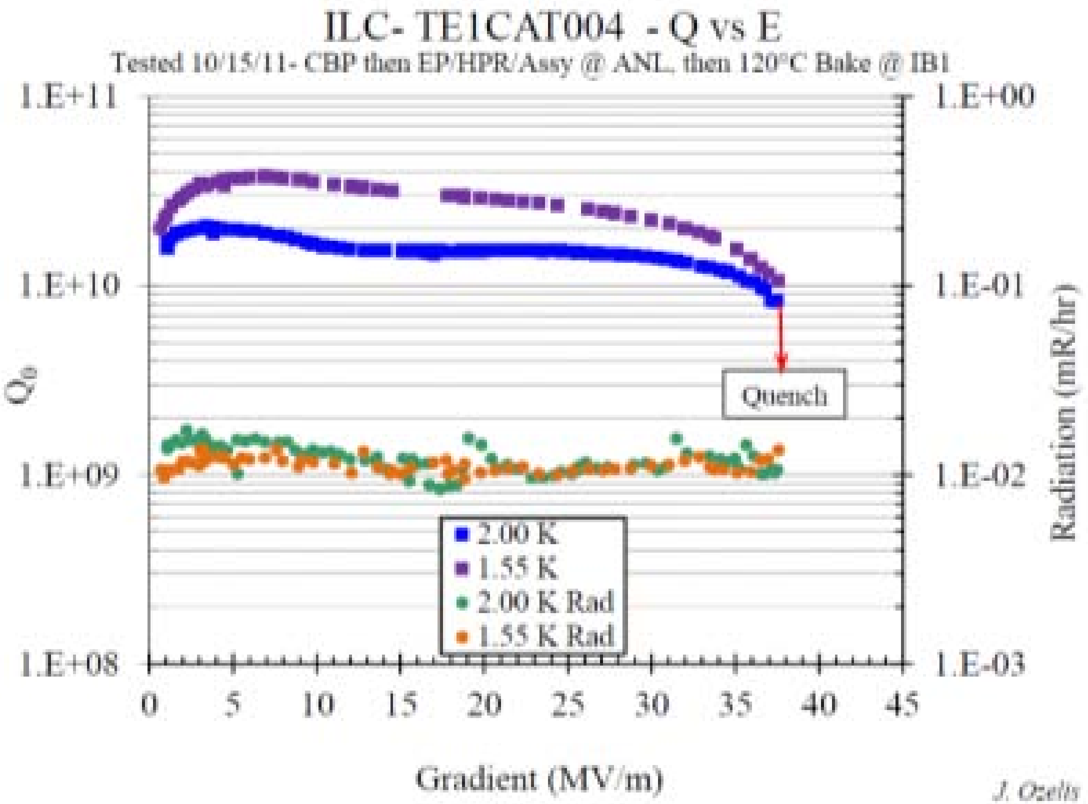
In August, 2010, Helium liquefaction achieved for the first time in the country using indigenously developed system




- Produced more than 150 litres of liquid helium in its maiden run, with an average liquefaction rate of 6 lit/hr. Present liquefaction rate of 10 lit/hr.
- Design work for second model of indigenous helium liquefier has been initiated. This will produce liquid helium at a liquefaction rate of about 35 lit/hr.
- Work is being initiated to develop cryogenic heat exchangers suitable for the development of helium liquefier with a liquefaction capacity of 100 – 200 litres/ hr.

# RECENT DEVELOPMENTS

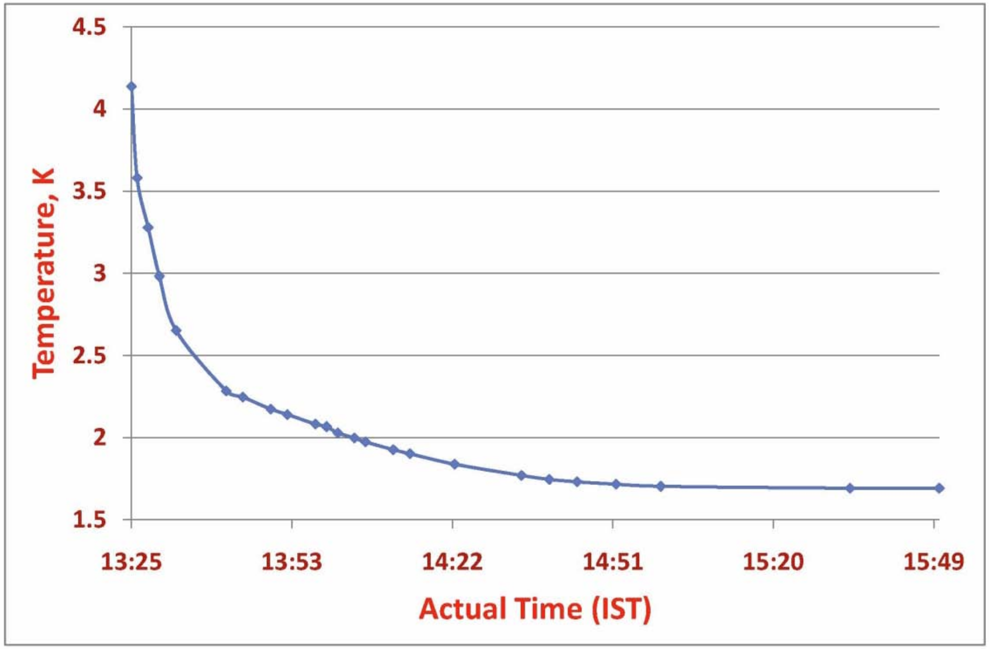
**1.3 GHz Nb Single Cell Cavity developed in India( RRCAT/IUAC)**




**Performance Tested at Fermi Lab Accelerating Gradient of 37.5 MV/m At 2 K achieved**

# Development of 2 K Cryostat

A 2K cryostat has been indigenously designed, built and commissioned




The cryostat has a working volume of cylinder of 200mm dia and 200mm height. It is being used for temperature sensor calibration down to 1.7K.

# Superconducting Materials R&D at RRCAT

- Niobium-based superconducting materials with optimized physical and metallurgical properties for fabrication of energy efficient and cost effective SC-RF accelerator structure.

- Specific roles of lower critical magnetic field ($H_{C1}$) and BCS surface resistance ($R_{BCS}$) on the achievable accelerating gradients in SCRF-cavities.

- Newer Nb, Ti and Mo based superconducting alloys for large current carrying applications.

# Indigenous Development of Nb-Materials

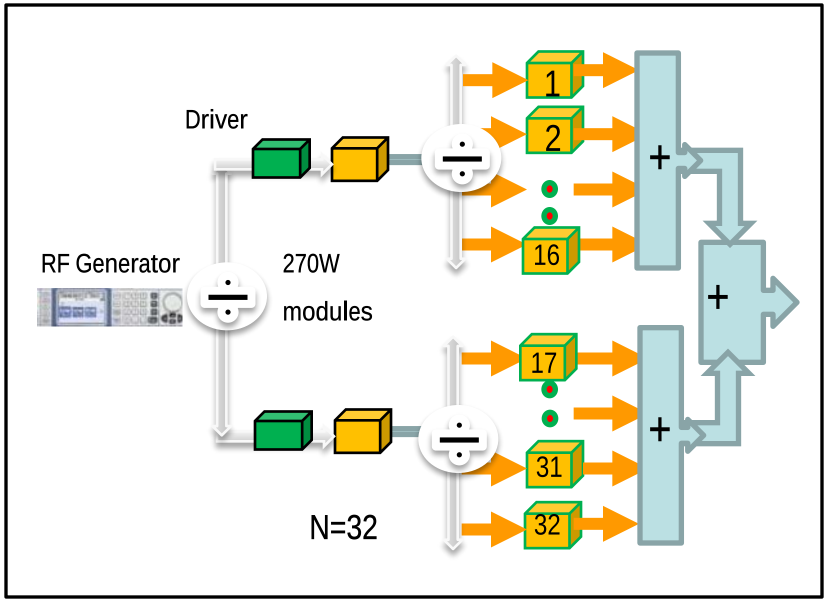
- NFC, Hyderabad
  - Development of materials and testing of mechanical properties
- RRCAT,Indore
  - Electrical and superconducting properties, elemental analysis

| Summary & Comparison of test results | | | |
|---|---|---|---|
| Sr.No. | Source | Nb Sample ID | Residual Resistivity Ratio (RRR) |
| 1 | NFC | *Nb/NFC/IC3/03-A* | **39 ( 25.02.08)** |
| 2 | NFC | *Nb/NFC/I80Nb III/U/B* | **96 ( 20.03.09)** |
| 3 | NFC | *Nb/NFC/IU1/Ti clad expt* | **98 ( 06.04.09)** |

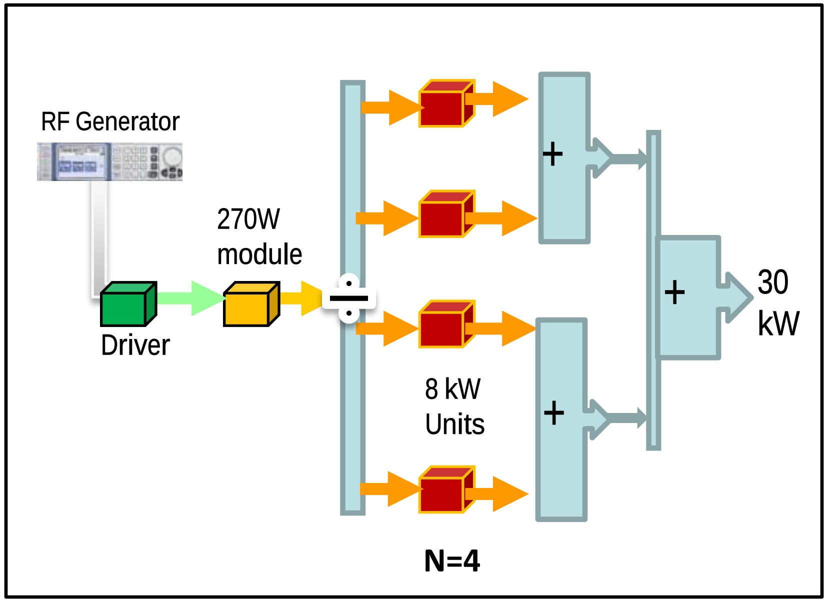
# High Power Solid State RF Amplifier Development

- RRCAT has taken up development of 30 kW CW 650 MHz solid state amplifiers for energizing SCRF cavities and 60 kW CW 505.8 MHz amplifiers for Indus-2

## 8kW Amplifier Scheme




## 30kW Amplifier Scheme




- 32 Nos. of 270 W RF modules are used with suitable combiners and dividers to make a 8 kW RF amplifier module. Four such modules are combined to obtain 30 kW RF power output.

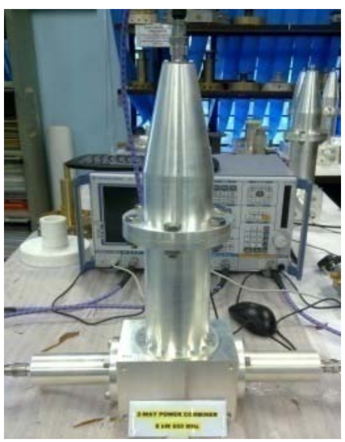
# Development of RF Components

- Several RF components have already been developed and tested for 650 MHz operation and 505.8 MHz operation

20W Low Power Driver

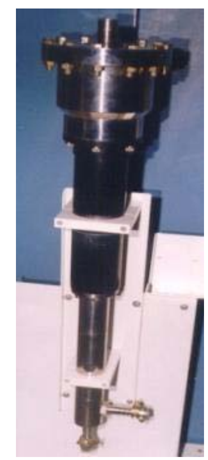

200 W Amplifier Module

Coaxial Transitions



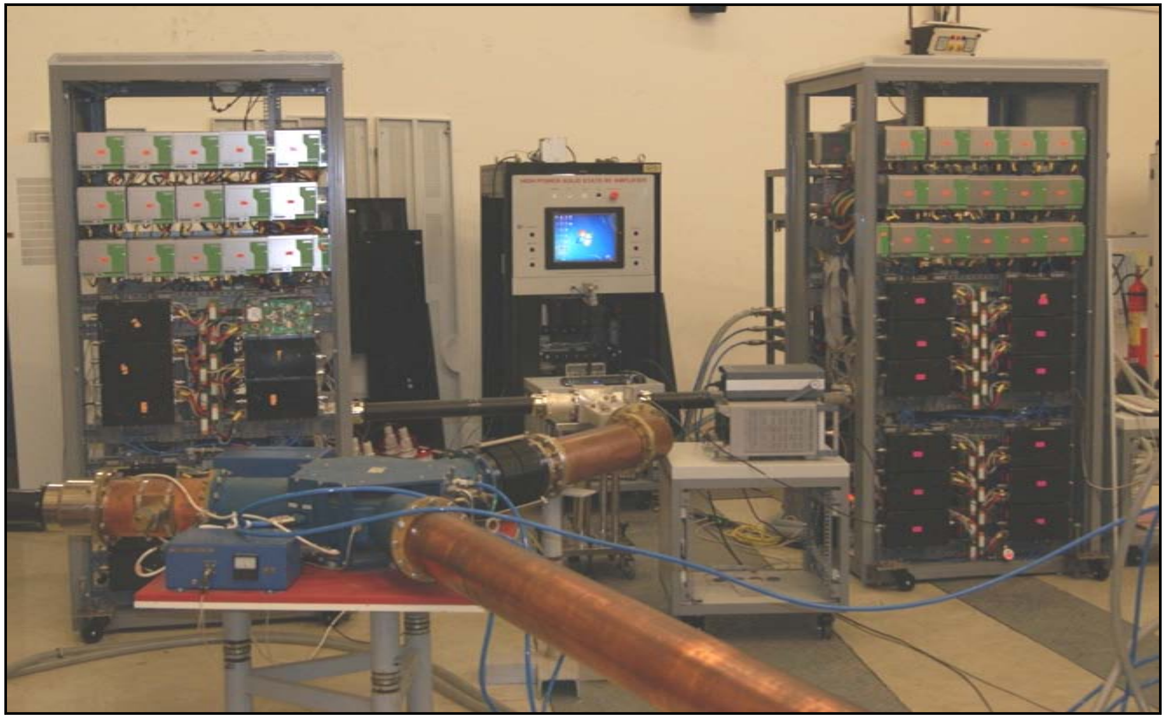
2-way 15kW Power Combiner

4kW & 1 kW Coaxial Directional Couplers



30 kW RF Dummy Load

# 15 kW Solid State Amplifier Units in Indus-2 RF Area



- A 15 kW unit has been coupled to RF Station # 1 and operated in round the clock mode. This has facilitated operation of Indus-2 at 2.2 GeV energy / 100 mA.
- One more such unit has been completed and coupled to RF Station # 3. This has enhanced operation of Indus-2 to 2.3 GeV / 100 mA.

# ADS Related Ongoing R & D Programmes At BARC

# Roadmap for Accelerator Development for ADS

**Modified**

**High current injector 20 MeV, 30 mA**

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

Phase 1

Normal Conducting

DTL/ CCDTL

Phase II

Super-conducting

100 MeV

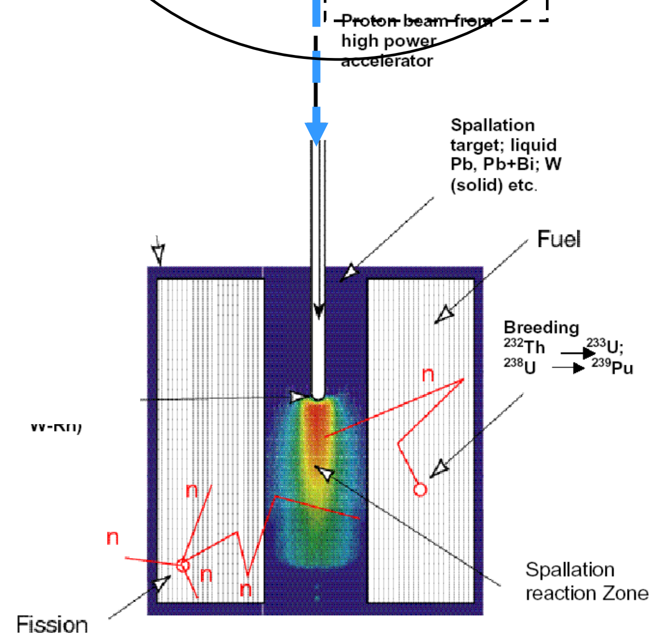
Phase III

SC Linac

1 GeV

**Super-conducting**

Spoke cavities or/ and HWR

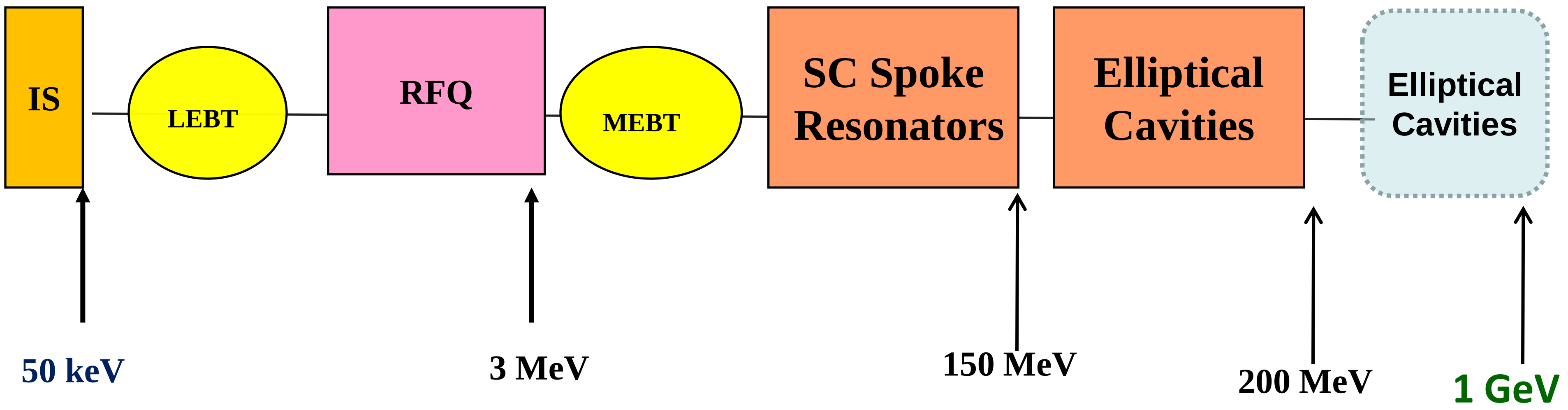



325 and 650 MHz under IIFC

# Frequency: 325 and 650 MHz

## (proposed)

## Scheme for 200 MeV High Intensity Proton Accelerator
## (a front end of the 1 GeV Linac)




## Current : 30 mA

**We may go in steps but the design needs to be done for 30 mA**

- **Activities related to development of LEHIPA at BARC**

- **Coupling of external neutrons to Critical Facility-**

- **LEHIPA with Critical facility**

- **PURNIMA 14 MeV Neutrons with sub-critical U core**

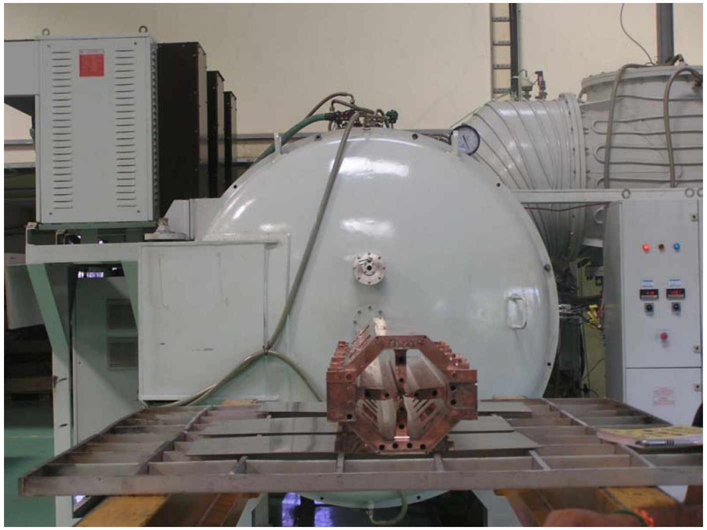
- **Reactor Schemes for coupled operation**

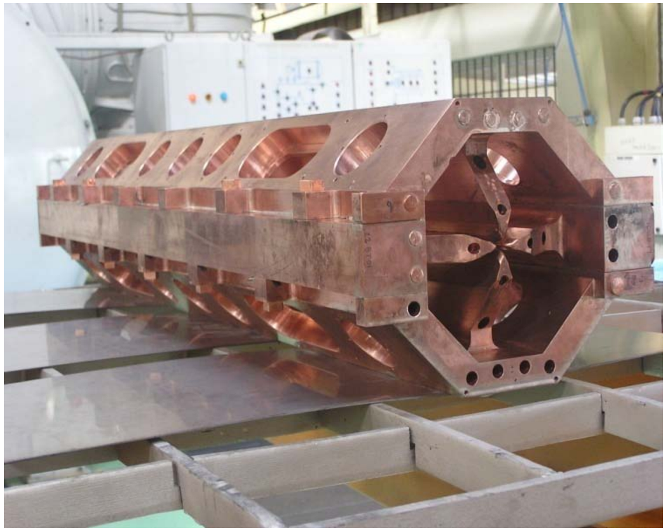
# 400 keV RFQ at BARC

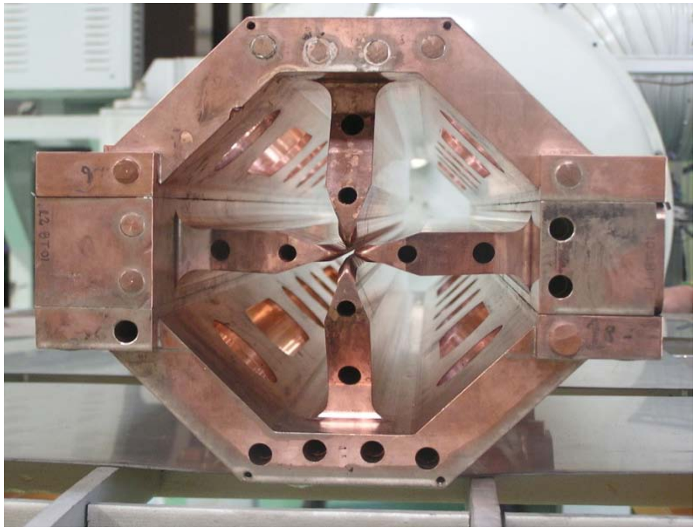
**Alignment of vanes at BATL:**
**within 30 µm**

**Bead pull measurement setup**

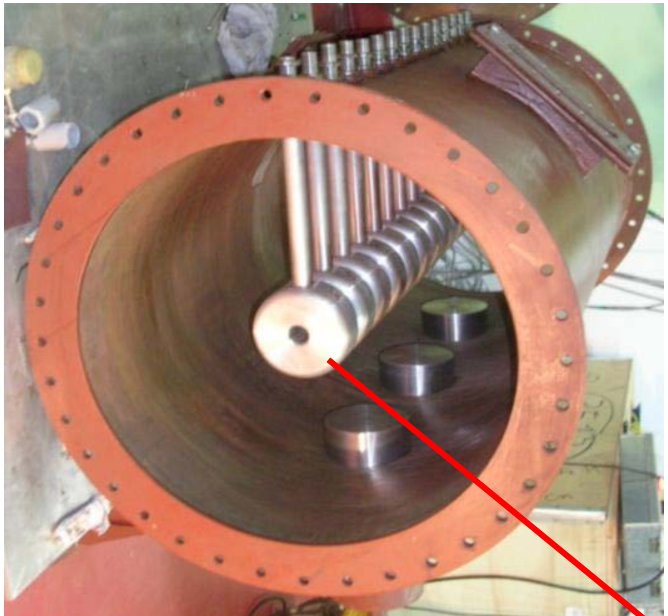
# RFQ after brazing of vanes

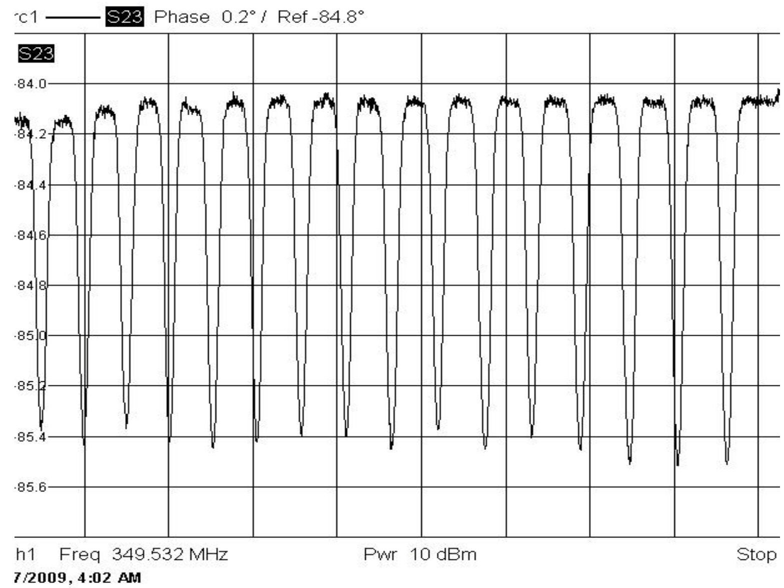






# DTL and PMQ Prototypes

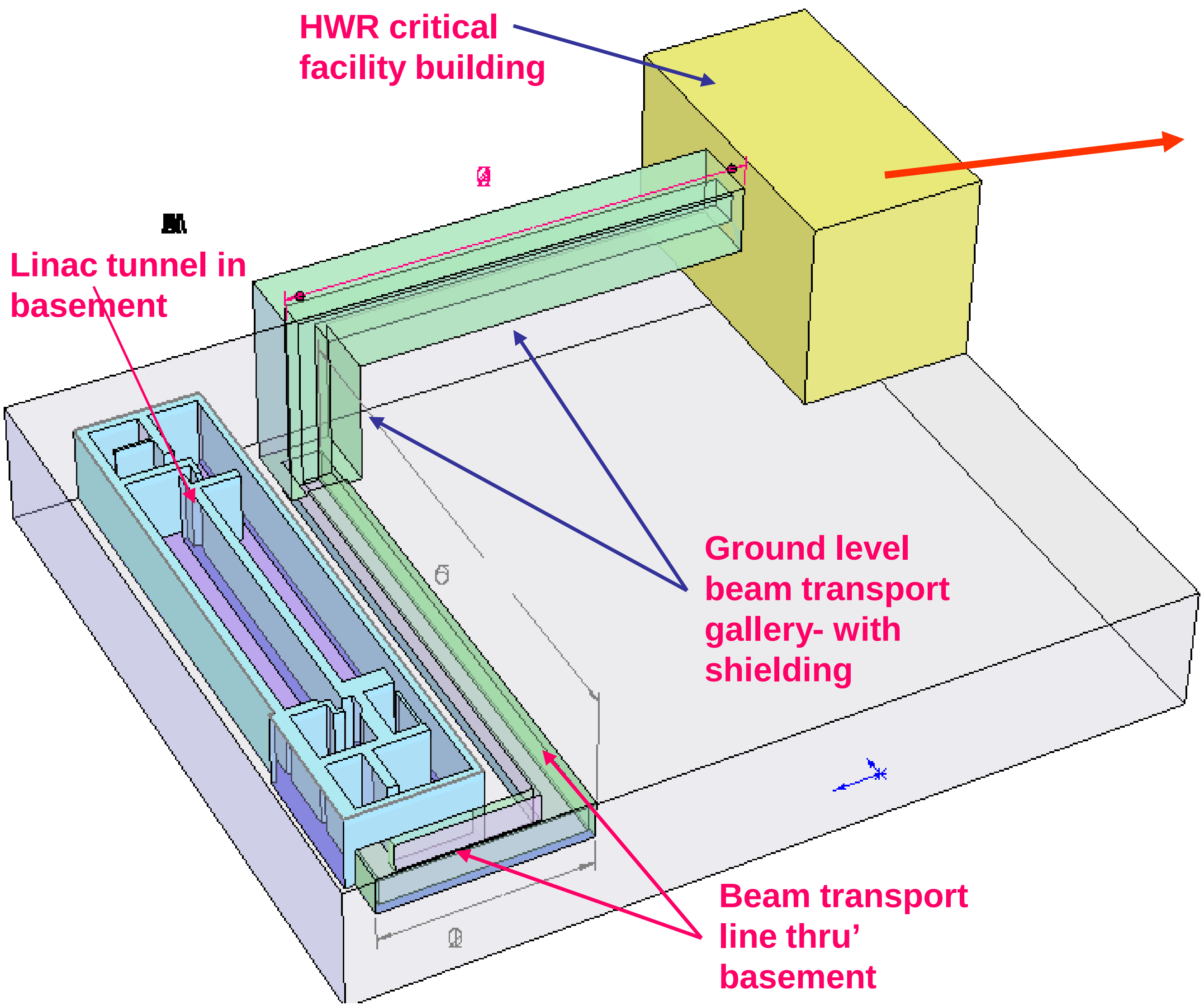





**Anatomy of drift tube**
**( exploded view)**

**Prototype Drift Tube with permanent magnet quadrupole focussing and coolant channels**

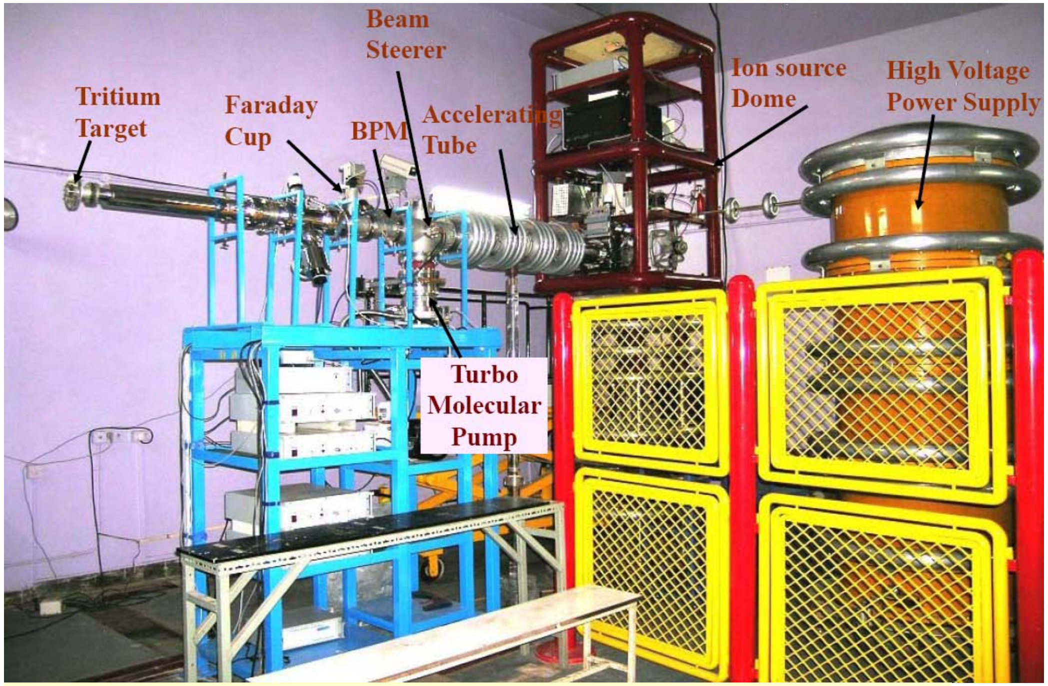
# 20 MeV Proton beam for ADS experiments in HWR critical facility

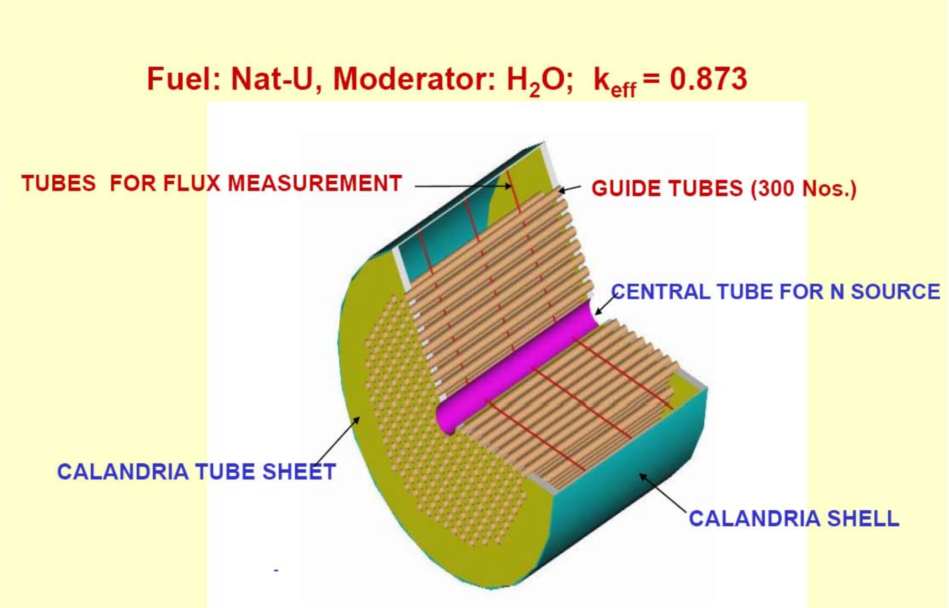



**Studies have confirmed feasibility of extending 20-MeV proton beam to a target in the core of nearby HWR Critical facility.**

# 14 MeV Neutron Generator - Experimental facility

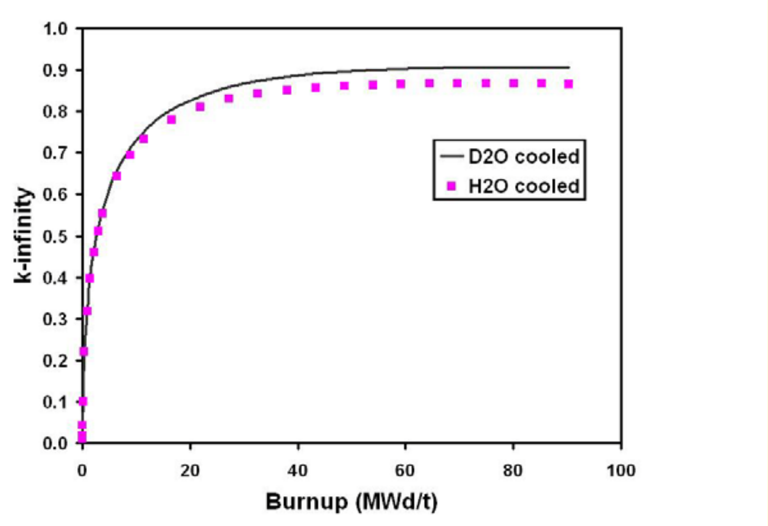
- **Experiments on physics of ADS and validation of simulations.**
- **use of 14-MeV neutrons produced by DC accelerator & D+T reaction. Also, a 400-keV RFQ is being built *for higher beam current.***
- **Simple sub-critical assembly ($k_{eff}$=0.87) of natural uranium and light water is chosen**
- **Plans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

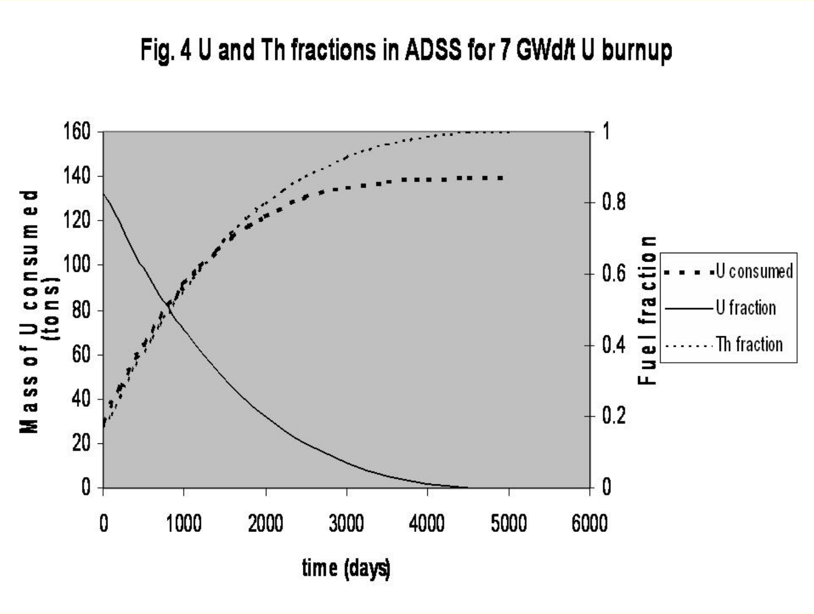


# Once through Th cycle PHWR ADS

- Initial fuel: Nat. U & Th
- Normal refuelling of U bundles (say 7 GWd/t)
- Th will reside longer
  - U-233 generation adds reactivity
  - Compensate by replacing some U by Th
- Th increases and U decreases
- Ultimately fully Th core
  - In situ breeding and burning Th
- Advantages
  - Use of natural fuels only
  - 140 tons U consumption during reactor life
  - High burnup of Th ~ 100 GWd/t
- Disavantage
  - Low $k_{eff}$ ~0.9 and gain < 20 with Pb target
  - Accelerator power ~ 30 MW for a 200 MWe ADS



# One way Coupled Booster Reactor Concept

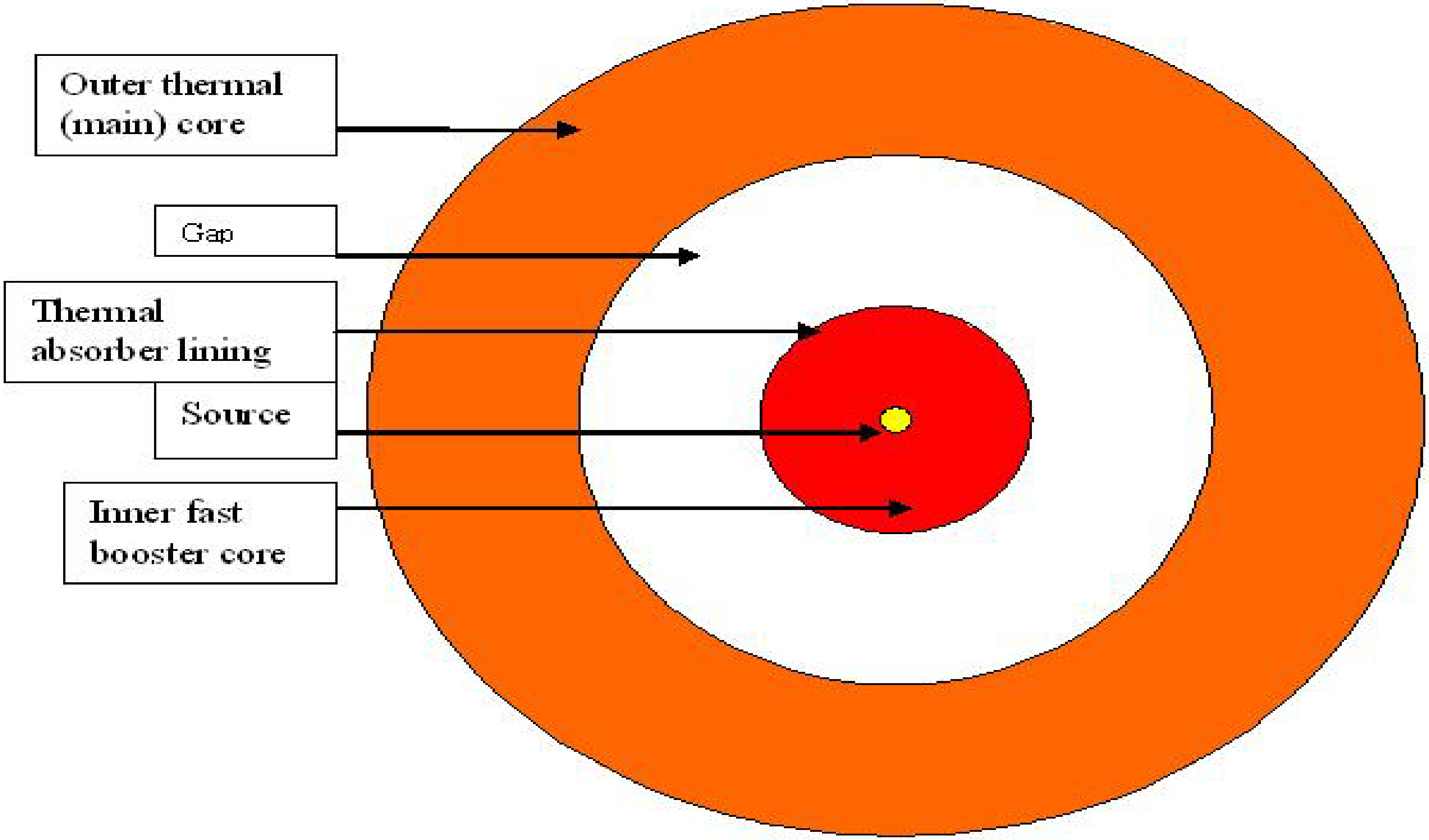
**Power in ADS is inversely proportional to sub-criticality and directly proportional to neutron source strength**

**In the control rod free concept, the operating keff is limited to the range 0.95-0.98**

**This requires accelerator beam power of about 10 MW**

**The one-way coupled booster-reactor concept can reduce this requirement five fold**

- **Inner fast core with source at centre boosts the neutron source**
- **These neutrons leak into the outer thermal (PHWR/AHWR) core where they undergo further multiplication This cascade multiplication gives very high energy gain  Due to the absorber lining and the gap very few neutrons return to the booster – i.e. there is a one way-coupling between the two**
- **The one-way coupling ensures that the overall keff is limited to the desired value**
- **Consequently, accelerator power requirement for 750 MW(t) is ~ 1-2 MW**




**ONE WAY COUPLED BOOSTER REACTOR CONCEPT**

**Less Accelerator Power Required !**

# Summary

- Thrust areas in High Intensity Proton Accelerator R&D program
  - Low energy front end NC Proton LINAC
  - High energy LINAC with SCRF technology
  - Spallation Neutron Source interfaced to multiplying medium
- Ongoing R&D activities
  - 20 MeV high current proton LINAC
  - Setting up of infrastructure for SCRF technology
  - Superconducting materials
  - SCRF cavities and cryomodule
  - SCRF cavity test facility ( VTS/HTS)
- ADS will contribute in the long term goal of India's Three-stage Nuclear power program
- International collaboration on common objectives for mutual benefit

# SUMMARY

- Th based Nuclear Energy systems will be a high priority in India.

- High Energy, High Intensity Accelerators will Play a strong role in this programme  In terms of Energy Generation, Breeding & Transmutation

- India would like to invite and participate in international R&D activities- on accelerator, nuclear data , spallation target and fuel cycle options.

*Thanks*